THE PROPERTIES OF ENSILED CROPS
AND
THE DESIGN OF SILOS.

JONATHAN G. M. WOOD.
B.Sc. Dunelm.

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CHAPTER 5

PHYSICAL AND BIOLOGICAL PROPERTIES OF ENSILED GRASS AND FORAGE CROPS

5.1. INTRODUCTION

For the design of silage silos it is necessary to know the physical properties of the crop and of the resulting silage for the calculation of:-

(a) The pressures on the silo walls and floor.

(b) The capacity of the silo.

(c) The fermentative and thermal behaviour of the crop and silage during filling, storage and unloading.

(d) The handling characteristics of the crop during filling and silage during unloading.

This chapter is, in layout, similar to the previous chapter on the properties of ensiled grain. It contains a review of the published data on crop and silage properties and the results of my own research into the density of silage.

The properties of crops and silage are variable to a far greater extent than those of any material normally encountered in Civil Engineering. The crop may be 6" high leafy grass or 8' high corn (maize). Properties are altered by the wilting, chopping and laceration of the crop before ensiling, and further changed by the biological processes of respiration and fermentation. It has therefore been necessary to briefly review the biological and agricultural factors that influence the physical properties.

5.2. REVIEW OF DATA REQUIRED

5.2.1. Classification of Crops and Silage

Before we can start the systematic measurement of the physical properties of crops and silage, it is necessary to draw up a classification such that all material in any particular category will have sensibly the same physical properties. This classification can be divided into:-

(a) Crop variables (variety, maturity, conditions of growth).

(b) Field treatment variables (moisture content, laceration, length of chop, field losses).

(c) Ensiling variables (in silo, respiration changes, fermentation changes).

5.2.2. Pressures in Silos

The most widely used silage pressure formulae (given by A.C.I.714(1) and NEUBAUER(86) were empirically derived from measured silage pressures. However, YU et al(143) have made the first attempt at obtaining a fundamental formula for silage pressures by developing Janssen's Theorem by expressing k, the density and wall friction as functions of the depth of silage. I have developed in Chapter 6 a new finite element method of calculation for silage pressures in which k, the density and wall friction in Janssen's Theorem are expressed not as constants but as functions of the appropriate variables.

Data required for full range of the classification:-

(a) Vertical Pressure/Bulk Density/Dry Density/Time relationship.

(b) Coefficient of Friction of Silage on the wall for the range wall finishes.

(c) k, the ratio of lateral to vertical pressure in Janssen's formula.

5.2.3. Capacity of Silos

The fundamental value of the capacity of a silo is the quantity of nutrient it contains. However it is more convenient to express capacity in terms of tons of dry matter, which can be easily converted to nutrient capacity using the analysis of the dry matter. Because of the compressibility of silage, the dry matter capacity of a silo is a variable quantity which depends, not only on the Vertical Pressure/Dry Density/Time relationship of the silage, but also on the Vertical Pressure variation in the silo. The vertical pressure is a function of density, coefficient of friction at wall, Janssen's k and the method of filling. For a standard crop and filling conditions, the dry matter capacity of a silo can be calculated using the method I have set out in Section 6.1. and in 6.2.5 This standard dry matter capacity provides a valid basis for the comparison of silo capacities. The capacity that will be obtained with non-standard crop and filling conditions can be expressed as a percentage of the standard dry matter capacity.

The capacity of a silo can be considerably affected by losses in storage which vary from 5% of dry matter (in an efficiently used silo) to over 50% loss of dry matter (which can occur with mismanagement and with poor silo design).

Nutrient loss is usually about twice the loss of dry matter as it is the most nutritive parts of the silage that are lost.

Additional data required for a full range of the classification:-

(a) The nutritive value of dry matter in the crop.

(b) The dry matter and nutrient loss in the silage.

5.2.4. Preservation of the Crop, Fermentative and Thermal Behaviour.

The successful conservation of the crop as silage depends on:-

(1) The removal of air from, and the sealing of the crop mass, to minimise initial respiration.

(2) The fermentation of sugars in the crop to produce lactic and acetic acid to produce a silage with a pH of about 4.0.

(3) Minimising the entry of air into the silage during storage and unloading.

The silo design must therefore ensure that the crop is rapidly consolidated to form as impermeable a mass as possible. If the fresh crop is deficient in sugars for satisfactory fermentation, it must be treated by wilting, and/or the addition of sugar or acid. The silage mass should be sealed during storage and as little exposed to air as is possible during unloading.

High losses of feeding value in the silo are the result of unsatisfactory butyric fermentations and/or excessive amounts of air entering the silage mass during filling, storage or unloading. The air entering the mass provides oxygen for the respiration of the crop, aerobic bacteria or moulds. This respiration gives out heat in proportion to the oxygen used and nutrients lost. Thus if the density and moisture content of the silage, the specific heat and specific gravity of dry matter, the thermal conductivity of the silage and the silo wall and the rate and quantity of heat production by respiration are known, the relationship between oxygen consumption, heat rise and dry matter loss in silage can be calculated. If the exposure of the silage mass to air and the permeability of the mass are known the rate of the fill necessary to prevent respiration heating in excess of the minimum due to initial entrapped air can be calculated. The conditions which give rise to fires and explosions in silos can also be determined from this data and a knowledge of the latent heat of evaporation of moisture and the movement of water vapour in the silage mass.

Additional data required for full range of the classification:-

(a) Requirements for satisfactory fermentation.

(b) The quantity and rate of heat output from the respiration and fermentation, at different temperatures and moisture contents, and its relation to oxygen consumption, quantity of fermentation products and the dry matter and nutrient loss.

(c) Specific gravity of dry matter.

(d) Specific heat of dry matter.

(e) The Thermal Conductivity and the permeability of the silage.

(f) The Thermal Conductivity and the permeability of the silo wall.

(g) Latent Heat of evaporation of moisture from the silage.

(h) The Exposure of the silage mass to air.

5.2.5. Properties of Silage during Filling and Unloading

The design of the silo cannot be separated from the design of the filling and unloading machinery. It is necessary to know the physical properties of the loose crop during filling and distribution and of the loose silage after unloading. To design top or bottom unloaders and to calculate the loads that will be exerted by the silage and the unloader on the silo as a result of their operation, we must know the mass strength of the silage.

Additional data required for the full range of classifications:-

(a) Loose density of crop and silage.

(b) The Kinetic Coefficient of friction of crop and silage on a range of surfaces.

(c) Aerodynamic properties of crop and silage.

(d) Tensile and Shear strength of the silage mass for a range of dry densities.

5.2.6. Combined List of Basic Data Required for the Design of Silage Silos.

A. Silo Structure.

(a) Dimensions.

(b) Thermal Conductivity, Permeability and Surface Finish of silo wall.

(c) Method of filling, distribution and unloading.

(d) Exposure of silage mass to air.

B. Crop and Silage, for full range of the classification.

(a) Crop Classification.

  (1) Crop variables

  (2) Field treatment variables

  (3) Ensilage variables

(b) Vertical Pressure/Bulk Density/Dry Density/Time Relationship.

(c) Specific Gravity of dry matter.

(d) k, ratio of lateral to vertical pressure in silage.

(e) Shear and Tensile Strength of silage mass for a range of dry densities.

(f) Static and Kinetic Coefficients of Friction.

(g) Aerodynamic properties and Permeability of Crop and Silage.

(h) Specific Heat of Dry matter.

(i) Thermal conductivity of silage for a range of dry densities.

(j) Latent Heat of evaporation of moisture in silage.

(k) The nature of biological processes in the crop and silage, the means of controling them, and their effect on physical properties.

(l) Quantity and Rate of Heat Output of respiration and fermentation and its relation to oxygen consumption and losses of dry matter and nutrients.

(m) The Nutritive Value of dry matter.

5.3. CLASSIFICATION

5.3.1. Introduction

A great variety of crops can be ensiled and the physical properties of these crops change as they mature and are modified by treatment during harvest and during the formentation into silage. The purpose of this section is to draw up a classification for silage, such that all material in any particular category will have sensibly the same physical properties. Much of the available data on the physical properties of crops and silage is of little value because the material on which the tests were conducted is inadequately described. The classification has been divided into three parts. The first deals with the Crop Variables, the second with the Field Treatment Variables, and the third with the Ensilage Variables.

5.3.2. Crop Variables

5.3.2.1. Crops for Silage. Most of the silage made in the U.K. is from mixed swards of grasses and legumes; e.g. rye grasses, cocksfoot, timothy, meadow fescue, clovers etc. M.A.F.F. Bulletin 154(76) "Grass and Grassland" gives details of these and the less common grasses and legumes. In America, where most of the research on tower silos has been done, the main crops for silage are corn (maize) and alfalfa (lucerne). In order to provide crops for harvesting over an extended period RAYMOND(100) and MORTIMER(79)(80) have suggested that maize, whole crop oats and barley, lucerne, sainfoin, rye etc. should be considered for ensilage in tower silos in the U.K. These suggestions have been taken up by a number of farmers. Silage is also made from the pea-haulm, sugar beet tops and other agricultural by-products.

The first section of the classification is botanical; giving the crop species and variety. It may be found on fuller investigation that some physical properties are not influenced by variety or even species. This would enable a simpler classification of the crop to be used.

5.3.2.2. Effect of Maturity of Crop. As a plant grows its structure and composition change and these changes are affected by the conditions under which it is grown. The influences of these changes of maturity on physical properties are closely interrelated with those of crop variety and species. They are partly direct (e.g. the plant structure increases in strength as it grows) and partly indirect (e.g. the fermentation, which influences physical properties, is affected by the water-soluble carbohydrate content of the crop which varies with maturity and variety).

Table 5.3/1 from ARMSTRONG(10) shows the change in chemical composition of S23 rye grass with increasing maturity; similar changes occur in other grasses, although the proportions of the constituents and the time at which these changes occur vary considerably.

TABLE 5.3/1

Changes in chemical composition of the dry matter of S23 ryegrass during growth

(from ARMSTRONG(10))

Stage when cut	Crude Protein	Sugars	Ash	Cell-wall constituents					Gross energy kcal/g
				Cell-ulose	Hemi-cell-ulose	Lignin	Total	Crude fibre	
% of dry matter									
Young leaf	18.6	13.8	8.1	21.3	15.8	3.2	40.3	21.2	4.63
Late leaf	15.2	11.8	8.5	22.1	18.9	3.9	44.9	24.8	4.48
Flower emergence	13.8	11.3	7.8	23.9	19.4	4.4	47.7	25.8	4.48
Seed	9.6	10.6	5.7	26.7	25.7	6.4	58.8	31.2	4.57

WAITE(125) describes the chemical and botanical changes that occur in Fescue, Cocksfoot, Timothy and Ryegrass as they mature. The initial young leafy stage is followed by the growth of the stem, and the formation of the flower head, within the leaf sheath. Next the flower head emerges from the leaf sheath and the stem elongates. Finally the seed head is formed and ripens. The leaf and leaf sheath are mainly of thin walled tissue owing their strength primarily to the osmotic pressure within the cells. As the stem emerges and has to support the weight of the flower and later the seed head, it is strengthened by the formation of a pericicle of lignified tissue. This change in structure can be observed in Table 5.3/1 by the increase in the percentage of cell wall constituent.

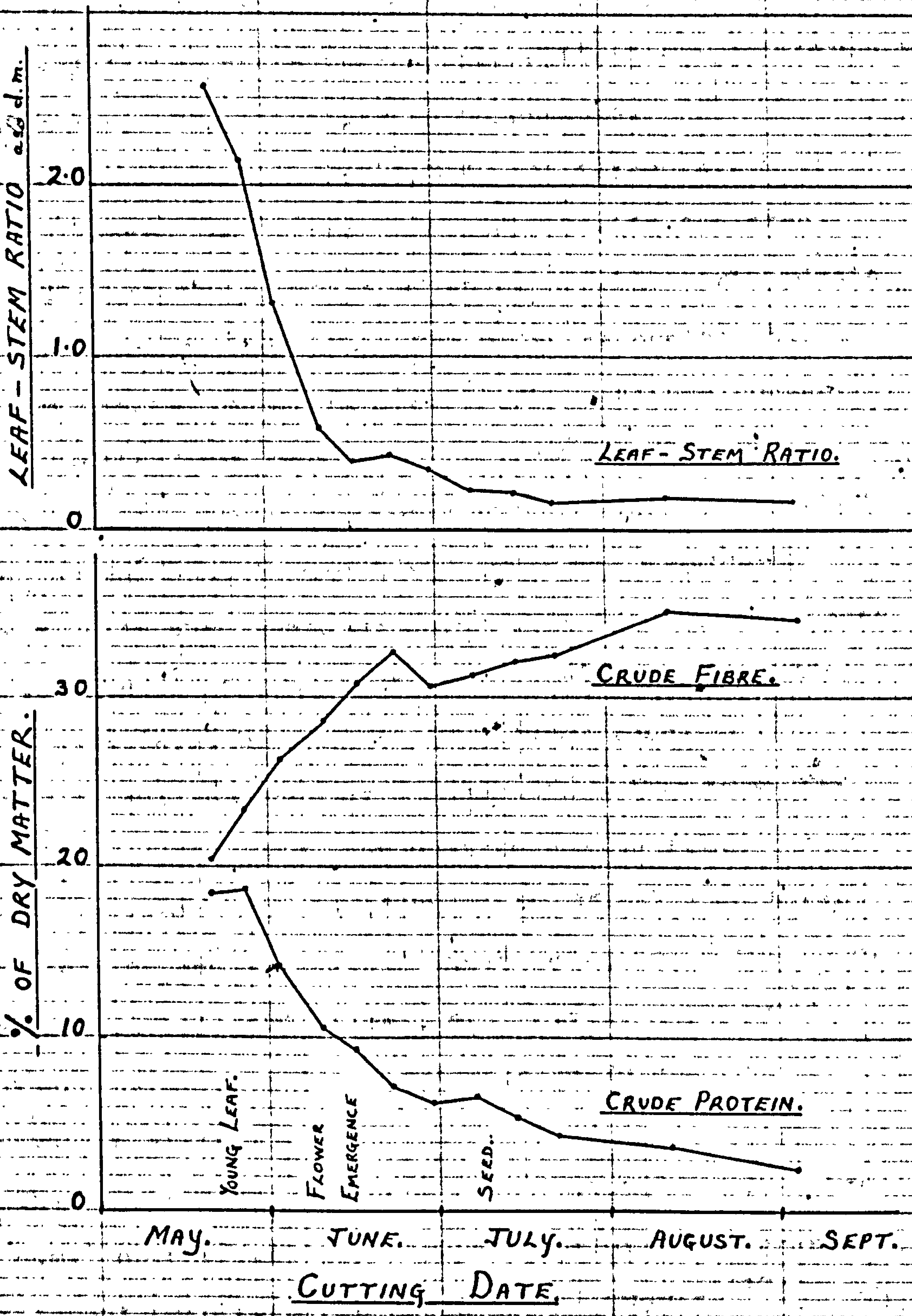
Graph 5.3/1 drawn using data from Waite and Sastry given in WATSON and NASH(126) shows how the growth of the grass is accompanied by a fall in the leaf-stem ratio, a rise in the Crude Fibre and a fall in Crude Protein.
As Crude Fibre and Crude Protein are the standard analyses carried out for feed value by the Nutrition Chemists, they provide a convenient indication of maturity. However, at a given stage of maturity of a given variety, the analysis can be effected by conditions of growth, e.g. the Crude Protein is increased by high nitrogen applications.

The maturing of grass is accompanied by an increase in its yield of dry matter per acre and afall in the nutritive value and digestibility of the dry matter. RAYMOND describes these changes in grass(98)(99) and whole

Graph 5.3/1

CRUDE PROTEIN, CRUDE FIBRE, AND LEAF~STEM RATIO OF TIMOTHY OF INCREASING MATURITY.

(after Waite and Sastry.)



crop barley(100) and GREEN(44) discusses the choice of cutting date of different grasses, legumes and whole crop cereals to provide the maximum yield of digestible nutrients of the required digestibility. In general crops intended for use as a production ration should be conserved at about 65% Digestible Organic Matter level, while for a maintainence ration, a lower digestibility is acceptable.

As discussed in Section 5.3.4. the fermentation of silage is controlled by the ratio of water in the crop when ensiled to the quantity of water-soluble carbohydrate (W.S.C.) in the dry matter. The moisture content in the crop when ensiled partly depends on the moisture content of the standing crop (which may be over 85% in a young grass and falls with increasing maturity) and the ease of wilting of the crop (young leafy crops are considered harder to wilt than a stemmy crop which forms a less dense swath). Thus in a conservation system in which wilting is important (e.g. hay and tower silage) there is a tendancy to cut the crop at a later stage than when the crop is direct cut (e.g. for unwilted clamp silage or grass drying). Crops which 'self-wilt' to 70% m.c. or lower before cutting and yet retain their nutritive value (e.g. whole crop cereals and maize), are felt by ALDERMAN(5) and others to have an important role in future crop conservation systems.

The water-soluble carbohydrate (W.S.C.) content (as % of d.m.) of different species and varieties of grass at different maturities is discussed by THOMAS(118). He gives 10% W.S.C. as the required level to ensure satisfactory fermentation with unwilted crops. He shows that, although ryegrasses consistently achieve this, Cocksfoot and Timothy do not reach this level of W.S.C. content until their digestibility has fallen to a low level. ALDERMAN(5) shows how the required W.S.C. content is related to moisture content and how for a wilted crop at 50% m.c. a 4% W.S.C. content will provide sufficient lactic acid to satisfactorily preserve the silage. Alderman also points out that the application of nitrogen in large quantities will depress the W.S.C. content and increase the moisture content and crude protein of a grass, so making it harder to achieve a satisfactory fermentation. Normally deficiences in W.S.C. are rectified by wilting, and/or the addition of molasses, acid or other additives. The plant species and maturity also influence fermentation as high protein contents and other factors have a buffering effect; so that more acid must be produced to lower the pH. sufficiently to preserve the silage. This is particularly marked in young, heavily fertilized grasses and in legumes such as lucerne and clover.

The proportion of sugars and gums in different crops and at different maturities has a considerable influence on the frictional properties of the crop and silage, as they tend to build up on the surfaces of machinery. These gums and sugars also effect the self adhesion and durability of pellets and wafers.

To summarise, maturity influences the physical properties in the following ways:

(a) Structural. Increase in strength of the maturing plant will increase its resistance to compression and effect the performance of field treatment machinery.

(b) Wilting. The initial moisture content and the plant strength will influence the moisture content on ensiling that can be achieved by wilting under given weather conditions.

(c) Fermentation. The moisture content on ensiling and the water-soluble carbohydrate content and buffering capacity of the plant, all of which are influenced by maturity, determine the fermentation.

Maturity is best defined by:

(a) visual assessment of height and stage of growth (i.e. for grasses: young leafy, late leafy, so many days after flower emergence, etc.)

(b) Cutting date and sward history including fertiliser application.

(c) Analysis of dry matter for Crude Fibre and Crude Protein.

(d) Leaf-stem ratio, % digestible organic matter, and proportion of cell wall constituents, might also be used if the accuracy of the research justifies the work required to determine these factors.

5.3.3. Field Treatment Variables

The field treatment of a crop is designed to achieve some or all the following objectives:-

(a) to cut it.

(b) to wilt it to reduce its moisture content to the desired level.

(c) to chop it to facilitate subsequent handling.

(d) to bruise it, crush and lacerate it to liberate the sap, which speeds wilting and makes sugars more readily available for fermentation.

(e) to separate it into parts, e.g. pea vining, beat topping.

(f) to haul it to the silo.

All these processes involve a risk of losses or contamination of the crop and these losses will alter the character of the crop. The main losses encountered are:-

(a) The height of the stubble left.

(b) Respiration losses in the cut plant.

(c) Leaching losses due to rain on cut crops.

(d) Mechanical losses due to fragments of plant being blown away in the wind or left on the ground.

(e) Leaf shatter when the over-dried leaf fragments to dust.

(f) Contamination with soil or stones.

There is an enormous variety of machinery used to carry out field treatment of crops for ensilage. Descriptions of particular machines can be found in manufacturers literature and N.I.A.E. Test Reports. A general description of machinery for silage making can be found in HESSAYON and WOOD(49) and for rapid wilting in MAFF BULLETIN 188(71).

The range of machinery used for crops for tower silos is limited by two restraints. The first is that the moisture content should be reduced into the range 50% - 65% to avoid effluent at higher m.c. and excessive losses at lower m.c. The second is that the chop length should be reduced to the ½" - 3" range if mechanical unloading and feed systems are to function satisfactorily. The most favoured machinery for ensiling grass crops in towers is a conventional mower, followed by a crimper and then a fly-wheel or cylinder-cutter metered full chop machine filling self unloading or tipping trailers. This system cuts the crop and leaves it with the stems lying parallel to the swath, to facilitate subsequent chopping. The crimper picks up the crop, crushes and bends the stems to liberate the sap and sets up the swath well for wilting, but maintains the stems parallel to swath. Except when there is heavy rain this swath is left untouched until it has reached the desired moisture content, usually in 24 - 48 hours. The metered chop machine set to give 3/16" theoretical chop will, if properly set up and sharpened, and working on a mown and crimped swath, chop over 90% of the material to below 1" with very little laceration.

In practice with tangled and laid crops, bad weather for wilting and a less than perfectly adjusted chopper, the crop will have a longer chop length and be more lacerated.

This is a consequence of the crop lying crosswise in the swath (because of the initial state of the crop and the tedding and turning necessary to wilt in bad weather) and blunt, chipped knives and a worn or improperly adjusted shear bar, on the field chopper which lacerates rather than cutting.

Sometimes the crop is flail mown instead of being cut with a mower and crimped. This machine which lacerates and batters the crop as it cuts, sets up a loose swath which, while ideal for wilting, feeds badly into the chopper and so increases chop length. The flail mower is favoured for its ability to deal with heavy tangled crops which block mowers and crimpers, but unless it is well set, it is liable to contaminate the swath with earth and stones which wear the chopper rapidly.

More detailed descriptions of the field treatments are given by SHEPPERSON (108)(111) CALVERLEY(24), SWEARINGEN(116), PARKE and HARDING(91), NEWMAN(87) and in Chapter 1 in which the equipment used at Glantlees and Bridgets is described.

Because of misinformation, mismanagement, and bad weather the material that is put into tower silos can in practice be anything from direct cut crop with dew or rain on it, to material of 25% m.c. fit for baling for hay. The necessity of filling at the optimum moisture content (normally 50% - 65%) that will give in silo densities in the 50 - 60 lb/cu.ft. range is discussed in Chapter 6. In our uncertain climate considerable management skill is required to wilt the crop to within ± 5% of the optimum moisture content. With strong winds of low humidity and sun, a crop can dry very rapidly (to 50% m.c. in less than 6 hours). In rainy weather or with the sea fret when still foggy weather persists for days, it can take several weeks for grass to wilt to 50% m.c. The rate of drying may be increased by crimping, turning, tedding etc. as described in M.A.F.F. BULLETIN 188(71).

The grass in the swath dries very unevenly. The top drying faster than the bottom and the leaves faster than the stems, and so a swath of 60% average moisture content can contain material of between 15% and 80% m.c. The driest parts, in particular the leaves, are brittle and tend to shatter when handled. This can cause the loss of a large proportion of the highly nutritious material if a crop is frequently handled when it is too dry. Lucerne in particular suffers from leaf shatter.

The more field wilting required, the greater the average losses that occur in the field. The actual losses depend on the weather, time in the field and the amount of field treatment. It is very difficult to determine accurately what the losses are, but some results for U.K. conditions are available from research at the N.I.A.E., by Shepperson and others, and at the Ministry Experimental Husbandry Farms.

In the classification we must describe as concisely as possible, the changes that have taken place in the crop. This can be done by describing the processes that the crop has been subjected to and/or by describing the physical consequences of these processes.

Thus our classification should ideally list:-

(1) Field treatment history including description of performance of machinery used and the weather.

(2) Physical condition, after field treatment, including moisture content, crude fibre, crude protein, and possibly water soluble carbohydrates and digestibility, leaf stem ratio, length of chop, degree of laceration.

(3) Losses.

The measurement of length of chop and degree of laceration and losses give particular problems as there are no standard tests for them. I have used a visual assessment of length of chop based on the longest and the shortest common length, being approximately the range of lengths of the middle 80% - 90% of the sample. Where samples were prepared by careful hand chopping or a guillotine, only the theoretical chop length is given as a uniform chop length was obtained.

SHEPPERSON(109), who has done considerable work requiring measurement of chop length of grass, makes the following comments on the existing methods of determining the length of chop. 'Photography on squared paper is of little value for comparison. Sorting the dried material into lengths can only be satisfactorily done by hand which is extremely laborious because of the large amount of material necessary to give a representative sample. The lengths can be plotted against dry weight % less the given length.'

This is similar to the technique used in grading and classifying soils as described in CAPPER and CASSIE(25). The distribution and range of lengths vary considerably, depending on the method of chopping, and two indexes are needed to describe length of chop, one giving a length measure and the other a measure of variation. In soils work the terms effective size (i.e. maximum size of smallest 10%) and uniformity coefficient (ratio of maximum size of smallest 60% to effective size) are used.

CALVERLEY(24) used a N.I.A.E. sieve grading technique in which the lengths are divided into

Dust	1/4"
Short	1/4" - 3/4"
Medium	3/4" - 3"
Long	3"

and he gives 50% short material and not more than 10% long material as the requirement for satisfactory performance of unloaders. It is not clear how he managed to overcome the problems of sieving encountered at the N.I.A.E. by Shepperson, unless he was prepared to accept some degree of inaccuracy.

WILLCOCKS(132) plotted fibre length against the % of total weight and the % of total number greater than that length.

There is no test for measuring laceration at present, and visual assessment (into unlacerated, slightly lacerated, lacerated, and heavily lacerated) is the only method available. The only possible accurate assessment method for grass would seem to be the loss of water soluble carbohydrates during a short standardised immersion in water, but the labour of this would only be justified in detailed work.

The accurate measurement of losses is very difficult as inaccurate sampling can give very misleading results. Some indication of losses can be obtained from the changes between cutting and ensiling in CP, CF, DCP, WSC, DOM, leaf-stem ratio and yield of dry matter, but without very accurate sampling techniques this can give results so inaccurate as to be useless.

5.3.4. Ensiling Variables

There is a profusion of published literature on the chemical and microbiological aspects of ensilage and crop conservation. In 1960 WATSON and NASH(126) produced a comprehensive, but not very critical, survey of over 2000 references on grass and forage conservation. Unfortunately, it makes almost no mention of the physical properties of silage which play a major part in controlling the fermentation. It also is primarily concerned with hay and with silages of more than 75% moisture content, and it gives little information on the high dry matter silages that are usually made in tower silos.

The fundamentals of the process of ensilage are best described by McDONALD and WHITTENBURY(68). Excellent, more general descriptions of farm scale ensilage are contained in the work of TRINDER(120) (122), ALDERMAN(5) and HESSAYON and WOOD(49). The particular problem of overheating is described in detail by WEIRINGA et al(128).

The changes that occur in a silo from when the crop is ensiled to when the silage is unloaded, may be divided up into:-

1. Initial Respiration
2. Fermentation
3. Effluent loss
4. Wastage Respiration
5. Chemical Oxidation

The crop, when placed in the silo is of low density and contains a high proportion of entrapped air. Some of this air may be removed by consolidation, but the oxygen in the remainder will oxidise sugars in the dry matter so that they are lost as CO_2. This normally results in a loss of about 1% of the dry matter and a temperature rise of about $4^{\circ}C$. Additional air entering the silage mass will cause further respiration accompanied by a heat rise and losses in proportion to the quantity of oxygen used.

Once the initial respiration is completed the anaerobic bacteria ferment the sugars to produce acid. For good silage the aim is to ensure that lactobaccilli become the dominant organism. These will lower the Ph to about 4.0 and preserve the silage with a maximum fermentation dry matter loss of 4% to 6% (depending on crop) and very little heat output. If however, clostridial bacteria multiply a larger loss of dry matter will occur and the protein will be broken down. Clostridial fermentation is favoured by low concentrations of water soluble carbohydrate in the moisture but is inhibited by low pH. Lactic fermentation requires a concentration of 2% of total weight as W.S.C. (i.e. 10% W.S.C. in d.m. at 80% m.c. 4% W.S.C. at 50% m.c.). To obtain lactic fermentation, the farmer must ensure adequate W.S.C. in the original crop, minimise the losses of W.S.C. in the field and due to initial respiration, and make up any deficiency of W.S.C. at the ensiling moisture content, by the addition of molasses. Direct acidification is sometimes used to artificially lower pH but tends to be an expensive substitute for good management.

With the wilted grass sealed immediately on ensiling and no effluent loss, silage can be made which conserves 95% of the ensiled dry matter and 90% of the ensiled nutrients (as nutrient loss with normal fermentation and respiration is approximately twice dry matter loss).

During this ensiling process an important change takes place in the physiology of the crop. The osmotic pressure in the plant cells which provides most of the strength of the leaves, and some of the strength of the stem in the living plant is relieved, and this cell moisture becomes freely available. Part of this cell moisture may have been liberated by laceration or crushing, and part of the pressure relieved by wilting before ensiling. Some of this liberated moisture runs freely as effluent from an unwilted silage, but with wilted silages a certain amount of pressure is required to express the moisture, which is held in the silage by capillary attraction. The effluent contains between 2% and 10% dry matter, 6% being the average encountered. Over 7% of dry matter, and over 30% total moisture can be lost in the effluent of unwilted silages in silos.

When silage is of low density and therefore porous, and the surface is ineffectively sealed, air will enter the silage mass throughout the filling, storage and feeding period, and a steady respiration of aerobic micro-organisms will result in a loss of dry matter and the production of heat. This production of heat can raise the temperature of the silage considerably and temperatures of 60° - 70° C can occur with bacterial heating. Under certain circumstances combining poor sealing, slow filling and over-wilting in tower silos, a process of direct chemical oxidation will start at about 60° - 70°C to raise the temperature above that at which bacteria die and, (after the silage has completely dried out) the temperature can rapidly rise to the point of ignition. The silage in a number of tower silos has caught fire and there are two reported cases of silos exploding, as a result of self-heating.

The consequence of over-heating are:-

1. the most nutritious parts of the silage are oxidised to produce heat.
2. the digestibility of the protein is markedly reduced when exposed to oxygen at temperatures of above 40°C.
3. the silage can dry out and become brittle.

Heating results from the penetration of oxygen deep into the silage mass. When the oxygen is all used up by wastage near the surface of the silage mass, the heat energy from oxidation is dissipated before a significant heat rise occurs. Under these circumstances wastage takes the form of moulding, or putrefaction, both of which lead, in extremes, to the complete breakdown of the silage.

The changes that occur during ensilage influence the chemical analysis in the following manner:-

(a) Moisture content. McDONALD et al(66) and WILSON et al(134) both discuss the difference between the true moisture content (i.e. % of H_2O, which can be determined by the Toluene distillation technique) and the oven drying moisture content of silage (16 hours at 100°C in Unitherm oven or equivalent). The difference is usually between 1.5% and 2.5% m.c. and is due to the volatile acids which evaporate in oven drying, in addition to the moisture. For precise work the Toluene distillation technique must be used but for most physical tests the oven dry matter will be adequate. The true moisture content of silage is fractionally increased by the water products of respiration. It may be reduced by loss of effluent or by drying out of over-heated or exposed silage.

(b) The Crude Fibre is unchanged during normal (lactic fermentation) and the increase in crude fibre as a % dry matter can be used as a rough measure of dry matter loss using the technique of TRINDER(122). Crude Fibre is lost in over-heating and putrifaction, and so this technique cannot be used when either has occured.

(c) The Crude Protein is lost in clostridial fermentations and putrifaction but is preserved in normal fermentation and the initial stages of over-heating, although its digestibility falls markedly.

(d) The pH of silage gives a very good indication of the fermentation of silage. Good lactic acid grass silages have a pH of 4.0 or less, Butyric silages a pH of more than 4.5. Lucerne silage even when of good fermentation usually has a higher pH than grass silages and pH of 5.0 - 5.5 are regarded as satisfactory. A pH of 4.0 - 5.0 can be perfectly satisfactory in high dry matter silages although they would indicate butyric fermentation in wetter silages.

The ensilage variables may be classified in the following way:-

1. Chemical Analysis.	Moisture content (oven dry and/ or Toluene distillation). C.F., C.P., D.C.P., W.S.C. and D.O.M. which may be compared with the 'as cut' and filling analysis to give an indication of losses.
2. Description.	Using the 7 categories described in detail by HESSAYON and WOOD(6) being:- (1) Well fermented lactic (2) Butyric silage (3) Putrid silage (4) Over-heated silage

(5) Seriously over-heated silage
(6) Mouldy silage
(7) Spoilage.

5.3.5. Classification of Ensiled Crops for Research on Physical Properties

Combining the requirements set out in 5.3.2., 5.3.3. and 5.3.4. the full set of information necessary to classify an ensiled crop is:-

(a) Crop
  (1) The proportions of species and varieties and their stage of growth and leaf-stem ratio.
  (2) Planting and previous cutting dates.
  (3) Fertiliser application.
  (4) Cutting date and time.

(b) Field Treatment
  (1) Description, performance and dates and times of use of field machinery.
  (2) Weather during wilting period.
  (3) Losses, visual assessment.
  (4) Chop and laceration.

(c) Ensiling Description and assessment of fermentation.

(d) Chemical Analysis on representative samples.
  (1) As cut: m.c. (oven), C.F., C.P., D.C.P., W.S.C., D.O.M.
  (2) As ensiled: m.c. (oven) C.F., C.P., D.C.P., W.S.C., D.O.M.
  (3) As ensilage: m.c. (oven and/or toluene) C.F., C.P., D.C.P., W.S.C. D.O.M., pH.

In this thesis I have endeavoured to classify the material as fully as possible but for a number of samples only partial classification was possible. In particular Chemical Analysis is a skilled and laborious process; it was only because of the generous help of N.Trinder, N.A.A.S. Regional Nutrition Chemist and the staff of Bridgets E.H.F. that analyses of a large number of samples were obtained.

5.4. DENSITY

5.4.1. Introduction

Existing data on the density has been obtained using a number of techniques, for example:-

Measurement of total capacity of silos(6)(62)(63)(74)(117)

Measurement of density of layers in the silo during unloading(88)(117)

Measurement of density of cores out from the silage surface(88)(130)(145)

Measurement of density by deep coring in the silage mass(88)(145)

Measurement of density by radioactive attenuation(130)

Measurement of pressure density relationship(63)(88)(92)(94)(132)(142)

We can also obtain information on the general nature of densities of materials similar to silage, for example:-

Density of grass in trailers(50)(91)
of loose hay(35)(81)(110)
of baled hay and straw(71)(81)
of hay wafers(22)(72)(93)

Pressure/Density relationship of wool(36)

Strength of fibres(64)

Strength of timber(135)

Consolidation of soils(25)

In this section I have firstly considered the fundamental factors effecting the density and compressibility of silage. Existing data is of limited use as it is largely on the density of particular silages under particular conditions. I have critically reviewed this existing data and endeavoured to restate the data in a uniform manner so that it can be compared. The major part of this section is concerned with experiments I have performed on silages of a wide range of crops, maturities and moisture contents to determine the density for the full range of pressures encountered in silos. From this data I have evolved a general theory for predicting the density of silage of any moisture content and maturity under any conditions, of pressure and time. The coefficients to be used in this formula are given for a range of silages.

5.4.2. The Fundamentals of Silage and Crop Densities

Density is defined as the mass per unit volume and is expressed in this thesis in lb/ft^3. Units used by other workers include kg/m^3 (the S.I.unit) g/cc and ft^3/ton, the conversion factors being:-

$$\begin{aligned} Y \text{ lb/ft}^3 &= 0.01602 \ Y \text{ g/cc} \\ &= 16.02 \ Y \text{ kg/m}^3 \\ &= \frac{2240}{Y} \text{ ft}^3\text{/ton} \end{aligned}$$

Specific gravity (the ratio of density of a material to density of water; numerically equal to density in g/cc) is used by some workers.

In the design of silos we are primarily concerned with the Bulk Density (Y) (usually referred to in this thesis as Density) and Bulk Dry Density (Y_d) (that is weight of dry matter per ft^3, and usually referred to as Dry Density).

At a moisture content (wet basis) of m %

$$Y_d = \frac{(100 - m)}{100} Y$$

Although silage and crops are highly compressible and their density can range from below 2 lb/ft^3 to over 70 lb/ft^3, their constituent parts have almost constant densities; it is the proportions of the volume occupied by three major constituents (water, gas and dry matter) that change.

The water in the crop has a sensibly constant density of 62.4 lb/ft^3. The slight changes in density due to temperature variation and pressure and the presence of other fluids can be ignored, except in the case of silage freezing which, though common in the U.S.A. is not found in the U.K.

The gas in the silage can vary in density due to the change in composition from Air to a Nitrogen + CO_2 + Water Vapour mixture, and due to temperature and gas pressure changes. In the calculation of the density of silage the variations in the density of the gas (actually from 0.07 - 0.12 lb/ft^3) have been ignored.

The solid density of dry matter is harder to determine and there do not appear to be any accurate direct measurements of it. Normal pycnometric methods using immersion in fluids give inaccurate results because of the virtual impossibility of removing all the entrapped air. LAWTON(60) used air pycnometry to determine the solid density of grass seeds at approx. 10% m.c. The solid densities of dry matter obtained ranged from 78 - 84.5 lb/ft^3. SHARP(107) found, using long term toluene pycnometry, solid densities of the dry matter of wheat grains of up to 93 lb/ft^3. However, grass seed and wheat grains have slightly different composition to the dry matter of grass. Probably the best figure for the solid density of dry matter can be obtained from German work on Hay Wafering. MATTHIES(72) shows that at a pressure of 10,000 to 14,000 lb/in^2 Lucerne and Meadow Hay (at 17% - 20% m.c.) both reach densities of 93.5 lb/ft^3. This corresponds to a solid density of dry matter of about 100 lb/ft^3. This is of the same order as the solid density of the constituents of the grass which are given by SHARP(107) as:

Starch	95.5 lb/ft^3
Sugar	100 lb/ft^3
Cellulose	95.5 lb/ft^3
Ash	158 lb/ft^3

The value of 100 lb/ft^3 is used in subsequent theoretical calculations.

Now since solid dry matter and water are sensibly incompressible, there is a maximum density of silage of any given moisture content which will be reached when it is compressed so that no gas remains in it.

The maximum density at m % moisture content

$$= 100 - 0.376\ m\ \text{lb/ft}^3$$

Corresponding to this there is a maximum dry density

$$= \frac{100 - m}{100}\ (100 - 0.376\ m)\ \text{lb/ft}^3$$

This maximum dry density is plotted against moisture content in Graph 5.4/1. The lines of dry density against moisture content for 10%, 20% and 30% of the volume occupied by gas are also shown. In practice one would not expect the full maximum density to be attained as some gas will always remain entrapped in the mass of particles.

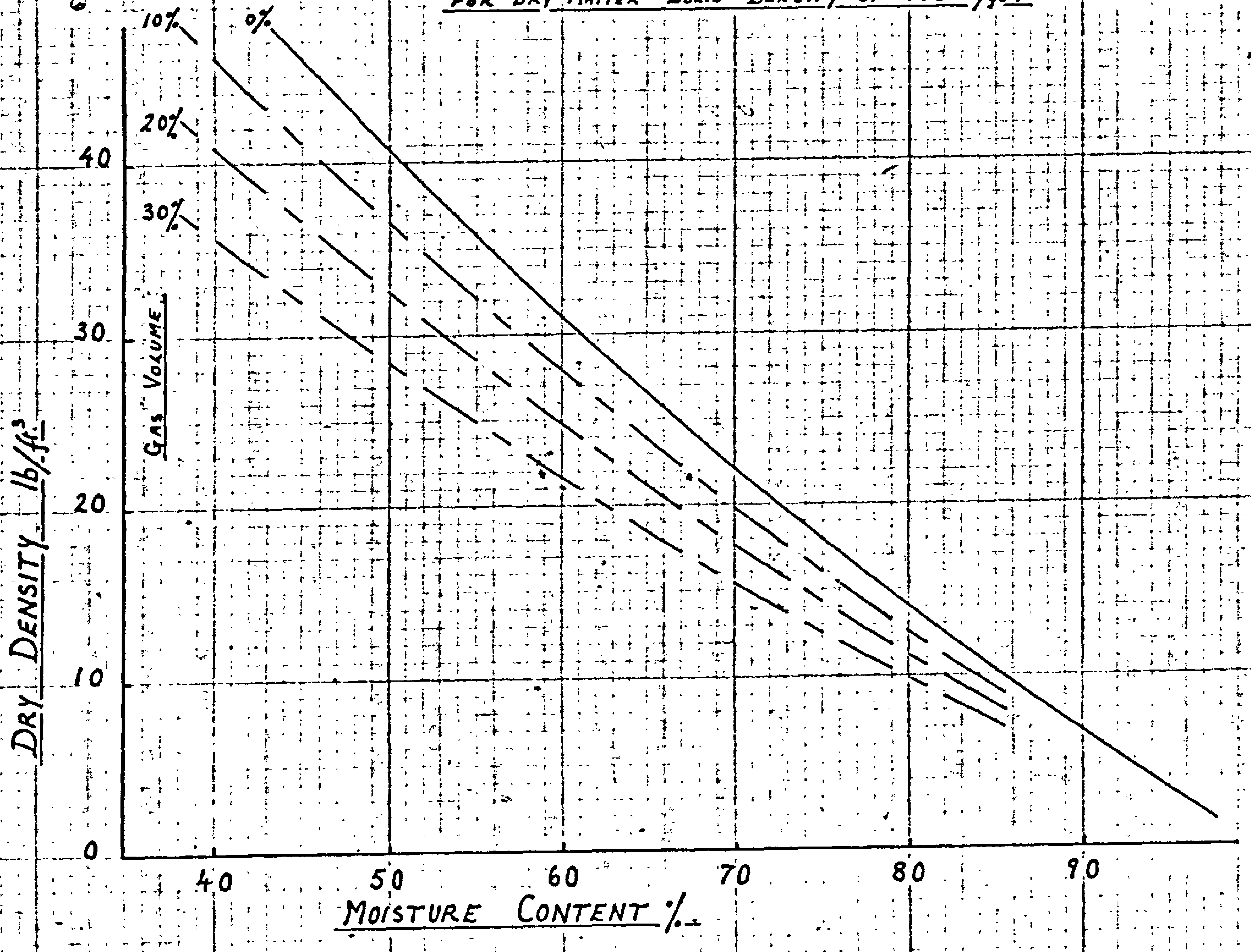
The minimum density of a crop depends on the initial arrangement of its particles. Grain can be considered as an assembly of spheres and its density related to the possible arrangement of spheres as in Section 4.4.13. Unfortunately, whole crops are too complex (i.e. leaf, stem, seed head, variously chopped and shattered) to use this approach for quantative prediction of density but it can be used to give some understanding of the process of compression.

Depending on how the crop is placed, the initial particle arrangement of the crop may be either a totally random orientation of lengths in all three directions, or with lengths tending to lie parallel to the surface deposited on, but being in random directions within the plane of that surface.

Graph 5.4/1

MAXIMUM THEORETICAL DRY DENSITY OF SILAGE.

FOR DRY MATTER SOLID DENSITY OF 100 lb/ft³.



When a pressure is applied to this initial assembly of crop particles, it will be compressed until the strength of the crop particles is sufficient to resist the pressure. The initial compression will cause the particle to slide over each other and rearrange themselves into lamina normal to direction of compression. Then increasingly the compression will bend the crop particles and the resistance to compression will be due to the strength in bending of the crop particles. As the gaps between particles are reduced so the compression will cause crushing of the plant and cell structure until the maximum density at which all gas has been expelled is reached.

The initial loose density will tend to be increased by the chopping of the crop; the maximum initial loose density will be obtained when the chop length equals the thickness of the material (i.e. for maize stems 3/4" dia., 3/4" chop will give the maximum initial density). The initial resistance to the compression of the mass due to friction will be highest for wet material, and decrease with drier material, as the coefficient of friction falls markedly with falling m.c. (see 5.6.2.).

In the next stage of compression in which the bending strength of the particles is the major resistance to compression, and in the final stage of compression when the particles are lying in lamina, (each particle acting, not as a beam, but bearing directly on the particle below), the structural strength of the plant structure will determine the resistance to compression. Length of chop becomes of negligable importance, but weakening of the plant structure by laceration or crushing in the field should reduce the resistance to compression. The resistance to compression will be high in this stage of compression in fresh material in which osmotic pressure in the cells (which gives plant some of its strength) is still high and can be expected to fall as the cell pressure falls during ensilage. We can expect an increase in crop particle strength at low moisture contents similar to that encountered in timber by WILSON et al(135) who found no change in strength properties of timber as it dried from 50% m.c. (its green state) to 20% m.c. (the fibre saturation point) but that between 20% and 10% m.c. the strength of the timber was doubled. Similarily McLINTOCK and ARGON(64) state that the tensile strengths of natural fibres increase as they dry out. PRINCE, WOLF and BARTOK(97) found that the minimum bending strength of the fresh alfalfa stems occurred between 45% and 55% m.c.

The resistance to compression of a grass increases markedly as its leaf stem ratio falls and as the stem is strengthened with increasing maturity.

The resistance to compression is due, at all stages except maximum density, to the arrangement and strength of the crop particles. The degree of compaction of the particles can be measured by the dry density. Once the initial osmotic pressure has been relieved the presence of moisture in the crop particles will only effect the dry density by its influence on the strength of dry matter.

Except near the maximum density, the presence or absence of moisture in the voids between crop particles offers an insignificant resistance to compression.

Once the silage has been compressed to 90%-95% of its maximum density (i.e. 10%-5% gas voids) the pore pressure of the moisture starts to rise and provides resistance to compression. In these conditions silage consolidates in a manner similar to a saturated clay, as described by CAPPER and CASSIE(25). The rise in pore pressure and rate of settlement depend on the rate of increase of consolidating pressure and the drainage conditions.

We can therefore expect that under a given pressure conditions the dry density of a given silage will be relatively constant between a point corresponding to the fibre saturation point in timber (probably between 15% and 25% m.c. in silage) and the moisture content at which it reaches 90% to 95% of maximum density. Hay and dried grass (below 15% - 25% m.c.) would be expected to have much lower dry densities than silage of the same material because of the increased fibre strength. Crops before ensilage, can be expected to have a lower dry density, under given conditions, than the resulting silage. The crop dry density, under given conditions, tends to increase as the initial high osmotic pressure in the cells falls due to wilting, laceration and fermentation. Short chopped crops will have a higher initial dry density but chop is unlikely to influence dry density at higher pressures.

The strength of crop particles is time dependent. I have found that the density of a sample of silage under constant pressure increases exponentially with time, and upon release of pressure it re-expands at an exponential rate. It is therefore essential that measurements of density should be made at a known time after the application of pressure.

From this survey of the fundamentals influencing silage consolidation (the conclusions of which have been confirmed by my experiments) a standard method of measuring the pressure density/time relationship has been evolved.

The density (Y lb/ft^3) of silage of m% moisture content is measured under conditions constant Vertical Pressure (V lb/ft^2) at suitable intervals of time (T hr) from the application of Vertical Pressure (V lb/ft^2). The density at each time at this pressure is plotted against $\log_{10} T$ and the density (Y' lb/ft^3) at $T = 1.0$ and the rate of increase in density with $\log_{10}$ time (C' lb/ft^3/$\log_{10}$ hr) obtained. The corresponding figures on a dry matter basis Yd' lb/ft^3 and Cd' lb/ft^3/$\log_{10}$ hr. are calculated from moisture content where:-

$$Yd' = \left(\frac{100 - m}{100}\right) Y' \quad \text{lb/ft}^3$$

and

$$Cd' = \left(\frac{100 - m}{100}\right) C' \quad \text{lb/ft}^3/\log_{10} \text{hrs.}$$

From a set of values of Yd', Cd' and m for a range of vertical pressures the dry density and density of the sample at any pressure and time can be predicted. A study of variations in Yd' and Cd' for a range of crop classifications enables the density of any silage to be predicted.

5.4.3. Published Densities for Calculating the Capacity of Tower Silos

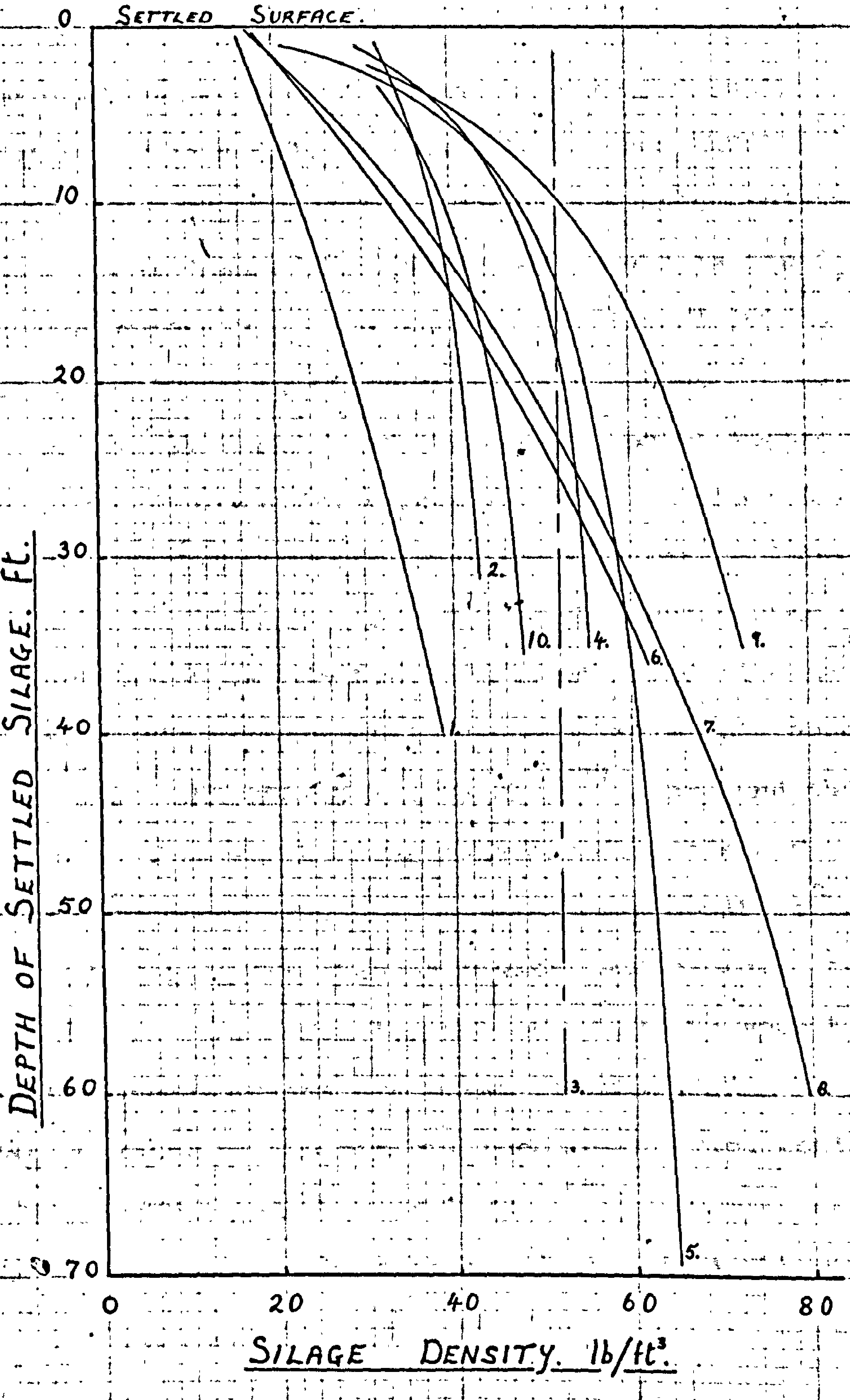
The three main tables of density currently used for the calculation of the capacities of tower silos are those of McCALMONT(63), which has been extrapolated by the N.S.A.(82), of ALDRICH(6), which is restated in terms of dry density against silo height by SUTER(114), and the crude table published by the E.D.A(38) and the I.A.E.(54). There are other less widely known tables which are quoted by TAMM(117) and OTIS and POMROY(88).

In Graph 5.4/2 nine different curves are plotted of density against settled depth. It will be seen that there are considerable differences in density but if we consider dry density, the figures become much more consistent. At 30 ft. depth of silage the range of dry densities was only from 14.8 to 17.6 lb/ft^3, compared with densities which ranged from 42.5 to 70 lb/ft^3 (for results where m.c. is known). Most of these curves are based on filling of silos and the maximum size of silo used in these tests was 18' dia. with a settled depth of less than 40'. The figures given by the N.S.A.(82) and ALDRICH(6) for silage depths over 40' are extrapolations.

In the U.S.A. it has been realised by a number of workers that in practice silo capacities vary from those predicted from the above figures. The reasons given for

DENSITY OF SILAGE IN TOWER SILOS. PUBLISHED DATA.

No.	Source.	Crop.	Average m.c. %	Density at 30 ft. Bulk lb/ft³	Dry lb/ft³	Date
1.	Chase	Corn	N.K.	34	N.K.	1917.
2.	Kansas	Corn	65	42.5	14.9	1919.
3.	E.D.A.	All	All	52	All	1964.
4.	U.S.D.A. Circ 603	Corn	72.4	54.5	15.05	1941.
5.	Aldrich	All	72.0	58.2	16.3	1959.
6.	King	Corn	N.K.	56.5	N.K.	1897.
7.	McCalmont	Corn	70	58.7	17.6	1939.
8.	N.S.A.	All	70	~	~	1960.
9.	Otis and Pomroy	Alfalfa	75	69.9	17.4	1957.
10.	Minnesota.	Corn	68.6	47	14.8	1940-42.



these variations are varied. SUTER(114) states that the dry matter capacity is not significantly effected by moisture content in the range 75% to 40% m.c., but that length of chop and rate of filling cause considerable variation. OTIS and POMROY(88) are primarily concerned with density rather than dry density, and give species of crop, moisture content, length of cut, maturity, preservative used and silo diameter as causes of density variation. The N.S.A.(82), GORDON(42) and ALDRICH(6) claim that the dry matter capacity of a silo remains relatively constant regardless of moisture content and is equal to the dry matter capacity of the silo calculated at 70% m.c. (N.S.A.) and 72% m.c. (Aldrich). The E.D.A.(38) claim that the average density of the silage can be regarded as constant at 52 lb/cu.ft. regardless of moisture content (i.e. the dry density doubles from 13 lb/ft^3 at 75% m.c. to 26 lb/ft^3 at 50% m.c.). This rather surprising statement, which is completely without foundation and contrary to all experimental evidence, is widely accepted in the U.K. SHEPPERSON and CORRIE(111) compound this error in a table which gives mean dry densities of 20.0 lb/ft^3 (for 30 ft. high silos) and 22.4 lb/ft^3 (for 60 ft high silos) for 'Sealed towers' and compared to only 17.5 and 19.6 lb/ft^3 for 'Open towers' of the same height. These irrational claims are based on multiplying the average density by the minimum recommended d.m. content!

McCLAMONT et al(62) and TAMM(117), both give details of the work on which the density figures in McCALMONT(63) are based, and later work on capacities and densities at the U.S.D.A. Beltsville and Rutgers. McCalmont et al state that although total capacity of alfalfa silage was usually greater than for corn, this was due to the higher moisture content of alfalfa silage and that the dry matter capacities were similar. They claim small silos will hold slightly less alfalfa d.m. than corn, while larger silos held slightly more alfalfa d.m. than corn. They also claim that "No comparisons between corn and grass (alfalfa) silage showed more than 13% differential between dry matter capacities". This statement gives a rather exagerated impression of the consistency of d.m. capacity figures given in their results.

In order to classify the effects of various factors on the dry matter capacity, I have carefully re-examined the data on the experiments at U.S.D.A. Beltsville and Rutgers as given by Tamm and McCalmont et al. Table 5.4/1 shows the results of this re-examination. I have only used the results of the best documented experiments and I have given the data (and its sources) on which the calculations are based. There are certain inconsistencies between the figures in different tables in McCalmont et al, and the figures in Tamm's thesis (e.g. Silo B4, 1940, maximum depth given variously as 35', 40' and 41'). Figures from all sources are therefore given in Table 5.4/1 but where there is a divergence, Tamm's figures are used for calculation. The two "actual" d.m. capacities (weight d.m. in, and weight d.m. out) have been compared with the d.m.

Table 5.4/1

COMPARISON OF PREDICTED AND MEASURED TOWER SILO CAPACITIES, USING THE METHODS AND DATA OF McCALMONT AND TAMM.

N.B. TONS ARE U.S. SHORT TONS OF 2000 lb.

SILO.	YEAR.	SIZE.	CROP.	ADDITIVE	CHOP.	MAXIMUM DEPTH.			SETTLED DEPTH.	AVERAGE MOISTURE	WEIGHT IN		ESTIMATED D.M. CAPACITY, AND ERROR.				WEIGHT OUT. C.		AVERAGE SETTLED DENSITY.	
						①	②	③	④	CONTENT	TOTAL	D.M.	A.		B.		D.M.	ERROR	BULK	DRY
		ft dia x ft.			in.	ft.	ft.	ft	ft.	%	TONS	TONS	TONS	~%	TONS	%	TONS	%	lb/ft³	lb/ft³
B6	1940	12 x 425	Alfalfa.	Acid	0·5	40·0	40·0	41·0	34·0	$70_{70·0}$	97	$29_{29·05}$	31	−6·5	25	+16·0	24·3	−3·0	45·1	12·65
B4	1939	18 x 42·5	do. + Clover	Acid	0·5	32·5	32·5	32·5	27·5	$68_{68·0}$	188	$60_{60·25}$	49	+22·5	42	+43·0	49·75	+18·5	45·7	14·2
B5	1939	18 x 425	do. + do.	Molasses	0·5	30·0	30·0	31·5	27·5	$68_{67·2}$	198	$63_{64·9}$	51	+23·5	42	+500	52·0	+24·0	47·4	14·9
B4	1940	18 x 425	Alfalfa.	Acid	0·5	400	35·0	41·0	35·0	$77_{77·1}$	333	$77_{77·9}$	69	+11·5	59	+31·0	61·0	+3·0	53·6	13·75
B5	1940	18 x 42·5	do.	Molasses	0·5	40·0	35·0	41·5	35·0	$77_{76·4}$	318	$73_{74·5}$	70	+4·0	59	+24·0	62·9	+6·5	54·7	14·1
B4	1941	18 x 42·5	do	Acid	0·41	26·5	26·0			76	207	50	37	+35·0						
B5	1941	18 x 425	do.	Molass.	0·375	26·5	27·5			78	208	46	41	+12·0						
B2	1938	18 x 42·5	Corn.	Nil.	0·5	410	41·0			74	264	69	69	✓						
B2	1939	18 x 42·5	do.	Nil.	0·5	20·0	20·0			74	127	33	26	+27·0						
B7	1940	16 x 425	do.	Nil.	0·5	400	40·0			81	209	40	53	−24·5						
B7	1941	16 x 42·5	do.	Nil.	0·25	37·5	37·5			74	198	51	48·5	+3·0						

① FROM TABLE 1 IN McCALMONT et al. (62).
② FROM TABLE 4 IN McCALMON et al. (62).
③ and ④ FROM TABLE 10 IN TAMM (117).
WEIGHT IN AND AV. M.C. % FROM AS ② and ③
SUFFIX VALUES FROM TABLE 7 IN McCALMONT et al (62)

ESTIMATED CAPACITIES.

A. BY TAMM, BASED ON MAX. DEPTH ③ AND TABLE 3 IN McCALMONT (63).
B. BY AUTHOR, BASED ON SETTLED DEPTH AND TABLE 4 IN McCALMONT (63).
C. BY AUTHOR, BASED ON SETTLED DEPTH AND D.M. OUT FROM TABLE 7 IN McCALMONT et al (62). ERROR, RELATIVE TO ESTIMATE B.

DENSITIES CALCULATED BY AUTHOR AS FOR C.

capacity of the silo calculated using Table 2 (for maximum depth) and Table 4 (for settled depth) from McCALMONT(63).

$$\text{The error }\% = \frac{(\text{actual capacity} - \text{estimated capacity})}{\text{estimated capacity}} \times 100$$

was calculated for:-

(A) actual d.m. in against estimated d.m. from maximum depth.

(B) actual d.m. in against estimated d.m. from settled depth.

(C) actual d.m. out against estimated d.m. from settled depth.

In case A the error with 7 alfalfa filled silos varied from -6.5% to +35% averaging +14.5%, while for the 4 corn filled silos the error ranged from -24.5% to 27.0% and averaged +1.5%. For the 5 fillings of alfalfa, for which data on the settled depth and weight d.m. out are available, the range of error was from +16.0 to +50.0%, average +32.8% for Case B, and from -3.0% to +24.0% average +9.8% for Case C. The other possible comparison, actual weight d.m. out against estimated d.m. from maximum depth gives a range of -21.6% to +2% with an average of -8.2%

From this re-examined data it becomes clear that, even when compared with the actual capacities of silos, of similar size (up to 18' dia., 40' of silage), filled with similar material (corn and alfalfa 65% to 75% m.c.) to that for which the McCalmont's tables were derived, these tables give only a very approximate estimate of capacity. The value of the N.S.A. table (which is an extrapolation of McCalmont's), when used for silos of up to 60' settled depth of silage and 30' dia., and filled at moisture contents ranging from 30% to 75%, for all crops is highly suspect.

As can be seen from the above case, the dry density in the silo varies due to the change in volume due to settlement and the loss of weight of dry matter (usually between 5% and 20%) between filling and unloading. The allowance for settlement is included in some tables of capacity. McCalmont allows for settlement as follows:-

Silo height ft.	20	30	35	40	45	50
Settled Silage depth ft.	20	29	33.5	38	42	46

The N.S.A. table is given as settled depth of silage and an allowance for settlement must be made when calculating silo height. DUFFEE et al(37), who recommend the N.S.A. table, recommend a 5 ft. settlement allowance for all heights and 5 ft. for the unloader.

Aldrich allows 1 ft. for settlement for the first 30 ft. and 1 ft. per 10 ft. above that (e.g. 56' settled silage in a 60' silo).

The graph on p.78 of SUTER(114) of dry density related to "silage depth" seems to be an elaborate rework of Aldrichs data, to suit the Harvestore silo. Its scales are, in fact, average dry density of settled silage, against height of silo. This becomes clear when one examines the worked examples on 20' x 50' silos on p.83 and p.224. For a 20' x 50' concrete stave silo a capacity of 109.3 tons (U.S.) d.m. is given, which is equivalent to 391 tons at 72% m.c. compared with 394 tons on Aldrichs table. For a 20' x 50' Harvestore a volume of 14,290 ft^3 is given which is the volume of a 20 ft. dia. cylinder 45.4 ft. high. However, Suter calculates the capacity using the dry density 14.80 lb/ft^3 for a 50' depth (not 45.4 ft., the true settled depth) to give a total capacity of 377.7 tons at 72% m.c. compared with 379 tons given by Aldrich for a 45.4 ft. settled depth.

The E.D.A. table allows 6 ft. for settlement regardless of depth. Despite losses of between 5% and 20% of the dry matter in silos, none of capacity tables are explicit about whether they refer to filling or unloading weight of dry matter.

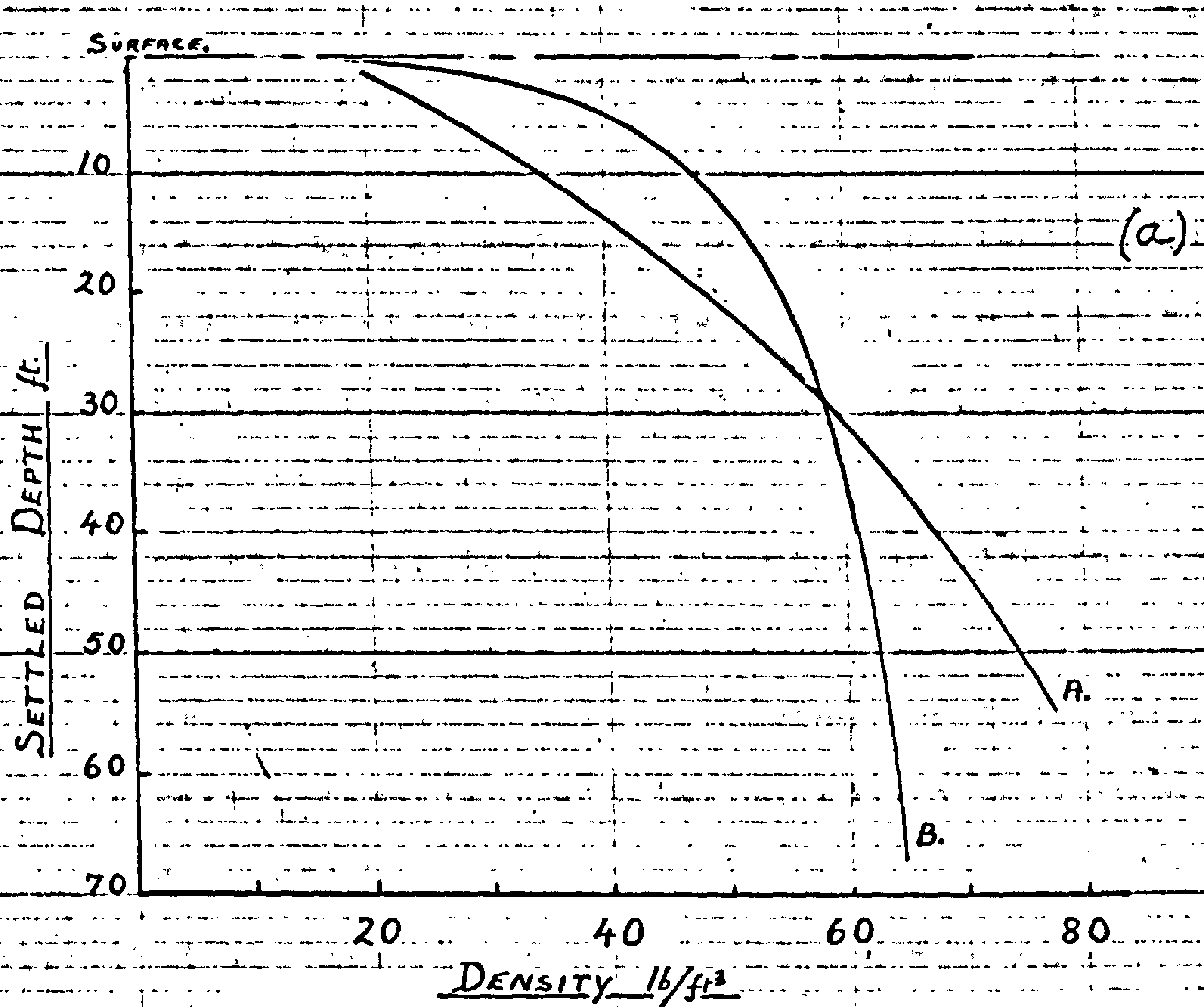
MEYER(74) gives the results of work at the University of Wisconsin in support of the claim that the N.S.A. capacity table for 70% m.c. is accurate for all crops and all moisture contents. In fact, the error between the d.m. capacities (based on filling weight) recorded for short chop (3/8 inch theoretical) early cut alfalfa-brome silages at Wisconsin, and those predicted by the N.S.A. table range from -15% to +24% and average +6.7%.

These average dry densities obtained at Wisconsin are plotted on Graph 5.4/3(b) of average dry density against settled depth, together with the Aldrich and N.S.A. curves and the results given in Table 5.4/1 and from my own

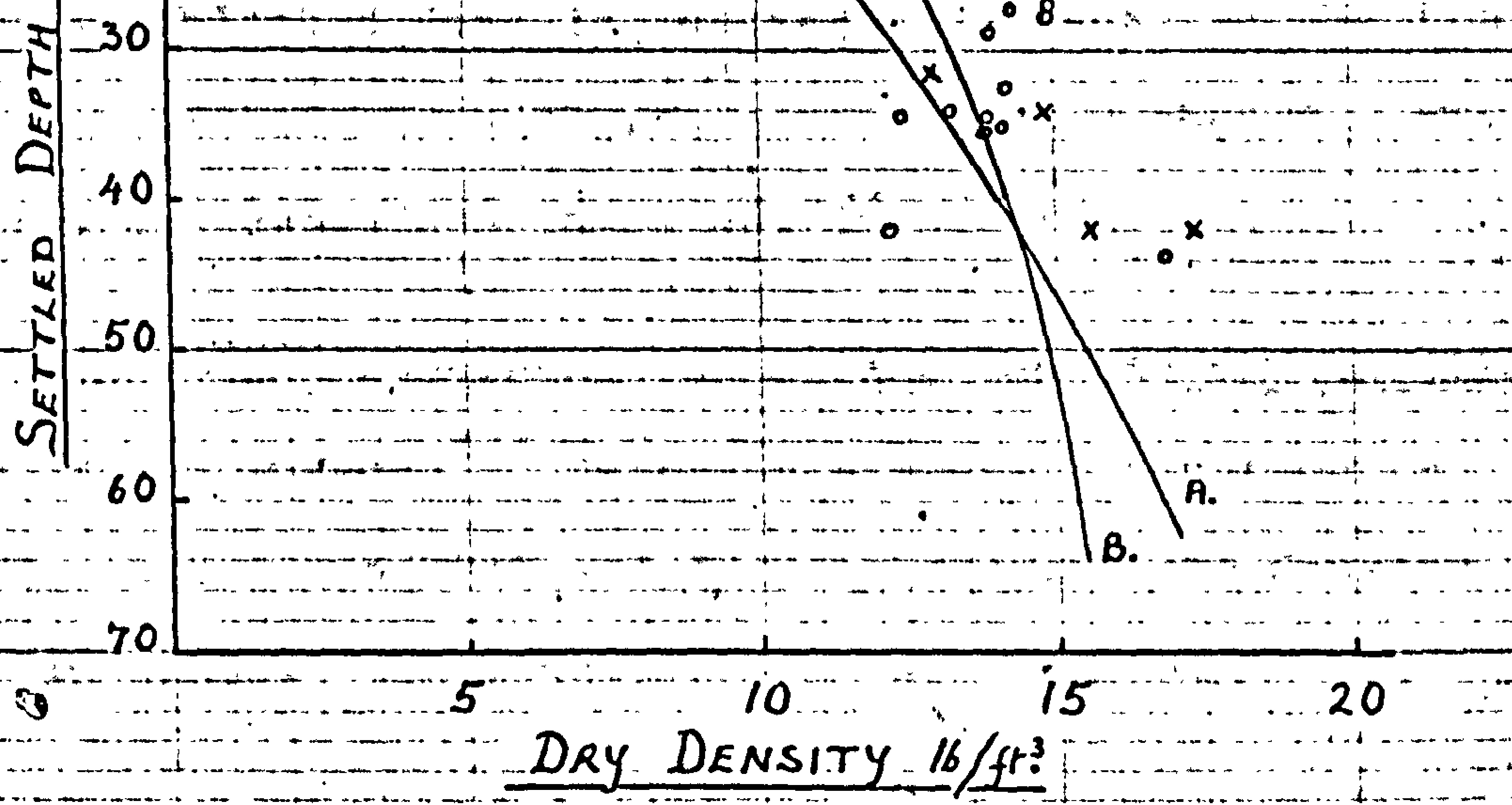
Graph 5.4/3

U.S. DATA ON SILAGE DENSITY.

DENSITY AT STATED DEPTH.



AVERAGE DRY DENSITY FOR TOTAL DEPTH.



experiments at Bridgets' E.H.F., Glantlees and the N.I.R.D.

To summarise, my evaluation of the published data on silo capacities is:-

1. That the N.S.A. and Aldrich capacity tables both provide an approximate basis for determining the capacity of silos in the absence of more accurate data.
2. That the Suter table is a confusing elaboration of Aldrich's table.
3. That the E.D.A., Inst. of Agricultural Engineering capacity figures are based on two false assumptions and should be discarded.
4. That the actual dry matter capacities vary considerably for reasons that cannot be discerned from published data.
5. That the reasons for variation of silo d.m. capacities need to be established so that accurate methods of calculating capacities can be developed and so that silos may be filled so as to obtain the maximum potential capacity.

This published data is further discussed, in the light of the results of the author's calculation method for the pressures and densities in silos, in Section 6.2.

5.4.4. Published Measurement of Silage Density in the Silo

OTIS and POMROY(88) describe extensive experiments carried out between 1940 and 1957 to measure the density of silage in silos. They have used the total weight in, surface coring, surface layer and horizontal coring at depth techniques to measure variation in density.

They considered the total weight method of predicting capacities as unreliable; because of the wide variation in capacities encountered in practice. The surface layer technique of measuring in silo density was considered most reliable, but the accurate weighing of the large quantities of silage and the error due to the springback of silage as it re-expands during unloading must be born in mind.

4" and 6" dia. core cutters and a cubic foot spiked cage sampler were used for measuring surface density. The 4" dia. sampler gave low results in comparison with the larger samplers. Core sampling gave results sometimes higher, sometimes lower than the surface layer technique. These differences can be attributed to:

1. Surface layer technique gives average density while core samples give point densities which will vary over surface of silage due to uneven distribution.
2. The surface silage has re-expanded during unloading and will have a lower density than when the silo was full. This will be more marked for core samples than in the deeper layers used in surface layer determination.
3. The cutting of a sample disturbs the silage and alters its density.
4. It is difficult to exactly measure the volume of silage cut out by a cutter.

Otis and Pomroy give their results in terms of density. Because density is highly variable with moisture content (for a given dry density, the density is 20% greater at 75% m.c. than at 70% m.c.) it is very hard to evaluate the results without converting to dry density. It is unfortunately not possible to read off Otis' graphs with sufficient accuracy to justify converting his figures to dry density against vertical pressure.

Otis and Pomroy also conducted a series of experiments to measure variation in density in the settled silage mass before unloading, by coring horizontally across the silo at 2'6" intervals down the silo. Their results show a variation in density across the silo due to the formation of columns of dense silage with uneven unloading. However, there may have been a constant dry density in each layer as variations in moisture content across the diameter could account for all the variation in density. Conversely the variations in moisture content may have masked the full extent of dry density variation.

Otis' method of predicting isopressure lines is questionable. Consolidation tests were conducted to reproduce the densities measured in the tower. Unless each sample tested is of identical moisture content to the corresponding sample for the tower, a large error can be produced. Also the pressures required to consolidate rapidly to a given density in a laboratory consolidation apparatus are very much higher than those required to consolidate to that density over 3 months or so in a tower.

Otis and Pomroy make no attempt to evolve any method of predicting densities in silos.

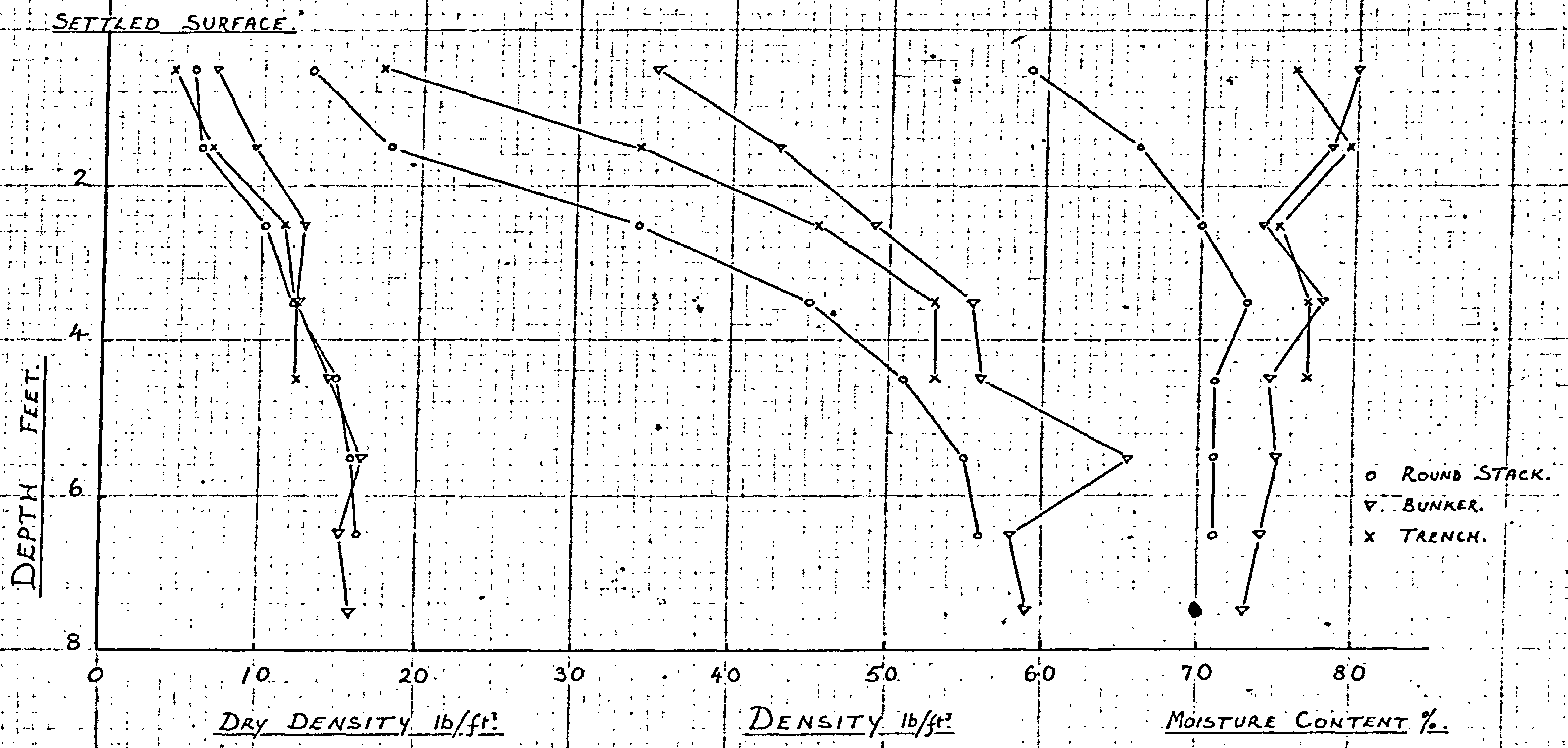
ZOERB et al(145) took 6¼" dia. core samples to determine the density of short chopped grass silage in clamp silos. The coring was carried out to the full depth of the silo, so no re-expansion error would have occured. These densities are similar to those likely to occur in the top layers of a tower silo. The losses in these clamp silos were higher than those that should occur in a tower and this may have effected the dry density slightly. In replotting Zoerb's results for Graph 5.4/4 I have calculated and plotted the dry density figures. These are also used in Graph 5.4/5 in which they are compared with my pressure density test results (Samples Br/65/C1V1 and C1V2 at 1000 hours) for clamp silage from Bridgets. Zoerbs' dry densities for the pressure range 70 - 330 lb/ft. are within the same range as the dry densities of the Bridget's clamp silage. Unfortunately no clear details of variety and maturity of grass are given by Zoerb.

TAMM(117) measured the density of silage by the layer method, but the results are of little value as there is no record of the moisture contents in each layer, so dry densities cannot be calculated.

WILKINS et al(130) used gamma energy attenuation to measure densities in a 12' dia. 25' high silo. A gamma radiation source was suspended in a steel tube up the centre of the silo, and a radiation detector could be positioned at any point on the outside of the silo. Thus the average

AVERAGE CORE DENSITY AND M.C.% FOR EACH FOOT DEPTH IN CLAMP SILOS.

SOUTH DAKOTA 1954. CHOPPED GRASS SILAGE. FROM ZOERB et al.



Graph 5.4/5

SETTLED DRY DENSITY IN SILOS, FROM ZOERB (145) AND WILKINS (130).

density of material along any radius at any height could be determined. The test was run in 1961 with 16' settled depth of wilted alfalfa of unspecified moisture content, which had an average density of 32 lb/ft^3 ranging from 20 - 40 lb/ft^3 top to bottom.

Wilkins, grasped the importance of dry density but his tests were too limited to explore the concept. I have recalculated Wilkin's second year results on corn into the form of Vertical Pressure against Dry Density (with and without ACl 714 wall friction correction to vertical pressure). These figures have been plotted on Graph 5.4/5 along with Zoerb's core test results and my pressure density tests for Bridgets clamp silage. The dry densities of this corn silage is markedly lower than that for the grass silage. This may be due to the particular circumstance of the relative maturities of the samples considered or due to the difference in crop.

Wilkins found that 1000 cc. core samples gave results in average about 5% lower than gamma energy. The average density determined from total volume and total weight was within 1% of the average calculated from gamma attenuation results.

Wilkin's conclusions must be considered in relation to the shallow depth of silage in these tests, but they include:-

1. Re-expansion occuring during unloading is localised near the surface.
2. Tramping of surface 2 months after filling produced a 2% increase in density 6' below the surface.

3. There was less than 20% variation in radial density when corn silage was filling with a stationary central spout with only surface leveling.

5.4.5. Published Work on the Pressure/Density Relationship of Silage.

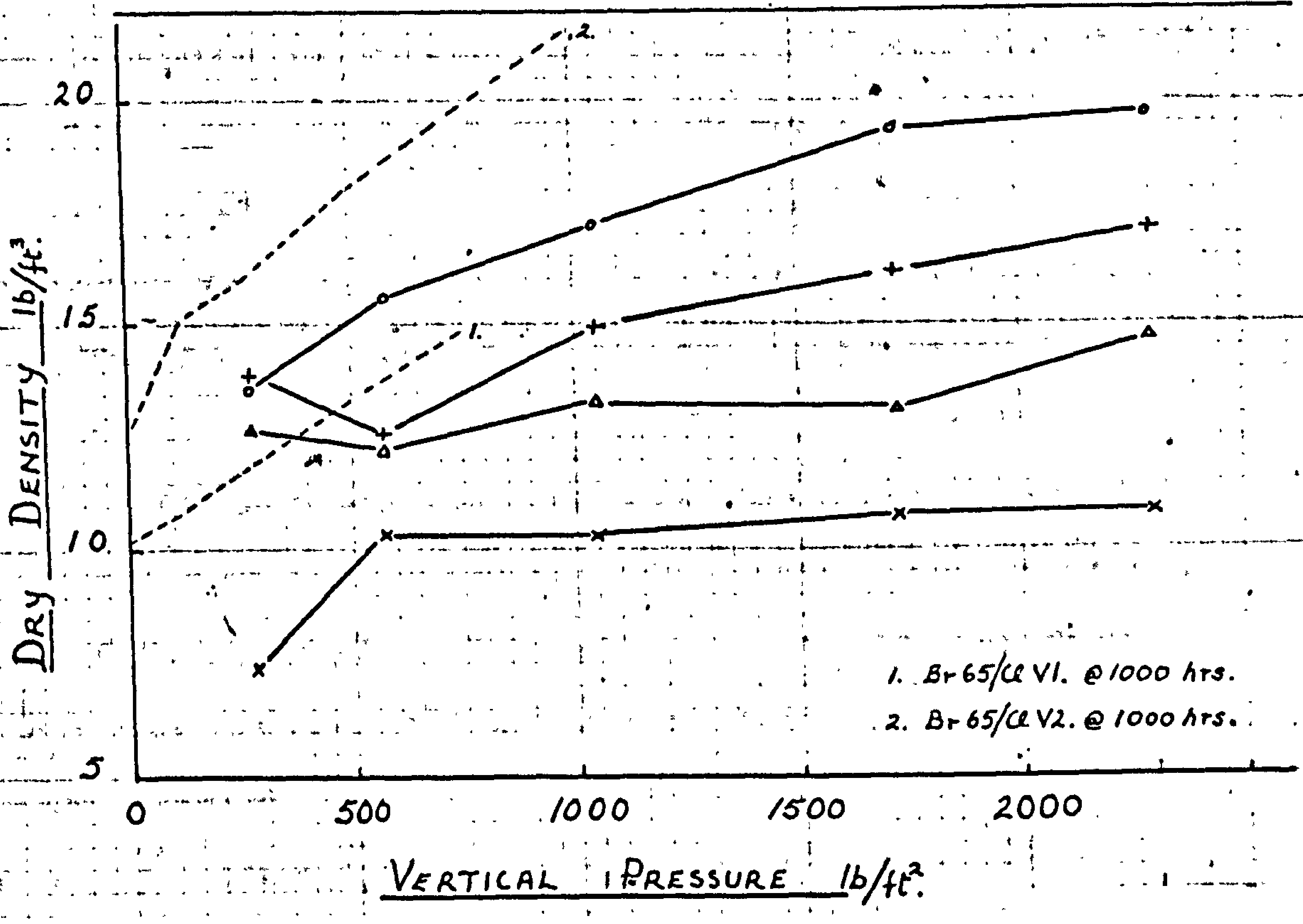
PERKINS, PRATT and ROGERS(92) conducted consolidation tests during the ensiling of 9 lb. samples of corn (maize) and meadow crops (i.e. grass and legumes). Their apparatus consisted of an 18" x 6" dia. tube screwed into a base plate fitted with an effluent drain to a sealed glass jar. The tube was filled with grass and a wooden piston placed on top. The sample was consolidated using weights on a frame fixed to the piston to give pressures of 2, 4, 8, 12, or 16 lb/in^2 (i.e. up to 2300 lb/ft^2). The tubes were initially of steel, which corroded, then of glass, which burst at high pressures, and for most of the tests of Harvestore type glass coated steel.

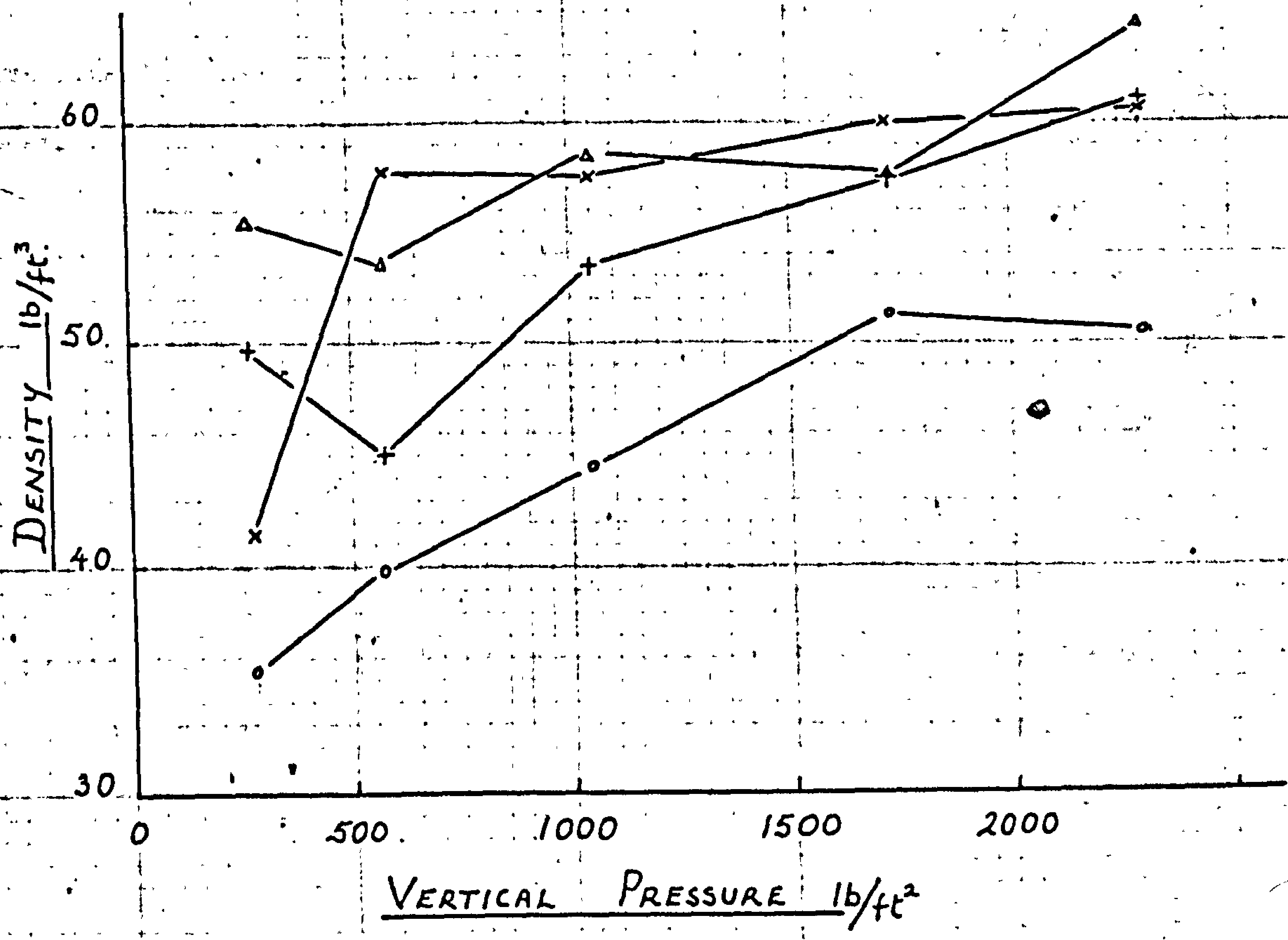
Each sample was kept at constant pressure for the duration of the test (usually between 30 and 40 days) and the weight and volume recorded at intervals. The results are given in terms of density and dry density. The effects of time, pressure, chop length, and maturity-moisture content on density were studied.

I have plotted their results on variation in density and dry density with pressure at four levels of maturity-moisture content for Meadow crop silage (from Perkins et al Table 4) on Graph 5.4/6. Considering dry density first we

PRESSURE/DENSITY RELATIONSHIP FOR MEADOW CROP. FROM TABLE 4 OF PERKINS ET.AL. ( ).

×	PRE BLOOM.	15·5 – 20·0% d.m.	11 OFF	AVERAGE 17·9% d.m.
△	EARLY BLOOM.	20·1 – 25·0% d.m.	19 OFF	AVERAGE 22·8% d.m.
+	FULL BLOOM.	25·1 – 30·0% d.m.	13 OFF	AVERAGE 28·0% d.m.
o	LATE BLOOM TO SEED OR WILTED.	30·1 – 54·0% d.m.	27 OFF	AVERAGE 39·0% d.m.





find that (ignoring erratic results at 250 lb/ft^2 pressure) the dry density at a given pressure increases with increasing maturity and dry matter content. Above 500 lb/ft^2 the rate of increase in dry density with pressure increases from very slight with the wettest samples to a consistent marked increase with pressure for the driest, most mature, samples. The density rises with increasing pressure but with the three wettest samples it levels off at about 60 lb/ft^3. Effluent was produced when the density exceeded 60 lb/ft^3, and a maximum density of 66.8 lb/ft^3 was recorded. Up to 30% of total sample weight was lost in effluent from the wettest samples and effluent dry matter contents of up to 10% were recorded.

The pressure/density relation of samples Br.65/C1V1 and V2 at 1000 hours has been shown on Graph 5.4/6. It will be noticed that Perkins' results fall in a lower range than the Bridgets results and also, refering back to Graph 5.4/5 are lower than Zoerbs' results.

Perkins graphs show a rapid initial increase in density with time; settling down after about four days to a slow steady increase. The loss of strength in the fermentation process and the exponential settlement of fibrous masses both contribute to the changes in density with time observed by Perkins.

Length of chop is stated to have a major influence on the dry density. For meadow crops at unspecified pressure, dry densities of 20.4, 16.7 and 13.9 lb/ft^3 were obtained with short (½" to ¾"), medium and long chop respectively.

Unfortunately there are fundamental defects in Perkins apparatus and techniques. The use of very deep cylinders with a sample size (for 9 lb. sample) of 18" x 6" dia. at 30 lb/ft^3 falling to 9" x 6" dia. at 60 lb/ft^3 results in the vertical pressure in the bottom of the sample being very much reduced by wall friction. The pressure in the bottom of an 18' long sample might only be 10% of that applied at the top in a 6" dia. cylinder.

In a silo the maximum length of long chop material is less than 5% of the silo diameter but in a 6" dia. core it is impossible to fill long chop evenly as the maximum length is of the same order as the core dia. The dry density variation with chop length given by Perkins is unlikely to be valid in a farm silo.

The combination of maturity and moisture content variables into one variable is only valid for unwilted crops. The apparent increase in dry density achieved with increasing maturity is solely due to the effect of moisture content which determines the maximum dry density at which the crop becomes saturated and incompressible. If we compare Perkins results shown in Graph 5.4/6(a) with Graph 5.4/1 of the maximum dry densities achievable at various moisture content levels we find that:

1. The wettest samples (17.9% d.m.) reached 84% of maximum dry density (Yd max.) at under 575 lb/ft^2 pressure and higher pressures only compressed it to 88% Yd max. at 2300 lb/ft^2.

2. The 22.8% d.m. samples reached 86% Yd max. at 2300 lb/ft^2.

3. The 28% d.m. samples reached 83% Yd max. at 2300 lb/ft^2.

4. The 39% d.m. samples reached only 65% Yd max. at 2300 lb/ft^2.

The increase in density of all the three wettest samples levelled off as they reached 80% - 85% Yd max. (approx. 60 lb/ft^3 density) and effluent flow started.

The work of Perkins et al is the earliest and probably the best of the studies of the consolidation of silage to date. Their technique of ensiling the crop in the test core is of particular interest. Their results give a good qualititative picture of pressure density relationship of unwilted crops. Quantitatively the results are highly suspect because of the depth of sample used. Their conclusions are not applicable to wilted crops. Their conclusions on the effect of chop length are unlikely to be valid for silos larger than 6" in diameter.

OTIS and POMROY's(88) tests to determine pressure required to reconsolidate a sample to its in-situ density, has been discussed in Section 5.4.4.

WILLCOCKS(132) in the course of his work on the tensile strength of silage did a few consolidation tests on silage. They were all conducted on short chopped rye silage, at approx. 40% m.c. The method of consolidation used, constant deformation rate to required density, followed by 24 hours relaxation of pressure at constant density, is totally unrelated to conditions in silos.

His conclusion that:-

$Y = a \log V + b$

where Y is density

a and b are constants

V is pressure after relaxation,

is not in good agreement with his own results for densities in the range 25 - 40 lb/ft^3, and when checked against my results for the full range of densities (see Graph 5.5/20) is found to be invalid.

POLLOCK(94) conducted a number of tests on the pressure density relationship of double-chopped Sorghum silage at 70%, 52%, 31% and 0.3% m.c. The constant deformation rate compression tests method which he used gives results which depend on the deformation rate used, and the sample weight used. Pollock's results are only valid for a set of conditions which are never likely to occur in a silo. Pollock's proposed equation, which only gives an approx. prediction of his experimental values is:-

$V = Vo\ Y^c$

Vo = vertical pressure for Y = 1

Y = density

c = constant

c was found to be between 3 and 5, depending on m.c.

The dry density against pressure curves obtained by Pollock are almost identical for the 52% and 31% m.c. samples (13.95 and 13.65 lb/ft^3 at 1500 lb/ft^2). The 70% m.c. sample had a lower dry density (12.8 lb/ft^3 at 1500 lb/ft^3) at all pressures and its resistance to consolidation increased rapidly as it neared its maximum density. The very rapid loading rate used would have produced a high fluid pressure in the sample as it neared its maximum (nil gas voids) density because there would have been little time for pressure relieving drainage under rapid loading. The oven dry sample (0.3% m.c.) had a much higher resistance to compression than the other three samples (dry density 11.75 lb/ft^3 at 1500 lb/ft^2).

The method of sample preparation used by Pollock (air drying loose silage for the lower moisture contents) probably caused some losses of dry matter, which would have caused a difference in the quality between samples in addition to that due to moisture content.

The pattern of variation of pressure density observed in Pollock's work is in general agreement with the results of my own work (i.e. (1) dry density at given pressure is relatively constant, regardless of m.c. in 70% - 25% m.c. range, but is reduced markedly as the sample is further dried. (2) as a sample approaches maximum density, the silage becomes increasingly incompressible as pore pressure mounts).

Although Pollock's experimental work is of little practical value, his consideration of the applicability of visco-elastic theory to the prediction of the physical behaviour of silage is of great interest. However, silage compresses in a complex manner and will require a very complex model to predict its behaviour. Pollock's very simple Kelvin unit with spring in series proved totally inadequate, but once a sufficient mass of good experimental data has been amassed, a non-linear visco-elastic model will become a possibility. In the interim empirical formulae would seem to have more potential value than visco-elastic formulae based on over-simplified assumptions.

Pollock also mentions the work of COWAN$^{(33)}$ who carried out compressive tests on silage for horizontal silos. He proposed an equation of the form:--

$$V = C\left(\frac{h^2 - h_o^2}{2h^2}\right)^K$$

where V is pressure
C and k are constants
h is sample height
h_o is original sample height.

The problem of time dependence of the pressure density relationship was sidestepped by considering density at a fixed time only. There would seem to be considerable practical problems in determining h_o for a material as compressible as silage. However, without access to the original, it is hard to fully evaluate this work. GRAHAM, BRATZLER and KJELGAARD$^{(43)}$ used a constant strain rate apparatus for comparitive compression tests on corn silage subject to a range of mechanical treatments. The 3 lb. samples of fresh corn and silage from trial silos in 5.75" dia. x 8" cores were subjected to a constant strain rate of 1" per minute until the resistance to compression reached 20 lb/in^2 (2880 lb/ft^2). Relaxation and re-expansion tests were then carried out. The sentence "Here again significant trends are absent" used by Graham et al concisely summarises the limitations of the constant strain rate and relaxation method for testing for silage consolidation.

YAREMENKO(16) worked on the physical properties of silage in connection with the design of consolidation machinery for silage in clamp silos. He carried out constant pressure consolidation tests on grass and maize at 3 levels of moisture content at pressures up to 400 lb/ft^3. He considered that for machine design it was only necessary to consider density at constant time after the application of pressure. He did not derive any relationship between pressure and density. He determined the specific impact force required to tamp to 500 kg/m^3 as 0.002 - 0.003 kg/cm^3 per sec. It is not clear whether Yaremenko worked on the fresh crop or on silage, but the former is more probable.

To summarise, published work on the pressure density relationship of silage is largely on particular crops under very particular conditions. The tests at a constant rate of deformation are of negligible practical value. Constant pressure tests show a general pattern of rapid initial consolidation levelling off at higher pressures and a re-expansion on the release of pressure. There is no accurate and generally applicable formulae for relating density and pressure for the range of crop maturities and moisture contents encountered in practice.

5.4.6. Published Work on the Densities of Related Materials.

Grass in Trailers The density of grass in trailers used in filling gives a useful indication of the densities likely to occur in the surface layers of silage before the loss of strength in ensilage. HUNDTOFT and GUEST(50) quote the results of Cornell research on capacity of long chopped hay of 15 - 48% m.c. in trailers and give the dry densities ranging from 3 to 4 lb/ft^3. They suggest that maximum capacity occurs at 60 - 70% m.c. outside the range of their results. This is contrary to my results for 40 - 80% m.c. short chopped grass (see Section 1.4.8.) which showed a maximum dry density in the trailer (of 4.5 lb/ft^3 average) occuring at 40% m.c. or just below. The higher dry densities in trailers in my results were probably due to differences in maturity and a shorter length of chop.

PARKE and HARDING(91), as part of a study of tower silo filling routines, measured densities in trailers filled with a different field choppers on 12 farms and found dry densities ranged from 3.0 to 7.8 lb/ft^3 with a mean of 4.95 lb/ft^3.

Hay The generally quoted values for the bulk density of hay expressed as dry density are:-

loose long	3.5 - 4.5 lb/ft^3
loose chopped	6.5 - 8.5 lb/ft^3
baled	6 - 12 lb/ft^3

SHEPPERSON and CORRIE(110) report dry densities of hay ranging from 3 to 6.5 lb/ft^3 and length of chop was found to be the most important variable effecting dry density. Shopperson's figures, which were a by-product of his work on hay drying, are for a wide range of crops and maturities in driers of various depths. It is therefore not possible to quantify the effect of any one variable or develop a general relationship for predicting in-drier densities from his data.

DAY and PANDA(62) carried out consolidation tests in a 12" square box on alfalfa hay for a range of moisture contents and chop lengths. The results of their consolidation tests restated in terms of dry density against vertical pressure are set out in Table 5.4/2.

TABLE 5.4/2

Dry densities of guillotine chop alfalfa (after Day and Panda)

Moisture Contents	Chop Length	Dry Density lb/ft^3 at Vertical Pressure		
		10 lb/ft^2	50 lb/ft^2	80 lb/ft^2
66%	4"	2.1	3.8	4.55
48%	4"	2.35	4.35	5.4
30%	4"	2.3	4.7	5.65
22%	4"	2.1	4.3	5.15
11%	4"	2.1	3.8	4.6
11%	6"	1.8	3.5	4.1
11%	4"	2.2	3.9	4.6
11%	2"	2.7	4.4	5.1

It will be seen that length of chop was a most significant variable. Its effect was greatest at low pressures (dry density of 2" chop was 50% greater than 6" chop at 10 lb/ft^2 but only 25% greater at 80 lb/ft^2). Moisture content only slightly effected dry density at 10 lb/ft^2 (12% greater at 48% m.c. than at 11% m.c.) but more so at 80 lb/ft^2 (25% greater at 30% than at 11%). The highest strengths (lowest densities) occur at high moisture contents due to cell pressure strength and at low moisture contents due to increase in strength of cellulose at very low moistures. Day and Panda's analysis of their results is much more complex than their data justifies and is based on false assumptions (.e.g. length of chop has an influence which is independent of the size of container; therefore 'length ratio' is not a fundamental variable).

Hay Wafering The compression characteristics of grass and lucerne have been studied to determine the mechanism of hay wafer formation. When hay is subjected to pressures in the range 2,000 lb/in^2 to 12,000 lb/in^2 (i.e. 300,000 lb/ft^2 to 1,750,000 lb/ft^2; 500 times the pressures encountered in tower silos) in a closed die or extrusion press, the fibres are interlaced, interlocked and stuck together by the natural gums. Densities of 90 lb/ft^3 can be achieved in the die but 60 - 80 lb/ft^3 is the normal range. On leaving the die the wafer immediately expands to about twice its original thickness and within half an hour will further expand to 3 to 4 times its original thickness to give a final wafer density of 20 - 30 lb/ft^3. The bulk density in store will be about 60% of the wafer density. Bulk dry densities of wafers in store will range between 12 and 20 lb/ft^3; very similar to the dry densities obtained in tower silos.

The influence of pressure, time pressure is held, moisture content, maturity, chopping, pre-maceration and sample size on the value of wafer density has been studied by PICKARD et al$^{(93)}$, BUTLER et al$^{(22)}$ and MATTHIES$^{(72)}$. Their conclusions may be summarised as follows:-

1. Wafer Density increases at a rate proportional to log pressure.
2. Wafer Density increases at a rate proportional to log hold time.
3. Mature alfalfa required approx. 50% greater pressure to achieve the same density as young alfalfa.
4. The presence of moisture in the cells prevented the stem cells being crushed, increased pressure requirement for a given density and increased re-expansion. The practical maximum moisture content for wafers seems to be about 25%.
5. Chopping reduced the pressure required for a given density but seriously reduced durability.
6. Pre-maceration facilitated wafering in all respects.
7. The diameter and length of the wafer significantly effect the pressures required and the effects of all the above variables.

Wool. A study of the pressure density relationshop of wool by DOWNES(36) shows it to have a similar compression and re-expansion curve to hay and silage. Densities of greasy wool were 15 lb/ft^3 at 800 lb/ft^2 rising to 25 lb/ft^3 at 2150 lb/ft^3.

5.4.7. Densities in McDonald's Experimental Silos at Edinburgh.

In 1957 four 1 ton experimental silos were constructed at the Edinburgh School of Agriculture. McDONALD et al(66) give a detailed description of these silos and the results of three experiments conducted with them. Using the results given in this and further data on the volumes of silage on different dates given by McDONALD(67), I have calculated the densities and dry densities in these silos. These figures are given in Table 5.4/3 and are plotted on Graphs 5.4/7, 5.4/8 and 5.4/9 of density against time (log scale) and on Graph 5.4/10 of dry density at 1000 hours against average vertical pressure.

The experiments by McDonald et al were conducted with exceptional care and accuracy and were primarily designed to study the chemical and microbiological changes during ensilage. Experiment 1 was conducted by filling all four silos in an identical manner to determine the consistency of results. Experiment 2 was conducted to determine the effect of varying the surface consolidation pressures from 5 - 75 lb/ft^2. In Experiment 3 an attempt was made to produce overheated silages in three of the silos by loose filling, low surface pressure and, for two of the silos,

Table 5.4/3

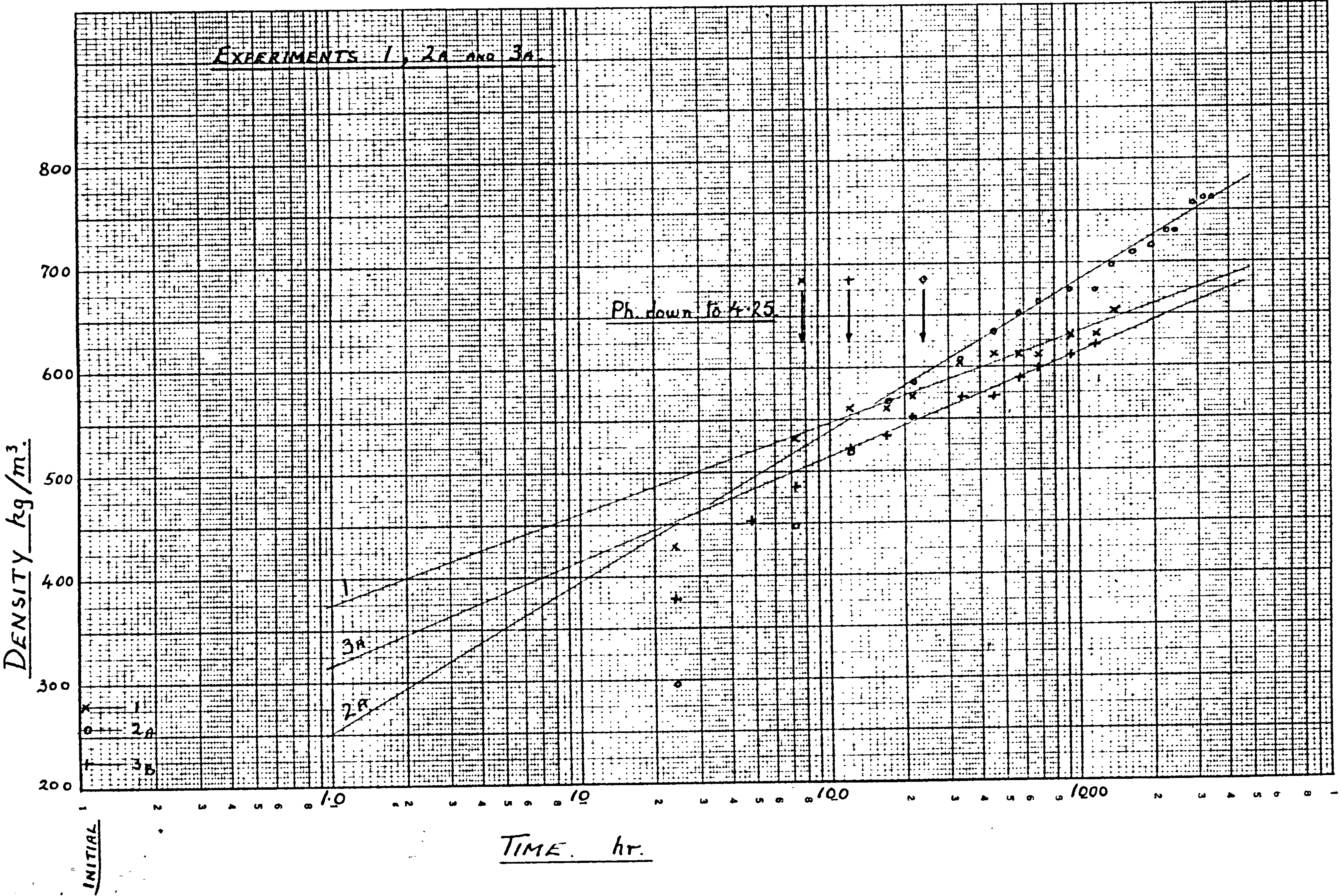
DENSITIES OF GRASS ENSILED IN EXPERIMENTAL SILOS BY McDONALD ET AL.

EXPERIMENT No.	SILO	GRASS ANALYSIS d.m. %	C.P. %	C.F. %	INITIAL DENSITY BULK lb/ft³	DRY lb/ft³	PRESSURE FILLING	SURFACE	AVERAGE	TOTAL LOSSES TOTAL %	EFF %	D. M. LOSSES TOTAL %	EFF %	SILAGE ANALYIS d.m. %	C.P. %	C.F. %	DENSITY lb/ft³ Y'	Y @ 1000h	C'	DAY DENSITY lb/ft³ Y'd	Yd @ 1000h	C'd	REMARKS
1	AVERAGE OF A, B, C, and D.	19·2	18·7	23·6	18·75	3·68	TRAMP	76 lb/ft²	126 lb/ft²	7·1	6·4	7·5	2·5	19·1	19·0	26·0	23·5	39·4	5·3	4·5	7·52	1·0	
2	A.	19·9	19·0	20·8	18·75	3·75	TRAMP	76	126	13·8	12·3	17·4	4·3	19·1	21·9	23·7	13·7	42·5	9·6	2·6	8·11	1·8	
2	B.						TRAMP	50	100	11·3	9·5	20·5	3·4	17·9	23·4	24·0	12·4	40·8	9·5	2·2	7·30	1·7	
2	C.						TRAMP	25	76	7·7	6·0	17·6	2·1	17·8	22·7	23·7	13·7	33·4	6·5	2·4	5·95	1·2	
2	D.						TRAMP	2·9	53	7·5	5·5	17·8	1·9	17·7	22·8	23·9	11·7	28·6	5·8	2·1	5·06	1·0	
3	A.	14·9	12·0	26·2	19·9	2·95	TRAMP	76	126	29·4	28·5	17·4	7·4	17·4	12·1	28·9	19·0	38·2	6·5	3·3	6·65	1·1	
3	B.				14·6	2·18	LOOSE	4·5	41	26·1	24·6	23·7	5·6	15·4	13·2	28·7	0·0	26·0	8·7	0·0	4·00	1·3	Oxygen Added
3	C.				14·6	2·18	LOOSE	3·1	40	34·3	29·5	34·6	7·7	14·8	12·5	29·9	4·9	23·0	6·0	0·7	3·40	0·9	Natural Overheat.
3	D_1				14·6	2·18	LOOSE	4·3	41	31·5	29·9	21·6	7·5	17·1	12·7	28·4	6·4	21·2	4·9	1·1	3·62	0·8	Oxygen Added
3	D_2 °				After 16 days.			81	112								19·0*	38·2	6·5*	3·2*	6·54	1·1*	* Y', C' Y'd and C'd. are only estimated

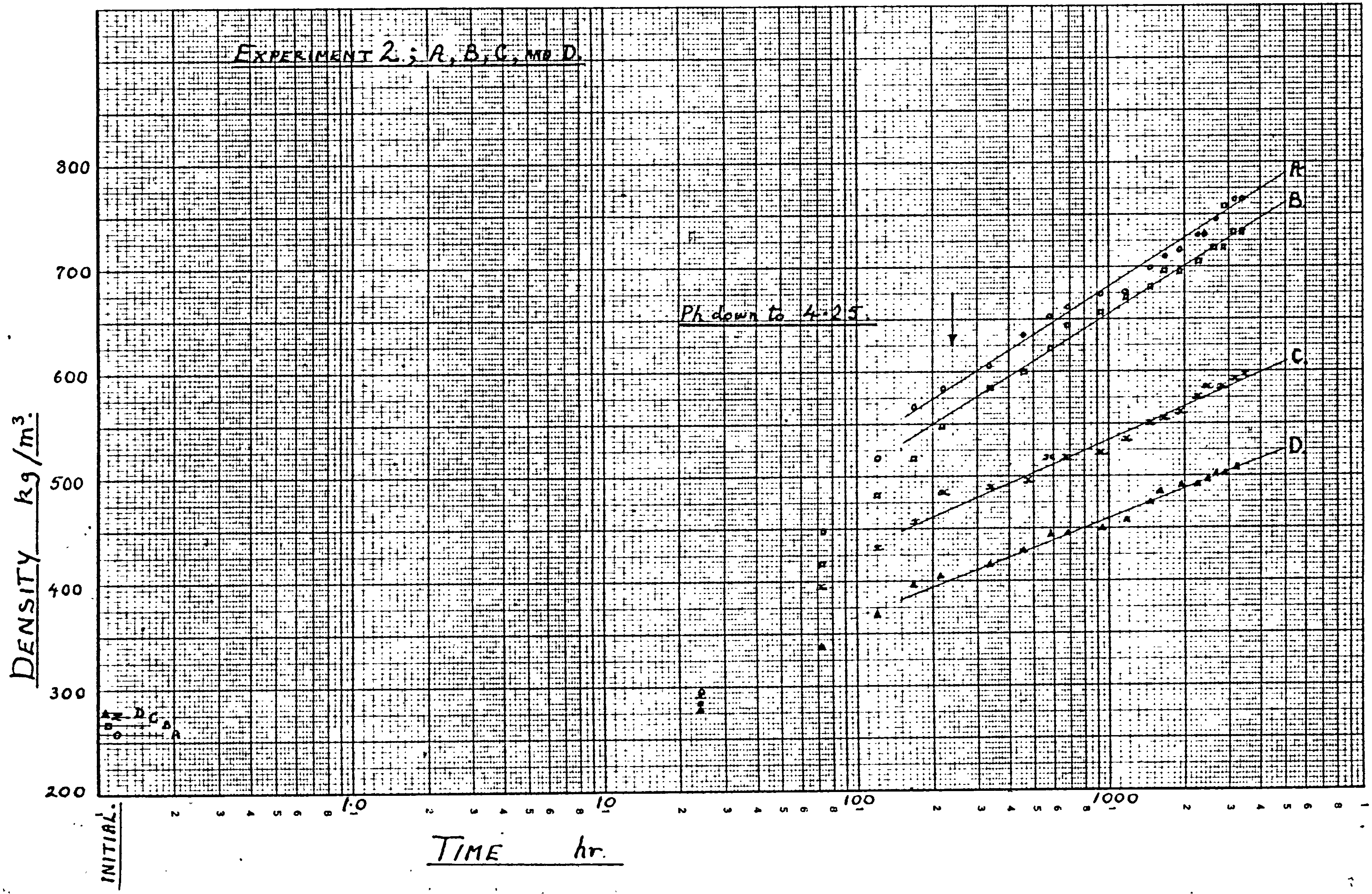
ALL GRASS - S22 Italian Ryegrass Regrowth. Mown, No Chop or Laceration.

GRAPH 5.4/7.

DENSITY OF GRASS ENSILED IN EXPERIMENTAL SILOS BY McDONALD ET AL.

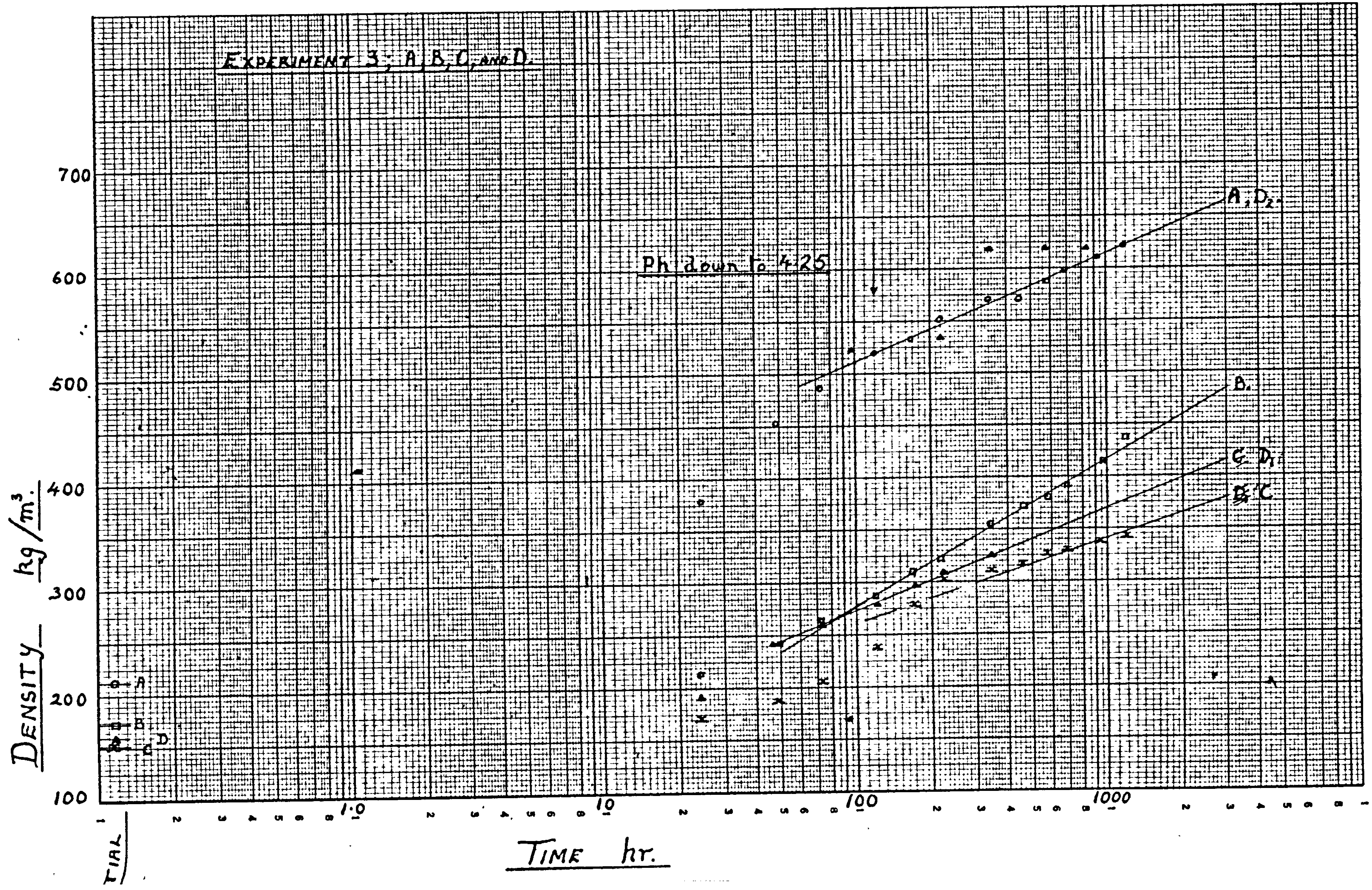


DENSITY OF GRASS ENSILED IN EXPERIMENTAL SILOS BY McDONALD ET AL.



GRAPH 5.4/8.

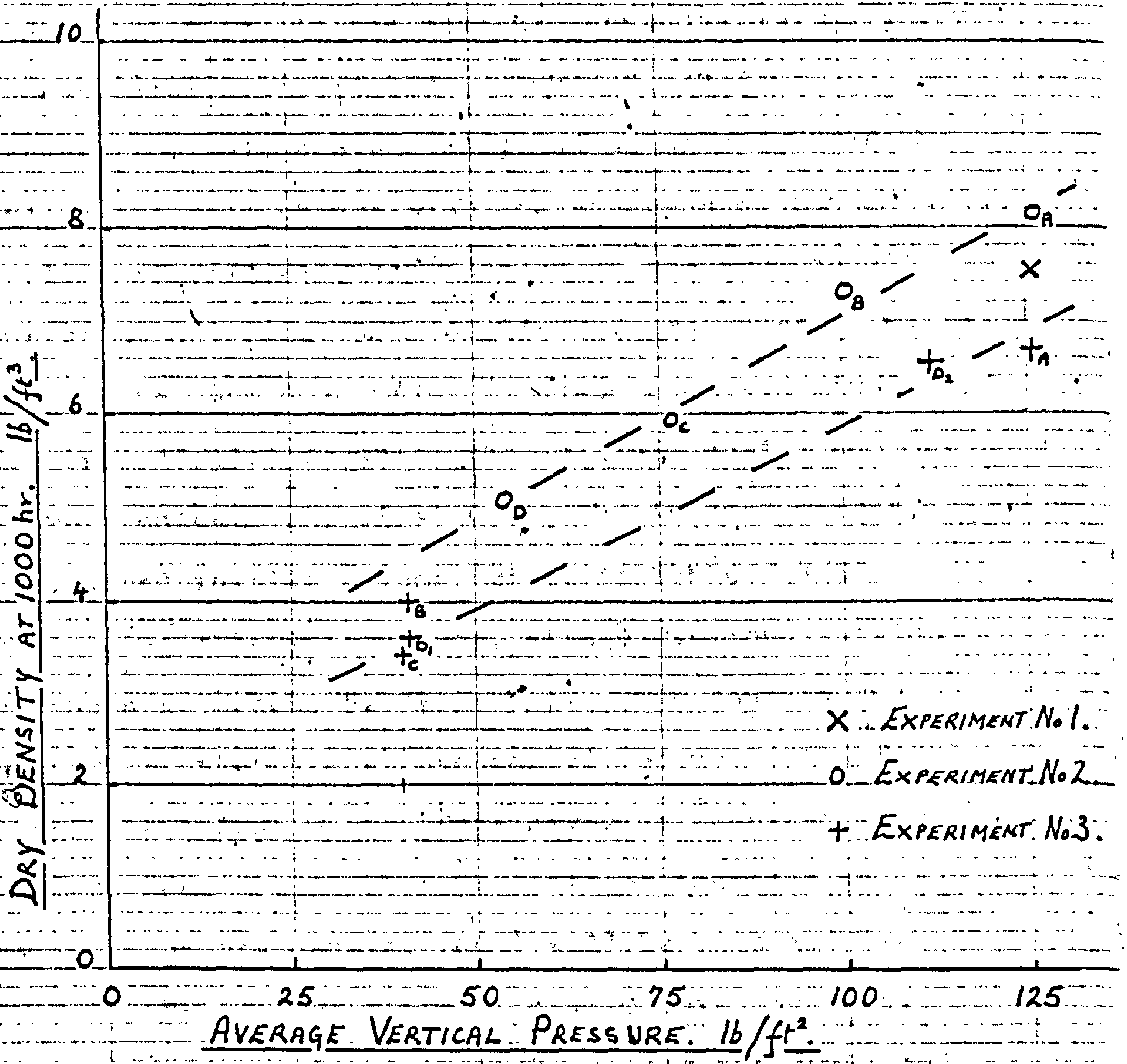
DENSITY OF GRASS ENSILED IN EXPERIMENTAL SILOS BY McDONALD ET AL.



GRAPH 5.4/9.

Graph 5.4/10

DRY DENSITY AT 1000 hr. AGAINST VERTICAL PRESSURE
CALCULATED FROM McDONALD'S DATA.



insulation and the injection of oxygen. The filling of Silo A was conducted in the same manner in all three experiments to provide a control. The grass used in all experiments was S22 Italian Ryegrass mown and ensiled the same day without wilting, chopping or laceration. However, there were variations in the moisture contents and maturity of the crop which are recorded on Table 5.4/3.

Because the moisture content, and total weight of the material in the silo change with the progress of fermentation and the loss of effluent, calculation of the true density and dry density at any time is a complicated procedure. While this could have been done using McDonald's data a simpler procedure was adopted in which the initial density and dry density were calculated, first using the initial weight, grass, m.c. and initial volume (given in Table 5.4/3), and then using the final weight, silage m.c. and initial volume (shown in Graphs 5.4/7 to 9.). The density and dry density at other times were calculated using the final weight and the silage m.c. This gives an accurate figure for the 1000 hour density but the rate of increase in density (C') and dry density (Cd') will be high and the densities in the earlier stages (1st. 10 days) too low. These errors will be slight when the losses are small but will be appreciable in Experiment 3 when the losses were 20% - 30%.

In Graph 5.4/7 the density is plotted against time (log scale) for the average results of Experiment 1, and for the results from the control Silo A in Experiments 2 and 3. The density increased slowly to start with, because of the prior over-consolidation due to tramping, then as fermentation takes place there is a more rapid increase in density which changes to an exponential increase when the fermentation is complete, (i.e. when pH$<$ 4.25). In these three experiments the time for the pH to fall to 4.25 was $3\frac{1}{2}$ days (Exp. 1), 10 days (Exp.2) and 5 days (Exp.3) and it was found that these times correspond to the end of the rapid and the start of the exponential stage of settlement. The best basis for comparison of the densities is the 1000 hour density which was read off the graph and recorded in Table 5.4/3. The values of Y' lb/ft^3 and C' lb/ft^3/log time in hours corresponding to those used in my pressure density tests were obtained from the slope of the exponential settlement and its intercept with the 1.0 hour line. These values are of limited value because

(1) C' is too great because of loss of d.m. and total weight with time.

(2) The datum time for the exponential settlement is not the time of ensiling, but the time when the rapid increase in density due to fermentation is completed.

Graphs 5.4/8 and 5.4/9 are similar to 5.4/7 but are for the results of Experiments 2 and 3. Graph 5.4/8 clearly shows the effect of varying surface pressure. Graph 5.4/9 is more confused because of the high losses deliberately produced in this experiment.

To compare these results the values of dry density (Yd) at 1000 hours have been plotted against the average vertical pressure in the silos (i.e. surface pressure + $\frac{1}{2}$ weight of grass - plan area of silo; wall friction ignored). It will be seen that the dry density is highest (8.11 lb/ft^2 at 126 lb/ft^2) in Experiment 2 which was the youngest grass (i.e. C.P. 19.0%, C.F. 20.8%). Experiments 1 (C.P. 19.2%, C.F. 23.6%) had an intermediate dry density (7.52 lb/ft^3 at 126 lb/ft^2) and the most mature grass from Experiment 3 (C.P. 12.0%, C.F. 26.2%) had the lowest dry density (6.65 lb/ft^3 at 126 lb/ft^2).

Conclusions

These experiments were on grass younger, considerably wetter and at a very much lower pressure than those covered by my experiments. They confirm a number of conclusions drawn from my experiments:

(1) That the initial rapid increase in density is due to a loss of the strength of grass as its cell pressure is released in the initial stages of fermentation.

(2) That once fermentation is completed density increases exponentially.

(3) That the dry density at a given pressure falls with increasing maturity.

(4) That effluent will drain out of silage of a high moisture content (> 80% m.c.) at considerably below saturation density.

In addition it has been possible to relate the start of the exponential settlement to the end of fermentation as indicated by the fall of pH to below 4.25.

5.5. AUTHOR'S DETERMINATION OF THE PRESSURE DENSITY RELATIONSHIP OF SILAGES AND HAY.

5.5.1. Development of Apparatus and Experimental Techniques

During the winter of 1963-64, because of the absence of reliable data on silage density, I decided to try to measure the density of silage using soil mechanics techniques. The starting point was the undisturbed sample method described in CAPPER and CASSIE(25) p.51. In practice I found that even a specially sharpened core cutter could not be rammed into the fibrous silage.

I then developed a technique for using a long chisel ended blade to pre-cut the silage below the sharpened cutting edge of the core cutter. The cutter was slowly worked into the silage surface, by first pre-cutting round with the blade, and then forcing the 6¼" dia. cutter down slightly rotating it back and forth. This technique is described in detail in Section 5.5.3.3.

Because of the slight disturbance of the sample in cutting and the re-expansion from the maximum in-situ density that occurs during unloading, I decided to re-apply vertical pressure to the sample before measuring its density. The densities obtained at pressures at and above the pressure which produces the in-situ density can then be used to calculate the in-situ density in the silo and the densities that would be obtained under higher vertical pressures.

In the first test a C.B.R. machine was used to recompress the sample at a constant deformation rate of 0.05 in/min. (the max. rate available). The load on the piston compressing the silage was measured using a proving ring. When the machine was stopped to take a reading of sample thickness, the pressure fell off rapidly. It was clear that a constant strain rate apparatus was unsuitable for obtaining useful data on the pressure density relationship of silage.

Next a K.C. Productions oedometer (Machine A) of obsolete design was adapted to accommodate silage cores so that constant pressure tests could be carried out. This type of machine can be seen in Fig.5.5/1, with a silage core under test. The lever arm gives a 10.56:1 mechanical advantage and there is a 0.6 inch range of movement on the plunger. The silage, in the cutting cylinder and end boards, rests on a base plate mounted on a screw, which can be raised up to 6" by rotating the base plate. So when the silage has consolidated sufficiently for the plunger to be nearing the limit of its travel the base plate is raised. In this way the very large settlements (up to 5" on some samples) can be accommodated. The area of the core was 0.213 ft^2 so that 10 lb. on the hanger gave 500 lb/ft^2 pressure on the piston. A maximum pressure of 5000 lb/ft^2 could be obtained with the 6¼" core.

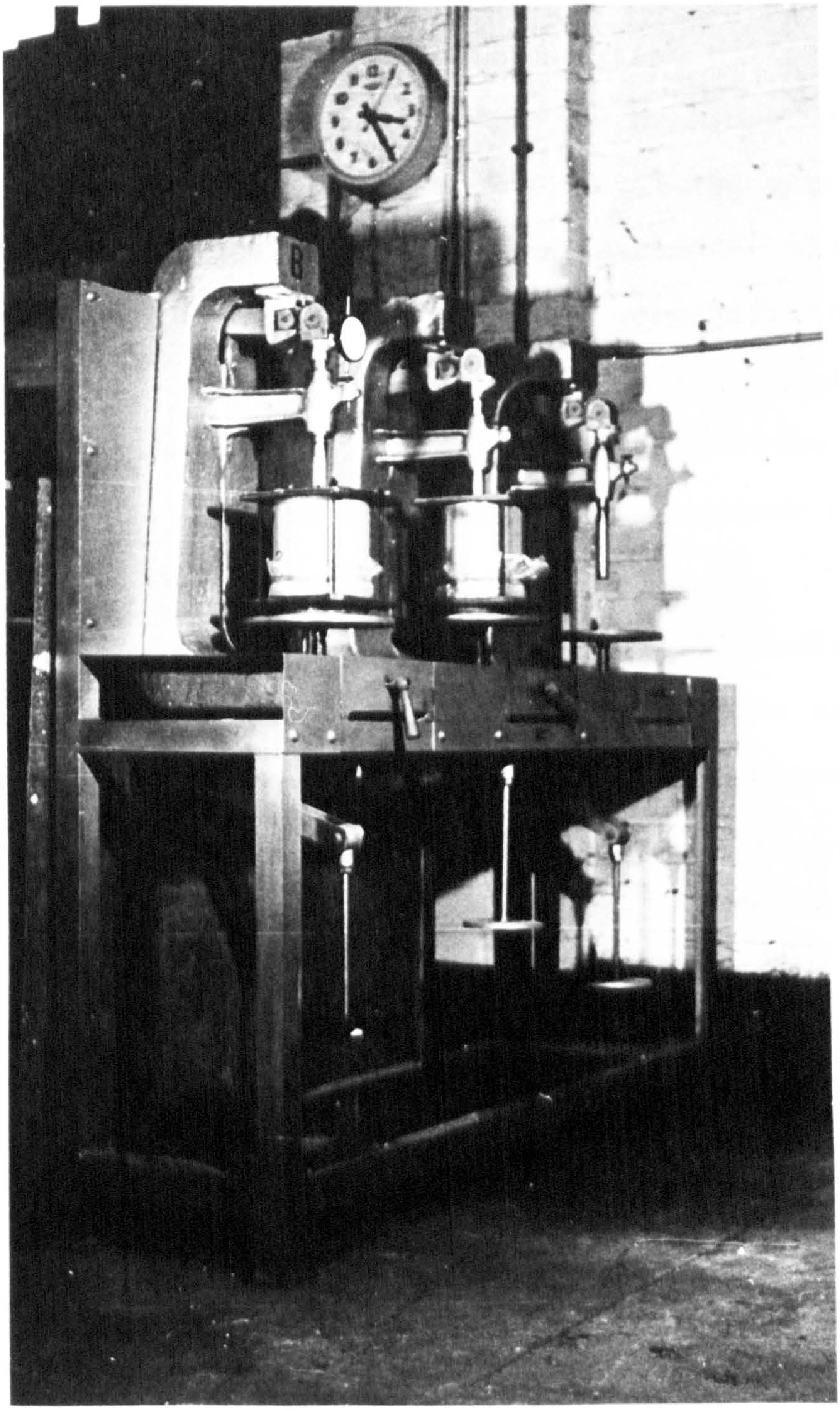


Fig.5.5/1 Lever arm consolidation machines with a sample under test. The base turntable is raised as the specimen consolidated.

In the initial consolidation test in the C.B.R. machine the silage core was compressed in the cutter using a loose fitting wooden piston. When the pressure was released at the end of the test I found that the core cutter was lifted off the base plate by the re-expanding silage.

To overcome the problem of the core lifting, to provide for an improved method of measuring the sample thickness and to facilitate the handling and storage of the sample between cutting and testing, the core cutter was clamped between two boards, grooved to locate it. This is shown in Fig.5.5/2. 4 slots were cut, equally spaced round the 4½" dia. hole in the top board, and they serve as guides for the vernier gauge used for measuring sample depth.

The sample thickness was measured with a vernier depth gauge by taking the average of four readings (one at each slot) of the distance (d) from the top of the piston to the top of the top board. The sample thickness is the difference between the average distance (d) obtained with the core empty and the average distance (d) at a given time during the test.

In the constant pressure consolidation it was found that there was a rapid initial increase in density but that the rate of increase become progressively slower. The density was therefore measured at suitable intervals of time after the application of pressure (usually 2 min, 6 min, 30 min, 1 hr, 6 hrs, 24 hrs). When the density was plotted against Log Time a straight line relationship was

FIG. NO. 5.5/2. SILAGE CORE CUTTER IN CONSOLIDATION MACHINE.

POLYTHENE SEALS NOT SHOWN.

obtained. The density was therefore stated in terms of density at a given time (initially 100 hrs from application of pressure but then standardised at 1.0 hrs from application of pressure, to simplify the mathematical expression for pressure density relationship) and a rate of increase in density with Log_{10} Time in hours.

Normally the test was run for 24 hours at each pressure level but some pressures were held for periods of up to 72 hours. To speed up testing, alternate 4 hr. and 20 hr. periods between pressure increases were used in some tests. The levels of pressure used were normally 125, 250, 500, 1000, 1500, 2000, 2500, 3000 and 4000 lb/ft^2 during loading. The test was only carried out at pressures up to that at which effluent was produced. Once effluent began to flow from the sample, the pressure was reduced to 250 lb/ft^2 then 0 lb/ft^2 to measure the re-expansion of the silage. The re-expansion had a similar linear $Density/Log_{10}$ Time relationship to the consolidation.

In the earliest tests it was found that the core cutter was severely corroded by the silage. This increased the friction between the silage and the core cutter wall, greatly increasing the error due to the reduction in pressure on the lower part of the sample. This was first countered by coating the core cutters with liquid Araldite and oven curing. This worked well until the wear from the knife during the cutting of the sample damaged the coating, necessitating frequent renewal of the coating. Later all the cores were given Metalife treatment; that is 2 coats of zinc flake in epoxy resin and two coats of stainless steel flake in epoxy resin. This gave a smooth corrosion and abrasion resistant finish which remained in good condition for three years of tests.

The loose fitting wooden piston originally used did not seal the sample from the air and some samples became slightly mouldy during the test. To reduce the risk of this a steel piston with rubber seal was developed and used in conjunction with a polythene disc to seal the top of the sample. The piston was Araldite coated to prevent corrosion. A polythene disc of diameter 10" approx. was placed over the bottom end of the core cutter and held in place by a rubber band to seal the lower end of the sample. These two measures much reduced the incidence of moulding and it was only a problem with one or two of the drier ensiled grass samples which were on test for a month.

Using one consolidation machine it was only possible to carry out 10 to 15 tests during the winter season in which silage was available. Also using samples from silos it was difficult to obtain a sufficient range of variation in the variables (variety, maturity, moisture content, length of chop, etc.) which effect the pressure density relationship, to establish the individual effects of any of these variables. This was further aggravated by the difficulties in quantitatively measuring many of these variables.

In 1964 three additional K.C. Productions oedometers (Machines B, C and D) were obtained and modified and a lever-arm consolidation machine (Machine E) was made in the Department workshops. This enabled five pressure density tests to be conducted similtaneously.

With five machines the labour of taking 4 vernier depth readings and averaging at each time interval became a problem. To overcome this each machine was fitted with a dial gauge to record the movement of the plunger. The sample thickness was obtained by measuring the thickness using the vernier depth gauge on at least 3 occasions at each level of the base plate and using the dial gauge to measure changes in thickness at other times. This considerably improved accuracy, especially for the readings shortly after load application when the sample was settling rapidly and could move appreciably in the 30 seconds required to take 4 vernier readings.

In order to be able to obtain data on the effect of variables on the pressure density relationship under controlled conditions I decided to ensile samples of grass in cores and to study the pressure density relationship before, during and after fermentation. This also enabled the apparatus to be fully utilised in the summer months.

The test procedure for ensiled grass adopted in 1964 was to spread the sample evenly in the core and then to consolidate it using the normal pressure density procedure of incremental loading. The load was held for extended periods at some suitable intermediate pressure to allow fermentation changes to be completed and then taken up to effluent pressure. In these continuous tests the effect of loss of strength during the fermentation was very hard to isolate from the pressure density relationship. In 1965 the samples were consolidated using the normal pressure density procedure up to 40 lb/ft^3; this took about 3 to 6 days. The sample was taken out of the consolidation machine and held at constant volume for one or two weeks at room temperature. It was then returned to the consolidation machine for the completion of the pressure density test up to effluent density and the re-expansion test. This two stage test with a rest in the middle enabled the pressure density relation at higher pressures to be obtained after the fermentation had been fully completed.

5.5.2. Accuracy of Pressure Density Test.

5.5.2.1. Area of Sample. The core cutters and the ensilage cores were turned to size and checked, after coating with Metalife. The nominal diameter was 6.250" and the average diameters of the cores determined across 6 diameters at 3 levels using internal calipers and vernier calipers all fell in the range 6.230" to 6.270". This would permit a maximum error in predicting area of the core of ± 0.65%. This error in area would produce an equal error, but of opposite sign, in density and in vertical pressure.

5.5.2.2. Error in Force on Piston. All five consolidation machines have been checked against a proving ring placed between turntable and plunger. The load was increased in 15 steps to that which would give 5000 lb/ft^2 pressure on a 6.250 dia. core, and then reduced in 15 steps to zero. Five replications were carried out on each machine.

The average piston pressure (for 6.250" dia. core), and the % error, at three nominal pressure levels for increasing and reducing load are shown in Table 5.5/1 for all five machines. The full results of this calibration test are in the collected data file.

From Table 5.5/1 it will be seen that for machines A to D for increasing pressure, the error ranges from + 2.0% to - 3.2%, while for decreasing pressure the error was from + 3.6% to - 0.8%. For machine E, which was built in the Department, there was a certain amount of stickiness and at 250 lb/ft^2 errors of up to 8% occured with pressure increasing and up to 20% with pressure decreasing. However these errors were much reduced at high pressures.

Because of this stickiness in Machine E, it was only used when 5 concurrent tests had to be run. Errors in the vertical pressure cause a relatively small error in the prediction of density from vertical pressure because of the flatness of the pressure density curve at all but low pressures.

In future tests machine E should be improved to minimise friction.

5.5.2.3. Error in Determining Sample Thickness. The calculated density of the silage is inversely proportional to its thickness. The thickness is calculated from the difference of two averaged measurements recorded to the

TABLE 5.5/1

Calibration Check on Pressure under Piston on Pressure Density Consolidation Machines

		Consolidation Machine				
		A	B	C	D	E
W	lb	5	5	5	5	10
Pn	lb/ft^2	250	250	250	250	250
Pi	lb/ft^2	242	242	250	248	272
ei	%	-3.2	-3.2	0.0	-0.8	+8.8
Pd	lb/ft^2	248	251	250	259	301
ed	%	-0.8	+0.4	0.0	+3.6	+20.4
W	lb	20	20	20	20	40
Pn	lb/ft^2	1000	1000	1000	1000	1000
Pi	lb/ft^2	989	1002	1012	991	984
ei	%	-1.1	+0.2	+1.2	-0.9	-1.6
Pd	lb/ft^2	1009	1015	1018	1025	1070
ed	%	+0.9	+1.5	+1.8	+2.5	+7.0
W	lb	60	60	60	60	120
Pn	lb/ft^2	3000	3000	3000	3000	3000
Pi	lb/ft^2	3015	3060	3060	3018	2955
ei	%	+0.5	+2.0	+2.0	+0.6	-1.5
Pd	lb/ft^2	3040	3070	3080	3100	3080
ed	%	+1.3	+2.3	+2.7	+2.7	+2.7

Where: W lb is load on hanger.
Pn lb/ft^2 is nominal pressure under piston in 6.25" core.
Pi lb/ft^2 is average pressure, with load increasing.
ei % is average error, with load increasing.
Pd lb/ft^2 is average pressure, with load decreasing.
ed % is average error with load decreasing.

nearest 0.005" and so the errors in measuring sample thickness can be expected to lie in the range ± 0.01". I have drawn Graph 5.5/1 on which, for given values of sample weight and density, the sample thickness can be read off and the percentage error in density per 0.01" error in thickness obtained. Provided the sample thickness does not fall below 1" the density error is less than 1%.

Because the determination of densities Y'. and Yd' is done graphically some of the errors in density will be averaged out.

In future tests the sample weight should be sufficient to give a thickness of at least 1" at maximum pressure.

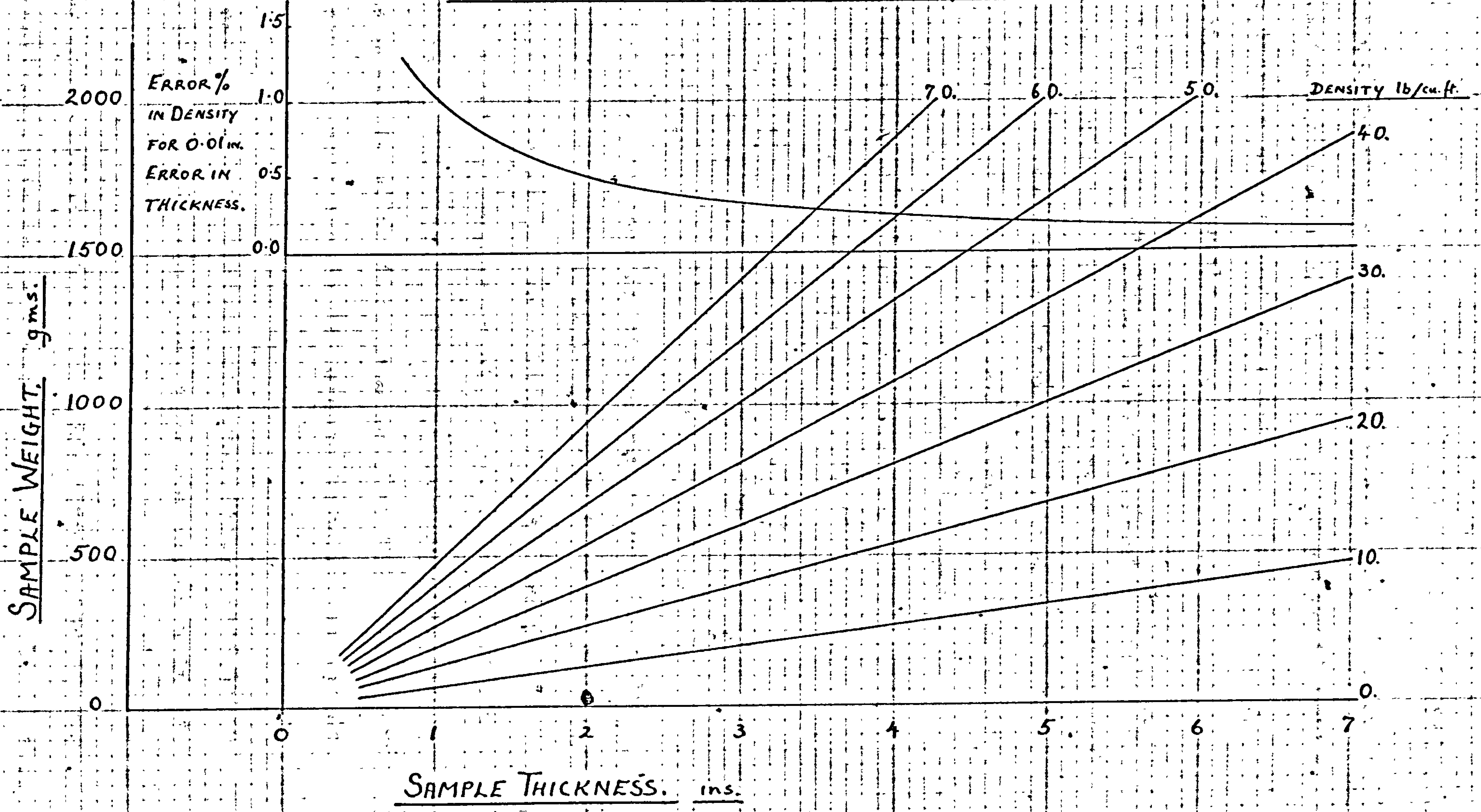
5.5.2.4. <u>Error in Determining Sample Weight</u>. The sample weight is obtained from the difference in two weights read to the nearest 0.5g. An error of ± 1g on the lightest samples (which were hay at 150 g) gives an error of ± 0.7% on density. The silage samples ranged from 400g to 1500g which gives error of ± 0.07% to 0.25% on density per ± 1g error in weight.

With the silage and ensiled grass samples there was a loss in total weight during the test. In the worst cases this amounted to 20g on a 400g sample between the start and end of test. As the average weight was used for calculating density this corresponds to an error of ± 2.5% on density. Normally the sample weight was higher and the loss was less so that this error in density was usually less than ± 1%. With ensiled grass tests the error

Graph 5.5/1

RELATIONSHIP OF SAMPLE WEIGHT, THICKNESS, DENSITY AND DENSITY ERROR.

FOR 6·25 in. dia. SILAGE CUTTER OR CYLINDER.



in density was further reduced by calculating the density for the 'before rest' period and for the 'after rest' period using the average weight for each period rather than the average weight for the whole test.

5.5.2.5. Error in Dry Density due to Errors in Determining Moisture Content. As moisture contents are expressed on wet basis relatively small errors in moisture content cause a considerable % error in dry densities. An error of ± 1% in the determination of moisture content will produce the following errors in dry density:

80% ± 1% m.c. gives dry density ± 5%
75% ± 1% m.c. " " " ± 4%
66% ± 1% m.c. " " " ± 3%
50% ± 1% m.c. " " " ± 2%

The moisture content of silage varies considerably in the silo. For example Sample Br 65/U/8, which was deliberately taken at the interface of first and second cut, had a moisture content of 61.7% in the top half and 49.3% in the bottom half. All other samples were taken as far as possible of uniform material but there is a more or less random variation in difference between the top and bottom moisture contents, ranging up to 6% m.c. As the 'after test' oven dry moisture content samples were taken one from the top half, the other from the bottom half of the core sample, and the two moisture content samples comprised about 20% to 30% of the core sample, the average 'after test' moisture content should lie within ± 1% of the true oven dry moisture content.

The 'after test' oven dry moisture content (24 hrs at 85°C) is used as the basis for calculating the dry density. The 'before test' m.c. serves only as a check in silage tests and it normally lies randomly in the range ± 2.5% m.c. relative to the after test m.c. The discrepancy is more likely to be due to variations in the silage than in experimental technique.

In ensiled grass tests the material is well mixed and there is much less variation in m.c. between samples. The difference between the before and after test samples is largely due to the fermentation changes which result in an apparent rise in moisture content of up to 5% m.c. Some of this due to respiration increasing the moisture content but most of it is due to the transformation of dry matter into volatile acids.

WILSON et al(134) discuss the errors in oven drying silage in detail. The difference between oven dry and true (toluene distillation) moisture content depends on the particular fermentation. In a series of typical comparisons on rye grass silage which R.G.Wilson of the G.R.I. provided me with, the toluene distillation moisture contents are 1.1% to 2.7% m.c. lower than the oven dry moisture contents. Although there was considerable variation the difference tended to be greatest at higher moisture contents. All dry matter densities in this thesis are expressed in terms of oven dry moisture content. The true (toluene-distillation) dry densities may be up to 10% greater depending on moisture content and fermentation.

5.5.2.6. **Error in Vertical Pressure in the Sample due to Wall Friction.** There is a frictional force between the sample of silage and the walls of the core which tends to resist the consolidation of the silage. Thus the vertical pressure (V_b) at the bottom of the core is less than the vertical pressure (V_t) applied by the piston to the top of the sample. For deep samples a full Janssen type analysis is required but where the sample thickness (T) is less than the sample diameter (d) there is little error in considering the total frictional force ($V_t - V_b$) as:

$$V_t - V_b = \left(\frac{V_t + V_b}{2}\right) k.\ u'.T.\ \frac{4\,\pi\,d}{\pi d^2}$$

where k is the ratio of lateral to vertical pressure

u' is the coefficient of friction between silage and core.

$$\therefore \quad V_b = \frac{1 - K}{1 + K} V_t$$

where $K = \frac{2\ k.u'.T.}{d}$

The coefficient of friction (u') of silage on Metalife is probably about 0.6 for wet silage but might reach 0.7. The value of k for silage is probably about 0.3 but might be as high as 0.5. Values of average vertical pressure $\frac{1}{2}(V_t + V_b)$ have been calculated for the case of k = 0.3 and u' = 0.6 and for k = 0.5 and u' = 0.7 for sample thickness of ½" to 5" with standard core diameter of 6.25'. These values are given in Table 5.5/2.

TABLE 5.5/2

Average Vertical Pressure in Sample expressed as percentage of Vertical Pressure exerted by Piston in 6.25" dia. core

Sample Thickness in.	Average Vertical Pressure % of V_t	
	for $k = 0.3$, $u' = 0.6$	for $k = 0.5$, $u' = 0.7$
0.5	97.25	94.8
1.0	94.5	89.9
1.5	92.0	85.6
2.0	89.6	81.7
3.0	85.2	74.8
4.0	81.1	69.1
5.0	77.5	64.1

The diameter of the cutting edge of the silage core cutter is fractionally smaller (approx. 1/32") than the diameter of the core body in which the sample is consolidated. This reduces the lateral pressure of the sample in the core and thus reduces the difference between V_t and V_a.

I have calculated the probable error between the vertical pressure on the piston (V_t) and the average vertical pressure on the sample $V_a = \frac{1}{2} (V_t + V_b)$ for a typical silage sample using the values of $k = 0.3$ and $u' = 0.6$.

Considering test G1/65/U/30/2 at piston vertical pressures (V_t) of 250 lb/ft^2 and 1500 lb/ft^2; sample weight was 1125 g.

When V_t = 250 lb/ft^2 1500 lb/ft^2

Y' = 39.6 lb/ft^3 59.6 lb/ft^3

Yd' = 10.5 lb/ft^3 15.85 lb/ft^3

T = 3.53 in. 2.34 in.

$\frac{V_a}{V_t}$ = 83% 88%

V_a = 208 lb/ft^2 1320 lb/ft^2

If V_a = 250 lb/ft^2 1500 lb/ft^2

Then V_t = 302 lb/ft^2 1705 lb/ft^2

for which

Yd' = 10.75 lb/ft^3 16.6 lb/ft^3

error on

Yd' = 0.25 lb/ft^3 0.75 lb/ft^3

error on

Yd' = 2.5% 4.7%

Thus although the error between V_a and V_t can reach 20% on the thicker samples the consequent error in predicting Yd' from V_t instead of V_a is less than 5%. Because of the uncertainty as to the exact values of k and u′ to use, and the effect of the reduced diameter of the cutting edge, it has been decided not to correct for this error. In the comparisons of pressure density relations to study the effect of variables this error will make little difference provided sample weights are similar. Densities and Dry Densities calculated using the uncorrected pressure density relationship will be slightly low but this will be less than 5%.

The error in ensiled grass and hay samples is much less than that for silage samples because of the lower sample weight and, for hay, the lower value of u'.

The error in pressure in the sample is likely to be greatest during the re-expansion of the sample. The friction tends to resist re-expansion. At zero piston pressure, the friction on the walls causes a significant pressure to remain on the silage in the bottom of a thick sample. For this reason the re-expansion densities recorded must be considered as approximate, the true re-expansion being greater than that recorded in these tests.

For future work the error due to wall friction could be further reduced by taking the following precautions:-

1. Restriction of the thickness of cut silage samples to about 3" (if they are thinner than this errors can arise from difficulty in measuring thickness at maximum density).
2. Coating the core with P.T.F.E. which has u' = 0.2 to 0.25.
3. If k and u' can be determined reasonably accurately a correction factor should be applied.

5.5.3. Description of the Pressure Density Test Procedure for a Silage Sample G1/65/U/30/2.

5.5.3.1. Introduction. This is a full description of the experimental procedure used for determining the pressure density relationship of silage sample G1/65/U/30/2. It is typical of the procedure used for all silage samples in this thesis, except those carried out in 1963 for which a slightly simpler procedure was used.

5.5.3.2. Preparation of Silage Core Cutter for Sampling.

The apparatus required for sampling is as follows:-

1 off 6.25" dia. silage core cutter complete with end boards and clamping rods.
1 off $7\frac{1}{2}$" dia. polythene piston seal disc.
1 off 12" dia. polythene base sealing disc.
1 off $\frac{1}{2}$" wide rubber band to fit round cutter.
1 off metal piston with rubber seal.
1 off wooden knife guide piston.
3 off 12" long chisel ended knives.
1 pr. leather gloves.
1 off 12" x 8" polythene sample bag.
1 off constant density holding clamp.

Before sampling the core cutter was sharpened and then assembled, complete with metal piston and all seals, for initial weighing and determination, with vernier depth gauge, of the average depth (d) of the piston below top board for empty core. These were recorded on the Sample Data Sheet, Table 5.5/3.

5.5.3.3. Sampling Technique for Silage Sample G1/65/U/30/2.

G1/65/U/30/2 was one of a series of moisture content, analysis and density samples taken on 20.12.65. during the unloading of the Glantlees silo. Full details of this programme of sampling are given in Section 5.5.8.5. and Graph 1.4/2. Details of sampling are recorded on the Data Sheet, Table 5.5/3.

The surface silage was cleared to a level surface 3" down before positioning the core cutter 1' to 1'6" from the wall along the sampling radius. The loose fitting wooden knife guide piston was then placed inside the core cutter and the long chisel ended knife used to pre-cut the silage round for ¼" to ½" below the cutting edge of the core cutter. The core cutter was then forced down and slightly rotated back and forth to work it down. By alternatively pre-cutting and forcing down (as shown in Fig.5.5/3 and 5.5/4) the core cutter was steadily worked down into the silage, ¼" at a time. As the cutter was worked down the silage round the outside was cleared away and a representative sample (500 g to 1000 g) of it put into the polythene bag for the 'before test' moisture content and nutrient analysis sample.

When the core cutter had been worked in about 5" it was dug out, complete with the bulb of silage below it. The silage in the inverted core cutter (with wooden piston in to prevent silage slipping down in the cutter) was then trimmed off level with the cutting edge. The metal consolidating piston with polythene sealing disc was placed on the trimmed surface of the silage. The sample was then eased down in the cutter by lowering the wooden piston and pressing the metal piston down (taking care not to cut the seals on the cutting edge) until the wooden piston was almost out of the bottom of the cutter. The cutter was then inverted (cutting edge down, wooden piston on top) and the wooden piston removed. The rubber band for

Fig.5.5/3 6¼" dia. Core Cutter in use at Glantlees. The piston inside the core cutter serves as a guide for the knife which is used to precut the silage below the core cutting edge.

Fig.5.5/4 6¼" dia. Core Cutter in use at Glantlees. The core cutter is slightly rotated back and forth as it is forced down.

sealing bottom polythene was fitted on to the core cutter. The open end was covered with the 12" dia. polythene sealing disc and the wooden bottom end board placed on it and located with the core cutter wall in its groove.

The core cutter was then turned the right way up (cutting edge up), and the top board located in place on the cutting edge, and clamped to the bottom board with four rods. The metal piston was gently pushed down to bring the sample into contact with bottom end board and the constant density holder fitted to keep the piston and sample in position, during transit, (see Fig.5.5/6). The bottom polythene sealing disc was sealed against the side of the core cutter with the elastic band.

The density sample and 'before test' m.c. and analysis samples were taken back to the Department and stored in a cold room until tested.

5.5.3.4. <u>Sample Analysis</u>. The 'before test' m.c. and analysis sample was taken to Norman Trinder, N.A.A.S. Northern Regional Nutrition Analyst who carried out the standard tests to determine:

Moisture content.	
Crude Fibre	C.F. % of d.m.
Crude Protein	C.P. % of d.m.
Digestible Crude Protein	D.C.P. % of d.m.
Digestibility of Crude Protein	% Dig.of C.P.
Acidity	pH

The results are shown on the Data Sheet, Table 5.5/3.

5.5.3.5. Pressure Density Consolidation Test for Silage Sample G1/65/U/30/2. The density sample was taken from the cold room and the piston holder removed. The 'before test' sample weight was measured and recorded to the nearest 0.5 g on the Data Sheet.

The sample was then placed on the turntable of the lever arm consolidation machine with a ball bearing in position in the seating on the metal piston. The turntable was raised until the consolidation machine plunger, at mid travel, was resting on the ball on the piston. The core was then centred and the turntable raised till the plunger was nearly at the top of its travel, and then locked. The initial depth reading (d) was taken by averaging (to the nearest 0.005") the vernier readings of distance from the top of the top board to the top of the piston, taken at each of the 4 slot positions. Fig.No.5.5/5 shows a vernier depth reading being taken. The depth reading (d) was recorded on the Data Sheet as d, (W = 0) and on the Consolidation Record (Table 5.5/4) in the vernier column for W = 2½. The time for start of consolidation and the dial gauge reading were also recorded in the appropriate columns on the Consolidation Record. The initial weight (W= of 2½ lb. (to give 125 lb/ft^2 vertical pressure) was placed on the hanger at 13.45 on 21.12.65.

Dial gauge readings (the dial gauge measures movement of the plunger) were taken at 13.47, 13.51, 14.40 and 15.15 (i.e. 2.6 and 45 mins. and 1 hr. 30 mins from application of load increment) and recorded to the nearest

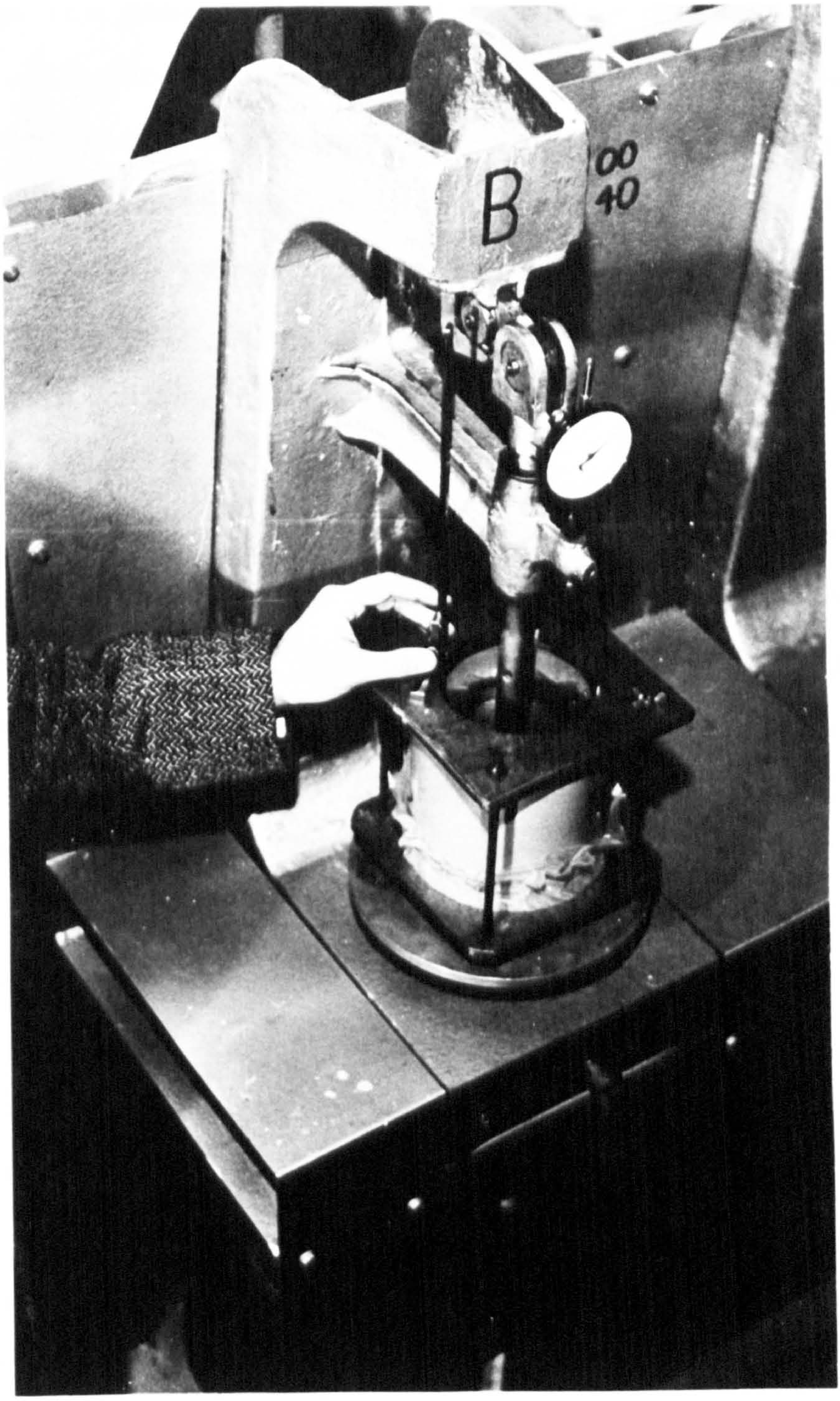


Fig.5.5/5 Silage sample under test in lever arm compression machine. The distance (d) of the top of the piston below the top of the end board is being measured with the vernier depth gauge. The polythene seals round the piston and the base of the sample can be seen.

0.005", with the time, in the Dial and Time Columns of Consolidation Record. At 14.37 and 15.37 average vernier depth and dial gauge readings were taken to the nearest 0.001" and recorded in ink on the Consolidation Record. Using these combined readings the depth readings (d) for times when no vernier reading was taken were interpolated from the dial readings and entered, in pencil to the nearest 0.005" in the Vernier Column.

Because the plunger was nearing the bottom of its travel after the vernier reading at 15.37 the turntable was raised to bring the plunger back to the top of its travel. This is marked as a double line across the Consolidation Record. At 15.43 a pair of vernier and dial readings were taken at the new turntable level.

At 15.45 the load (W) was increased to 5 lb. (250 lb/ft^2) and dial and vernier readings were taken as shown on Consolidation Record sheet. The progress of this test can be followed on the Consolidation Record sheet and it was carried according to the following rules.

1. The load was increased to give pressures in the sequence 125, 250, 500, 1000, 1500, 2000, 2500, 3000 and 4000 lb/ft^2, up to the pressure at which effluent was produced. When effluent appeared or after the period at 4000 lb/ft^2, the pressure was reduced to 250 lb/ft^2 and then to 0 lb/ft^2.
2. At each pressure at least four (usually six) depth readings (d) were taken after load application usually at 2, 6 and 30 min. and 1, 6 and 24 hours.

3. Each pressure was normally held for 24 hours. For some samples one pressure was held for up to 72 hours. On other samples alternate short (2 - 4 hr.) and long periods of pressure hold were used to reduce test time.

4. The turntable was raised whenever the plunger was nearing the bottom of its travel (dial reading more than 0.500) normally just before an increase in pressure. For re-expansion this procedure is reversed.

5. Paired vernier depth readings (d) and Dial readings were taken immediately before and after the raising of the turntable, and on at least one other occasion at each turntable level.

With Sample GD/65/U/30/2 the short test procedure of using alternate short and long periods at each pressure was used in order to complete the loading cycle before Xmas. Effluent appeared between the cutter wall and the piston polythene seal after 2.0 hours at 1500 lb/ft^2 and this was noted on the Consolidation Record. The final stage of re-expansion was carried out with the sample out of the consolidation machine using the vernier for all piston depth readings.

After the consolidation and re-expansion test was finished the core cutter was weighted for the 'after test' weight, which was recorded on the Data Sheet. The silage sample was then removed from the core as shown in Fig.5.5/7. This clearly shows the clean cut of the core and the laminated nature of silage.

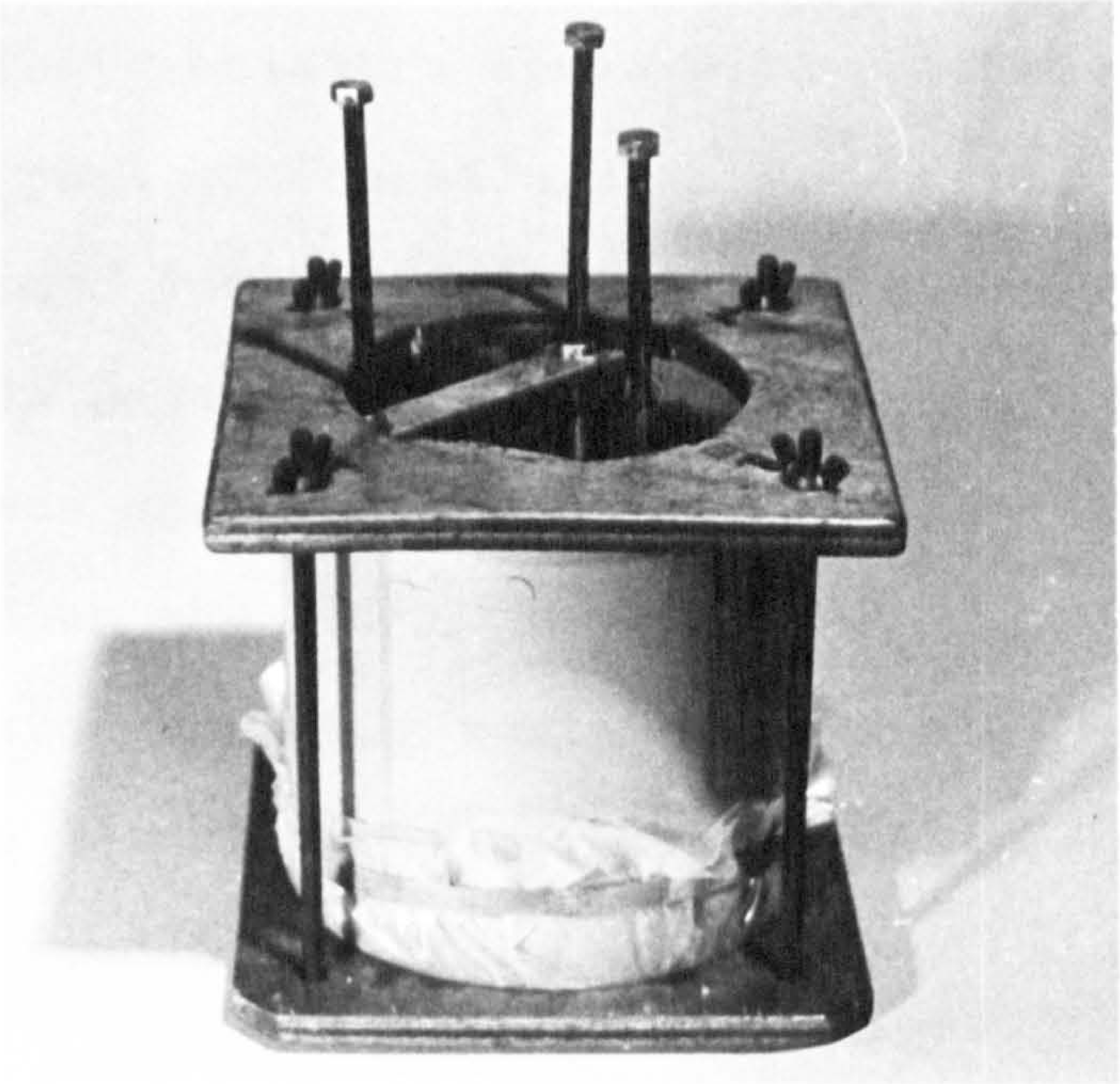


Fig.5.5/6 Core cutter with constant density holder in position as for transport and for constant density in ensiled grass test.

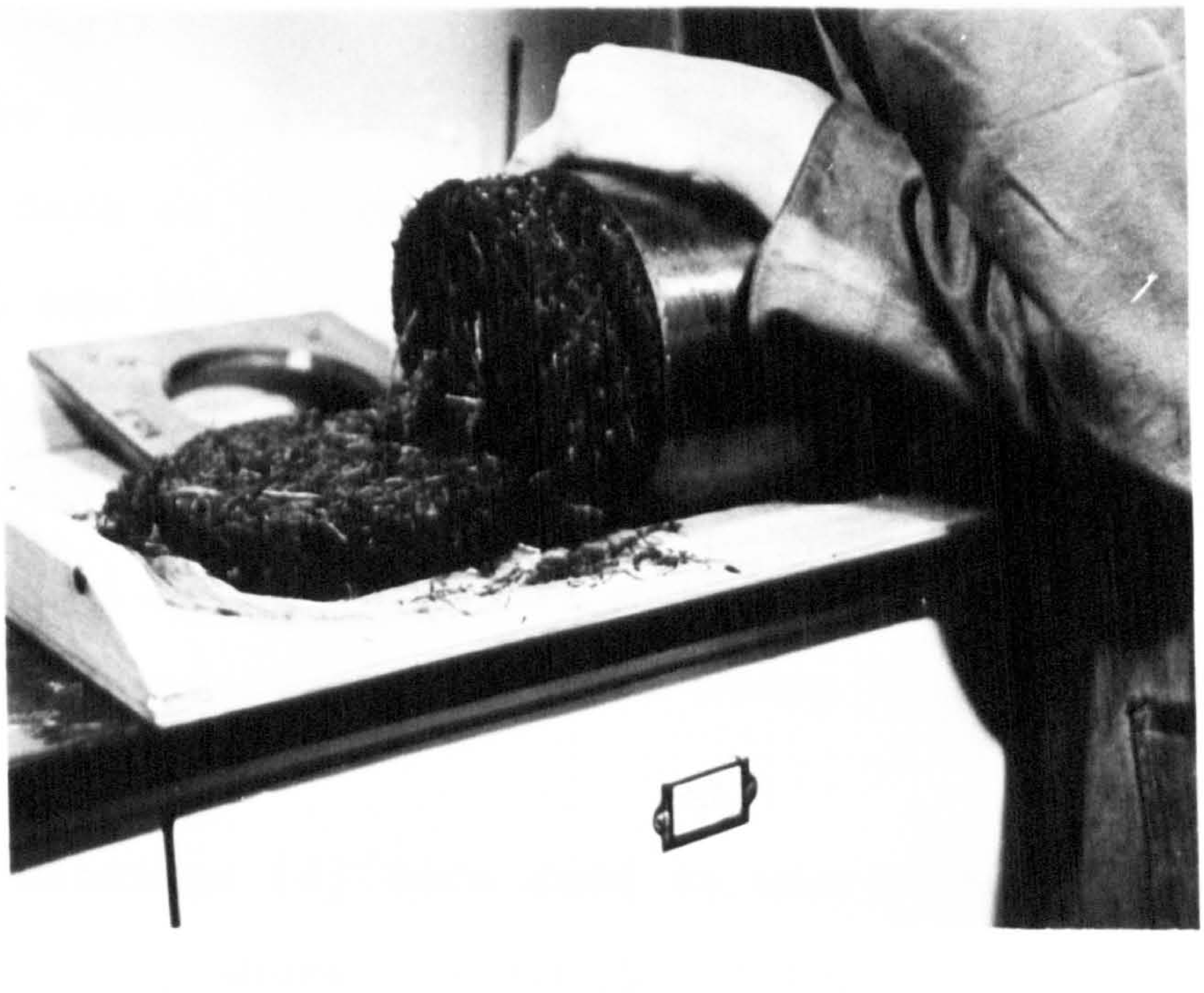


Fig.5.5/7 Silage sample being removed from core cutter after test. Note clean cut and laminated nature of silage.

Two 'after test' moisture content samples were taken, one from the top part of the silage core, the other from the bottom part, and weighed and dried for 24 hours at 85°C as recorded on the Data Sheet.

The sample was checked for mould and none was found. This was recorded on the Data Sheet.

The core cutter assembly was cleaned inside and reassembled for the 'after test' determination of empty weight and depth reading (d) for recording on the Data Sheet.

5.5.3.6. Processing of Results for Silage Sample G1/65/U/30/2

From the information on the Data Sheet (Table 5.5/3) the following figures were calculated:-

1. The average after test oven dry moisture content (73.4%);
2. The average (x) of the sample weights before and after test (1124g);
3. The average depth reading (d) in the empty core (7.055").

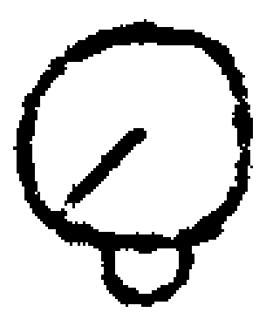
The raw data on the Consolidation Record sheet (Table 5.5/4) was then processed on the Calculation Sheet (Table 5.5/5) as follows.

1. The load (w) on the hanger was multiplied by 50 to give the vertical pressure on the piston in lb/ft^2.
2. The time was converted to Time in hours from the load increment.
3. The depth readings (d) were used to calculate the sample thickness (T), where $T = 7.055 - d$ in.
4. The sample thickness (T) was used with the sample weight (x) to calculate the sample density (Y) at each time,

Table 5.5/3

Pressure Density Data Sheet **Ref. No.** Gl/65/U/30/2

Sample from: Glantlees Silo Field:
Date: 20/12/65
Load No.
Time of Sampling: 3 pm
Level of Silage Surface 30'2" above foundation.
Field History: Sample 3" to 8" below surface, 1' to 1'6" from the silo wall along radius



Chop:

Sward:

Core/Piston: Cutter / A. Machine: A.
Core area = 0.213 ft^2 Vertical Pressure = 50 xW lb/sq ft.
Wilting:
Time of filling core: d, (W = 0) = 2.705 in.
Test Start:- Rest Start:- Rest End:- Test End:-

Storage:

Moisture Content 24 hrs. @ 85°C Oven Dry

NAAS ANALYSIS OF D.M.
C.P. 9.07 %
C.F. 34.30 %
D.C.P. 6.25 %
pH 3.7
% Dig. of C.P.
68.9 %

		T	E	F	D	G	W	m.c.	Av.m.c.	Av.D.M.
Before Test	To N.A.A.S								73.0 %	27.0 %
After Test.	Top	1	19.2	145.85	54.0	126.65	91.85	72.5	73.4 %	26.6 %
	Base	2	19.15	169.5	57.85	150.35	111.65	74.3		

	Before test			After test
When T = 0, d =	7.055 in			7.055 in.
Wt. of Empty Core	3,330.0 g.	Losses g. %		3,341.5 g.
Wt. of Full Core	4,457.0 g.	g %	% g.	4,462.0 g.
Wt. of Full Core (λ = 40)	g.	0.52 % 6 g.		g.
do. + Holder	g.	Holder Wt.	g.	g.
Wt. of Sample	x_0 = g.	AV.x_1 =	g.	AV.x_2 =
Wt. of Sample (λ= 40)	g.	1127 g.	g.	1121 g.
Wt. of D.M.	g.	Loss g.	%	299 g.

No mould on Sample after test.

Table 5.5/4

PRESSURE DENSITY TEST CONSOLIDATION RECORD.

Sample GL/65/U/30/2

LOAD W	2½			5			10			20			30			5			0		
Date	21/12/65			21/12			22/12			22/12			23/12			23/12			23/12		
	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial
	13.45	2.705	.020	15.45	3.185	.080	9.00	3.60	.065	11.00	3.94	.415	9.00	4.54	.020	11.20	4.655	.599	13.30	4.515	.460
	13.47	3.045	.370	15.47	.445	.345	9.02	.805	.280	11.01	4.215	.690	9.02	.625	.105	11.22	.575	.520	13.32	4.280	.2[illegible]
	13.51	3.07	.395	15.51	.475	.375	9.06	.835	.310	11.02	4.26	.060 .110	9.06	.65	.130	11.30	.545	.490	13.36	4.215	.100
	14.30	.12	.445	16.15	.52	.420	9.30	.885	.360	11.06	.31	.160	9.30	.69	.170	11.45	.535	.480	13.57	4.09	
	14.37	3.135	.458	16.21	3.525	.427	9.37	3.993	.373	11.08	4.320	.171	9.37	4.699	.176	13.23	4.514	.459	14.27	4.039	
	15.15	.145	.470	22.30	.575	.478	10.51	3.938	.411	11.30	.385	.235	10.55	4.14	.225×				9/12 9.00	3.957	
	15.37	3.155	.482	22/12 8.15	.585	.485				11.40	4.398	.248	11.07	4.751	.669						
	15.43	3.1[illegible]	.078	8.44	3.586	.490				13.15	.45	.300									
				8.48	3.593	.059				15.00	.475	.325									
										16.00	4.498	.339									
										23/12 8.59	4.536	.587									
										8.45	4.536	.017									

×QUANTITY OF EFFLUENT AT BASE.

Table 5.5/5

CALCULATION SHEET.

PRESSURE DENSITY RELATION TEST

Sample No. Gl/65/U/30/2

Taken on. 20/12/65.

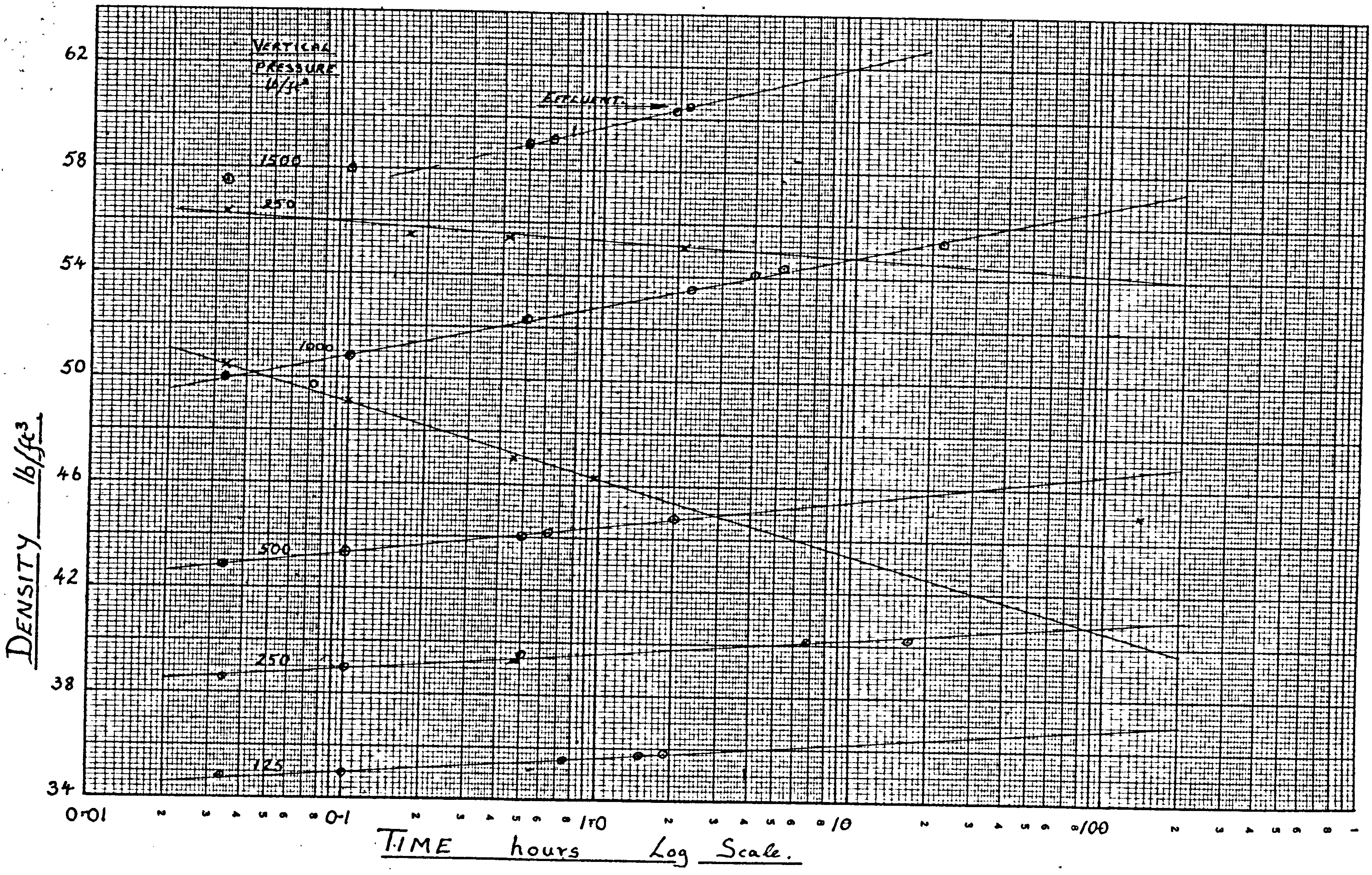
Taken from Glantees Silo

Moisture Content 73·4%

Load on Hanger	Vertical Pressure	Time from start of test	Time from load increment	Depth Reading	Sample Thickness 7·055-d.	Density 139·5/T
W.lb.	lb/ft^2	hrs. min	hrs.	d. in	T. in	lb/ft^3
0	0		0·00	2·705	4·35	32·1
2½	125		0·033	3·045	4·01	34·8
			0·10	3·07	3·985	35·0
			0·75	3·12	3·935	35·5
			1·50	3·145	3·91	35·7
			1·87	3·155	3·90	35·8
5	250		0·00	3·185	3·87	36·1
			0·033	·445	3·61	38·6
			0·10	·475	3·58	39·0
			0·50	·52	3·535	39·5
			6·75	·575	3·48	40·1
			17·00	3·585	3·47	40·2
10	500		0·00	3·60	3·455	40·4
			0·033	·805	3·25	42·9
			0·10	·835	3·22	43·4
			0·50	·885	3·17	44·0
			0·62	·90	3·155	44·2
			2·00	3·94	3·115	44·8
20	1000		0·00	3·94	3·115	44·8
			0·033	4·26	2·795	50·0
			0·10	4·31	2·745	50·8
			0·50	4·385	2·67	52·3
			2·25	4·45	2·605	53·5
			4·00	·475	2·58	54·1
			5·13	·49	2·565	54·4
			21·75	4·535	2·52	55·4
30	1500		0·00	4·54	2·515	55·4
			0·033	·625	2·43	57·5
			0·10	·65	2·405	58·0
			0·50	·69	2·365	59·0
			0·62	·70	2·355	59·2
			1·92	·74	2·315	60·3
		QUANTITY OF EFFLUENT, FROM BASE.	2·12	4·75	2·305	60·5
5	250		0·00	4·655	2·40	58·1
			0·033	·575	2·48	56·3
			0·17	·545	2·51	55·5
			0·42	·535	2·52	55·4
			2·05	4·515	2·53	55·1
0	0		0·00	4·515	2·53	55·1
			0·033	·28	2·775	50·4
			0·10	·215	2·84	49·1
			0·45	·09	2·965	47·0
			0·95	4·04	3·015	46·3
			139·5	3·96	3·095	45·0

GL/65/U/30/2.

DENSITY AGAINST TIME.



GRAPH 5.5/2.

where $Y = \frac{x}{8.05T}$ lb/ft^3.

$$Y = \frac{139.5}{T} \text{ lb/ft}^3.$$

The values of time and density for each pressure level were then plotted on Graph 5.5/2 with time on the log axis. The excellent fit of a straight line to experimental points can be seen in this graph. The only erratic points are the 2 and 6 min. points at the 1500 lb/ft^2 pressure level.

TABLE 5.5/6

Pressure Density Relation of Sample G1/65/U/30/2

Moisture Content 73.4% m.c. i.e. 26.6% d.m.

Initial Density $Y = 32.1$ lb/ft^3

$Y_d = 8.54$ lb/ft^3

V	Y'	Yd'	C'	Cd'
125	35.6	9.45	0.62	0.16
250	39.6	10.5	0.63	0.17
500	44.4	11.8	1.07	0.28
1000	52.8	14.05	1.95	0.52
1500	59.65	15.85	2.35	0.62
250	55.3	14.7	-0.6	-0.16
0	46.5	12.4	-2.7	-0.72

Where V is Vertical Pressure on Piston; in lb/ft^2

Y' and Yd' are the Density and Dry Density, 1 hour after the application of pressure; in lb/ft^3.

C' and Cd' are the rate of increase of Density and Dry Density per Log_{10} hours from application of Pressure V; in lb/ft^3/Log_{10}hr.

Effluent flowed from base of the sample at:

$Y = 60.5$ lb/ft^3 after 2.0 hrs at $V = 1500$ lb/ft^3

$Yd = 16.1$ lb/ft^3.

This is due to the prior over-consolidation of the sample at the 1000 lb/ft^2 pressure level at which it reached 55.4 lb/ft^3. The effect of prior over-consolidation is discussed in Section 5.5.6.

The 140 hour reading for re-expansion of 0 lb/ft^2 is way off and it would appear that the dried effluent made the seal sticky and jammed the piston during the final stages of re-expansion.

The density (Y^T lb/ft^3) at time T hrs. after the application of pressure increment can be expressed in the form $Y^T = Y' + C' \; Log_{10}T$

where Y' is the density when T = 1.00 hrs.

The dry density (Yd^T lb/ft^3) can be expressed as

$Yd^T = Yd' + Cd' \; Log_{10}T$

where Yd' is the dry density when T = 1.00 hrs.

$$Yd' = Y' \times \left(\frac{100 - m}{100}\right)$$

$$Cd' = C' \times \left(\frac{100 - m}{100}\right)$$

where m% is the wet basis moisture content.

In Table 5.5/6 the results of the test are summarised and the values of Y', Yd', C' and Cd' obtained from Graph 5.5/2 are set out.

These figures (except Cd') are set out with full details of the sample in Table 5.5/14 with the results of the other pressure density samples taken during the unloading of Glantlees in 1965. The dry density at 1.00 hr. (Yd') is plotted on Graph 5.5/9, against Vertical Pressure with the results of the other samples from the top 20 ft. of Glantlees in 1965.

In Graph 5.5/21, $e^{\frac{Yd'}{70}}$ is plotted against vertical pressure (V) and a straight line relationship obtained to give the values of E and F in the equation

$$Yd' = 23.03 \ \mathrm{Log}_{10} \ (E + F \times V \times 10^{-3}).$$

The plot for G1/65/U/30/2 is not shown but is similar to G1/65/U/30/3. The values of E and F obtained from the plot of G1/65/U/30/2 where E = 2.40 and F = 1.75 and these are recorded with sample details in Table 5.5/22 along with all the other silage samples.

The values of Cd' for G1/65/U/30/2 have been recorded with the values for all other silage samples in Table 5.5/25. The averaged values of Cd' for groups of tests, given in Table 5.5/27 have been used to study the relationship of Cd' to Vertical Pressure.

5.5.4. Description of the Pressure Density Test Procedure for the Ensiled Grass Sample GD/65/3/1

5.5.4.1. Introduction. This is a description of the experimental procedure used for determining the pressure density relationship of ensiled grass sample GD/65/3/1. It is typical of the technique used for all ensiled grass samples in 1965 and similar to that used in 1964. Where the technique used for a sample was materially different from that described here, the variations in procedure are noted in the Review of pressure density tests, Section 5.5.8.

5.5.4.2. Preparation of Core Cylinder for Test. The apparatus required differed from that used for cut silage in the following respects.

1. The core cylinder had no cutting edge and was a true cylinder.
2. The knives, leather gloves and wooden piston were not required.
3. A wooden sample mixing tray approx. 30" x 18" with three edges was used.
4. A camera and scale stick marked in inches and 6" were used for recording the appearance of the standing and chopped crop.
5. A bottle of silage lacto-bacilli culture and syringe for application was used.

As with the silage sample the 'before test' empty weight and average depth reading (d) were obtained on the fully assembled core cylinder and recorded on the Data Sheet, Table 5.5/7.

5.5.4.3. Sampling Technique for Ensiled Grass Sample GD/65/3/1. GD/65/3/1 was the third of a series of 5 samples for measuring the pressure density relationship of material, as filled, in the Glantlees Silo. The aim being to enable a comparison to be made between the results obtained from the ensiled grass test and the results for the same material cut as a silage core during the unloading of the silo. Details of the sampling are given in Section 5.5.8.3. and Graph 1.4/2 of the filling record of Glantlees.

Grass was collected as it fell from the Gehl trailer onto the blower feed table during the unloading of Load No. 130 at 16.00 on 29.6.65. and placed in a pillow case. The grass had been cut that morning in Cow Pasture with a flail mower. The sward was predominately rye grass. The grass had been chopped and blown into the trailer using a N.H.717 chopper set to 3/16" theoretical which gave a chop length range of 3/16" - 2", well lacerated. Because of the use of a (possibly badly set) flail mower there was a certain amount of soil in the sample. The level in the silo was 37'6". All these details were recorded on the sample Data Sheet, Table 5.5/7.

The pillow case sample was emptied onto the sample mixing tray. Following the poor fermentations obtained with the samples from Bridgets and the N.I.R.D. I decided to inoculate the sample with a lactobacilli culture obtained from the M.A.F.F. to ensure a supply of the right bacteria. The culture was sprinkled onto the sample using a syringe and the sample then thoroughly mixed. The open core cylinder was placed on the sample tray beside the polythene 'before test' m.c. and analysis sample bag. The core cylinder was filled in three layers. Each layer was built up by evenly sprinkling material alternately in the core cylinder and into the m.c. sample bag. Each layer was gently prodded down with the fingers before the next layer was filled. Fig.5.5/8 shows a core cylinder (for sample GD/65/5/1) full, just before the piston was fitted. The sprinkled out material on the tray gives an idea of the

Fig.5.5/8 Ensiled grass sample GD/65/5/1
showing filled core and length of chop.

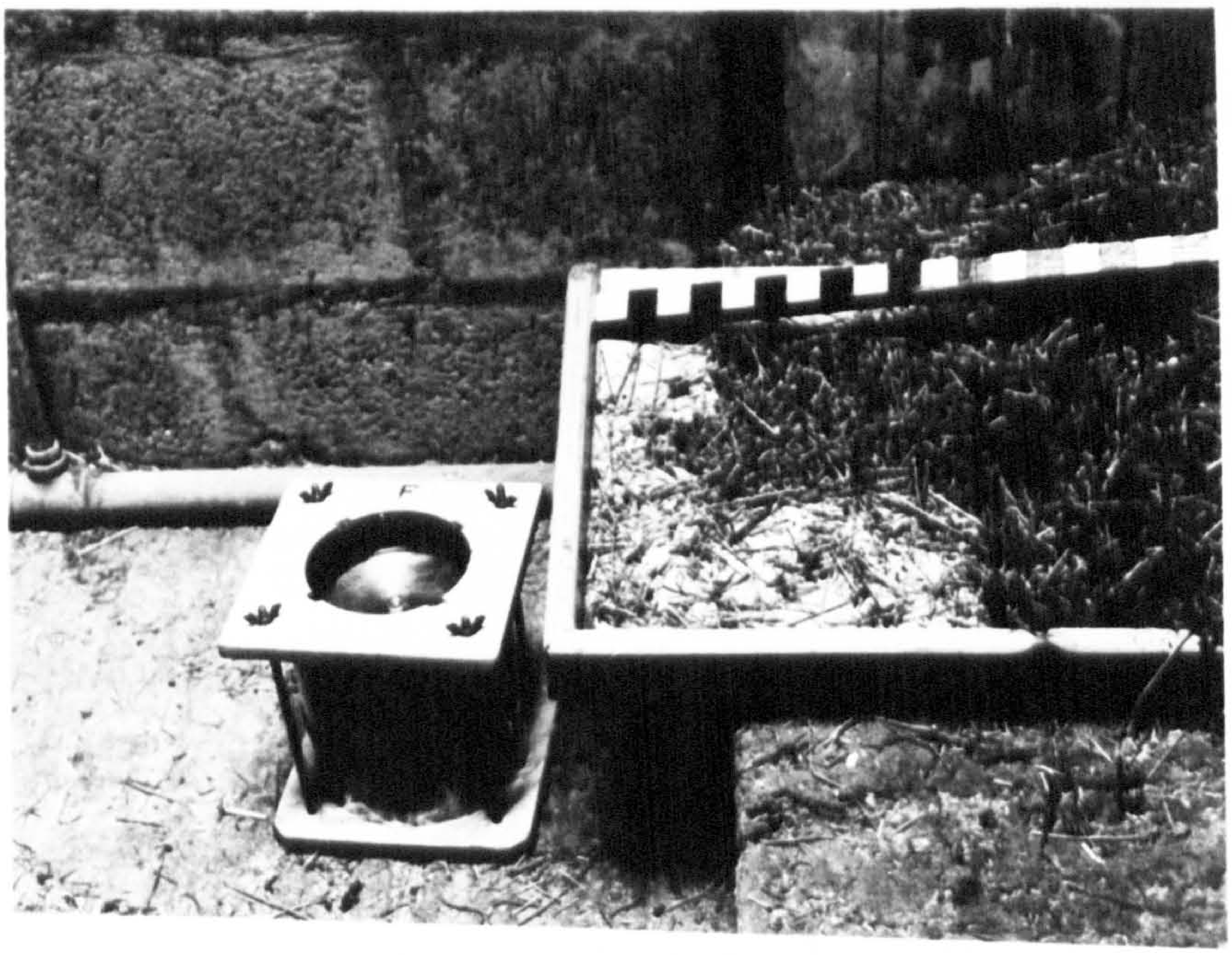


Fig.5.5/9 Ensiled grass sample GD/65/1/1
showing core cylinder full and assembled.

chop length (the scale stick is marked with 1" squares) which was encountered at Glantlees. The piston and polythene seal were fitted to the core cylinder, the top board clamped on and the piston gently pushed down onto the surface of the sample. The assembled core (for test GD/65/1/1) is shown in Fig.5.5/9. The m.c. sample bag was sealed and labelled. The remaining part of the original sample, which was to be dried for Hay sample GD/65/3/2, was returned to the pillow case bag.

The three samples were taken back to the department. The 'before test' moisture content sample was stored in the cold room until testing.

The sample in the pillow case was put in the lab. drier and dried with warm air to hay. The dry sample was stored in a polythene bag until a pressure density test was carried out on it, as Hay sample G1/65/3/2 in April 1966.

The density sample was stored in the lab. overnight and on the morning of 30.6.65. it was weighed and the initial depth reading (d) taken; these were recorded on the Data Sheet, Table 5.5/7. From the sample weight the depth reading (d) to give a density of 40 lb/ft^3 was calculated and entered on the Consolidation record sheet (Table 5.5/8(a)).

The consolidation test was then carried out as for silage samples except that:-

1. The first part of the test, on the ensiling grass, was taken up only to 40 lb/ft^3.
2. Because of the low initial density of the grass the turntable had to be raised more frequently.

3. As sample was nearing the required 40 lb/ft^3 density at the end of 24 hours at 500 lb/ft^2; the pressure was only raised to 625 lb/ft^2 at the next increment.

When the required 5.245" depth reading was reached (to give 40 lb/ft^3) the constant density holder (which had previously been weighed) was fitted and the weight on the consolidation machine removed. The record of this 'before test' consolidation is on the Consolidation Record Sheet, (Table 5.5/8(a)).

The sample was then taken from the consolidation machine, weighed and stored in the laboratory for a week at constant density to enable fermentation to be completed. On all other sets of tests (i.e. except GD/65/1-5/1) this rest period was two weeks to enable the machines to be kept in constant use.

On the 10.7.69. Sample GD/65/3/1 was weighed and then returned to the consolidation machine where the consolidation was restarted. The test was continued as shown on the 'after test' Consolidation Record Sheet, Table 5.5/8(b). At 500 lb/ft^2 there was negligable movement of the piston and the holder remained fixed in. On the 11.7.65. the pressure was increased to 1000 lb/ft^2 and consolidation restarted; the holder came free at between the 6 min. and the 15 min. reading. The test was continued using the same procedure as for silage. Effluent appeared at the top of the sample after 6 min. at 3000 lb/ft^2. When the re-expansion test was completed the final weight, moisture content and empty depth readings were obtained as for silage.

The small amount of mould observed was recorded on the Data Sheet. The quality of the silage produced was noted and its pH was measured. This sample had produced excellent acetic silage with a pH of 3.55.

The 'before test' moisture content sample was divided in two and weighed and oven dried and the dry matter was stored and taken to Norman Trinder of the N.A.A.S. for analysis for Crude Protein and Crude Fibre; the results of which were added to the Data Sheet when available.

5.5.4.4. Processing of Data for Ensiled Grass Sample GD/65/3/

The processing of the data for ensiled grass is almost identical to that for silage. Only the differences in procedure are described in this section.

In the calculation of densities on the Calculation Sheets (Tables 5.5/9(a) and (b)) the average of the initial and 'before rest' sample weights was used for the first part of the consolidation test (up to 40 lb/ft^3) and the average of the 'after rest' and final sample weights used for the second part of the consolidation record; the density being $\frac{68.4}{T}$ lb/ft^3 'before rest' and $\frac{67.2}{T}$ lb/ft^3 after rest. On Graphs 5.5/3 and 5.5/4 of the Density Time relationship it will be noticed that at the 625 lb/ft^2 pressure before the rest not enough points were obtained to give an accurate value of Y' or C'; the approximate values are therefore bracketed in Tables 5.5/10 and 5.5/12.

Similarily with the restart of the test there was no settlement at 500 lb/ft^2 and so the values of Y' and C' are bracketed and crossed through.

The total elapsed time from the start of the test (i.e. sealing of sample in core cylinder) is calculated on the Calculation sheet (Table 5.5/9) and given on Table 5.5/10 and Table 5.5/12 as the time to application of increment of Vertical pressure. The 'after rest' density and dry density are given in addition to the initial density and dry density in Tables 5.5/10 and 5.5/12.

In plotting Yd' against Vertical pressure the 'before rest' and 'after rest' sections have been considered separately. In Table 5.5/21 of the coefficients E and F, the values for 'before rest' are given above those for the 'after rest' period (E = 1.60 before rest, 2.00 after rest). Similarily in Table 5.5/26 of Cd' the 'before rest' values are given above the 'after rest' value.

5.5.5. Procedure for Hay Samples.

The procedure for carrying out consolidation tests on hay samples was the same as that for ensiled grass except that:-

1. The sample was usually of grass identical with that used in silage tests but dried to about 10% m.c. in a warm air lab. drier or Unitherm drier at 40°C.
2. The test was run up to 4000 lb/ft^2 without a rest period as there were no fermentation changes.

Pressure Density Data Sheet **Ref. No.** GD 65/3/1.

Sample from: Glantlees
Field: Cow Pasture
Date: 29/6/65
Load No. 130
Time of Sampling: 16.00
Level: 37'6"
Field History: Cut a.m. 29/6 with flail mower

Chop: New Holland 717 Set to 3/16" theoretical. 3/16" – 2" well lacerated. Silage Inoculated.

Sward: Mainly Rye Grass. see Photo. Less earth in sample than in GD 65/1, and GD 65/2.

Core/Piston: H
Machine: C
Core area = 0.213 ft^2
Vertical Pressure = .50 xW lb/sq ft.
Wilting: as filled.
Time of filling core: 17.00
d (W = 0) = 2.63" in.
Test Start:- 0900, 30/6. Rest Start:- 1130, 3/7. Rest End:- 2030 [illegible] Test End:- 1400 [illegible]

Storage: At Lab room temperature during rest period.

Moisture Content 24 hrs. @ 85°C Oven Dry

N.A.A.S. Analysis
C.F. 30.1 %
[illegible] 3.01 %

		T	E	F	D	G	W	m.c.	Av.m.c.	Av.D.M.
Before Test		18	18.95	135.3	57.4	116.32	77.9	67.0	67.2 %	32.8 %
		19	18.65	152.85	62.3	134.2	90.55	67.5		
After Test	Top	19	18.7	141.5	56.9	122.8	84.6	68.9	69.0 %	31.0 %
	Base	20	18.8	102.1	44.6	63.3	51.5	69.0		

	Before test			After test
When T = 0, d =	6.965 in			6.96 in.
Wt. of Empty Core	4390.5 g.	Losses 13 g. → 2.36 %		4392.0 g.
Wt. of Full Core	4945.5 g.	8.5 g ↓ % % ↑ 0 g.		4934.0 g.
Wt. of Full Core (λ = 40)	4937.0 g.	% → 3 g.		4934.0 g.
do. + Holder	5148.0 g.	Holder Wt. 211g g.		5145.0 g.
Wt. of Sample	x_0 = 555.0 g.	Av. x_1 =	542 g.	Av. x_2 =
Wt. of Sample (λ = 40)	546.5 g.	551 g.	542 g.	542 g.
Wt. of D.M. INITIAL AND FINAL	182 g.	LOSS, apparent. 14 g.	7.7 %	168 g.

No effluent at base.
Good Acetic Fruity silage pH 3.55
Mould 0-5/8" from wall 3/8" deep round top only.

Table 5.5/8(a)

PRESSURE DENSITY TEST CONSOLIDATION RECORD

Sample: GD 65/3/1 BEFORE REST.

Estimated vernier reading for density of 40 lb/ft³ · 5·245

LOAD W	2½			5			10			12½		
Date:	30/6	Vernier	Dial	1/7	Vernier	Dial	2/7	Vernier	Dial	3/7	Vernier	Dial
	9·00	·263	·040	9·00	3·845	·015	9·00	4·645	·065	10·45	5·205	·190 ·240
	9·01	3·16	·570	9·02	4·16	·330	9·02	·875	·295	10·47	·225	·210
	9·02	·255	·095	9·06	·215	·385	9·06	4·925	·345	10·51	·23	·215
	9·04	3·334	·175	9·30	·29	·460	9·35	5·00	·420	11·30	·25	·235
	9·06	·415	·255	9·31	4·296	·465	9·45	·015	·435	11·35	·255	·240
	9·08	·445	·285	9·37	4·336	·064	9·49	5·015	·439	Holder in		
	9·20	·525	·365	11·00	·42	·150	9·54	5·03	·016	to keep at constant		
	9·31	·56	·400	11·55	·445	·175	11·56	·09	·075	density during rest period.		
	9·37	3·579	·420	13·15	·475	·205	15·15	·13	·115			
	10·44	3·628	·471	15·00	·505	·235	16·30	·14	·125			
	10·54	3·644	·056	15·50	·52	·250	19·30	·16	·145			
	12·00	·68	·090	4/7 00·30	·60	·330	3/7 10·15	5·205	·190			
	15·00	·725	·135	8·15	·635	·365						
	16·30	·74	·150	8·13	4·635	·366						
	23·30	·78	·190	8·25	4·639	·061						
	1/1 8·15	·83	·240									
	8·35	3·835	·247									
	8·45	3·846	·007									

Note Vernier readings in ink are actual readings taken with vernier the pencil figures are values calculated from dial readings.

PRESSURE DENSITY TEST. CONSOLIDATION RECORD.

Sample	GD 65/3/1			AFTER REST.			⊗-														
LOAD W.	10.			20			30			40			60			5			0		
Date	10/7/69			11/7			12/7			13/7			13/7			13/7			14/7		
	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial	Time	Vernier	Dial
	20.30	5.26	.000	10.45	.27	.010	9.00	.590	.020	8.30	.78	.215	16.00	.86	.300	16.15	.905	.345	8.30	.69	.485
	20.32	.26	.000	10.47	.40	.140	9.02	.635	.070	8.32	.80	.235	16.02	.895	.335	16.17	.78	.205	8.32	.595	.390
	20.36	.26	.000	10.51	.43	.170 ⊗	9.06	.65	.085	8.36	.805	.240	16.06	.90	.340*	16.21	.76	.185	8.36	.565	.360
	22.15	.26	.000	11.00	.455	.195	9.30	.675	.110	9.00	.82	.255	16.10	5.905	.344	16.22	5.758	.181	9.00	.51	.305
	11/7 10.30	.27	.010	11.15	.475	.215	10.37	5.705	.139	9.20	5.829	.263		-		16.26	5.728	.526	9.04	5.508	.300
				12.45	.515	.255	11.45	.715	.150	11.45	.85	.285				16.30	.73	.525	9.45	.47	.265
				15.45	.545	.285	15.00	.74	.175	15.00	.865	.300				19.30	.705	.500	11.45	.425	.220
				17.45	5.555	.295	16.30	.745	.180							21.30	.70	.495	14.00	.405	.200
				12/7 8.15	.59	.330	13/7 8.10	5.781	.213							14/7 8.05	5.689	.486	14.05	5.40	.195
				8.35	5.591	.332															
				8.49	5.594	.022															

⊗ HOLLER CUT.

*QUANTITY OF EFFLUENT AT TOP.

Table 5.5/8(b)

CALCULATION SHEET

PRESSURE DENSITY RELATION TEST

Table 5.5/9(a)

Sample No. GD 65/3/1

Taken on. 29/6/65.

Taken from Glantlees

Moisture Content 69·0% a.r.

BEFORE. REST.

Load on Hanger	Vertical Pressure	Time from start of test	Time from load increment	Depth Reading	Sample Thickness 6·96 − d	Density 68·4 / T.
W.lb.	lb/ft^2	hrs. min	hrs.	d. in	T.in	lb/ft^3
0	0	0	0·00	2·63	4·33	15·8
2½	125	18	0·033	3·255	3·705	18·4
			0·10	3·415	3·545	19·25
			0·33	·525	·435	19·85
			0·50	·56	·40	20·1
			1·75	·63	·33	20·55
			3·00	·68	·28	20·8
			6·00	·725	·235	21·15
			7·50	·74	·22	21·2
			14·50	·78	·18	21·45
			23·25	3·83	3·13	21·8
5	250	42	0·00	3·845	3·115	21·95
			0·033	4·16	2·80	24·4
			0·10	·215	·745	24·85
			0·50	·29	·67	25·6
			2·00	·42	·54	26·9
			2·92	·445	·515	27·2
			4·25	·475	·485	27·45
			6·00	·505	·455	27·8
			6·83	·52	·44	28·0
			15·50	·60	·36	28·95
			23·25	4·635	2·325	29·35
10	500	66	0·00	4·645	2·315	29·5
			0·033	·875	·085	32·7
			0·10	4·925	2·035	33·6
			0·58	5·00	1·96	34·8
			0·75	·015	·945	35·1
			2·93	·09	·87	36·5
			6·25	·13	·83	37·3
			7·50	·14	·82	37·5
			10·50	·16	·80	37·95
			25·25	5·205	1·755	38·95
12½	625	90	0·00	5·21	1·75	39·0
			0·033	·225	·735	39·4
			0·10	·23	·73	39·4
			0·75	·25	·71	39·95
			0·83	·255	1·705	40·1
		HOLDER IN FOR REST PERIOD				

PRESSURE DENSITY RELATION TEST
CALCULATION SHEET.

Table 5.5/9(b)

Sample No. GD 65/3/1
Taken on. 29/6/65

Taken from G.Lantzo
Moisture Content 69·0 % a.t.

AFTER REST.

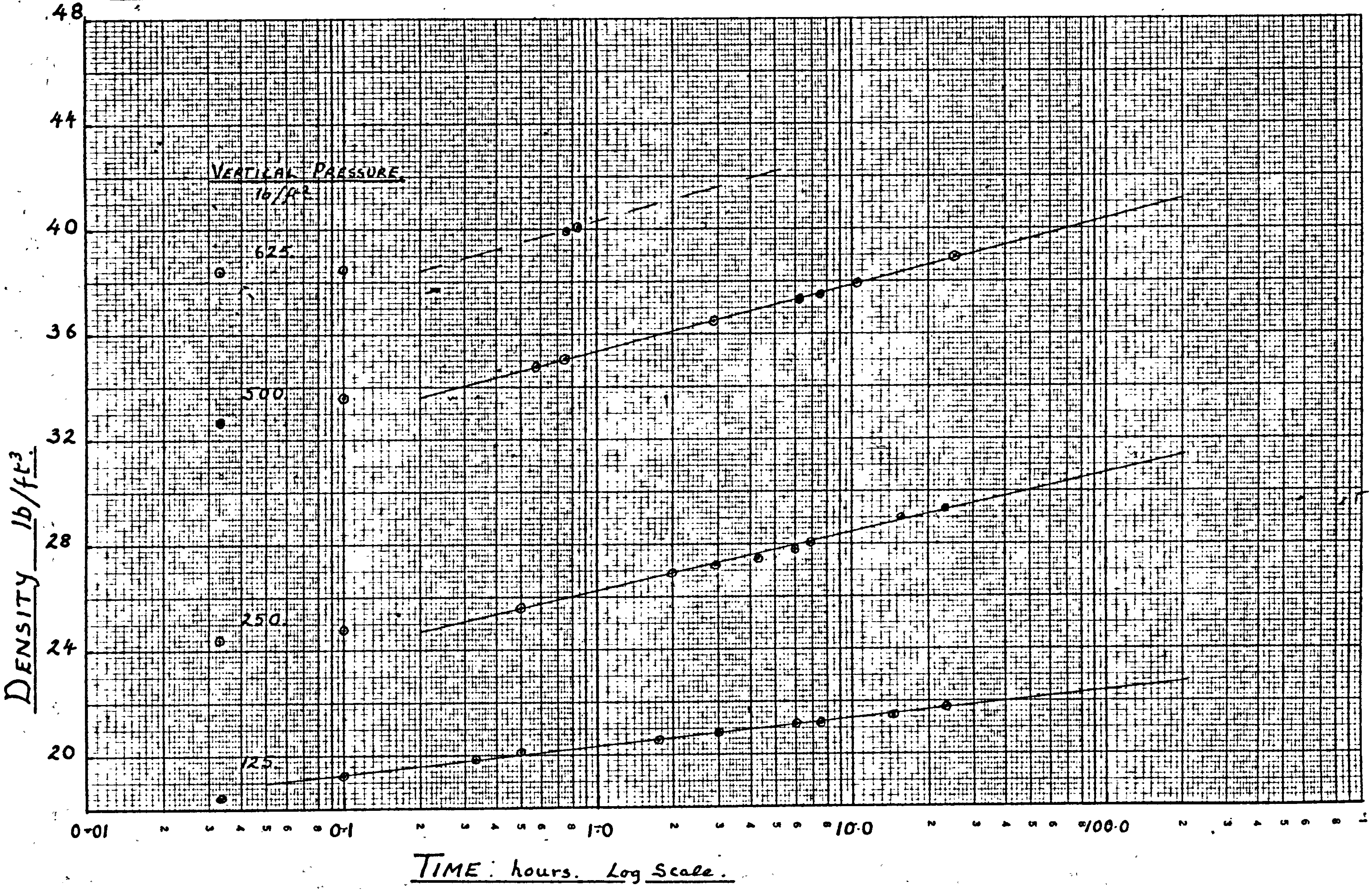
Load on Hanger	Vertical Pressure	Time from start of test	Time from load increment	Depth Reading	Sample Thickness $6{\cdot}96 - d$	Density $\frac{67{\cdot}2}{T}$
W.lb.	lb/ft^2	hrs. min	hrs.	d. in	T.in	lb/ft^3
10	500	270	0·00	5·26	1·70	39·5
			1·75	5·26	1·70	39·5
			14·00	5·27	1·69	39·8
20	1000	284	0·00	5·27	1·69	39·8
			0·033	·40	·56	43·1
	HOLDER OUT →		0·10	·43	·53	44·0
			0·25	·455	·505	44·7
			0·50	·475	·485	45·3
			2·00	·515	·445	46·5
			5·00	·545	·415	47·5
			7·00	·555	·405	47·9
			21·50	5·59	1·37	49·1
30	1500	306	0·00	5·59	1·37	49·1
			0·033	·635	·325	50·7
			·10	·65	·31	51·4
			·50	·675	·285	52·4
			1·61	·705	·255	53·55
			2·75	·715	·245	54·0
			6·00	·74	·22	55·1
			7·50	·745	·215	55·4
			23·25	·78	1·18	57·0
40	2000	330	0·00	·78	1·18	57·0
			0·033	·80	·16	57·9
			0·10	·805	·155	58·2
			0·50	·82	·14	59·0
			0·83	·83	·13	59·5
			3·25	·85	·11	60·6
			6·50	·865	1·095	61·4
60	3000	337	0·00	·86	1·10	61·1
			0·033	·895	·065	63·2
			0·10	·90	·06	63·4
QUANTITY OF EFFLUENT AT TOP. →			0·17	5·905	1·055	63·8
5	250	337	0·000	5·905	1·055	63·8
			0·033	·78	·18	57·0
			0·10	·76	·20	56·0
			0·25	·73	·23	54·6
			3·25	·705	·255	53·6
			5·25	·70	·26	53·4
			15·83	5·69	1·27	53·0
0	0	354	0·00	5·69	1·27	53·0
			0·033	·595	·365	49·3
			0·10	·565	·395	48·2
			0·50	·51	·45	46·4
			1·25	·47	·49	45·1
			3·25	·425	·535	43·8
			5·50	5·40	1·56	43·1

CHARTWELL GRAPH SHEET No 5551 LOG 5 CYCLES X MM. & CM

GRAPH 5.5/3.

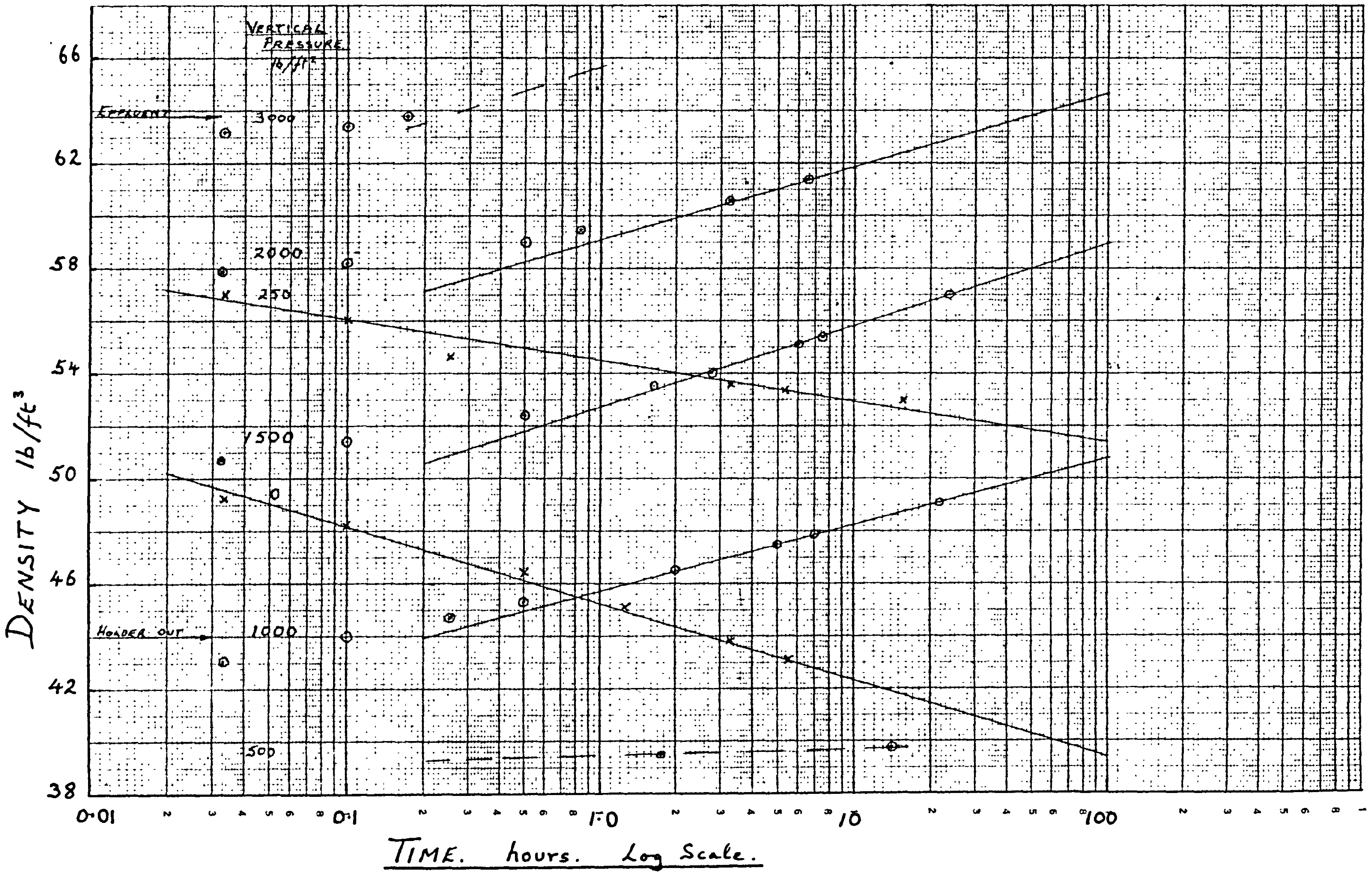
DENSITY AGAINST TIME.

GD 65/3/1. BEFORE REST.



DENSITY AGAINST TIME.

GD 65/3/1. AFTER REST.



GRAPH 5.5/4.

TABLE 5.5/10

Pressure Density Relation of Sample GD/65/2/1

Moisture Content before test 67.2% m.c.

after 69.0% m.c. i.e. 31.0% d.m.

Initial Density $Y = 15.8$ lb/ft^3

$Yd = 4.9$ lb/ft^3

After Rest Density $Y = 39.5$ lb/ft^3

$Yd = 12.25$ lb/ft^3

V	Y'	Yd'	C'	Cd'	T
125	20.35	6.3	1.0	0.31	18
250	26.25	8.14	2.25	0.70	42
500	35.35	10.98	2.45	0.76	66
625	(40.3)	(12.5)	-	-	90
500					270
1000	45.7	14.2	2.55	7.9	284
1500	52.7	16.35	3.08	0.96	306
2000	59.1	18.35	3.00	0.93	330
3000	-	-	-		337
250	54.5	16.9	-2.1	-0.65	337
0	45.3	14.05	-2.9	-0.90	354

Where V is Vertical Pressure on piston; in lb/ft^2

Y' and Yd' are the Density and Dry Density 1 hour after the application of pressure; in lb/ft^2

C' and Cd' are the rate of increase of Density and Dry Density per Log_{10} hours from application of Pressure V; in lb/ft^3 Log_{10} hr.

T is the Time from the filling of core to application of pressure V; in hours.

Effluent flowed from the top of the sample at

$Y = 63.8$ lb/ft^3 after 0.17 hours at $V = 3000$ lb/ft^2

$Yd = 19.8$ lb/ft^3.

5.5.6. Density Time Relationship at Constant Pressure.

It was found in the earliest pressure density tests that if the density was plotted against time from the application of load increment, in hours, a straight line plot was obtained as in Graph 5.5/2 for V = 125, 250, 500, 1000 lb/ft^2. This enables the density Y^T at time T hours after the application of pressure increment to be expressed as

$$Y^T = Y' + C' \, \mathrm{Log}_{10} \, T$$

and for dry density Yd^T

$$Yd^T = Yd' + Cd' \, \mathrm{Log}_{10} \, T$$

where Y' is the density when T = 1.0 hours; in lb/ft^3

Yd' is the dry density when T = 1.0 hours; in lb/ft^3

C' is the rate of increase in density per Log_{10} hours, in lb/ft^3/Log_{10} hr.

Cd' is the rate of increase in dry density per Log_{10} hours, in lb/ft^3/Log_{10} hr.

The values of Y' and C' are read off the Density/Log_{10} Time graph and the values of Yd' and Cd' calculated using the after test moisture content (m).

$$\text{where } Yd' = \left\{\frac{100 - m}{100}\right\} Y', \text{ and } Cd' = \left\{\frac{100 - m}{100}\right\} C'$$

The density departs from the straight line relationship in two ways, prior over-consolidation and fermentation rise.

(a) Prior over-consolidation. This effect is explained in Section 4.4.5.1. and Graph 4.4/6 for grain. Silage and ensiled grass behave in the same manner. It can be seen on Graph 5.5/2 for V = 1500 lb/ft^2 and Graph 5.5/4 at V = 1000, 1500 and 2000 lb/ft^2.

The error is greatest when T is small and is negligable above T = 1.0. Because of this the line drawn for obtaining Y' and C' is fitted primarily to the points for T greater than 1.0.

Because of the prior over-consolidation effect the requirements for running the pressure density test to obtain accurate values of Y' at a number of pressures conflict with those for obtaining accurate values of Cd'. For accurate values of Cd' can only be obtained by increasing the increment between pressures and carrying out the test at fewer pressure levels and/or by increasing the hold time at each pressure level which increases the time for test and reduces the number of tests possible in a season. My experiments were primarily carried out to determine accurate values of Y' and so in some instances (particularly at the higher pressures whereprior over-consolidation is most marked) the values of C' are only approximate.

(b) <u>Fermentation Rise.</u> As with grain there is a loss of strength (with consequential increase in density) due to fermentation changes. In Section 4.4.5.2. the effect of a uniform loss of strength with time due to fermentation was evaluated for grain. With grass and silage there is probably a similar effect due to a steady but slight ingress of air into the sample leading eventually to moulding, but it would be expected to be less than with grain because of the lower permeability of grass and silage. Fermentation rise of this type is unlikely to cause any significant error in density for T less than 12 hours.

In ensiled grass samples a different type of fermentation rise must be considered. This is the loss of strength in the change from fresh or wilted grass to silage. This seems to be due to the loss of that part of plant strength that is due to the osmotic pressure in plant cells. The rate and amount of this change depends on the moisture content of the grass, the degree of laceration and other factors. This initial fermentation rise is hard to isolate in the 'before rest' density time relationship as in Graph 5.5/3 of GD/65/3/1 but probably tends to increase the apparent value of C'. Values of Y' for the 'before rest' period will initially approximate to those for fresh grass but will tend towards the higher values for silage as the test continues. The full effect of this initial fermentation rise can be noticed in the difference between the before and after rest values of Y'.

In the after rest period the initial fermentation changes will be complete and so the sample will act as silage. Some of the samples did not ensile properly and so the results for these tests are suspect.

5.5.7. Factors Influencing the Fermentation of Ensiled Grass Samples.

All the ensiled grass samples from Glantlees, except wetter samples in 1964, gave good fermentations (i.e. pH less than 4.25). All other ensiled samples gave poor or bad fermentations. After the failure of the samples from Bridgets and N.I.R.D. to ensile properly, one possible explanation offered was the lack of silage lactobacilli.

For all subsequent ensiled grass samples silage lactobacilli culture (obtained from the N.A.A.S. Regional Microbiologist) was added, but still the non-Glantlees samples gave poor fermentations.

Laceration seemed to markedly improve fermentation. The best fermentations GD/65/1/1 to 5/1 (with pH of 3.55 to 3.9) were obtained with well lacerated material. In samples GD/Ch/1/1 - 3/1, the lacerated 1" chop sample had a lower pH (4.00) than the 1" chop sample (pH 4.25) and 3/8" chop sample (pH 4.20). The 30 samples (from Hurley) that gave poor fermentation were 1" chop unlacerated, 6 (from Bridgets and N.I.R.D.) were 1 3/4" unlacerated and 4 (from Bridgets and N.I.R.D.) were partly lacerated by field chopping; before guillotining to 1 3/4" max. In theory laceration, by releasing the sugars from the plant cells, speeds and improves fermentation. From my tests it appears that laceration improves fermentation but, by itself, gives no guarantee of good fermentation.

Moisture content seems to influence the fermentations in two ways. As fermentation depends on there being a sufficiently high ratio of sugar to water the chances of a good fermentation increase with wilting. This is born out by the test series GD/64/6/1 - 5 in which the two wettest samples had a poor fermentation and the driest pair had a good silage fermentation. Similarily with all the ensiled grass tests at Hurley the least bad fermentations were obtained with the drier samples although the driest samples gave trouble with mould. This moulding of the driest samples, which did not give a good fermentation, was because the fermentation failed to lower the pH sufficiently to inhibit mould and the porous nature of these samples makes it easier for air to enter.

Maturity and variety effect fermentation by their influence on the sugar-water ratio and the buffering effect of high protein content. Lucerne (used in 15 of the Hurley tests) is particularily hard to ensile unless it is heavily wilted or molasses is added. The successful fermentations were all of reasonably mature rye grass (C.P. less than 12%) while the unsuccessful fermentations were of young rye grass or lucerne.

The other factor which may have contributed to the poor fermentation is the time between ensiling and application of pressure. For the successful fermentations from Glantlees this was normally less than 12 hours. For the unsuccessful fermentations from Bridgets, Hurley and the N.I.R.D. it was between 24 and 48 hours; during which time respiration would have probably reduced the supply of sugars.

The occurence of poor fermentations cannot be related to any one factor. As the Bridgets and N.I.R.D. samples produced good silage in the tower but poor fermentation in the ensiled grass test, the fault must lie in part in the test procedure.

In future tests the following precautions should be taken if not inconsistant with the purpose of the particular test.

1. Consolidation should be started as soon as possible after ensiling.
2. Lacerated material should be used.
3. Sufficient sugar should be added to high moisture and high protein samples to ensure acidification; on the same basis as the farm practice of adding molasses.
4. The sealing method should be further improved to prevent moulding of the drier samples.

5.5.8. Review of Pressure Density Test Carried Out.

5.5.8.1. Introduction. In this review I have described the main points and discussed the results of each of the main series of pressure density tests. The detailed results are given in Tables 5.5/11 to 5.5/20 and the dry densities (Yd') have been plotted against vertical pressure for comparison in Graph 5.5/5 to 5.5/19. I have omitted the detailed results for a number of the tests on ensiled grass when the fermentations went wrong, but these tests are discussed. I have also omitted the results of a number of silage tests, mostly the earlier tests, where there was inadequate information on the crop and treatment variables and where prior to the introduction of the metal piston and polythene seals, the sample had moulded.

5.5.8.2. Ensiled Grass Samples Series CD/64/6/1-6. The details and results of this series will be found on Table 5.5/11. The samples were all of identical fresh cut material chopped to ¼" - 6" well lacerated using a

New Holland 616 field chopper. Sample GD/64/6/1 was of 'as cut' material; the other samples were taken at suitable time intervals during wilting in the lab. drier. This gave sample moisture contents (after test) of 81.3%, 76.6%, 75.0%, 68.25%, 58.0%, and 17.85% for samples 6/1 to 6/6 respectively. The fermentation of the 2 wettest samples (6/1 and 6/2) was suspect and that of the 6/3 slightly suspect. This may have been due to the duration of test being insufficient to permit fermentation to be completed or too inadequate sugars being available. Samples 6/4 and 6/5 gave good silage and sample 6/6 was hay.

On all before test samples the material was analysed for nutrients (C.P., D.C.P. and C.F.) and for samples 6/4 6/5 and 6/6 the after test samples were also analysed. The total weights of each constituent were calculated for before and after tests 6/4, 6/5 and 6/6 and the % change in weight in each constituent calculated. This showed that for samples 6/4, 6/5 and 6/6 the actual (oven dry) dry matter losses were 7.95%, 7.0% and 0.2% respectively. The dry matter losses calculated using TRINDER's(122) fibre rise technique (which is valid for normal fermentations) were 8.6%, 6.1% and a 0.25% gain, which confirms the utility of the fibre rise technique for predicting dry matter losses in silos from the initial and final analysis.

The normal range of dry matter loss reported in tower silos is from 5% to 10% so the losses obtained in the pressure density tests 6/4 and 6/5 can be regarded as typical of that occuring in silos. The sample 6/6 showed no loss as would be expected with hay.

Table 5.5/11

GLANTLEES 1964, PRESSURE/DENSITY RESULTS, EFFECT OF WILTING.

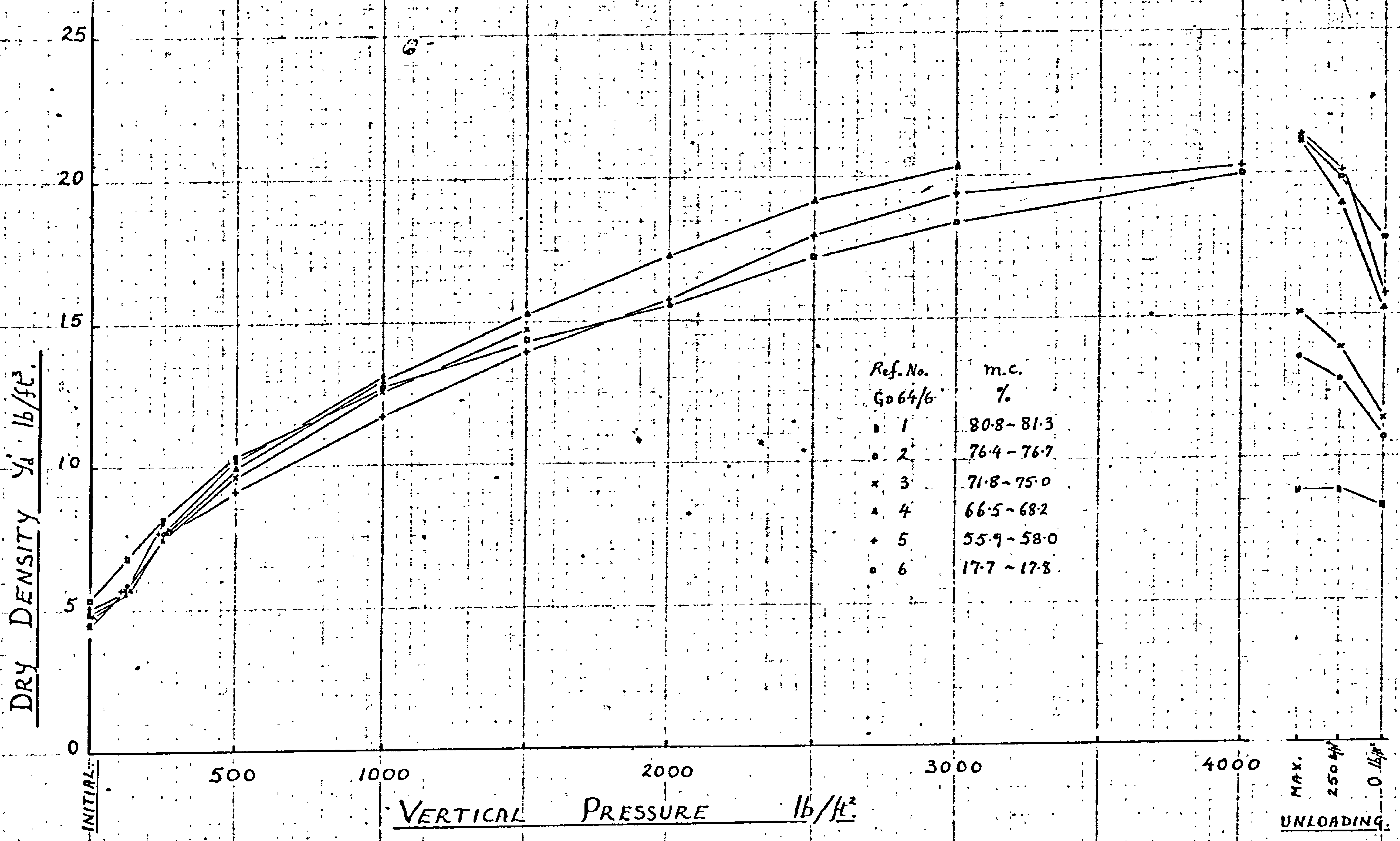
ENSILED GRASS SAMPLES.

All Samples cut 1600 22/7/64; 2nd Cut
18" Rye Grass Sward; Cow Pasture Glantlees.
Chopped in field before wilting to ¼"–6" well lacerated.
with New Holland 616 Chopper, Wilted in Lab Drier.

SAMPLE Ref. Go64/6	Ensiled at. Resulting Silage.	M.C.% D.M.%	C.P. Dg.P C.F. % of D.M.	SAMPLE Gross & DRY Wt. g.	Losses % ① Gross Wt.% ② C.F. Wt.% ③ C.P. Wt.%	D.M. Loss % ① D.M. Wt ② Fibre Rise ③ Protein Rise	Initial. Density and Dry Density	Effluent V lb/sq.ft time hrs Y. Yd.	Y', lb/cu.ft.; Y'd, lb/cu.ft.; and C' lb/cu.ft./Log.hr; after 1.0 hr @ V lb/sq.ft. and T. hr after ensiling.											
									125.	250.	250.	500.	1000.	1500.	2000.	2500.	3000	4000	250	0
1.	1900 22/7 No Mold Pale Khaki but wet Silage Smell	808 19.2 81.3 18.7	11.7 30.7 30.6	1138 218.2 1124.5 210.2	① 1.18	① 3.36.	26.4 4.95	V = 250 t: 22.5h 47.3 8.85	29.6 1.1 5.54 14	43.25 227 8.09 39	44.25 (2.27) 8.28 110									44.8 −0.65 8.39 133
2.	1230 23/7 No Mold. Silage Peach Smell	76.4 23.6 76.7 23.3	11.7 6.7 30.7	853.5 2015 818 190.5	4.17	5.48	19.5 4.61	V = 1000 t = 4.7 58.0 13.5	25.25 1.42 5.88 21	33.15 1.7 7.71 93		43.5 2.5 10.12 117	56.35 2.5 13.1 141						54.75 −0.77 12.75 146	45.7 −2.5 10.65 170
3.	14.00 23/7 No Mold. Silage faintly ammoniacal	71.8 28.2 75.0 25.0	11.3 6.5 30.3	725.5 204.5 711.5 178.0	1.79	12.9	16.1 4.54	V = 1500 5.0h 60.1 15.03	22.4 1.4 5.60 20	30.0 1.73 7.5 92		385 2.03 9.62 116	50.2 3.2 12.55 140	59.0 2.15 14.76 164					55.3 −0.8 13.82 169	45.4 −3.12 11.35 188
4.	14.30 23/7 No Mold Good Acetic Silage	66.5 33.5 68.25 31.75	11.3 6.7 30.8 12.0 6.6 33.7	639.5 214 620.5 197	① 3.06 ② +0.76 gain ③ 2.4	① 7.95 ② 8.6 ③ 5.7	14.65 4.91	V = 3000 18.0h 66.9 21.2	18.0 0.67 5.71 20	24.2 0.80 7.68 92		31.4 1.4 9.96 115	41.1 1.95 13.05 139	48.35 1.83 15.32 163	54.7 2.30 17.38 187	60.2 1.95 19.11 202	64.6 (1.9) 20.5 254		59.7 −2.1 18.95 272	48.0 −4.2 15.22 296
5.	16.15 23/7 Machine E No Mold. Good Acetic Silage.	55.9 44.1 58.0 42.0	11.6 6.9 31.6 12.4 7.3 33.7	493.5 217.5 481.5 202.2	2.44 −0.44 −0.40	7.03 6.10 6.50	11.4 5.04	No effluent to V=4000	13.55 0.42 5.67 18	(18.2) (0.033) (7.65) 91		21.43 (0.70) 9.01 114	28.0 1.2 11.77 138	33.18 1.43 13.91 162	37.22 1.83 15.62 186	428 1.8 17.95 211	46.75 1.83 19.38 239	48.30 1.86 20.27 258	47.6 −1.0 20.00 282	37.45 −3.2 15.72 308
6.	14.00 30/7 No Mold Hay smell slight Acetic Smell.	17.75 82.25 17.85 82.15	11.6 8.1 31.1 12.2 9.0 31.0	281 49.9 279 49.8	0.72 0.52 +4.8 gain	0.2 +025 gain 48	6.5 5.34	No effluent to V=4000	8.4 0.32 6.90 2	9.97 0.41 8.19 20		12.35 0.58 10.13 44	15.4 0.97 12.65 97	17.58 1.05 14.42 116	19.05 1.25 15.62 140	21.1 0.90 17.3 164	22.4 0.87 18.4 188	24.4 1.10 20.0 262	24.28 −0.45 19.9 287	21.50 −0.85 17.7 332

Graph 5.5/5

PRESSURE/DENSITY RELATIONSHIP. ENSILED GRASS, GLANTLEES 1964. EFFECT OF WILTING.



Graph 5.5/5 shows that at each pressure the dry densities of all 6 samples (up to effluent stage) lie within a small range (about ± 7% of mean). The silage samples (6/1 - 6/5) had lower dry densities than the hay sample (6/6) at below 250 lb/ft^2, but higher dry densities above 2000 lb/ft^2. This may well be because the densities at low pressures were measured, in this continuous test, before the fermentation was complete and so the resistance to consolidation would have been greater than for fully fermentated silage.

It appears from this series of tests that in the range 20% - 80% moisture content the dry density of silage of a given crop at a given pressure is not significantly influenced by moisture content, provided the silage is below saturation density (i.e. when effluent occurs).

5.5.8.3. Ensiled Grass Samples Series GD/65/1/1 - 5/1 and Hay Samples Series GD/65/1/2 - 5/2. Table 5.5/12 gives details and results for these two series of tests. The samples GD/65/1/1 - 5/1 were taken from five different loads of grass from Cow Pasture during the filling of the Glantlees Silo as shown on the filling record, Graph 1.4/2. It was possible to trace the level of this material during unloading and Ensiled Grass Samples GD/3/1 and 4/1 are of almost identical material to unloading Silage samples GD/U/24/2, 24/3 and 24/4. The comparison of their pressure density test results is discussed in Section 5.5.8.6.

Table 5.5/12

GLANTLEES 1965, PRESSURE/DENSITY RESULTS. TOWER FILLING. ENSILED GRASS SAMPLES.

SAMPLE Ref. GD/65/	All from Ryegrass Cocksfoot, Clover Headland Sward from Cow Pasture, Glantlees Flail mown, Field wilt	Ph.	M.C.% D.M.%	INITIAL C.P.% C.F.%	All Field Chop N.H.717. 3/16"th. CHOP AND LACERATION	SAMPLE Wt. g.	DENSITY AND DRY DENSITY. Initial and after rest.	EFFLUENT Y lb/sq.ft. Time hrs. Y. Yd.	Y', lb/cu.ft.; Y'd lb/cu.ft.; and C' lb/cu.ft./kgm hr.; after 1.0 hr. @ V lb/sq.ft. and T. hr after ensiling.											
									V 125	250	500	625	1000	1500	2000	2500	3000	4000	250	0
1/1.	Load 108. 27/6.		58.6	7.80 27.36	717 sharpened at Load 107 3/16"-2½" well Lacerated	559 553	Y 15.1 Yd 5.98		Y' 17.15 C' 0.49 Y'd 6.8 T 5	21.35 1.05 8.45 17	27.7 1.5 10.98 41		36.75 1.82 14.55 65							
	Earth in Sample	3.7	60.4 39.6.			548 550.5	39.7 15.7	No Eff. to V=4000 t 3.5h. Y 65.0 Yd 25.8			~~(39.8)~~ ~~(0.05)~~ ~~(15.8)~~ 318		(40.5) (0.86) (16.05) 332	43.9 2.5 17.4 354	49.5 217 19.6 378		57.0 28 22.6 385	63.4 2.6 25.1 402	54.1 -2.45 21.4 405	46.4 -3.5 18.4 407
2/1.	Load 114. 28/6.		66.05	7.08 26.90	3/16"-2½" well lacerated	562.5 556.5	15.1 4.99		18.75 0.68 6.2 9	24.8 1.3 8.2 20	32.6 2.03 10.78 44		~~(41.2)~~ — ~~(13.6)~~ 68							
	Earth in Sample	3.55	66.95 33.05			551 550.5	38.8 12.8	V = 3000 t = 3.5h. 64.3 21.25			~~(39.3)~~ ~~(0.01)~~ ~~(12.98)~~ 295		42.9 2.0 14.18 309	49.2 2.53 16.25 331	55.0 2.8 18.2 355		63.0 3.2 208 363		55.6 -20 187 366	46.4 -3.2 153 379
3/1.	Load 130. 29/6.		67.2	8.07 30.69	3/16"-2" well lacerated	554.5 546	15.8 4.90		20.35 1.0 6.3 18	26.25 225 8.14 42	35.35 2.45 10.98 66	(40.3) — (12.5) 90								
	Silage Inoc. Earth in Sample	3.55	69.0 31.0			543 543	39.5 12.25	V = 3000 t = 0.17h. 63.8 19.8			~~(39.5)~~ ~~(0.00)~~ ~~(12.25)~~ 270		45.7 2.55 14.2 284	52.7 3.08 16.35 306	59.1 3.00 18.35 330				54.5 -2.1 16.9 337	45.3 -2.9 14.05 354
4/1.	Load 136. 29/6.		65.6	8.88 27.55	3/16"-2" well lacerated	631 623.5	16.85 5.63		19.45 0.93 6.5 13	25.9 1.47 8.65 27	34.5 2.07 11.52 51	(37.6) — (12.56) 77								
	Silage Inoc. Earth in Sample.	3.6	66.6 33.4			621.5 621.5	39.4 13.15	V = 3000 t = 0.2h 65.1 21.78			~~(39.6)~~ ~~(0.10)~~ ~~(13.22)~~ 265		45.7 2.23 15.28 279	52.9 26 1768 301	54.0 275 19.7 324		(66.3) — (22.15) 332		56.8 -1.0 18.95 332	48.7 -2.6 16.28 348
5/1.	Load 141. 1/7.		53.1	7.59 29.92	717 sharpened at Load 137. 3/16"-2½" better chop and less laceration than 1/1-4/1.	541.5 530.5	12.5 5.56		15.2 0.47 6.76 8	18.1 0.70 8.06 17	22.9 1.13 10.2 42		28.45 1.52 12.68 69	33.3 2.5 14.8 89	(38.3) — (17.05) 113					
	Silage Inoc. Less Earth in Sample.	3.9	55.5 44.5			528 529	37.55 16.7	No eff to V=4000			~~(39.65)~~ ~~(0.0)~~ ~~(16.7)~~ 220		~~(37.8)~~ ~~(0.1)~~ ~~(16.8)~~ 235	(38.5) (0.5) (17.15) 257	(40.4) (1.2) (18.0) 281		45.8 2.47 20.4 288	50.9 2.5 22.6 305	45.6 -1.47 20.3 308	36.0 -3.57 16.0 310

Average before test anal. of 1/1-5/1 was C.P. 7.88% C.F. 28.48%

LAB. DRIED HAY SAMPLES.

1/2.	14/4/66		8.0 92.0	7.80 27.36	As 1/1	164	4.67 4.3	No eff to V=4000	6.15 0.117 5.66	7.18 0.127 6.66	8.73 0.307 8.03		10.62 0.337 9.78	12.40 0.53 11.40	13.81 0.73 12.7	(15.0) — (13.8)	16.05 — 14.78	18.11 0.725 16.68	16.5 -0.4 15.18	12.9 -0.92 11.88
2/2.	14/4/66		8.0 92.0	7.08 26.90	As 2/1	167	4.58 4.21	No eff to V=4000	6.08 0.07 5.59	7.05 0.13 6.49	8.55 0.31 7.86		10.43 0.37 9.60	12.12 0.48 11.17	13.52 0.65 12.43		15.65 0.63 14.4	17.35 0.65 15.98	15.95 -0.37 14.68	12.5 -0.83 11.5
3/2.	6/4/66		8.4 91.6	8.07 30.69	As 3/1	137	3.75 3.44	No eff to V=4000	5.42 0.19 4.97	6.60 0.19 6.05	8.30 0.33 7.60		10.11 0.37 9.26	11.85 0.55 10.87	13.31 0.5 12.2		15.5 0.7 14.2	17.27 0.52 15.82	15.31 -0.33 14.03	11.8 -0.87 10.8
4/2.	6/4/66		8.0 92.0	8.88 27.55	As 4/1	166	4.65 4.28	No eff to V=4000	6.40 0.16 5.89	7.60 0.19 7.00	9.35 0.33 8.60		11.18 0.32 10.28	12.82 0.56 11.80	14.35 0.56 13.20		16.4 0.68 15.09	18.2 0.61 16.75	16.32 -0.37 15.02	12.95 -0.87 11.91
5/2.	23/3/66.		7.65 92.35	7.59 29.92	As 5/1	173	4.88 4.5	No eff to V=4000	6.03 0.13 5.57	7.00 0.15 6.46	8.48 0.27 7.82		10.65 0.39 9.83	12.03 0.42 11.1	13.38 0.70 12.32	14.7 0.86 13.57	(15.8) — (14.58)	17.15 0.80 15.81	16.3 -0.23 15.03	13.45 -0.85 12.4

PRESSURE/DENSITY RELATIONSHIP. ENSILED GRASS. TOWER FILLING GLANTLEES 1965.

	Ref No. Go/65	m.c. %	Ref No. Go/65	m.c. %	C.P. %	C.F. %
○	1/1	58.6-60.4	1/2	8.0	7.80	27.35
×	2/1	66.0-66.9	2/2	8.0	7.08	26.9
△	3/1	67.2-69.0	3/2	8.4	8.07	30.6
□	4/1	65.6-66.6	4/2	8.0	8.88	27.5
+	5/1	53.1-55.5	5/2	7.6	7.59	29.9

All the samples gave good silages with a pH of less than 4.00. The dry matter losses (oven dry basis) ranged between 5% and 7.5%. The samples GD/65/1/2 - 5/2 were of identical material to the corresponding 1-5/1 samples but had been dried in the lab. drier to hay at 8% m.c.

In Graph 5.5/6 of the dry density against vertical pressure for these two series, the plots for the ensiled grass samples before rest (i.e. up to 40 lb/ft^3 density) and after rest are not linked. However in this case there is little discrepancy between the values of dry density obtained immediately before and after rest, probably because the well lacerated sampleshad completed fermentation before the rest period. Only the 'after rest' results can be considered directly comparable with silage. The 'before rest' results are of particular interest in predicting the rate of consolidatinn during filling.

The five ensiled grass samples give very similar pressure density results. The range of Yd' at 1500 lb/ft^2 'after rest' being

Ensiled Grass		Hay	
GD/65/1/1	17.4	GD/65/1/2	11.4
2/1	16.25	2/2	11.15
3/1	16.35	3/2	10.85
4/1	17.7	4/2	11.8
5/1	(17.15)	5/2	11.1

Samples 4/1 and 1/1 had the highest dry densities as silage and the corresponding hay samples 4/2 and 1/2 also had the highest dry densities. The 'dry densities' of the 8% m.c. hay was markedly lower than that of the identical material as silage.

These two series of tests give a very good picture of the pressure density relationship of typical "as filled" material both during and after fermentation, and of the same material as 8% m.c. hay. They show the uniformity of results that are obtainable using the ensiled grass technique where satisfactory fermentations are obtained.

5.5.8.4. **Ensiled Grass Samples Series GD/Ch/1/1, 2/1, 3/1, 1/2, 1/3, 3/2.** This series of tests was run to investigate the effects of chopping and laceration on an ensiled grass and hay sample. The original plan was to simultaneously test 5 samples of identical field wilted grass as follows:

(a) field chopped with N.H.717. (not done).
(b) hand guillotine chop to 1" lengths with minimum of laceration (1/1).
(c) as (b) but lacerated in hand mincer auger (2/1).
(d) hand guillotine to 3/3" lengths with minimum laceration (3/1).
(e) as (d) but lacerated in hand mincer auger (not done).

The 1" chop length was chosen as the long length as it was considered that with lengths longer than 1/6th of the core diameter there was a risk of reduction in density due to core size rather than chop length. The 3/8" chop length was selected as the short length as this was the shortest length for which the guillotine chopper could be set. The laceration was obtained by passing the pre-chopped grass through a hand mincer without end plate.

In practice because of a breakdown of the N.H.717 field chopped at Glantlees there was no field-wilted material available. The grass was cut with a scythe and then wilted in the lab. drier to 65% m.c. No field chopped sample was available. The lacerator broke after only 350 g of 1" lacerated material (2/1) had been prepared; so there was no before test moisture content sample for sample 2/1 and there was no material for a hay sample 2/2. It was not possible to do a lacerated 3/8" chop sample. Fig.5.5/10 and 5.5/11 show the standing crop and the three chopped samples.

The test were conducted in the standard method for ensiled grass and hay. Half of the hay sample 1/2 was additionally dried in an oven at 85°C to bring down the moisture content to 2.65% to give further information on the effect of drying out on strength.

The nutrient analysis were carried out on a bulked sample of 1/1 and 3/1 before test and a bulked sample of 1/1, 2/1 and 3/1 after test. The fibre rise estimate of the average dry matter loss was 21% and the oven dry matter losses were 19% on 1/1 and 17.5% on 3/1. This loss was more than twice that with the other two series of ensiled grass tests at Glantlees; 15% - 20% dry matter loss is fairly typical for clamp silos. The fermentations all appeared good and satisfactory pH's of 4.0 to 4.25 were obtained.

Fig.5.5/10 The standing crop, predominately of ryegrass, from Pond Field, Glantlees, used for Sample GD/Ch 1/1 - 3/1.

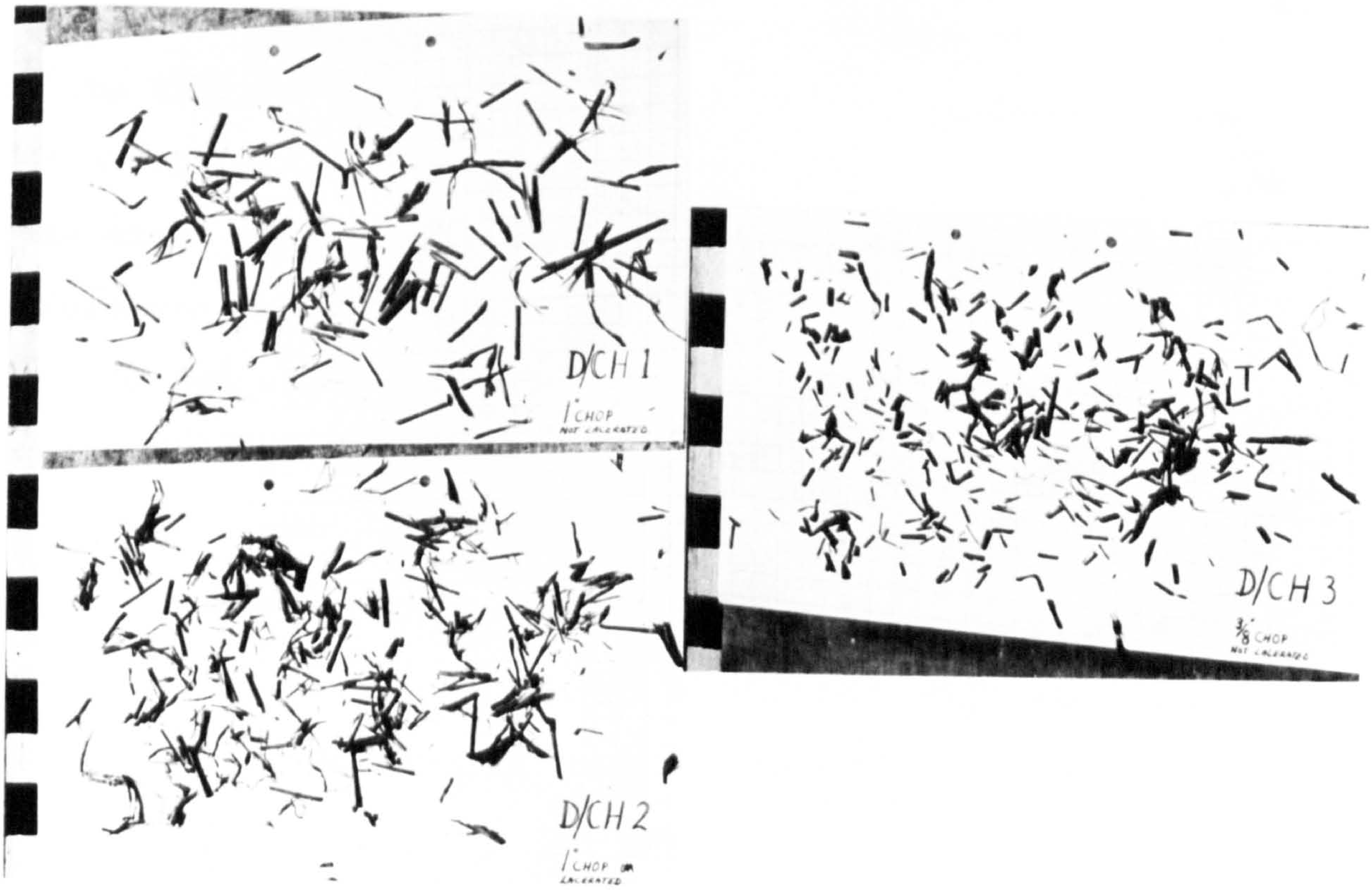


Fig.5.5/11 Chopped grass for Samples GD/Ch 1/1, 2/1 and 3/1.

The details and results of these tests are on Table 5.5/13. Graph 5.5/7 shows the before and after rest consolidation curves of samples 1/1, 2/1 and 3/1. The after rest curves for all three samples are almost identical (at Yd' at 1500 lb/ft^2, 15.4, 15.45, 15.6 resp.) and from this we can definitely state that at pressures above 500 lb/ft^2 once fermentation is complete chop and laceration make no significant difference to density. This conclusion applies to the storage densities in silos.

Before rest, while fermentation is in progress, the three samples behaved very differently. The initial density recorded is of little significance as it depends largely on the touch of the experimenter. At 125 lb/ft^2 (approx. 12 hours from sealing) the 1" lacerated (2/1) sample and 3/8" (3/1) sample had a 25% greater dry density than the 1" (1/1) sample. At 750 lb/ft^3 the 1" lacerated had the highest dry density (10.95 lb/ft^3) followed by the 3/8" at 10.3 lb/ft^3 while the 1" had only reached 8.45 lb/ft^3. It is clear that cutting and laceration increase the rate of fermentation and so the rate at which the dry density tends to its silage value. This supports the theory that the additional strength of grass above that of silage is due to the osmotic pressure, which is released in fermentation. It also links in with my analysis of McDonald's results in Section 5.4.7. which shows that there is, at constant pressure, a rapid rise in density until the pH has fallen to 4.25 (i.e. fermentation complete), after which it becomes exponential.

Table 5.5/13

GLANTLEES 1965, PRESSURE/DENSITY RESULTS, EFFECT OF CHOP AND LACERATION.

ENSILED GRASS SAMPLES.

Sample Ref. GD/Ch/	All from Ryegrass cut 16.00, 5/7/65 Pond Field, Glantlees Lab. Willed Ensiled at.	M.C. % D.M.	Av. of all Samples C.P. % C.F. % Prot. Dig %	CHOP LACERATION	Sample Wt. g.	DENSITY AND DRY DENSITY Initial and after Rest.	EFFLUENT V. lb/sq ft. time hrs. Y. Yd	Y', lb/cu.ft.; Y'd, lb/cu.ft.; and C' lb/cu ft/log10 hr.; after 1.0 hr. @ V lb/sq ft. and T. hr after ensiling.												
								125	250	500	750	1000	1250.	1500	2000	2500	3000	4000	250	0.
1/1.	22.00 5/7/65.	65.6	7.27 27.31 70.8	G. to 1"	409	Y. 11.15 Yd. 3.18		Y' 15.8 C' 0.53 Y'd. 4.5 T. 13	19.6 0.80 5.58 36	25.2 1.33 7.18 60	29.6 1.4 8.44 86	33.0 1.83 9.40 95	36.4 1.86 10.38 109	(39.3) (11.2) 117						
	Ph 4.25	71.5 28.5	8.54 34.6 65.0		397.5	38.4 10.93	V = 2000 3.25h. Y. 62.4 Yd 17.8			40.0 0.5 11.4 475		46.2 2.66 13.15 493		54.0 2.87 15.4 517	61.0 2.73 17.4 543				55.2 -1.53 15.7 546	46.2 -3.05 13.15 565
2/1.	22.15 5/7/65.	ESTIMATE 65.5	av. as above	G. to 1" + Laceration	357	15.6 4.46		20.0 0.67 5.72 12	24.6 1.3 7.05 36	31.8 1.73 9.1 60	38.3 2.23 10.95 86									
	Ph 4.0	71.4 28.6	av. as above		349	37.8 10.8	V = 2000 3.25h 61.4 17.55			39.4 0.23 11.28 475		46.1 2.5 13.2 493		54.0 2.83 15.45 517	(60.6) (17.35) 543				54.8 -0.78 15.7 546	46.6 -2.73 13.3 565
3/1.	22.30 5/7/65.	64.9	av. as above	G. to 3/8"	437	12.35 3.68		19.65 0.75 5.85 12	23.65 0.85 7.05 36	29.5 1.6 8.8 60	34.6 1.7 10.3 86	38.7 1.9 11.53 95								
	Ph 4.2	70.2 29.8	av. as above		425	38.2 11.4	V = 2000 8.0h 61.8 18.4			39.6 0.37 11.8 475		45.7 2.03 13.6 493		52.4 3.03 15.6 517	59.2 2.87 17.65 543				54.2 -1.33 16.15 551	43.6 -3.1 13.0 565

LAB. DRIED HAY SAMPLES.

1/2.	20/1/66.	8.45 91.55	Av. anal. see above	G. to 1"	142	4.07 3.73	Nil to. V = 4000	5.15 0.117 4.715	6.3 0.2 5.77	8.18 0.33 7.50		10.8 0.54 9.9		13.28 0.76 12.15	15.3 0.80 14.0	(17.1)	18.1 0.90 16.6	20.4 0.93 18.7	18.6 -0.55 17.03	14.8 -1.15 13.55
1/3.	21/1/66	2.65 97.35	Av. anal. see above.	G. to 1"	139.5	4.06 3.95	Nil to V = 4000	4.95 0.09 4.81	5.68 0.05 5.52	6.95 0.17 6.76		9.22 0.13 8.96		11.0 0.23 10.7	12.55 0.30 12.2	13.6 0.30 13.22	14.8 0.33 14.4	16.9 0.32 16.42	14.53 -0.16 14.13	10.18 -0.32 9.90
3/2	20/1/66.	9.35 90.65	Av. anal. see above.	G. to 3/8"	144	6.05 5.48	Nil to V = 4000	7.05 0.13 6.39	8.1 0.22 7.34	9.78 0.33 8.86		11.8 0.52 10.7		13.85 0.60 12.53	15.8 0.73 14.3	(19.35)	18.15 0.925 16.42	20.5 1.00 18.58	18.6 -0.50 16.85	15.25 -1.00 13.8

Graph 5.5/7

PRESSURE/DENSITY RELATIONSHIP. ENSILED GRASS, GLANTLEES 1965.

EFFECT OF CHOP AND LACERATION.

Graph 5.5/8

PRESSURE/DENSITY RELATIONSHIP. ENSILED GRASS AND HAY. GLANTLEES 1965.

EFFECT OF CHOP.

	Ref. No. Gd/Ch	m.c. %	CHOP.
○	1/1	65·6 ~ 71·5	1"
▲	3/1	64·9 ~ 70·2	3/8"
□	1/2	8·45	1"
=	1/3	2·65	1"
×	3/2	9·35	3/8"

From the before rest results the conclusion is that laceration increases the rate at which the dry density rises from the value for grass to that for silage. The dry density of a silage being, under similar conditions, perhaps 50% greater (e.g. for 1/1 at 1000 lb/ft^2, Yd' = 9.4 lb/ft^3 before rest and 13.15 lb/ft^3 after rest) than that of the grass from which it is made. The effect of chop, other than its lacerating effect, is not clear from these tests but it does not appear very significant. The practical importance of these before rest results is in the filling of clamp and tower silos where a high density is required as rapidly as possible to minimise losses; laceration can be of great value in this.

The hay samples results for 1/2 (1" chop no laceration 8.5% m.c.) 1/3 (as 1/2 but 2.6% m.c.) and 3/2 (3/8" chop 9.35% m.c.) are plotted on Graph 5.5/8 with the after rest ensiled grass results for comparison. From this graph it appears that at 8 - 9% m.c. chop length has a marked effect on initial and low pressure densities (36% higher dry density at 125 lb/ft^2 for 3/8" than for 1" chop) but at high pressures chop makes no noticeable difference. Comparing samples 1/1, 1/2 and 1/3 it appears that moisture content (71.5%, 8.45%, 2.65% m.c. resp.) does not effect dry densities at low pressures (Yd' at 125 lb/ft^2, 4.5, 4.7 and 4.8) but drying out causes a significant reduction in dry density at higher pressures (e.g. Yd' at 2000 lb/ft^2; 17.4, 14.0 and 12.2 lb/ft^3).

5.5.8.5. Silage Samples G1/65/U/40/1 to U/5/7. These samples were taken during the unloading of the Glantlees Silo during the winter of 1965-66. Details of the samples are given in Table 5.5/4 and also Graph 1.4/2 and Section 1.4 on the unloading of Glantlees. The dry densities are plotted against vertical pressure in Graphs 5.5/9 and 5.5/10. The curves at low pressures are influenced by the fact that the silage had already been consolidated in the silo. Vertical bars on the graphs show the vertical pressure that would have been on the sample in the silo assuming no wall friction.

The samples from the bottom of the silo tended to have higher densities (Yd' 18.5 to 21.5 lb/ft^3 at 1500 lb/ft^2) than those from the top of the silo (Yd' 15.5 to 18.5 lb/ft^3 at 1500 lb/ft^2). This may be due to the higher in-situ vertical pressure or a variation in maturity. Except samples U/40/1 and U/40/3 (with C.P. of 12.5%) all the samples had very similar analysis with C.P. between 7.5% and 10%. The U/40 samples showed a steeper rise in dry density with vertical pressure than the more mature samples. There was good correspondence between tests on similar samples (e.g. U/40/1 and U/40/3 also U/24/2 and U/24/3).

5.5.8.6. Comparison of Ensiled Grass and Silage Pressure Density Results. The ensiled grass samples GD/65/3/1 and 4/1, (from loads 130 and 136 respectively during the filling of Glantlees) are of very similar material to samples G1/65/U/24/2, /3 and /4 which are estimated (from the comparison of filling and unloading records in Graph 1.4/2) to come from load 132.

Table 5.5/14

GLANTLEES 1965~66.; PRESSURE/DENSITY RESULTS; TOWER UNLOADING.

Ref. No. Gl/65	Date of Sampling	Over-burden ft. in	Dist-ance from Wall	In-Situ Vertical Pressure lb/ft²		Probable Filling Zone and Load	m.c. % Ph.	C.F. C.P. Prot.Dig. % of D.M.	Chop. in.	Sample Wt. g.	Initial Density and Dry Density lb/ft³	Effluent at V lb/ft² Time hr Density Dry Density	Y', lb/ft³; Y'd, lb/ft³; and C' lb/ft³/Log₁₀ hrs.; at V, lb/ft²; after 1·0 hr.										
				No Wall Friction	A.C.I. Wall Friction								V 125	250	500	1000	1500	2000	2500	3000	4000	250	0
U/40/1	11/11	5'2"	1'9"	208	195	24, 219	63·4 4·1	32·15 12·75 71·5	3/8"-4" Av 3/4	933 930	21·9 8·0	2500 6·5 62·5 22·85	Y' 25·3 C' ·47 Y'd 925	28·8 ·77 10·55	34·2 1·25 12·5	42·4 2·08 15·5	49·2 2·30 18·0	54·6 3·13 20·0	60·4 2·5 22·1			52·8 -1·6 19·3	43·2 -3·9 15·8
U/40/3	11/11	5'2"	7'3"	208	195	24, 219	65·7 4·1	31·67 12·95 64·0	3/8"-4" Av 3/4	985 981·5	23·0 7·9	2000 230 63·0 21·6	27·8 ·50 9·5	31·6 ·73 10·8	36·7 1·03 12·6	45·6 2·20 15·6	53·1 2·4 18·2	58·9 3·0 20·2				55·3 -1·8 18·9	46·2 -3·0 15·8
U/33/2	7/12	12'4"	1'3"	442	352	19, 187	73·5 4·2	34·28 9·61 69·1	1/4"-3"	962 955	30·6 8·1	1500 7·0 60·7 16·1	33·4 ·63 8·85	37·7 ·86 10·0	43·8 1·36 11·6	52·7 2·27 14·0	59·2 1·70 15·7					57·0 -·67 15·1	47·0 -2·8 12·5
U/30/2	20/12	15'0"	1'3"	548	422	18, 174	73·4 3·7	34·3 9·07 68·9	1/4"-2½"	1127 1121	32·1 8·54	1500 2·0 60·5 16·1	35·6 ·62 9·45	39·6 ·63 10·5	44·4 1·07 11·8	52·8 1·95 14·05	59·65 2·35 15·85					55·3 -·6 14·7	46·5 -2·7 12·4
U/30/3	20/12	15'0"	3'3"	548	422	18, 174	67·1 3·9	33·07 9·01 64·8	1/4"-2½"	1215 1215	33·6 11·05	2000 20 60·5 198	35·9 ·60 11·8	39·2 ·60 12·9	43·0 ·65 14·15	49·5 1·6 16·3	54·7 1·3 18·0	59·8 2·25 19·7				54·8 -1·1 18·0	45·3 -2·9 14·9
U/30/4	20/12	15'0"	7'3"	548	422	18, 174	69·9 3·9	35·35 8·69 57·8	1/4"-2½"	1249 1238	38·5 11·6	2000 0·4 62·5 18·8	42·1 ·50 12·7	45·3 ·50 13·6	48·8 ·60 14·65	53·9 1·2 16·2	58·0 1·1 17·45	63·2 1·8 19·0				55·2 -1·2 16·6	48·2 -1·7 14·5
U/30/8	20/12	15'5"	3'3"	580	444	18, 170	66·2 3·8	31·13 9·58 69·9	1/4"-2½"	1244 1242	35·9 12·25	2000 2·5 61·2 20·7	37·9 ·45 12·8	40·6 ·50 13·7	43·9 ·85 14·8	50·0 1·3 16·9	55·0 1·75 18·6	60·2 2·2 20·3				56·0 -1·2 18·9	46·4 -2·8 15·7
U/24/3	27/1	21'5"	3'3"	865	620	14, 132	66·8 3·8	34·28 9·10 63·5	1/4"-3"	903	27·2 9·04	2500 18·5 61·4 20·4	32·1 ·50 10·65	35·7 ·50 11·85	39·25 ·70 13·05	44·5 1·20 14·8	49·7 1·70 16·5	54·1 1·90 17·95	58·5 2·3 19·4			54·2 -1·8 18·0	44·0 -3·1 14·6
U/24/4	27/1	21'5"	7'9"	865	620	14, 132	63·3 3·8	30·96 8·49 48·4	1/4"-3"	1195	31·0 11·4	3000 30·0 63·5 23·3	35·05 0·60 12·85	38·3 0·50 14·05	42·15 ·70 15·5	46·95 1·1 17·2	50·85 1·6 18·65	54·4 1·6 19·9	57·75 1·8 21·1	61·0 Est 1·8 22·4		54·3 -1·75 19·9	46·4 -2·7 17·0
U/24/2	27/1	21'5"	1'3"	865	620	14, 132	66·0 3·8	34·49 8·71 65·3	1/4"-3"	1088·5	27·4 9·3	3000 4·6 60·5 20·6	30·3 0·30 10·3	33·0 ·40 11·2	37·0 ·60 12·6	42·1 1·2 14·3	47·4 1·95 16·1	51·4 1·8 17·5	55 65 2·3 18·9	59·4 2·0 Est 20·2		53·6 -1·65 18·2	42·7 -3·3 14·5
U/13/3	2/3	32'8"	3'3"	1472	842	6·7, 58	57·5 4·0	3275 7·55 71·9	1/4"-3"	1146 1145·5	292 12·4	No eff at 4000 2·0 61·25 260	31·95 ·35 13·6	34·85 ·55 14·8	38·25 ·60 16·25	42·6 ·90 18·1	46·1 1·10 19·6	49·1 ? 20·85	52·0 1·75 22·1	55·2 1·65 23·45	60·6 2·1 25·75	51·0 -2·4 21·65	41·9 -2·8 17·8
U/13/4	2/3	32'8"	7'9"	1472	842	6·7, 58	62·8 3·8	33·98 8·10 70·9	1/4"-3"	1231·5 1226	34·3 12·75	3000 0·75 64·0 238	37·0 ·65 13·75	41·15 ·70 15·3	45·2 1·05 16·8	50·9 1·40 18·9	54·95 1·25 20·4	58·25 ? 21·65	61·25 1·90 22·8	64·2 Est ? 23·9		55·95 -1·6 20·8	49·55 -2·3 18·45
U/7/3	18/3	38'5"	3'9"	1799	899	3, 25	64·7 3·9	3155 8·40 74·5	1/4"-3"	1388 1388	37·8 13·3	1500 18·0 62·05 219	41·8 ·60 14·75	45·6 ·60 16·1	49·85 ·80 17·6	55·8 1·35 197	60·2 1·4 2125					56·6 -13 20·0	48·15 -2·6 17·0
U/7/7	18/3	38'10"	3'9"	1831	906	3, 22	65·1 3·9	3186 8·45 71·7	1/4"-3"	1350·5 1349	39·6 13·8	1500 18·0 62·4 21·8	41·25 ·55 14·4	45·2 ·70 15·8	49·75 ·80 17·85	55·9 1·3 19·5	60·5 1·5 21·1					58·75 -105 20·35	49·7 -2·4 173
U/5/3	30/3	40'11"	3'9"	1930	910	2, 12	66·5 3·8	364 9·1 67·2	1/8"-1½"	1684 1674·5	42·0 14·1	1500 2·5 617 20·7	43·9 ·30 147	4735 ·60 15·8	51·6 ·65 17·3	56·85 ·90 19·0	61·2 1·2 20·5					57·2 -·85 19·15	50·9 -1·8 17·0
U/5/7	30/3	41'4"	3'9"	1954	904	2, 10	66·1 3·9	34·95 991 62·1	1/8-1½	1523 1516	394 13·35	1500 40 622 211	41·8 ·60 14·2	45·2 ·60 153	49·8 ·80 1685	55·4 ·90 18·75	59·9 1·4 20·25					56·9 -11 1925	49·5 -22 16·75

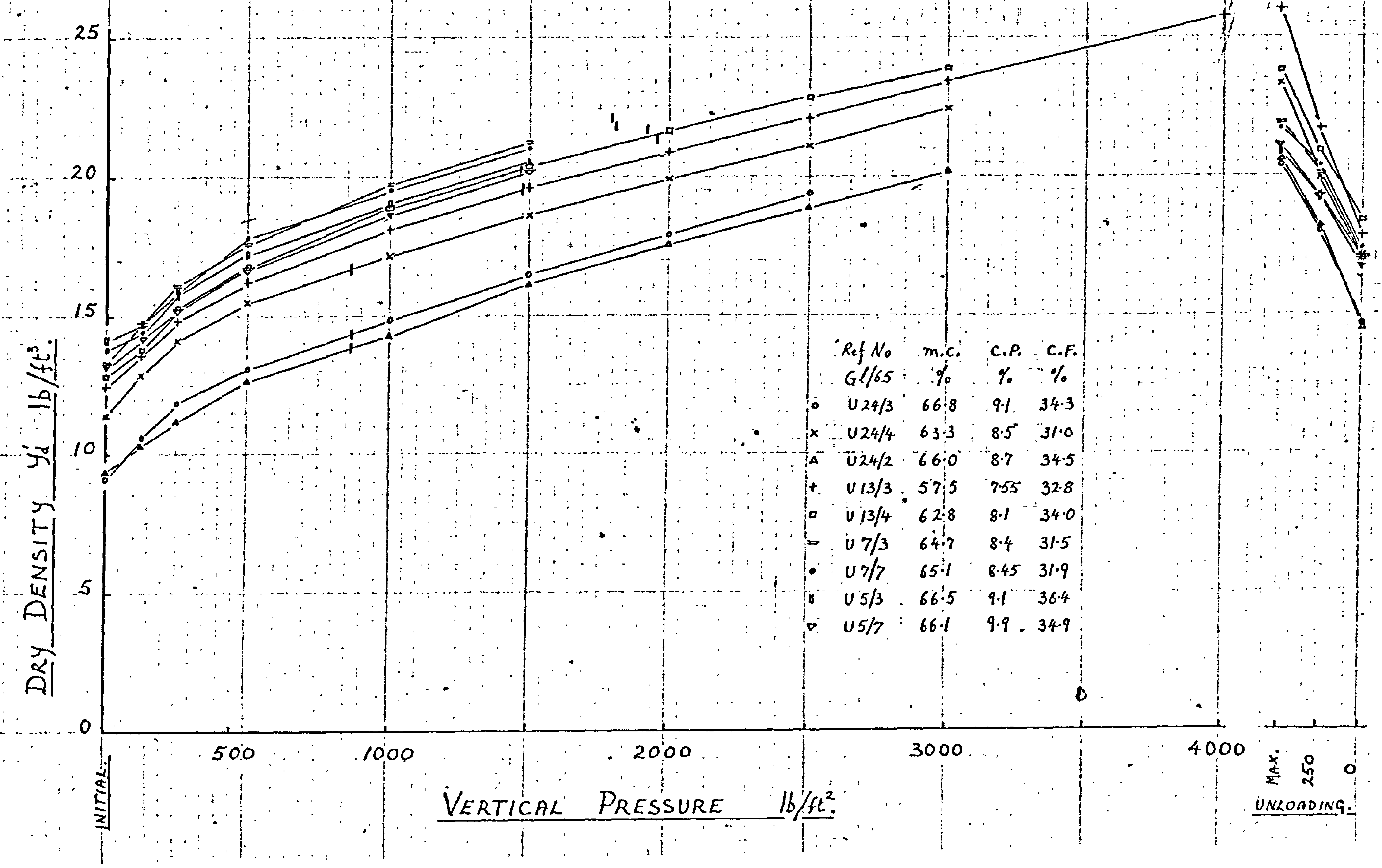
Graph 5.5/9

PRESSURE/DENSITY RELATIONSHIP. SILAGE FROM GLANTLEES. 1965-66. TOP 20 ft.

Ref. No Gl/65	m.c. %	c.P. %	c.F. %
○ U40/1	63·4	12·7	32·1
× U40/3	65·7	12·9	31·7
▲ U33/2	73·5	9·6	34·3
+ U30/2	73·4	9·1	34·3
□ U30/3	67·1	9·0	33·1
= U30/4	69·9	8·7	35·3
• U30/8	66·2	9·6	31·1

Graph 5.5/10

PRESSURE/DENSITY RELATIONSHIP. SILAGE FROM GLANTLEES. 1965-66. 20'-42' DOWN.

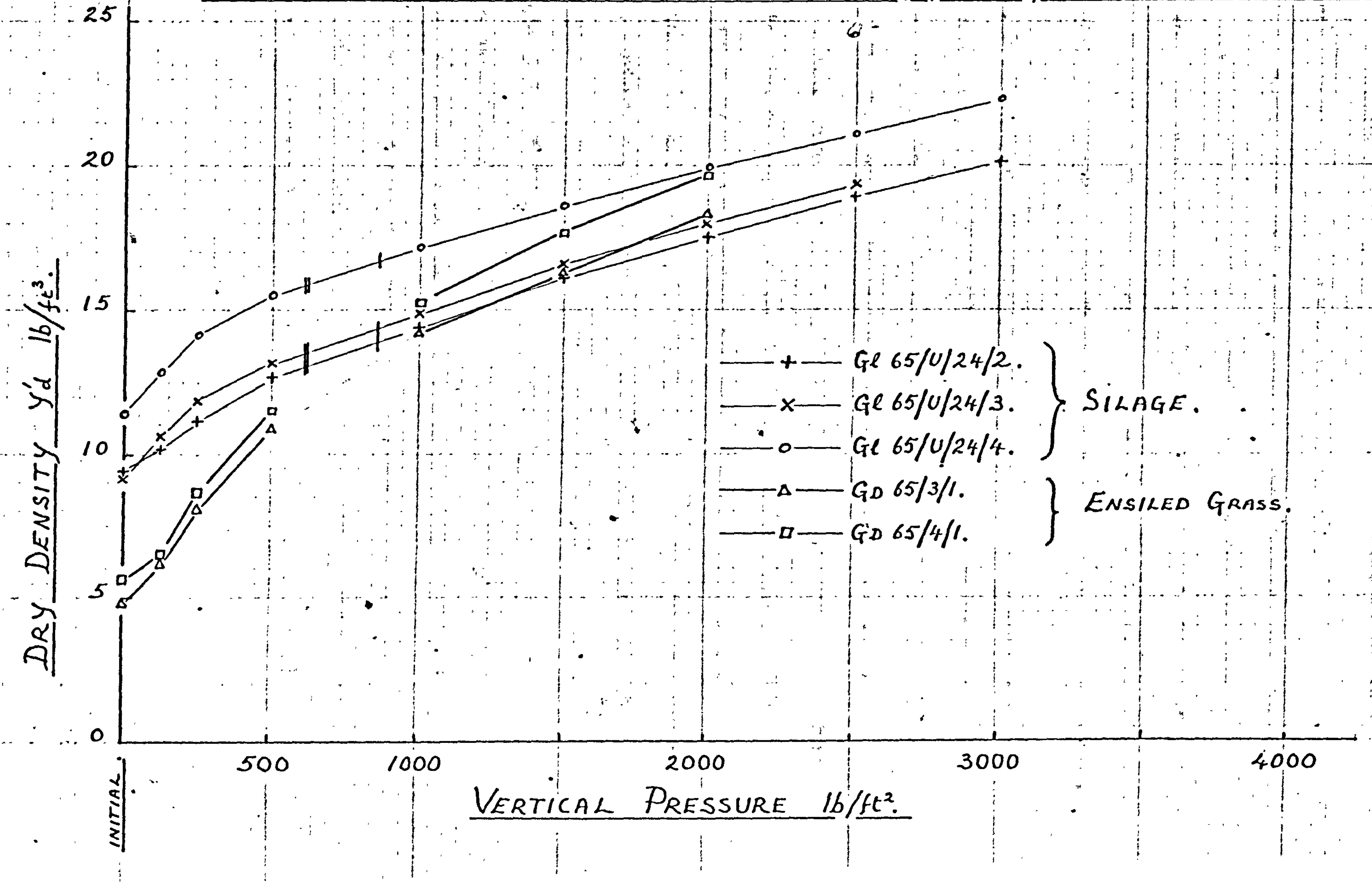


	Ref No Gl/65	m.c. %	C.P. %	C.F. %
○	U24/3	66·8	9·1	34·3
×	U24/4	63·3	8·5	31·0
△	U24/2	66·0	8·7	34·5
+	U13/3	57·5	7·55	32·8
□	U13/4	62·8	8·1	34·0
=	U7/3	64·7	8·4	31·5
●	U7/7	65·1	8·45	31·9
▮	U5/3	66·5	9·1	36·4
▽	U5/7	66·1	9·9	34·9

Graph 5.5/11

PRESSURE DENSITY RELATIONSHIP.

COMPARISON OF ENSILED GRASS SAMPLES GD 65/3/1 AND 4/1 WITH SILAGE SAMPLES,



Graph 5.5/11 shows the dry densities of all 5 samples plotted against vertical pressure. Above the in situ vertical pressure marked by a single bar (assuming no wall friction) there is a very reasonable agreement between the 'after rest' ensiled grass results and the silage results.

At lower pressures the prior consolidation of the silage and the only partially fermented state of the 'before rest' sample give an unreliable picture. The true virgin silage consolidation curve lies above the ensiled grass curve.

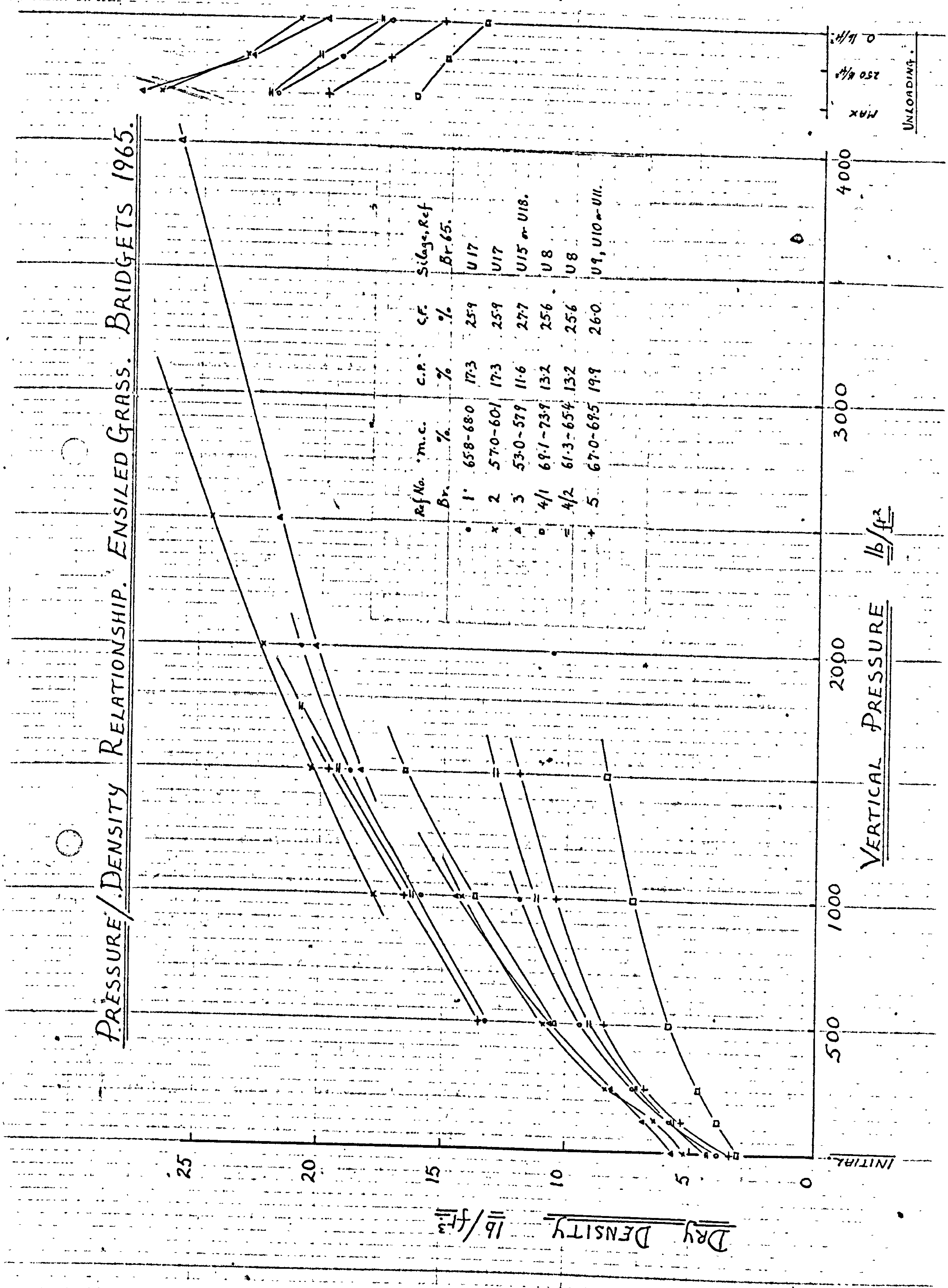
5.5.8.7. <u>Ensiled Grass Samples Br 1 - 5</u>. These samples were taken during the filling of the silo at Bridgets E.H.F. as described in Section 1.5. Samples Br/1, 2 and 3 were taken at the blower. They had already been through a Gehl Chopper which gave a chop length of 1" - 5" to 1" - 10", but to enable the cores to be evenly filled they were further chopped to 1 3/4" max. using the guillotine. Samples Br 4/1 and 4/2 and 5 were taken from the swath, wilted using the lab. drier, and chopped to 1 3/4" with the guillotine. None of these samples gave a satisfactory fermentation (pH range 5.1 - 6.9).

The results given in Table 5.5/15 and Graph 5.5/12 are mainly of interest for the difference between the 'before and after rest' densities and the comparison with the pressure density results for the corresponding silage from the tower; traced using Bridgets filling record Graph 1.5/1

Table 5.5/15

BRIDGET'S 1965, PRESSURE/DENSITY RESULTS, ENSILED GRASS, TOWER FILLING.

Sample Ref.	Date of Ensiling	Filling Zone.	M.C. %	C.P.% C.F.% Ph.	CHOP	Sample Wt g.	DENSITY and DRY DENSITY Initial and after Rest.	EFFLUENT AT V lb/sqft time hr. Y Density Yd Dry Density	Y', lb/cuft; Y'd, lb/cuft; and C' lb/cuft/log$_{10}$ hr.; after 1.0 hr. @ V, lb/sqft. and T hr. after ensiling.												
									V 125	250	500	1000	1250	1500	1750	2000	2500	3000	4000	250	0
Br 1.	11.30 18/5	B.	65.8	17.3 25.9	1"-5" G.t 1¾"	491.5	Y. 12.3 Yd. 3.94		Y' 18.35 C' 1.18 Y'd 5.87 T 54.	23.05 1.72 7.38 71.	29.5 1.97 9.45 74.	36.85 2.65 11.8 148.							V=1500↓		
			68.0 D.M. 32.0	5.5		479	38.9 12.45	V= 2000 6.0h. Y. 66.0 Yd. 22.15			41.4 1.2 13.25 482.	49.4 2.53 15.8 503.		58.8 2.77 18.8 551.		(65.2) — (20.85) 575.			65.5 -0.14 21.0 581.	60.9 -0.9 19.5 599.	54.75 -2.85 17.5 646.
Br 2.	18.30 19/5	B.	57.0	17.3 25.9	1"-7" Gt 1¾"	524.5	13.1 5.2		16.25 0.53 6.48 23.	21.0 0.93 8.4 40.	27.3 1.2 10.9 66.	35.8 1.6 14.25 93.	(39.3) — (15.65) 114.								
			60.15 39.85	6.0		512	38.8 15.55	V= 3000 6.0h. 67.4 26.8			(37.7) (.53) (15.0) 451.	44.6 1.55 17.8 472.		51.1 1.97 20.4 520.		56.2 3.03 22.4 534.	61.5 2.23 24.5 558.	(66.5) — (26.4) 606.		58.55 -1.23 23.3 612.	53.4 -2.63 21.2 632.
Br 3.	18.00 19/5	C.	53.0	11.6 27.7	1"-10" Gt 1¾"	548	13.65 5.75		16.0 0.67 6.75 23.	19.35 1.17 8.15 39.	25.5 1.47 10.75 67.	34.2 1.97 14.4 93.	(39.0) — (16.45) 115.	(41.1) — (17.3) 135.							
			57.95 42.05	5.3		530	39.0 16.4	V=4000 TRACE 20h. 65.4 27.6			(39.8) (0.0) (16.8) 451.	(40.2) (1.27) (16.9) 472.		44.25 1.62 18.65 520.		47.9 2.33 20.2 544.	51.6 2.66 21.8 569.	(56.9) (1.5) (24.0) 616.	61.8 2.6 26.0 642.	54.8 -2.6 23.1 664.	47.6 -2.9 20.05 688.
Br 4/1	18.45 27/5	H.	69.1	13.2 25.6	SWARTH SAMPLE. Gt 1¾"	447.5	11.6 3.03		15.35 .22 3.98 53	18.15 .55 4.74 113	22.9 .87 5.97 138	28.1 1.3 7.34 159		32.45 1.05 8.47 183	(34.2) — (8.92) 188						
			73.9 26.1	5.1		425	32.8 8.57	V= 1500 0.5h. 63.2 16.5			40.2 2.2 10.5 522	52.7 3.97 13.78 543		(63.4) — (16.55) 570						57.2 -1.23 15.2 571	51.9 -2.06 13.55. 591.
Br 4/2	19.15 27/5	H.	61.3	13.2 25.6	SWARTH SAMPLE Gt 1¾"	428	12.5 4.33		16.5 0.83 5.7 53	20.9 0.93 7.25 113	25.95 1.26 9.0 138	32.4 1.53 11.2 159		37.6 1.93 13.0 183							
			65.4 34.6	5.1		407.5	36.8 12.7	V=1750 25.5h 64.9 22.4			(40.1) (1.00) (13.9) 527	47.3 2.96 16.35 543		55.8 313 19.3 570	60.4 3.26 20.9 591					54.0 -1.66 20.4 617.	51.8 -2.46 17.4 640.
Br 5.	11.00 28/5	F-G	67.0	19.7-20.1 25.4-26.6	SWARTH SAMPLE Gt 1¾"	418	10.5 3.2		16.8 0.73 5.3 37	21.85 0.72 6.88 97	26.9 1.17 8.47 122	33.05 1.18 10.4 143		37.9 123 11.93 167							
			69.5 30.5	6.9		401	37.05 11.3	V=1500 25h. 63.5 20.0			42.9 1.37 13.5 505	52.6 2.33 16.6 527		62.4 2.9 19.65 554						55.5 -2.16 17.5 557	48.6 -2.38 153. 575



PRESSURE/DENSITY RELATIONSHIP. ENSILED GRASS. BRIDGETS 1965.

TABLE 5.5/16

Comparison of Ensiled Grass and Silage Dry Densities at V = 1000 lb/ft^2

Bridgets 1965-66

Ensiled Grass Sample.	m.c. %	'before rest' Yd' lb/ft^3	'after rest' Yd' lb/ft^3	Silage Sample	Yd' lb/ft^3
Br 1	68.0	11.8	15.8	65/U/17	20.3
Br 2	60.5	14.2	17.8		
Br 3	57.9	14.4	16.9	65/U/15	18.1
				65/U/18	22.9
Br 4/1	73.9	7.3	13.8	65/U/8	17.1
4/2	65.4	11.2	16.3		
Br 5	69.5	10.4	16.3	65/U/9	19.7
				65/U/10	21.8
				65/U/11	20.1

Table 5.5/16 sets out the dry densities (Yd') at 1000 lb/ft^2 for the ensiled grass before and after rest and for the corresponding silages. It can be seen that the 'before rest' dry densities were very much lower than the 'after rest' dry densities, the difference being greatest for the highest moisture contents (at 73.9%, 7.3 to 13.8 lb/ft^3; at 57.9%, 14.4 to 16.9 lb/ft^3). This higher 'before rest' dry density with the more wilted material is consistent with the extra strength of grass compared with the resulting silage being due to the osmotic pressure, in the cells, which would be reduced by wilting. The 'after

rest' dry densities all have lower values than the comparable silage densities (unlike in the Glantlees comparison) and this can only be attributed to the poor fermentation.

Hay samples corresponding to Br 1 - 5 were obtained using the lab. drier but unfortunately being insufficiently dried and stored in a warm place they moulded and had to be discarded.

5.5.8.8. <u>Silage Samples Br 65/U1 - U19</u>. During the unloading of the silo at Bridgets E.H.F. density samples were taken at intervals as recorded on Graph 1.5/1. The results of these tests are given in Table 5.5/17 and plotted on Graphs 5.5/13, 5.5/14 and 5.5/15. The analysis was estimated from the sampling that was carried out by the E.H.F. staff, the results of which are shown on Graph 1.5/1.

The grass in the silo was from predominately rye grass swards similar to those at Glantlees but the crop was cut very much younger (C.P. range 11.5 - 22%), than that in the Glantlees silo (C.P.7.5 - 13%). The range of densities obtained at Bridgets (Yd' 13.05 - 26.9 lb/ft^3 at 1000 lb/ft^2) was greater than that at Glantlees (Yd' 14.0 - 19.7 lb/ft^3 at 1000 lb/ft^2).

There was good agreement between the results of similar tests on similar material (e.g. Br 65/U1 and U2). The comparison of Br 65/U/11 and U/12 is of particular interest, U/11 was cut in the standard manner, but U/12 was of identical material from around the core U/11 but packed into the core in three layers as in the ensiled grass technique.

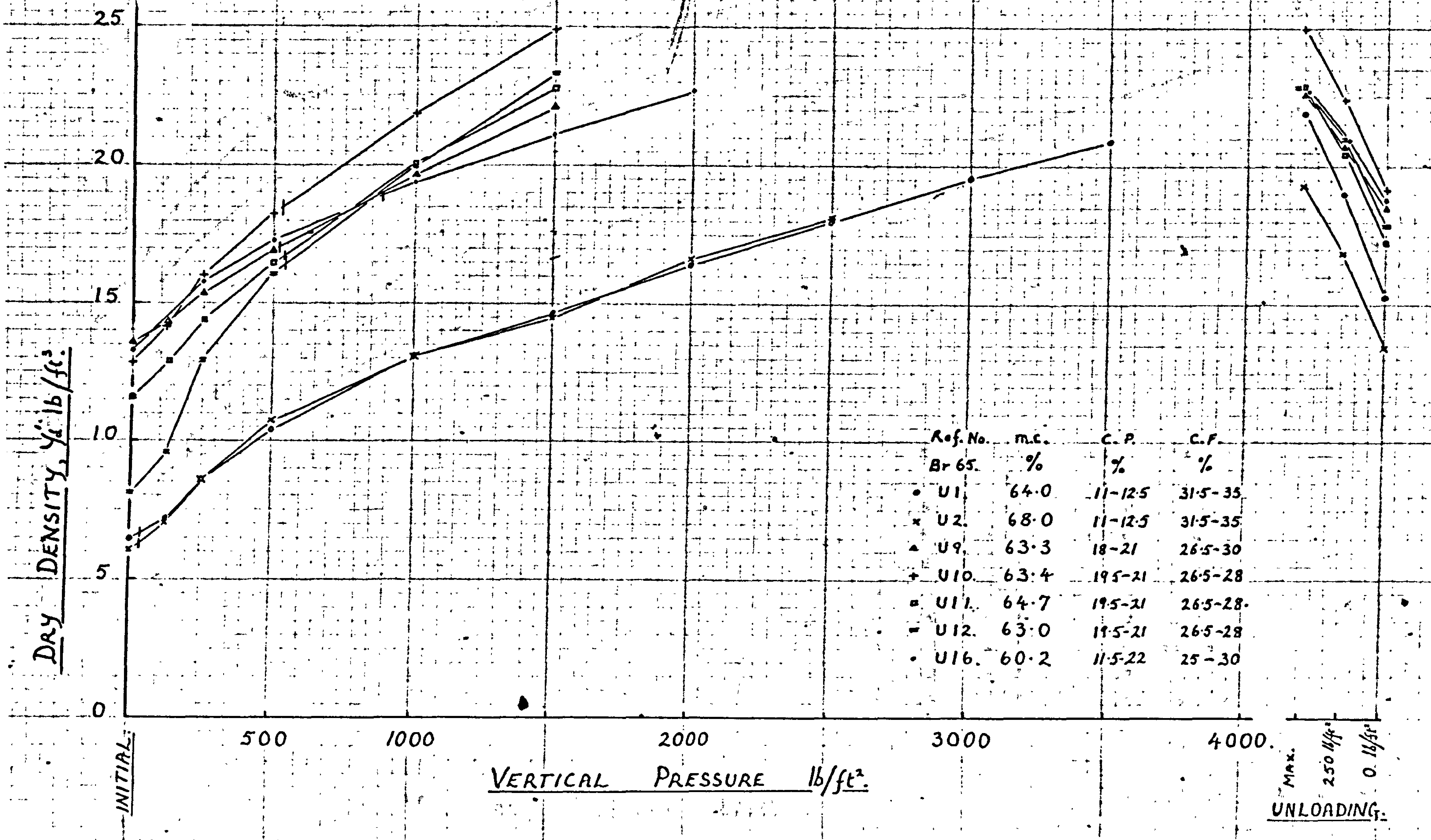
Table 5.5/17

BRIDGET'S 1965-66 PRESSURE/DENSITY RESULTS TOWER UNLOADING.

Ref. No. Br 65/	Date of Sampling	Q f.w. Packing.	Over-burden.	V^0 Insitu. lb/sq ft.	m.c.%	Possible Range C.P.% C.F.%	CHOP.	Sample Weight g.	Initial Density and Dry Density	Effluent. Vertical Pre Time Density Dry Density	Y', lb/cuft; Y'_d, lb/cuft; and C' lb/cuft/$\log_{10}$ hours; at V, lb/sq ft; after 1.0 hr.												
											V 125.	250.	500.	1000.	1500.	2000.	2500.	3000.	3500.	4000.	250	50	0.
U1.	30/10	Q 4'	41½"	43	64.0	11 – 12.5 31.5–35	½"–3"	578.5 570.0	Y' 18.0 Yd 6.5	V=3500 35h 61.4–60.4 22.1–21.7	Y' 19.8 C' 0.4 Yd' 9.15	23.8 0.9 8.6	28.8 1.25 10.4	36.25 1.5 13.05	40.9 2.05 14.7	45.7 2.25 16.45	50.0 2.5 18.0	54.25 2.25 19.55	58.0 2.2 20.9		52.9 −1.7 19.0		42.4 −4.0 15.25
U2.	1/11.	Q 6'	40"	42	68.0	11 – 12.5 31.5–35	½"–3"	744 734	18.9 6.05	V=2500 23h. 60.8–60.0 19.5–19.2	22.25 0.9 7.1	26.8 1.0 8.6	32.6 1.45 10.85	40.7 1.6 13.05	45.4 2.55 14.5	51.8 2.75 16.6	56.6 3.15 18.1				52.8 −1.4 16.9		42.0 −4.15 13.45
U3.	22/11.	Q 1'9"	108"	158	48.3	12.0–13.5 31.–34	½"–4"	514.5 513.5	11.7 6.05	Nil to V=4000	15.7 0.4 8.12	18.4 0.65 9.5	22.2 1.4 11.5	28.35 1.75 14.65	32.8 1.8 16.95	36.9 1.95 19.1		42.4 2.65 21.9		48.1 2.03 24.85	45.9 −1.6 23.75		38.0 −3.5 19.65
U4.	22/11.	Q 1'9"	113½"	170	53.0	12 – 13.5 31 – 34	½"–4"	600.5 597	17.05 8.0	Nil to V=4000.	20.7 0.45 9.725	23.8 0.75 11.2	28.2 1.3 13.35	34.4 1.65 16.2	38.55 1.6 18.1	42.3 1.7 19.9		46.4 2.7 21.8		53.4 2.05 25.1	50.0 −2.05 23.5		40.7 −4.0 19.15
U5.	22/11.	Q 5'9"	102"	145	53.0	11.5–13.5 31 – 34	½"–4"	686 674.5	16.6 7.8	Nil to V=4000.	20.3 0.5 9.55	22.7 0.45 10.65	25.9 0.85 12.15	31.0 1.3 14.55	34.4 1.45 16.15	37.2 1.35 17.5		41.6 2.3 19.55		46.4 1.8 21.8	44.85 −1.2 21.05		37.8 −3.45 18.2
U6.	10/12.	Q 2' 30°	174½"	302	35.8	10 – 11.5 31 – 33	½"–6"	416 402.5	13.05 8.4	Nil to V=4000.	16.1 0.4 10.3	18.7 0.6 12.0	22.8 1.0 14.65	28.0 1.35 17.95	31.7 1.45 20.3	35.15 1.6 22.5		39.7 1.25 25.5		43.2 1.35 27.7	36.35 −1.5 23.3		28.15 −2.65 18.05
U7.	13/12.	Q 3'9" 45° PART REPACK	178½"	308	35.4	10 – 11.5 31 – 33	½"–9"	565 554	12.7 8.2	Nil to V=4000.	15.75 0.6 10.15	18.2 0.6 11.75	21.55 0.95 13.9	25.8 1.2 16.65	28.9 0.975 18.65	31.5 1.5 20.3		35.0 1.45 22.5		38.0 1.3 24.5	33.9 −1.2 21.9		27.2 −2.05 17.55
U8.	13/12.	Q 3'3"	190½"	61.7 55.5 49.3	332	13 – 15 25.5–27.5	½"–4"	1022 1016	24.0 10.7	V=3000 30h. 56.2 25.0 Trace	25.0 0.175 11.1	27.4 0.5 12.2	31.6 1.2 14.05	38.3 2.0 17.05	43.2 0.9? 19.2	47.6 2.0 21.2		53.5 1.85 23.8			50.55 −1.55 22.5		43.1 −2.4 19.2
U9.	31/12.	Q 2'3"	250½"	514	63.3	18 – 21 26.5–30	½"–4" ESI	1460 1456	37.0 13.6	V=1500 15h 61.6– 22.6	39.2 0.35 14.4	42.1 0.7 15.45	46.2 1.25 16.95	53.6 2.15 19.7	60.5 1.8 22.2						56.5 −0.85 20.7	53.8 −0.775 19.7	50.4 −1.65 18.5
U10.	3/1.	Q 1'9"	255½"	530	63.4	19.5–21 26.5–28	½"–4" ESI	1112 1007	35.15 12.85	V=1500 13h 68.5–68.0 25.1–24.9	39.3 0.7 14.35	43.7 1.0 16.0	49.9 1.65 18.25	59.7 2.4 21.8	68.2^E 2.5 24.9						61.2 −1.5 22.4	56.5 −1.25 20.6	52.1 −2.35 19.05
U11.	3/1.	Q 1'9"	260½"	549	64.7	19.5–21 26.5–28	½"–4" ESI	1247 1224	32.8 11.55	V=1500 13h 64.8–63.8 22.8–22.5	36.6 0.75 12.9	40.7 0.975 14.4	46.8 1.45 16.5	56.8 2.95 20.05	64.6 1.85 22.8						57.9 −1.2 20.4	53.5 −1.5 18.9	48.8 −2.35 17.2
U12.	3/1.	Q 1'9" AS U11 BUT 3 LAYER REPACK	260½"	549	63.0	19.5–21 26.5–28	½"–4" ESI	794 779	21.95 8.1	V=1500 13h 62.5–61.4 23.1–22.7	25.9 1.9 9.6	35.0 2.05 12.95	43.5 2.2 16.1	54.0 3.3 20.0	63.2^E 2.6 23.4^E						56.7 −1.3 21.0	53.2 −1.0 19.7	48.2 −3.0 17.85
U13.	3/2.	Q 1'6"	307½"	755	51.9	19.5–20.5 25.5–27	¾"–5"	901.5 899	26.4 12.7	V=4000 0.5h 64.0 30.8	30.5 0.45 14.7	33.45 0.7 16.1	37.4 1.0 18.0	43.4 1.5 20.9	47.9 1.4 23.0	52.1 2.0 25.1	56.0 2.25 26.9	(59.6) ? (28.7)		64.5^E 2.4 31.0	54.6 −2.1 26.3		46.3 −3.77 22.3
U14.	3/2.	Q 7'3"	296½"	702.5	55.1	19.5–20.5 25.5–27	¾"–5"	1116 1117	36.0 16.15	V=2500 20h 68.0 30.5	42.0 0.95 18.85	45.6 0.75 20.45	50.5 1.125 22.7	56.1 1.0 25.2	59.7 1.4 26.8	63.1 1.4 28.3	66.1 1.5 29.7				60.3 −1.775 27.05		54.3 −2.2 24.4
U15.	22/2.	Q 2'3"	332½"	885	57.9	11.5–22 25 – 30	½"–7" TOP 5" BASE	964.5 964	24.9 10.5	V=3000 25h 60.5 25.4	29.6 0.75 12.45	33.2 0.75 14.0	37.2 .975 15.65	43.0 1.775 18.1	48.3 2.475 20.35	52.7 2.8 22.2	(57.3) ? (24.15)	59.5 2.55 25.0			53.0 −1.6 22.35		44.2 −2.75 18.6
U16.	22/1.	Q 7'3"	329½"	870	60.2	11.5–22 25 – 30	½"–7" TOP 5" BASE	1453.5 1454	33.5 13.35	V=2000 1.0h 56.8 22.6	36.0 0.55 14.35	39.6 0.8 15.8	43.4 1.0 17.3	48.7 1.4 19.4	53.0 1.65 21.1	57.0 2.1 22.7					52.6 −1.0 21.0		47.0 −2.0 18.7
U17.	7/3.	Q 1'9"	365½"	1022	57.7	11.5–19 26 – 30	1"–6"	1045. 1046	28.0 11.8	V=2500 30h 62.5 26.4	33.7 0.6 14.25	36.9 0.65 15.6	41.2 0.95 17.4	48.0 1.375 20.3	53.2 1.9 22.5	(58.7) ? (24.8)	(62.0) ? (26.2)				53.3 −1.8 22.5		43.5 −2.75 18.4
U18.	7/3.	Q 6'6"	349"	940	59.7	11.5–19 26–29.5	1"–6"	1343.5 1344.5	38.6 15.55	V=2500 25h 67.6 27.2	41.8 0.65 16.8	45.4 1.025 18.3	50.4 1.2 20.3	57.0 1.275 22.95	60.9 1.275 24.5	65.7 1.1 26.5	68.5^E 1.1 27.6				61.7 −1.325 24.8		52.7 −2.65 21.2
U19.	4/4.	Q 7'9"	393"	1185	57.7	18 – 20.5 24.5–25.	1"–7"	1379 1380	44.1 18.7.	V=1000 18.0h 65.3 27.6.	48.0 .65 20.3	51.8 .975 21.9	56.7 1.025 24.0	63.6 1.675 26.9							62.1 −1.5 26.3		55.8 −2.1 23.6

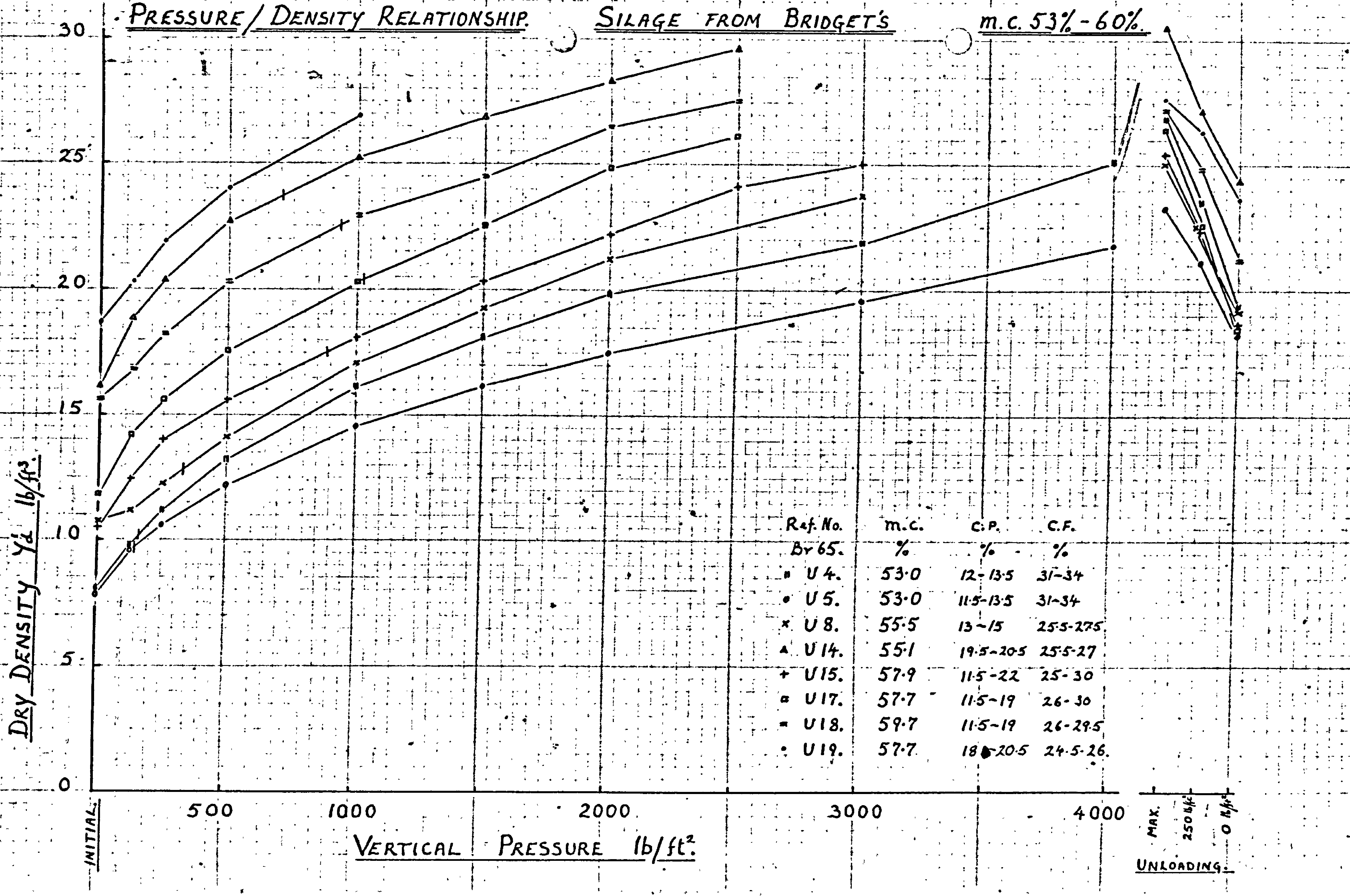
Graph 5.5/13

PRESSURE/DENSITY RELATIONSHIP, SILAGE FROM BRIDGET'S. m.c. 60% - 68%.

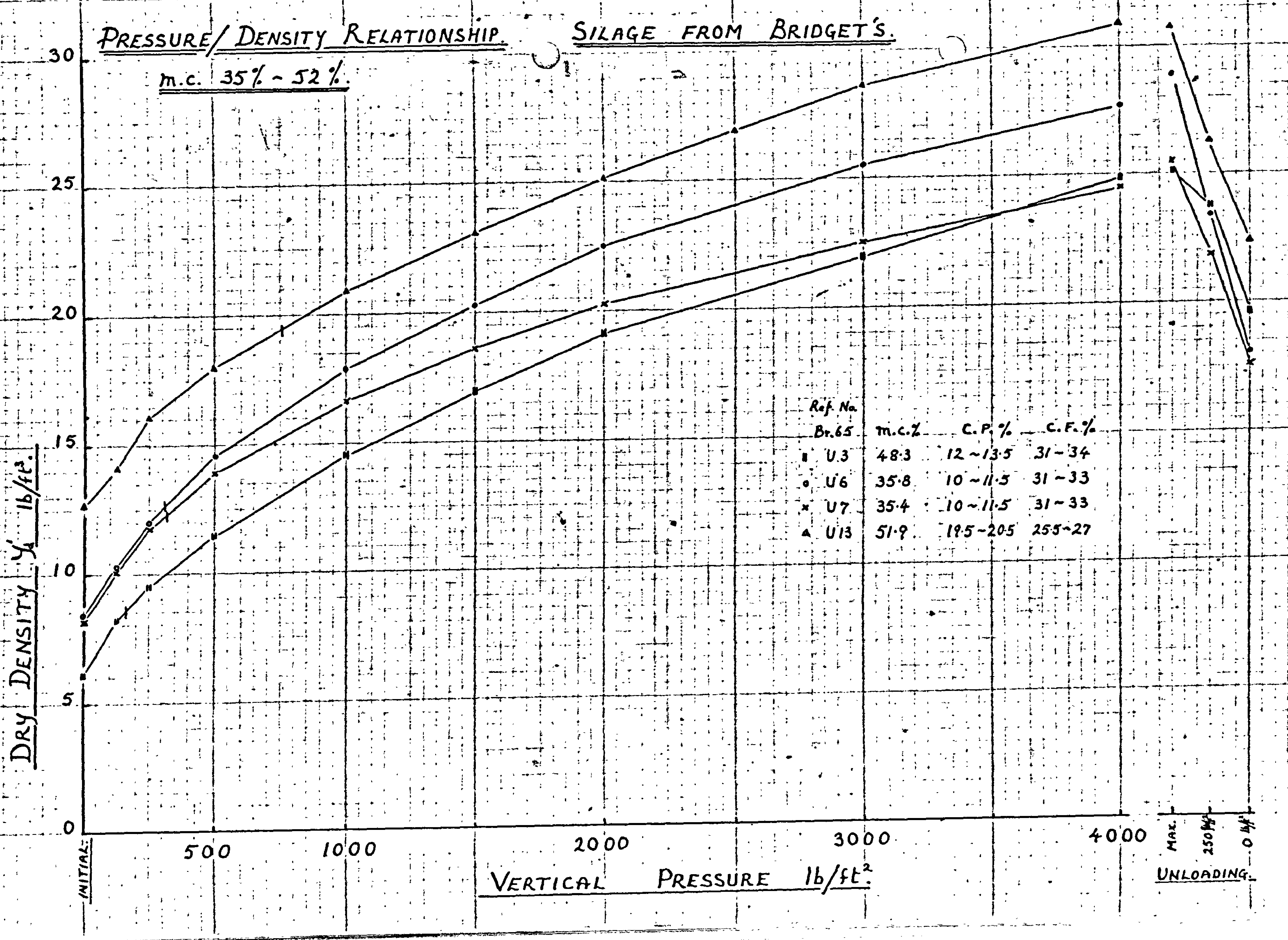


	Ref. No. Br 65.	m.c. %	C.P. %	C.F. %
•	U1.	64.0	11-12.5	31.5-35
×	U2.	68.0	11-12.5	31.5-35
▲	U9.	63.3	18-21	26.5-30
+	U10.	63.4	19.5-21	26.5-28
▫	U11.	64.7	19.5-21	26.5-28.
▬	U12.	63.0	19.5-21	26.5-28
•	U16.	60.2	11.5-22	25-30

Graph 5.5/14



Ref. No.	m.c.	C.P.	C.F.
Br 65.	%	%	%
▪ U 4.	53·0	12-13·5	31-34
• U 5.	53·0	11·5-13·5	31-34
× U 8.	55·5	13-15	25·5-27·5
▲ U 14.	55·1	19·5-20·5	25·5-27
+ U 15.	57·9	11·5-22	25-30
□ U 17.	57·7	11·5-19	26-30
= U 18.	59·7	11·5-19	26-29·5
• U 19.	57·7	18-20·5	24·5-26.



PRESSURE/DENSITY RELATIONSHIP. SILAGE FROM BRIDGET'S.

m.c. 35% - 52%.

Graph 5.5/15

While at low pressures the U/12 samples had a lower dry density, at 500 lb/ft^2 and above the densities of the two samples are very similar. The in situ vertical pressure of these samples was 550 lb/ft^2 (assuming no wall friction). U/12 probably gives a good indication of the virgin consolidation curve for silage. The sampling technique used for U/12 might well be used in further work in place of the cut sample technique if further comparative tests show similar agreement; for it is much easier to carry out.

Samples Br 65/U/1 and U/2 and to a lesser extent Br 65/U/3 and U/4 have virgin consolidation curves, the in situ vertical pressures being 43, 42, 158 and 170 lb/ft^2 respectively.

5.5.8.9. Silage Samples Br 65/C1 V1 - V3, Br 64/V1 and Wo 63/V1. Concurrently with the filling of the tower silo at Bridgets E.H.F. identical grass, but less wilted, was being used to make clamp silage. The covered clamp had sloping concrete side walls and a central concrete dividing wall. The first cut grass was ensiled in one half, the second cut in the other. The silage was consolidated using a tractor, covered with polythene and finally straw was stacked on top.

One density sample (Br 65/C1 V2) was taken from first cut material and two density samples (Br 65/C1 V1 and V3) from the second cut material. The results are given in Table 5.5/18 and plotted on Graph 5.5/16.

BRIDGET'S PRESSURE/DENSITY RESULTS, SILAGE.

CLAMP UNLOADING, 1965-66.

Ref. No. Br	Date of Sampling	Q fw.	Over-burden	V^0 in situ.	m.c.% D.M.%	C.P.% C.F.% Possible range.	CHOP	Sample Weight g.	INITIAL Density and Dry Density	EFFLUENT Vertical Pressure Time Density Dry Density.	Y', lb/cu.ft.; Y'_d. lb/cu.ft.; and C' lb/cu.ft./log₁₀hours; after 1·0 hr. at V lb/sq.ft.									
											V 125	250	500	750	1000	1500	2000	2500	250	0.
Br. 65/CV1	1/11 65.		21" +8' Straw	158	76·3 237	9–11 31–33·5 2nd cut.	1"–7" long corner	1711	Y 43·0 Y_d 10·2	V = 750 t = 2·0h Y 58·9 Y_d 13·95	Y' 44·6 C' 0·33 Y'_d 10·55	47·4 0·7 11·2	52·8 1·27 12·5	58·3 1·47 13·8					57·4 −0·77 13·6	50·9 −1·50 12·05
Br. 65/CV2	7/3 66.		30" +8' Straw.	170	60·2 39·8	11–20 27–29 1st cut.	1"–10"	884	32·0 12·7	V = 2500 2·0h 64·8 25·8	35·8 0·7 14·25	38·8 0·4 15·45	42·4 0·93 16·9		49·35 1·68 19·6	54·7 2·03 21·8	59·8 – 23·8	63·9 2·03 25·4	55·6 −2·2 22·5	47·9 −2·58 19·1
Br 65/CV3	4/4 66		63" +8' Straw.	226	67·5 32·5	9–12 31–35 2nd cut.	4–16"	786·5	25·45 8·28	V = 2000 0·5h 55·6 18·1	27·85 0·35 9·05	30·9 ·77 10·05	35·6 1·0 11·55		44·1 2·125 14·3	50·7 2·1 16·5	56·1 2·2 18·2		49·7 −·83 16·15	43·3 −3·2 14·1

TOWER UNLOADING, 1964-65.

Br 64/U1.	25/1 65.	Q 4'	348"	800	71·4 28·6	14·2 33·8	½"–5"	1273	43·9 12·55	V = 1500 24h 643–640 18·4–18·3	46·9 0·53 13·4	49·8 0·57 14·25	52·9 0·60 15·1		57·6 0·97 16·5	61·7 1·9 17·65			59·4 −1·0 17·0.	54·4 −1·57 15·55.

CLAMP UNLOADING. 1963-64. AT WEST END FARM?

WE 63/U1	9/12 63		6"	20	77·2 22·8	--- 34·4	None	1617	36·1 8·25	V = 500 16 51·5 11·7		42·1 1·15 9·6	49·4 1·5 11·25							

Table 5.5/18

Graph 5.5/16

PRESSURE/DENSITY RELATIONSHIP. SILAGE FROM BRIDGET'S AND WEST END.

The higher dry densities of the less mature first cut sample (V2) compared with the second cut material (V1 and V3) shows clearly on Graph 5.5/16. In this case (unlike in the tower where the first cut material had all been subject to a much higher in situ pressure than the second cut) maturity is clearly the cause of the difference; as moisture content has been shown not to be a significant variable in this context.

Sample V2 has a very similar consolidation curve to some of the first cut samples from the tower (e.g. Br 65/U/16 and U/17). Samples V1 and V3 had similar consolidation curves to 2nd cut material from the tower (e.g. Br 65/U/3 and U/5). No exact comparison of the identical crop from clamp and tower can be made as it was not possible to locate the final position of material in the clamp due to the complex inter-layering in filling. Sample Br 64/V1 was taken from the bottom layer of silage in the Bridgets tower for the 1964-65 season. It was of a lucerne mixture. The slope of the consolidation curve was much flatter than for mature grass. It is not possible to say, from this one silage test, if this is a universal characteristic in lucernes. The ensiled grass tests on lucerne at Hurley, discussed in Section 5.5.8.10. don't give reliable data on this because of the poor fermentations. As much American work on silos is on lucerne (alfalfa), it is unfortunate that no more lucerne silage samples could be obtained. This would have greatly helped establish the relevance, or otherwise, of work on densities, pressures and capacities, carried out in the U.S. on lucerne, to silos filled with

British type grass crops.

Sample We 63/V1 was from a typical covered sleeper walled clamp at West End Farm, Surrey, filled with slightly wilted grass. The consolidation curve is very similar to that of Br 65/C1 V3.

5.5.8.10. Hurley Ensiled Grass Samples HL/1-3/1-6 and HR/1-3/1-6. In the summer of 1965 the Grassland Research Institute at Hurley provided me with the crops and the sample preparation facilities to enable two series of ensiled grass tests to be carried out with a proper control of variables.

The first series was on a second cut of a pure stand of lucerne from High Field. This was cut at three maturities; HL/1 on 20.7.65. (before flowering), HL/2 on 3.8.65. (in flower) and HL/3 on 17.8.65. (late flower, some in seed). The second series was on a pure stand of third cut S24 rye grass from Lime Kiln 111 cut at three maturities; i.e. HR/1 on 31.8.65. (6" - 8" leafy), HR/2 on 14.9.65. (8" - 12" leafy, little stem) and HR/3 on 28.9.65. (10" - 14" leafy, little stem, some dead leaf in base, a few in ear).

At each maturity in each series, 6 pressure density tests were carried out at moisture contents of unwilted, approx.70%, 60%, 50% and 40% and hay at 7 - 9%. All samples were guillotine chopped to 1" after being wilted to the required moisture content in a Unitherm Drier set at 35°C, 80% recirculation. The filled cores of ensiled grass were taken overnight to Newcastle and placed in the consolidation machine next day. The hay samples were stored in polythene bags until tested later in the year.

For the reasons discussed in Section 5.5.7. no really satisfactory fermentations were obtained in these tests. In consequence only the hay results can be reguarded as reliable.

All the results for hay samples are given. Those for rye grass HR/1/6, HR/2/6, and HR/3/6 in Table 5.5/20 and Graph 5.5/18. The results for lucerne hay, HL/1/6, HL/2/6, HL/3/6A and HL/3/6B given in Table 5.5/19 and Graph 5.5/17, along with the results for the ensiled grass tests for the most mature of the lucerne series HL/3/1 - 4. HL/3/5 at 36.9% m.c. was rejected as it had completely moulded and had a pH of 8.2. The results of the other ensiled grass tests have also been rejected because of bad fermentations, but the data on them is available in the data file.

These ensiled grass tests (HL/3/1-4) on lucerne, despite the poor fermentations, indicate the following:

1. That dry density of the 'before test' samples at 125 lb/ft^2 was least for the unwilted sample HL/3/1 (4.95 lb/ft^2 at 77% m.c.) and increased with wilting up to HL/3/4 (7.7 lb/ft^3 at 48% m.c.).
2. There is relatively little variation between the dry densities 'after rest' but because of the unknown effect of poor fermentation no significance can be attached to these results.

3. The consolidation curves 'after rest' are of similar shape to those for ensiled grass 'after rest' from Glantlees. They have a slightly lower dry density than that in GD/65/1/1 - 5/1 but slightly higher dry densities than GD/64/6/1 - 6.

The lucerne hay samples HL/1/6, HL/2/6 and HL/3/6A had very similar consolidation curves (Yd' 6.7, 7.2 and 6.9 lb/ft^3 resp. at 125 lb/ft^2 and 11.9, 12.0 and 11.6 lb/ft^3 at 1500 lb/ft^2). It appears that at low moisture contents (7 - 9%) maturity makes no difference to dry densities of lucerne hay for the full range of normal cutting maturities. This seems reasonable as the lucerne does not appear to change in structure between bud and seed, unlike grasses which are changing from a predominantly leafy state to a predominately stemmy state. There is no evidence to show what effect maturity has at silage moisture contents.

Samples HL/3/6A and 3/6B were from the same sample bag but, due to segregation, 3/6A was predominately of stemmy material and 3/6B predominately of leafy material. 3/6A behaved like 1/6 and 2/6, but 3/6B had a much lower dry density at low pressures (4.8 lb/ft^3 at 125 lb/ft^2 against 6.9 lb/ft^3 for 3/6A). But it was more compressible and had a higher dry density at high pressures (17.2 lb/ft^3 at 4000 lb/ft^2 against 15.6 lb/ft^3 for 3/6A).

As with grass samples the dry densities at 7.9% m.c. were 25% to 30% lower than the 'after rest' densities at the silage moisture contents.

Table 5.5/19

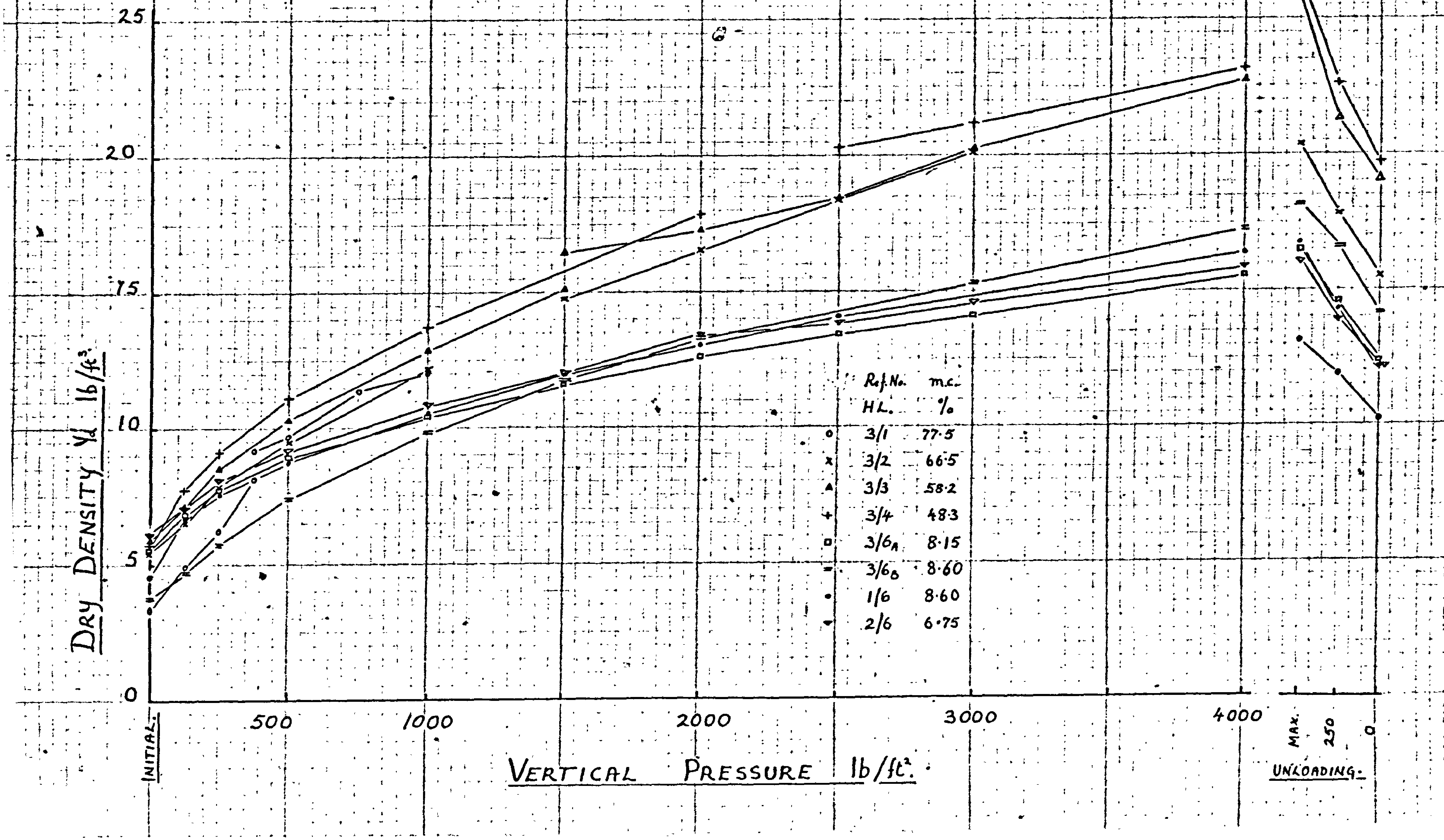
G.R.I. HURLEY 1965, PRESSURE/DENSITY RESULTS FOR ENSILED LUCERNE AND LUCERNE HAY.

ALL SAMPLES OF LUCERNE REGROWTH FROM HIGH FIELD, CHOPPED TO 1" WITH GUILLOTINE, NO LACERATION.

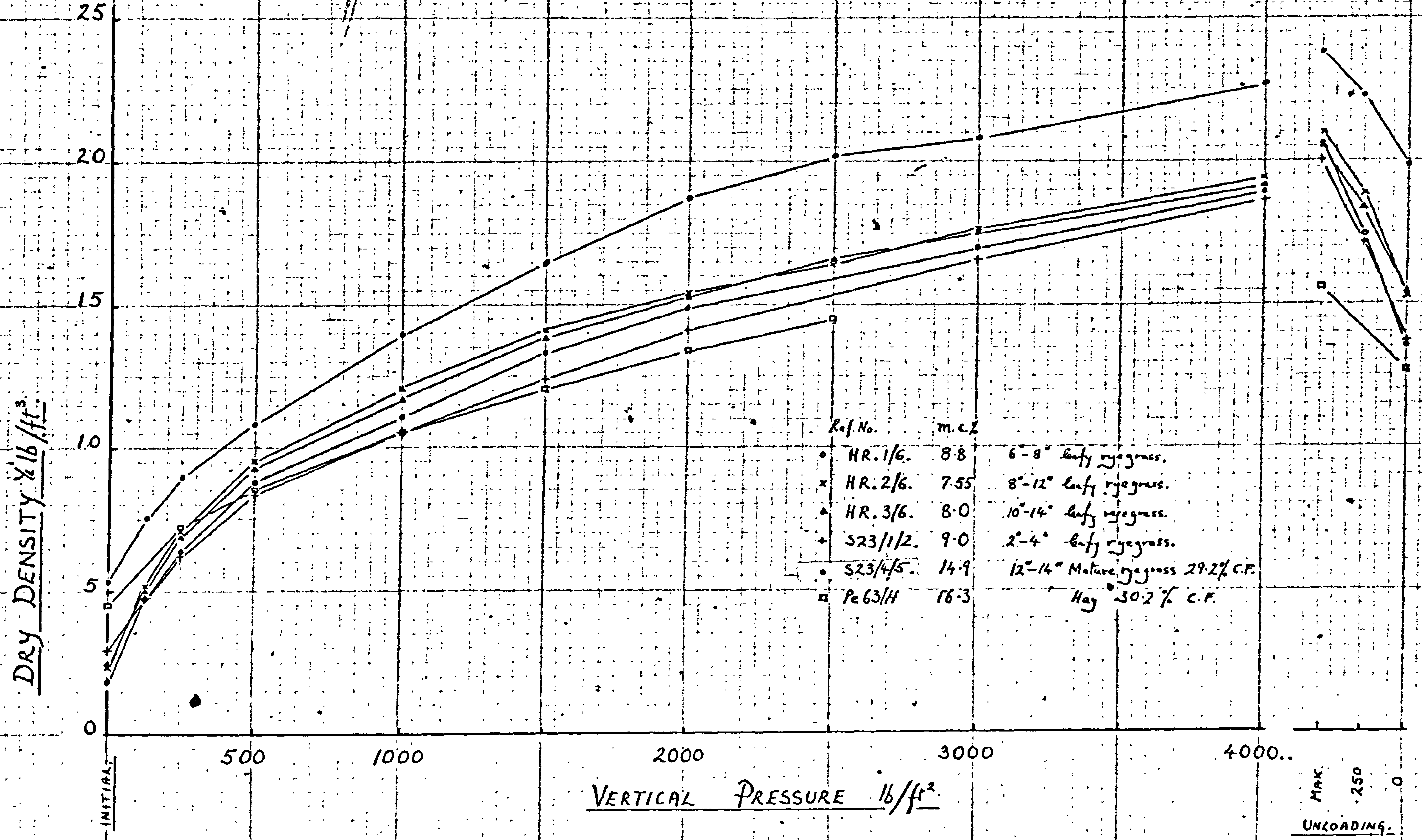
SAMPLE REF.	MOISTURE CONTENT %	GRASS AND SILAGE DESCRIPTION	SAMPLE WEIGHT Initial and Final. g.	DENSITY AND DRY DENSITY Initial and After Rest	EFFLUENT AT	Y' lb/ft³, Yd lb/ft³ and C' lb/ft³/Log₁₀ hr, after 1·0 hr at V lb/ft² and T hr after ensiling.													
						V= 125	250	375	500	750	1000	1500	2000	2500	3000	4000	5000	250	0
HL. 3/1	76·5	Cut 17/8/65 late flower some in seed	586	Y 14·95 Yd 3·39		Y' 21·8 C' n.c Yd 4·95 T. 34	27·5 n.c. 6·25	35·8 n.c. 8·15 70											
	77·3	Ph 5·7, No Mould Nasty Smell of Protein Decay.	567·5	39·4 8·95	V= 1000 2·5h Y· 57·8 Yd 13·1			40·4 ·9 9·15 483	42·8 1·7 9·7	50·2 1·8 11·4	53·0 1·2 12·0 576							52·7 −0·6 11·95	44·9 −2·2 10·2
HL. 3/2	65·2	as 3/1	646	16·15 5·45		19·5 ·9 6·6 30	23·2 1·2 7·85		28·2 1·6 9·5		35·7 2·1 12·1 93								
	66·2	Ph 5·2, No Mould, Sweeter than 3/1, v. little Protein decay.	632·5	39·0 13·2	3000 10·25 60·3 20·4						(40·0) (·6) (13·5) 480	43·6 2·1 14·75	48·8 2·2 16·5	54·5 2·4 18·4	59·5 ·75 20·1 571			52·7 −1·9 17·8	45·9 −2·3 15·5
HL. 3/3	55·5	as 3/1	505	14·2 5·95		17·1 0·55 7·15 29	20·4 1·0 8·5		24·65 1·2 10·3		30·7 1·9 12·8	36·2 2·1 15·1 118							
	58·2	Ph 5·6, Mould at edges, Centre well preserved.	495	38·0 15·9	None at 5000 10 62·1 26·0							39·5 0·5 16·5 477	41·5 1·3 17·3	440 2·4 18·4	48·5 2·5 20·2	54·5 2·9 22·8	59·7 2·6 24·9 595	51·0 −1·2 21·3	45·6 −1·6 19·0
HL 3/4	45·9	as 3/1	391	11·2 5·8		14·9 ·65 7·7 27	17·8 ·95 9·2		21·4 1·1 11·05		26·5 1·45 13·7		34·6 2·3 17·9 117						
	48·3	Ph 6·1 Deeper Mould, Centre well preserved with good smell.	382	37·0 19·1	None at 5000 18 51·4 26·6									39·2 1·2 20·25 475	41·0 1·4 21·2	44·9 1·7 23·2	49·0 1·8 25·3 545	43·7 −1·2 22·6	38·1 −1·7 19·7
HL 3/6A	8·15	as 3/1, but high proportion of stem HAY.	209·5	5·9 5·5	None at 4000 43 17·95 16·5	7·5 ·10 6·9	8·45 ·15 7·75		9·70 ·16 8·90		11·32 ·25 10·4	12·62 ·32 11·6	13·7 ·31 12·6	14·65 ·20 13·45	15·45 ·40 14·2	17·00 ·58 15·6		15·95 −·44 14·65	13·45 −·58 12·35
HL 3/6B	8·60	as 3/1, but low proportion of stem HAY.	134·5	4·12 3·76	None at 4000 18 19·85 18·15	5·10 ·19 4·76	6·25 ·20 5·71		8·10 ·31 7·40		10·75 ·48 9·8	12·85 ·58 11·75	14·6 ·60 13·3		16·85 ·45 15·4	18·9 ·72 17·25		18·2 −·31 16·6	15·15 −·8 14·15
HL 1/6	8·60	Cut 20/7/65. Young before flower. HAY.	196	5·02 4·6	None at 4000 3 18·25 16·7	7·3 ·2 6·7	8·3 ·13 7·6		9·65 ·2 8·8		11·5 ·3 10·5	13·0 ·4 11·9	14·2 ·45 13·0	15·45 ·5 14·1		17·95 ·6 16·4		15·7 −·35 14·35	13·3 −·35 12·2
HL 2/6	6·75	Cut 3/8/65. In flower. HAY.	226	6·50 6·06	None at 4000 3 17·21 16·05	7·7 ·12 7·2	8·65 ·13 8·05		9·8 ·13 9·14		11·6 ·21 10·8	12·85 ·24 12·0	13·85 ·21 12·9	14·8 ·31 13·8	15·7 ·21 14·65	17·0 ·39 15·85		14·9 −·20 13·9	13·0 −·21 12·1

Graph 5.5/17

PRESSURE/DENSITY RELATIONSHIP. ENSILED AND HAY LUCERNE, HURLEY 1965.



PRESSURE/DENSITY RELATIONSHIP. HAY SAMPLES



Graph 5.5/18

The hay samples HR/1/6, 2/6 and 3/6 have very similar consolidation curves their dry densities being:

At 125 lb/ft^2, 4.75 5.2 and 5.0 lb/ft^3 resp.
and at 1500 lb/ft^2, 13.3 14.2 and 13.9 lb/ft^3 resp.
The 125 lb/ft^2 densities for HR/1-3/6 are slightly lower than those for the more mature rye grass samples from Glantlees GD/Ch/1/2 and 3/2 and GD/65/1/2 - 5/2 but at higher pressures the HR samples had higher densities.

	HR/1/6	GD/Ch/1/2	GD/65/1/2
at 125 lb/ft^2	4.75	5.15	5.7 lb/ft^3
at 1500 lb/ft^2	13.3	12.1	11.4 lb/ft^3

The rye grass samples from Hurley being third cut, did not go stemmy as they matured as the first cut crop in May - June does. As it remained predominately leafy little change in pressure density characteristics could be expected with increasing age. The maturity effect does show up in the comparison with the stemmy Glantlees material. Unfortunately the poor fermentations of the ensiled grass samples prevented the effect of maturity being determined at silage moisture contents.

5.5.8.11. Miscellaneous Samples. The results on a number of pressure density tests of particular interest are given in Table 5.5/20 and the results for hay samples are shown on Graph 5.5/18 and for silage and ensiled grass on Graph 5.5/19.

S23 1/2, 2/4 and 4/5 were from a series of continuous ensiled grass tests similar to test GD/64/6/1-6 carried out at intervals on a predominately S23 sward at Cockle Park farm, during 1964. The results of this series of tests are not given in full because some of the samples did not give very good fermentations, and the continuous test made it hard to distinguish if increases in density were due to pressure or fermentation.

Sample S23/1/2 was of leafy first growth S23 rye grass, 2" - 4" high, little more than lawn mowings, at 9.0% m.c. its consolidation curve was similar but about 1 lb/ft^3 less than those for the Hurley samples of similar material (HR/1 - 3/6).

Samples S23/2/4 was of 5" - 7" leafy S23 rye grass at 29.5% m.c. After the test it had a hay like smell and was only slightly moulded. It is remarkable for the very high dry densities obtained (10.9 lb/ft^3 at 125 lb/ft^2, 24.5 lb/ft^3 at 1000 lb/ft^2, and 40.6 lb/ft^3 at 4000 lb/ft^2).

Although very much higher than obtained with any of the Glantlees tests, this is similar to the dry densities of silage samples of the youngest material from Bridgets; e.g. Br 65/U/14 (25.2 lb/ft^3 at 1000 lb/ft^2) and Br 65/U/19 (26.9 lb/ft^3 at 1000 lb/ft^2). It therefore appears that at silage moisture contents young leafy samples are very much more compressible than mature grasses.

Sample S23/4/5 was of the same S23 sward, but 12" - 14" high and in ear; it had been wilted in a lab. drier to 14.9% m.c. It had dry densities (e.g. Yd' 16.5 lb/ft^3 at 1500 lb/ft^2) higher than the 7 - 9% m.c. rye grass hays from Hurley (Yd' 13.3 - 14.1 lb/ft^3 at 1500 lb/ft^2) and the 17.8% m.c. mature rye grass hay GD/64/6/6 from Glantlees

Table 5.5/20

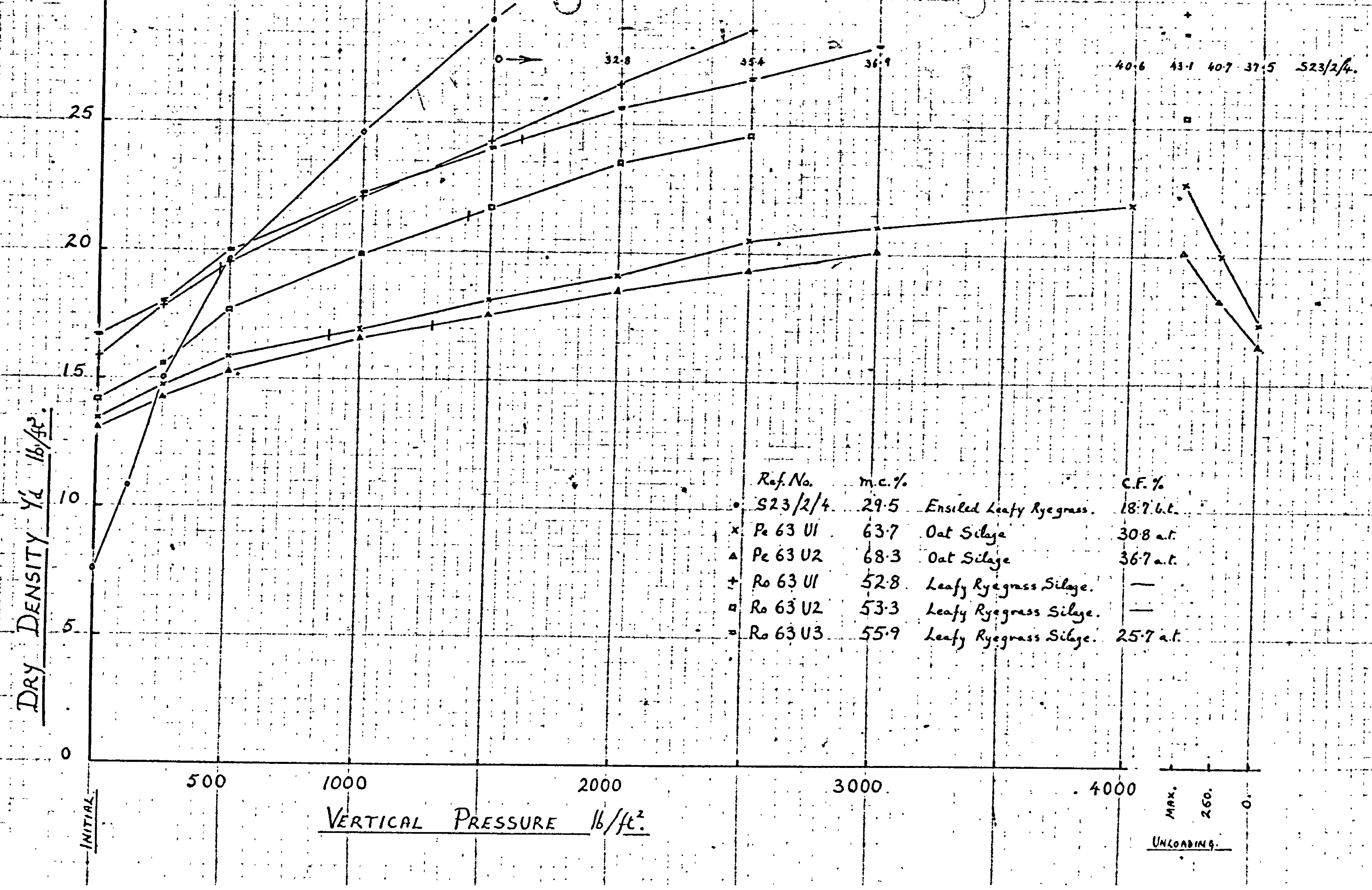
MISCELLANEOUS PRESSURE/DENSITY RESULTS 1963~65.

SAMPLE REF.	DESCRIPTION	MOISTURE CONTENT %	ANALYSIS C.P.% C.F.%	CHOP LENGTH	INITIAL DENSITY AND DRY DENSITY lb/ft^3	EFFLUENT AT	γ' lb/ft^3, γ_d lb/ft^3 and C' lb/ft^3/$\log_{10}$ hr, after 1.0 hr* at V lb/ft^2.											
							V 125	250	500	1000	1500	2000	2500	3000	3500	4000	250	0
HR.1/6	UNITHERM DRIED 3RD CUT S24 RYEGRASS, LIME KILN III, HURLEY 31/8/65, 6"-8" LEAFY. HAY	8.8		1" G	2.10 1.92	NONE 4000 42 22.6 20.6	γ' 5.2 C' ·26 γ_d 4.75	7.1 ·4 6.48	9.65 ·55 8.80	12.3 ·52 11.2	14.6 ·8 13.3	16.3 ·65 14.9		18.65 ·5 17.0		20.75 1.15 18.9	19.1 −·8 17.4	14.8 −1.2 13.5
HR.2/6	AS HR.1/6. 14/9/65, 8"-12" LEAFY, LITTLE STEM. HAY.	7.55		1" G	2.60 2.40	NONE 4000 71 22.7 21.0	5.6 ·28 5.17	7.65 ·42 7.06	10.3 ·60 9.51	13.1 ·60 12.1	15.3 ·65 14.15	16.7 ·6 15.41	17.8 ·8 16.45	19.05 ·9 17.6		21.05 ·9 19.45	20.5 −·5 18.9	16.45 −·95 15.2
HR.3/6	AS HR.1/6. 28/9/65 10"-14" LEAF, LITTLE STEM. SOME DEAD BASE, SOME IN EAR	8.0		1" G	2.64 2.43	NONE 4000 66 22.4 20.6	5.5 ·35 5.05	7.5 ·5 6.90	10.1 ·7 9.3	12.8 ·8 11.8	15.1 1.0 13.9	16.75 ·75 15.4	18.0 16.55	19.0 ·7 17.55		20.8 ·9 19.1	20.0 −·5 18.4	16.8 −·8 15.45
S23.1/2	LAB DRIED 1ST SET S23 RYEGRASS, ON 6/5/64. COCKLE PK. 2"-4", VERY YOUNG LEAFY.	9.0	b.t. 23.6 22.6	½" G	3.25 2.95	NONE 4000 18 22.0 20.0	5.2 ·25 4.75	6.95 ·55 6.35	9.15 ·5 8.35	11.5 ·65 10.5	13.6 ·95 12.35	15.5 1.15 14.1		18.3 1.2 16.6		20.4 1.3 18.6	18.9 −·8 17.2	15.0 −1.50 13.6
S23.2/4	LAB. DRIED 2ND SET S23 RYEGRASS, ON 15/5/64. COCKLE PK. 5"-7" LEAFY. SMELL HAY, SLIGHT MOULD AFTER TEST.	29.5	b.t. 18.3 18.7	½" G	10.8 7.6	NONE 4000 67 61.1 43.1	15.4 11 10.85	21.35 ·9 15.0	27.8 1.1 19.6	35.0 2.3 24.65	41.2 1.8 29.0	46.6 1.6 32.8	50.2 1.3 35.4	52.4 2.1 36.9		57.8 1.8 40.6	57.9 −1.2 40.7	53.2 −1.8 37.5
S23.4/5	LAB. DRIED 4TH SET S23 RYEGRASS, 1/7/64. COCKLE PK. 12"-14" MATURE HAY.	14.9	b.t. 7.2 29.2	½" G	6.36 5.41	NONE 4000 14 27.95 23.8	8.9 ·42 7.6	10.55 ·38 9.0	12.8 ·57 10.9	16.4 ·90 14.0	19.35 1.0 16.5	22.0 1.0 18.7	23.8 ·8 20.2	24.5 1.0 20.8		26.7 1.0 22.7	26.2 −·35 22.3	23.25 −1.0 19.8
Pe.63/H	FROM BALE OF HAY PEEPY FARM 16/12/63	16.3	a.t. --- 30.2	1" G	5.4 4.5	NONE 2500 147 18.6 15.6		8.6 ·3 7.2	10.2 ·3 8.55	12.55 ·57 10.5	14.4 ·4 12.0	16.0 ·5 13.4	17.4 ·45 14.5					15.2 12.7
Pe.63/U1.	OAT FORAGE SILAGE FROM PEEPY FARM BOYTHORPE SILO 6/3/64. 22' OVERBURDEN, APPROX V^0 880 lb/ft^2	63.7	a.t. --- 30.8	⅓"-2" F	36.9 13.4	V 4000 T ·3 γ 63.0 γ_d 22.8		40.95 ·5 14.8	43.5 ·35 15.8	46.9 ·72 17.0	50.1 ·70 18.2	52.9 ·85 19.2	55.7 ·9 20.55	58.0 1.4 21.05	60.6 1.25 22.0		55.2 −1.4 20.0	47.7 −2.2 17.3
Pe.63/U2	OAT FORAGE SILAGE FROM PEEPY BOYTHORPE SILO 9/4/64 31' OVERBURDEN, APPROX V^0 1280 lb/ft^2	68.3	a.t. 36.7	½"-2½" F	41.4 13.1	3000 ·8 63.8 20.2.		45.2 ·55 14.35	48.4 ·55 15.3	52.45 ·80 16.6	55.6 1.05 17.6	58.45 1.20 18.5	61.0 1.50 19.3	63.6 20.2			57.9 −1.1 18.3	52.0 −2.0 16.5
Ro.63/U1	YOUNG LEAFY GRASS SILAGE FROM ROPSLEY SILO 26/11/63 13'6" OVERBURDEN, APPROX V^0 470 lb/ft^2	52.8		¼"-3" F	33.6 15.8	NONE 2500 255 62.5 29.5		38.0 ·37 17.95	41.35 ·83 19.5	46.7 1.20 22.1	51.5 1.27 24.3	56.1 1.53 26.5	60.7 1.00 28.7					
Ro.63/U2	YOUNG LEAFY GRASS SILAGE FROM ROPSLEY SILO 17/1/64 34' OVERBURDEN, APPROX V^0 1420 lb/ft^2	53.3		¼"-1½" F	30.4 14.2	NONE 2500 30 54.4 25.4		33.55 ·85 15.65	38.0 ·75 17.75	42.7 1.1 19.9	46.5 1.45 21.7	49.9 1.15 23.5	52.9 1.1 24.7					
Ro.63/U3	YOUNG LEAFY GRASS SILAGE FROM ROPSLEY SILO 29/1/64 37'6" OVERBURDEN APPROX V^0 1610 lb/ft^2	55.9	a.t. 25.7	½"-3" F	37.8 16.7	NONE 3000 24 65.1 28.7		40.8 1.0 18.0	45.3 ·57 20.0	50.4 ·9 22.2	54.4 1.03 24.0	58.0 1.00 25.6	60.8 1.23 26.8	63.6 1.03 28.1				

b.t.: BEFORE TEST. a.t.: AFTER TEST. F.: FIELD CHOP G.: GUILLOTINE.

Graph 5.5/19

PRESSURE/DENSITY RELATIONSHIP MISCELLANEOUS SAMPLES.



(Yd' 14.4 lb/ft^3 at 1500 lb/ft^2). As in the 0 - 25% m.c. range, moisture content, as well as maturity, has a major effect on dry density, the relative importance of these two variables cannot be assessed.

Sample Pe 63/U1 at 16.3% m.c. was from a bale of field cured hay from Peepy farm. It would seem that the C.F. of 30.8% did not fully reflect the maturity of the sample which had a dry density (12.0 lb/ft^3 at 1500 lb/ft^2) much lower than that of S23/4/5 (16.5 lb/ft^3 at 1500 lb/ft^2) which had a C.F. of 29.2%. It may be that the field curing of the Peepy sample had toughened it compared with S23/4/5 which was lab. dried.

Pe 63/U1 and U2 were samples of oat forage silage cut from the Boythorpe tower at Peepy farm. Although the dry densities are as high as for the more mature grass samples at 1000 lb/ft^2, at 3000 lb/ft^2 the dry densities are lower because of the flat slope of the consolidation curve.

Sample	Yd' at 1000 lb/ft^2	at Yd' at 3000 lb/ft^2
Pe 63/U1	17.0 lb/ft^3	21.05 lb/ft^3
Pe 63/U2	16.6	20.2
Br 65/U4	16.2	21.8
Br 65/U8	17.05	23.8
Gl 65/U24/4	17.2	22.4

Samples Ro 63/U1 - U3 were all of leafy young rye grass ensiled at Ropsley Farm in 1963. The consolidation curves are very similar to those for the younger material in Bridgets Tower, e.g. Br 65/U12, /U17 and /U18.

5.5.9. The Choice of a Mathematical Expression to Describe the Pressure Density Relationship of Silage.

The calculation of the capacity of a silo or the pressures in it requires that the pressure density relation of a given silage be expressed in a mathematical form. This can be done either as a single equation relating dry density to pressure or by a series of equations each one for a defined pressure or dry density range. If a computer is available for the computational work the pressure density relation can be defined by an array of dry densities at given pressures and an interpolation method. The figures in Tables 5.5/11 to 5.5/20 could be used. in this way with linear interpolation. However, an equation to define the curves would be simpler and more elegant.

The curves of dry density (Yd') at 1 hour against Vertical Pressure (V) in Graphs 5.5/5 to 5.5/19 show a uniform pattern of rapidly increasing dry density at low pressures with the curve flattening and tending to a straight line at higher pressures.

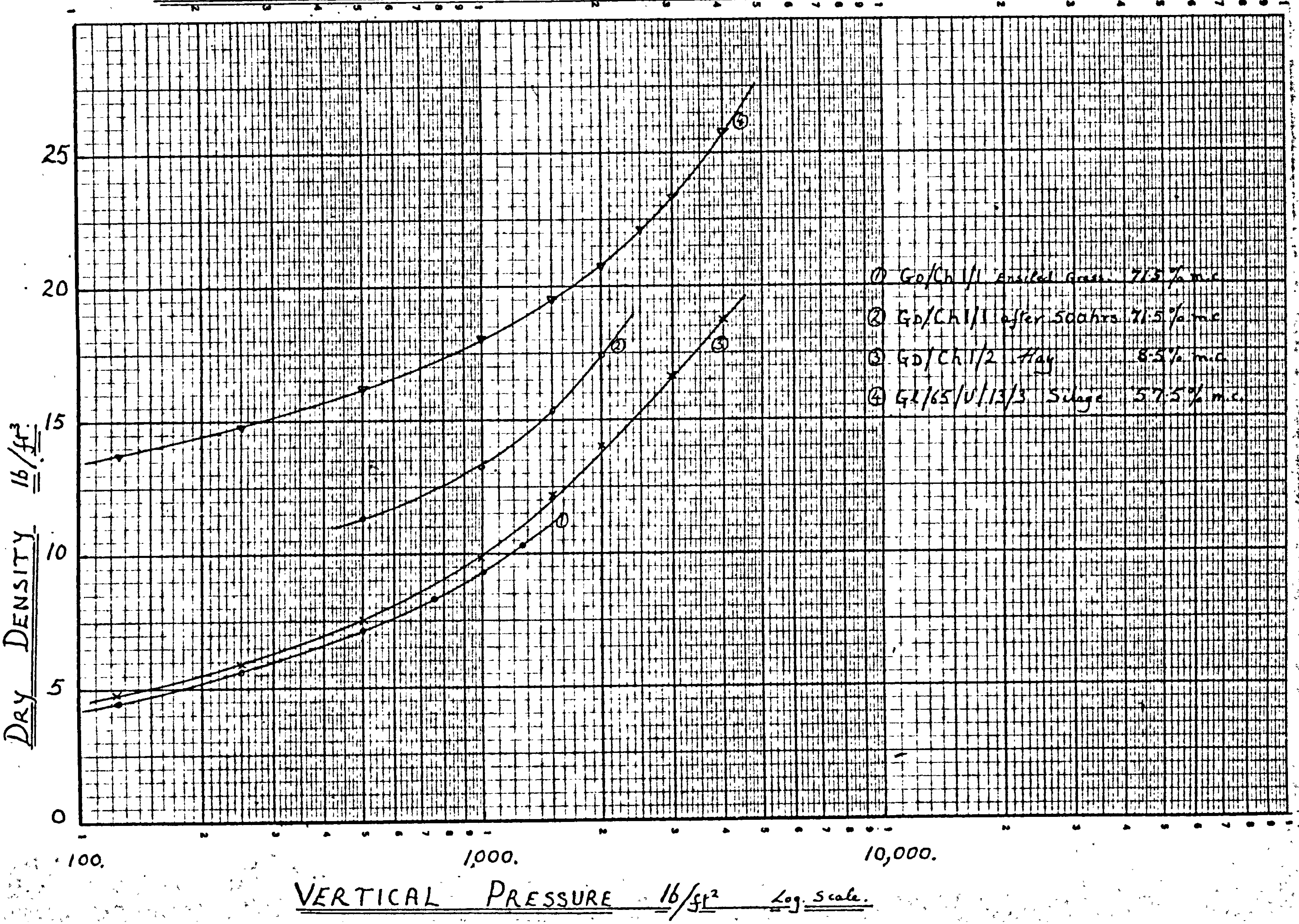
WILLCOCKS(132) has proposed that density can be expressed as:

$Y = a + b \text{ Log}_{10}V$ where a and b are constants.

Even his limited data does not fit this relationship well. On Graph 5.5/20 I have plotted dry density against Log_{10} Vertical pressure for Samples GD/Ch/1/1 (ensiled grass before and after rest) GD/Ch/1/2 (Hay) and G1/65/U/13/3 (silage). It is clear from these plots that the relationship is not of this form at the pressures

GRAPH 5.5/20.

DRY DENSITY at 1.0 hr AGAINST LOG VERTICAL PRESSURE.



encountered in silos although BUTLER and McCOLLY(22) show it to hold at the very much higher pressures encountered in hay wafering.

When $e^{\frac{Yd'}{10}}$ is plotted against Vertical Pressure as in Graph 5.5/21 a straight line relationship is obtained. So the pressure density relationship can be expressed in the form

$$e^{\frac{Yd'}{10}} = E + F \times V \times 10^{-3}$$

$$\therefore \frac{Yd'}{10} = \mathrm{Log}_e \left(E + F \times V \times 10^{-3}\right)$$

$\therefore$ $Yd' = 23.03\ \mathrm{Log}_{10} \left(E + F \times V \times 10^{-3}\right)$ where E is a constant related to the dry density at zero pressure and F is a constant related to the rate of increase of dry density with pressure.

The curves of the pressure density relationship in Graphs 5.5/5 to 5.5/19 are of five types.

1. Silage samples for which the low pressure part of the curve is distorted by the sample having been previously consolidated in the silo, but for which the curve above the in-situ density would be as for the virgin consolidation curve. The vertical bar on each graph gives the approximate position of the in-situ density.
2. Ensiled grass samples 'before rest' which give a consolidation curve rising from that for the grass towards that for the silage.

3. Ensiled grass samples 'after rest' with a good fermentation, these except at their initial pressure level will consolidate along the virgin consolidation curve.

4. Poor fermentation results which must be discounted.

5. Hay samples which are likely to have consolidated in a similar manner to the virgin silage consolidation curve.

The virgin consolidation curve we wish to obtain will fit the silage consolidation curves above the in-situ density, the ensiled grass 'after rest' curves after the initial pressure level and will have the same shape as the hay curve.

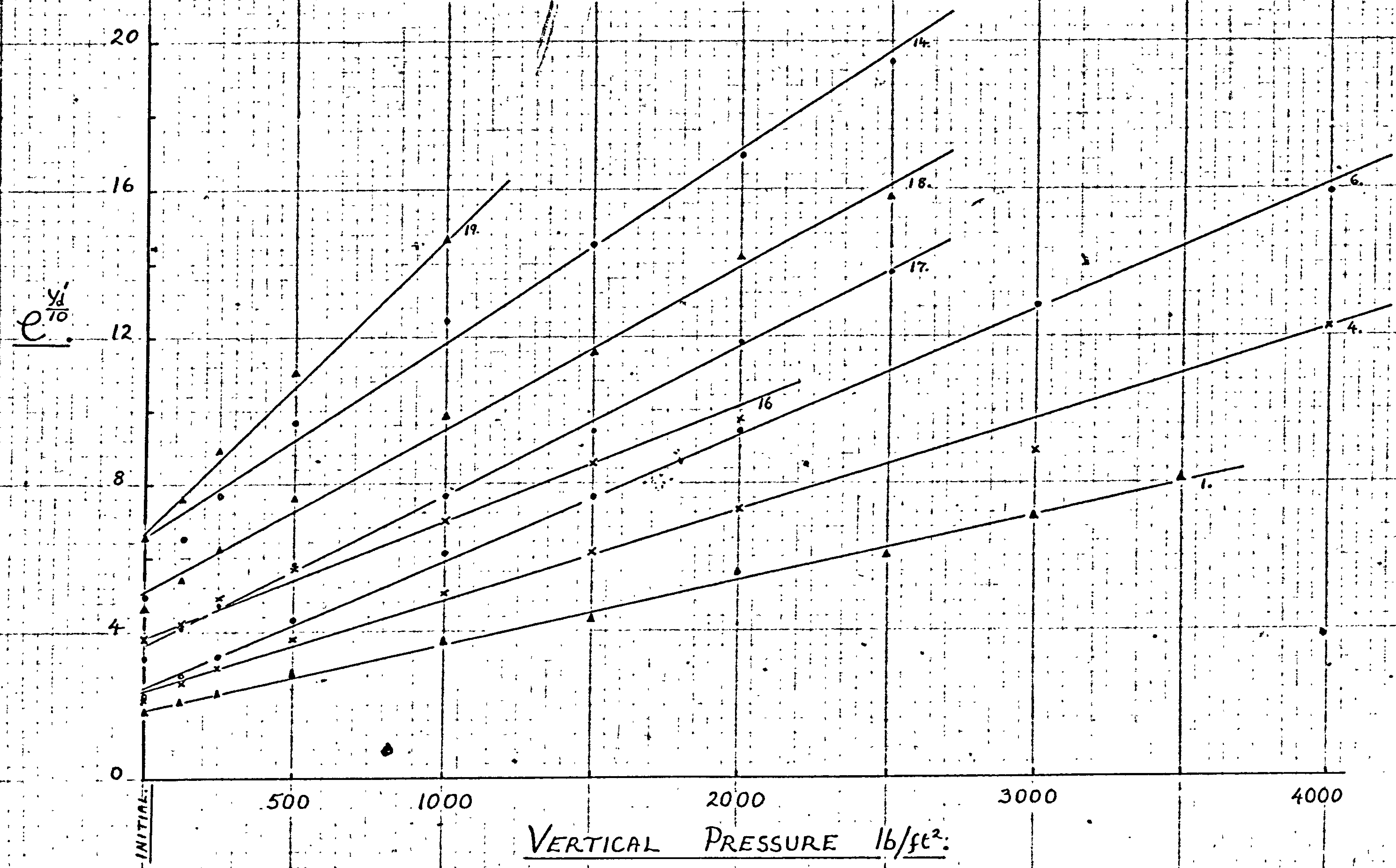
The $Yd' = 23.03 \, \mathrm{Log}_{10} \, (E + F{\times}V \times 10^{-3})$ relationship meets these requirements well, as can be seen from Graphs 5.5/21 and 5.5/22.

Graph 5.5/21 is of samples from Glantlees. The silage samples G1/65/U/30/3, 24/3, 13/3 and 7/3 all give a reasonable fit to a straightline. It will be noted that the fit is better for samples 30/3 and 24/3 which had a low in-situ vertical pressure (550 and 865 lb/ft^2 resp.) than samples 13/3 and 7/3 which had in-situ vertical pressures (no wall friction) of 1475 and 1800 lb/ft^2 resp. It should be noted that the initial dry density plotted is not (because of the test technique) the zero pressure dry density and so it has not been considered in fitting the straight lines.

Graph 5.5/21

$e^{\frac{\gamma' d}{10}}$ AGAINST VERTICAL PRESSURE. GLANTLEES SAMPLES.

$e^{\frac{y'_d}{10}}$ AGAINST VERTICAL PRESSURE. BRIDGET'S SAMPLES.



Graph 5.5/22

The ensiled grass sample GD/Ch/1/1 gave a straight line relationship both 'before rest' and (ignoring the initial pressure level) after rest. The hay sample GD/Ch/1/2 gave an excellent fit at all pressures.

Graph 5.5/22 of silage samples Br 65/U1, 4, 6, 14, 16 17, 18 and 19, shows that these also give a straight line relationship.

The validity of the $Yd' = 23.03 \text{ Log}_{10} (E + F \times V \times 10^{-3})$ for describing the pressure density relationship enables all the consolidation curves to be described in terms of E and F.

The values of E and F, obtained graphically, for all silage samples is given in Table 5.5/21 along with the moisture content, analysis, in situ vertical pressure (no wall friction) and dry densities at 125 and 1500 lb/ft^2 vertical pressure. Table 5.5/22 gives similar data for the ensiled grass and hay samples and includes details of the fermentation type. For ensiled grass the values of E and F on the upper line are for the 'before rest' period and on the lower line for the 'after rest' period.

Table 5.5/23 is a comparison chart for the values of coefficients E and F for all samples. The samples are grouped according to type. For ensiled grass the 'before rest' values of E and F are on the upper line the 'after rest' values on the lower.

VALUES OF E AND F, COEFFICIENTS IN THE FORMULA $Y'_d = 23{\cdot}03 \, Log_{10} (E + F \times V \times 10^{-3})$.

FROM PRESSURE/DENSITY TESTS ON SILAGE.

SAMPLE REF.	m.c. %	ANALYSIS		$V^{①}$ IN SITU lb/ft²	Y'_d lb/ft³		COEFFICIENTS	
		C.P.%	C.F.%		V= 125 lb/ft²	V= 1500 lb/ft²	E.	F.
Br 65 Cl V1	76·3	9–11	31–33·5	158	10·55		2·60	1·80
Br 65 Cl V2	60·2	11–20	27–29	170	14·25	21·8	3·70	3·45
Br 65 Cl V3	67·5	9–12	31–35	226	9·05	16·5	2·20	2·00
Br 64 U/1	71·4	14·2	33·8	800	13·4	17·65	3·70	1·45
Br 65 U1	64·0	11–12·5	31·5–35	43	7·15	14·7	1·90	1·80
2	68·0	11–12·5	31·5–35	42	7·1	14·5	1·90	1·10
3	48·3	12–13·5	31–34	158	8·1	16·95	1·90	2·40
4	53·0	12–13·5	31–34	170	9·7	18·1	2·40	2·45
5	53·0	11·5–13·5	31–34	145	9·55	16·15	2·40	1·68
6	35·8	10–11·5	31–33	302	10·3	20·3	2·45	3·45
7	35·4	10–11·5	31–33	308	10·15	18·65	2·70	2·40
8	55·5	13–15	25·5–27·5	332	11·1	19·2	2·70	2·78
9	63·3	18–21	26·5–30	514	14·4	22·2	3·80	3·40
10	63·4	19–21	26·5–28	530	14·35	24·9	3·60	5·45
11	64·7	19·5–21	26·5–28	549	12·9	22·8	3·10	3·30
12	63·0	19·5–21	26·5–28	549	9·6	23·4	2·20	3·95
13	51·9	19·5–20·5	25·5–27	755	14·7	23·0	3·60	4·55
14	55·1	19·5–20·5	25·5–27	703	18·85	26·8	6·60	5·20
15	57·9	11·5–22	25–30	885	12·45	20·35	3·10	3·05
16	60·2	11·5–22	25–30	870	14·35	21·1	3·85	3·12
17	57·7	11·5–19	26–30	1022	14·25	22·5	3·60	4·10
18	59·7	11·5–19	26–29·5	940	16·8	24·5	5·05	4·42
Br 65 U19	57·7	18–20·5	24·5–26	1185	20·3	28·5	6·65	8·00

SAMPLE REF.	m.c. %	ANALYSIS		$V^{①}$ IN SITU lb/ft²	Y'_d lb/ft³		COEFFICIENTS	
		C.P.%	C.F.%		V= 125 lb/ft²	V= 1500 lb/ft²	E.	F.
Gl 65 U/40/1	63·4	12·75	32·15	208	9·25	18·0	2·20	2·55
40/3	65·7	12·95	31·67	208	9·5	18·2	2·20	2·65
33/2	73·5	9·61	34·28	442	8·85	15·7	2·20	1·85
30/2	73·4	9·07	34·3	548	9·45	15·85	2·40	1·75
30/3	67·1	9·01	33·07	548	11·8	18·0	3·05	2·02
30/4	69·9	8·69	35·35	548	12·7	17·45	3·40	1·65
30/8	66·2	9·58	31·13	580	12·8	18·6	3·40	2·10
24/3	66·8	9·10	34·28	865	10·65	16·5	2·70	1·68
24/4	63·3	8·48	30·96	865	12·85	18·65	3·40	2·05
24/2	66·0	8·71	34·49	865	10·3	16·1	2·60	1·60
13/3	57·5	7·55	32·75	1472	13·6	19·6	3·70	2·22
13/4	62·8	8·10	33·98	1472	13·75	20·4	4·00	2·35
7/3	64·7	8·40	31·55	1799	14·75	21·25	4·20	2·80
7/7	65·1	8·45	31·86	1831	14·4	21·1	4·10	2·10
5/3	66·5	9·10	36·4	1930	14·7	20·5	4·10	1·90
Gl 65 U/5/7	66·1	9·91	34·95	1954	14·2	20·25	3·80	2·70
Ro 63 U/1.	52·8			c.470		24·3	4·80	4·55
Ro 63 U/2	53·3			c.1420		21·7	4·10	3·10
Ro 63 U/3	55·9		25·7	c.1610		24·0	5·30	3·75
We Cl 63 U/1	77·2		34·4	20			2·30	1·55
Pe 63 U/1	63·7		30·8	c.880		18·2	4·00	1·45
Pe 63 U/2	68·3		36·7	c.1280		17·6	3·90	1·22

VALUES OF E AND F, FROM PRESSURE/DENSITY TESTS ON ENSILED GRASS AND HAY.

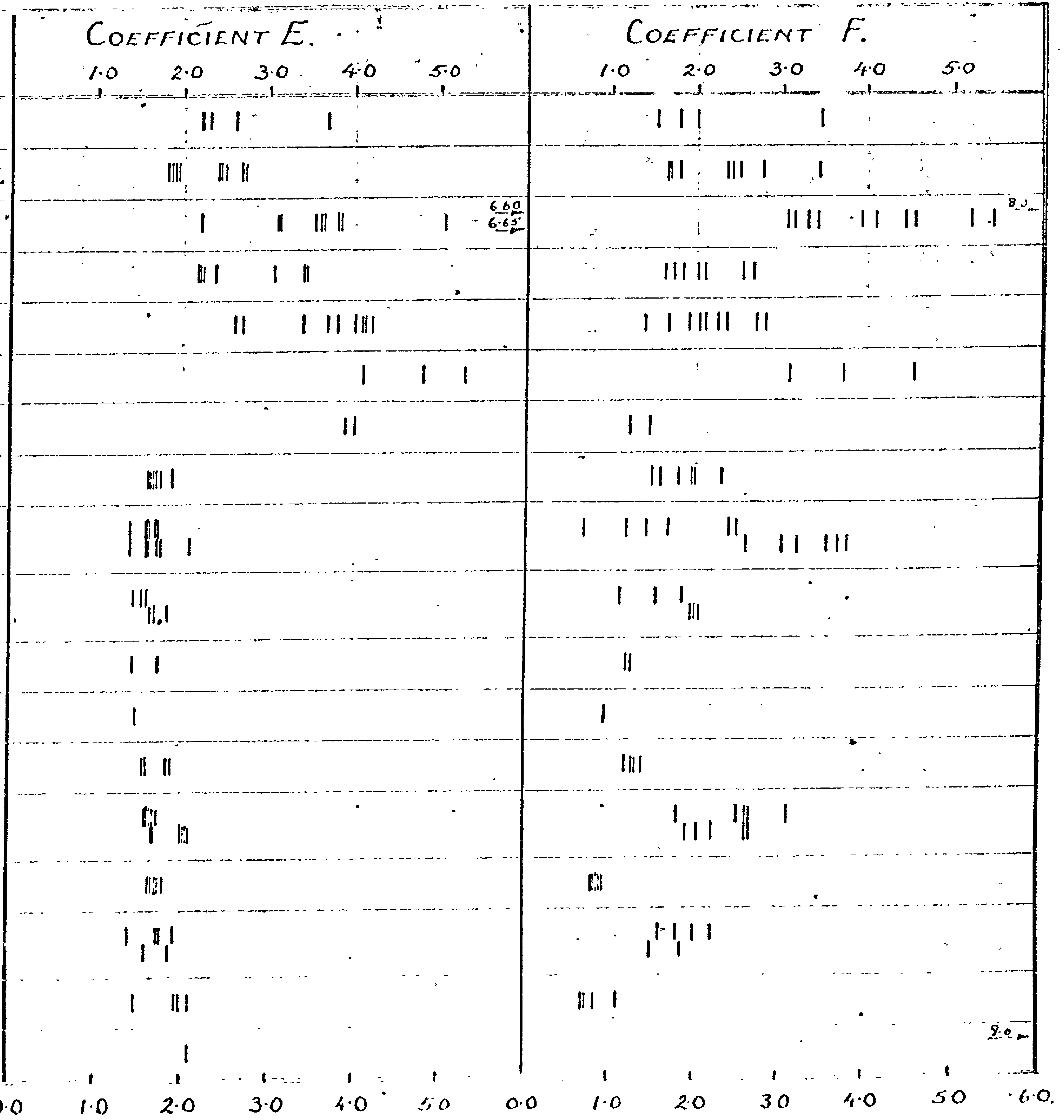
SAMPLE REF.	m.c. %	ANALYSIS		FERMENT-ATION.	Yd' lb/ft³		COEFFICIENTS	
		C.P.%	C.F.%		V= 125 lb/ft²	V= 1500 lb/ft²	E.	F.
Br 1.	68·0	17·3 br	25·9	B.	5·87	18·80	1·60 1·75	1·70 3·20
Br 2.	60·15	17·3	25·9	B.	6·48	20·40	1·70 2·10	2·40 3·80
Br 3.	57·95	11·6	27·7	B.	6·75	18·65	1·70 1·70	2·50 3·00
Br 4/1.	73·9	13·2	25·6	B.	3·95	16·55	1·40 1·40	0·70 2·60
Br 4/2.	65·4	13·2	25·6	B.	5·70	19·30	1·60 1·60	1·45 3·55
Br 5	69·5	b.t. 19·7–20·1	25·4–26·6	B.	5·30	19·65	1·60 1·60	1·20 3·70
Gl 64/6/1	81·3	11·7 b.r.	30·6	S.	5·55		1·65	2·30
Gl 64/6/2	76·7	11·7	30·7	S.	5·90		1·75	2·00
Gl 64/6/3	75·0	11·3 br	30·3	S.	5·60	14·75	1·70	1·80
Gl 64/6/4	68·25	12·0 ar	33·7	S.	5·70	15·32	1·65	2·00
Gl 64/6/5	58·0	12·4 ar	33·7	S.	5·65	13·90	1·65	1·60
Gl 64/6/6	17·85	12·2 ar	31·0	H.	6·90	14·42	1·90	1·50
GD/Ch 1/1	71·5	7·3 b.r. 8·5 ar	27·3 34·6	S.	4·50	15·40	1·45 1·70	1·13 2·00
GD/Ch 2/1	71·4	do.	do.	S.	5·70	15·45	1·55 1·65	1·87 2·00
GD/Ch 3/1	70·2	do.	do.	S.	5·85	15·60	1·60 1·85	1·55 2·00
GD/Ch 1/2	8·45	7·3 br	27·3	H.	4·71	12·15	1·45	1·27
GD/Ch 1/3	2·65	do.	do.	H.	4·81	10·70	1·48	0·95
GD/Ch 3/2	9·35	do.	do.	H.	6·3[illegible]	12·53	1·75	1·20
HR 1/6	8·8			H	4·75	13·30	1·60	1·40
HR 2/6	7·55			H.	5·15	14·15	1·90	1·30
HR 3/6	8·0			H	5·05	13·90	1·85	1·30

SAMPLE REF.	m.c. %	ANALYSIS		FERMENT-ATION.	Yd' lb/ft³		COEFFICIENT	
		C.P.%	C.F.%		V= 125 lb/ft²	V= 1500 lb/ft²	E.	F.
GD 65/1/1	60·4	7·8 b.r.	27·4	S.	6·80	17·40	1·65 1·70	2·65 2·65
GD 65/2/1	66·95	7·1	26·9	S.	6·20	16·25	1·65 2·05	2·50 2·05
GD 65/3/1	69·0	8·1	30·7	S.	6·30	16·35	1·60 2·00	2·60 2·21
GD 65/4/1	66·6	8·9	27·5	S.	6·50	17·70	1·60 2·05	3·10 2·60
GD 65/5/1	55·5	7·6 b.r.	29·9	S.	6·75	17·10 Ed	1·75 2·00	1·80 1·90
GD 65/1/2	8·0	7·8 br.	27·4	H.	5·65	11·40	1·70	0·93
GD 65/2/2	8·0	71	26·9	H.	5·60	11·20	1·65	0·91
GD 65/3/2	8·4	8·1	30·7	H.	5·00	10·9	1·65	0·84
GD 65/4/2	8·0	8·9	27·5	H.	5·90	11·8	1·80	0·95
GD 65/5/2	7·65	7·6 br	29·9	H.	5·60	11·1	1·70	0·86
S23 1/2	9·0	23·6 b.r.	22·[illegible]	H.	4·75	12·35	1·60	1·20
S23 2/4	29·5	18·3	18·7	S.–H.	10·85	29·00	2·10	9·60
S23 4/5	14·9	7·2 b.r.	29·2	H.	7·60	16·50	1·80	2·30
HL 3/1	77·3			B.	4·95	14·75 E	1·40 1·90	2·20 1·50
HL 3/2	66·2			B.	6·60	14·75	1·75 1·60	1·60 1·85
HL 3/3	58·2			B.	7·15	16·5	1·80	1·80
HL 3/4	48·3			B.	7·70	15·8 E	1·95	2·00
HL 3/6A	8·15			H.	6·90	11·6	2·00	0·75
HL 3/6B	8·60			H.	4·75	11·75	1·50	1·10
HL 1/6	8·60			H.	6·70	11·90	1·95	0·85
HL 2/6	6·75			H.	7·20	12·00	2·10	0·75

b.r. BEFORE TEST. a.r. AFTER TEST. S. ACETIC SILAGE. B. BAD FERMENTATION PROTEIN BREAKDOWN, HIGH pH. H. HAY.

COMPARISON CHART FOR COEFFICIENTS E AND F FOR ALL SAMPLES.

SAMPLES.	m.c.% range.
Br 65 Cl V1-V3, We 63 Cl U1. (4) Clamp. V° 0-250. S.	60-77.
Br 65 U1-U8. (8) Top of Tower. 2nd Cut. V° 0-350. S.	35-68.
Br 65 U9-U19. (11) Bottom of Tower 1st Cut V° 500-1200. S.	52-65.
Gl 65 U40, U33, U30. (7) Top of Tower V° 200-600. S.	63-74.
Gl 65 U24, U13, U7, U5. (9) Bottom of Tower V° 600-2000. S.	57-67.
Ro 63 U1-U3 (3) Leafy Ryegrass V° 500-1600. S.	53-56.
Pe 63 U1-U2 (2) Oats V° 900-1300 S.	64-68.
Gl 64 6/1-6/6 (6) Mature Rye Grass. E.G.	17-81.
Br 1-5 (6) Leafy Rye Grass E.G.	58-70.
Gd Ch 1/1-3/1 (3) Mature Ryegrass E.G.	70-72.
Gd Ch 1/2-3/2 (2) do. H.	8.5-9.4.
Gd Ch 1/3. (1) do. H.	2.6.
Hr 1/6-3/6 + S23 1/2 (4) Leafy Ryegrass H.	7.5-9.0.
Gd 65 1/1-5/1. (5) Mature Ryegrass E.G	55-69.
Gd 65 1/2-5/2 (5) do. H	7.5-8.5
HL 3/1-3/4 (4) Lucerne. E.G.	48-77.
HL 1/6-3/6B (4) Lucerne. H.	67-86
S23 2/4 (1) Leafy Ryegrass E.G.	29.5



5.5.10. The Influence of In-Situ Vertical Pressure, Maturity, Moisture Content and Variety on Coefficients E and F.

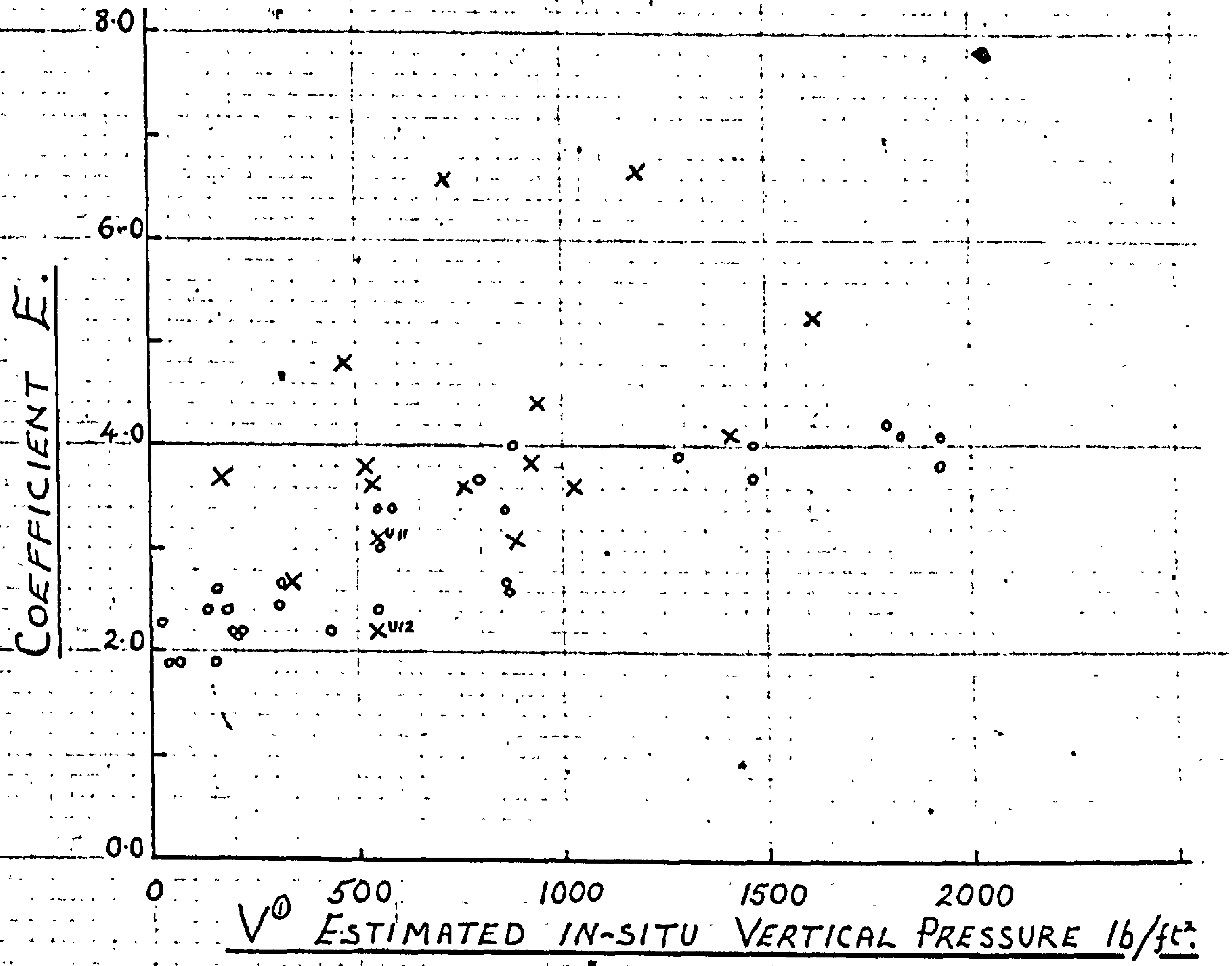
The coefficients E and F for silage samples have been plotted against in-situ vertical pressure (no wall friction) in Graph 5.5/23. The samples above and below 30% C.F. being indicated by circles and crosses respectively. It is clear that the value of E is significantly influenced by the in-situ vertical pressure. For the over 30% C.F. samples, E rises from about 2.0 to 4.0, between 0 and 2000 lb/ft^2. The less mature samples seem to have higher values of E than the over 30% C.F. samples. The comparison of Br 65/V/11 (the cut sample) with Br 65/V12 (the packed sample) is of interest.

The value of coefficient F appears uninfluenced by the in-situ vertical pressure although one would expect a slight lowering of F to compensate for the raised values of E. The over 30% C.F. samples have markedly lower values of F (mostly in range 1.5 - 2.75) than the under 30% C.F. samples (mostly over 3.0).

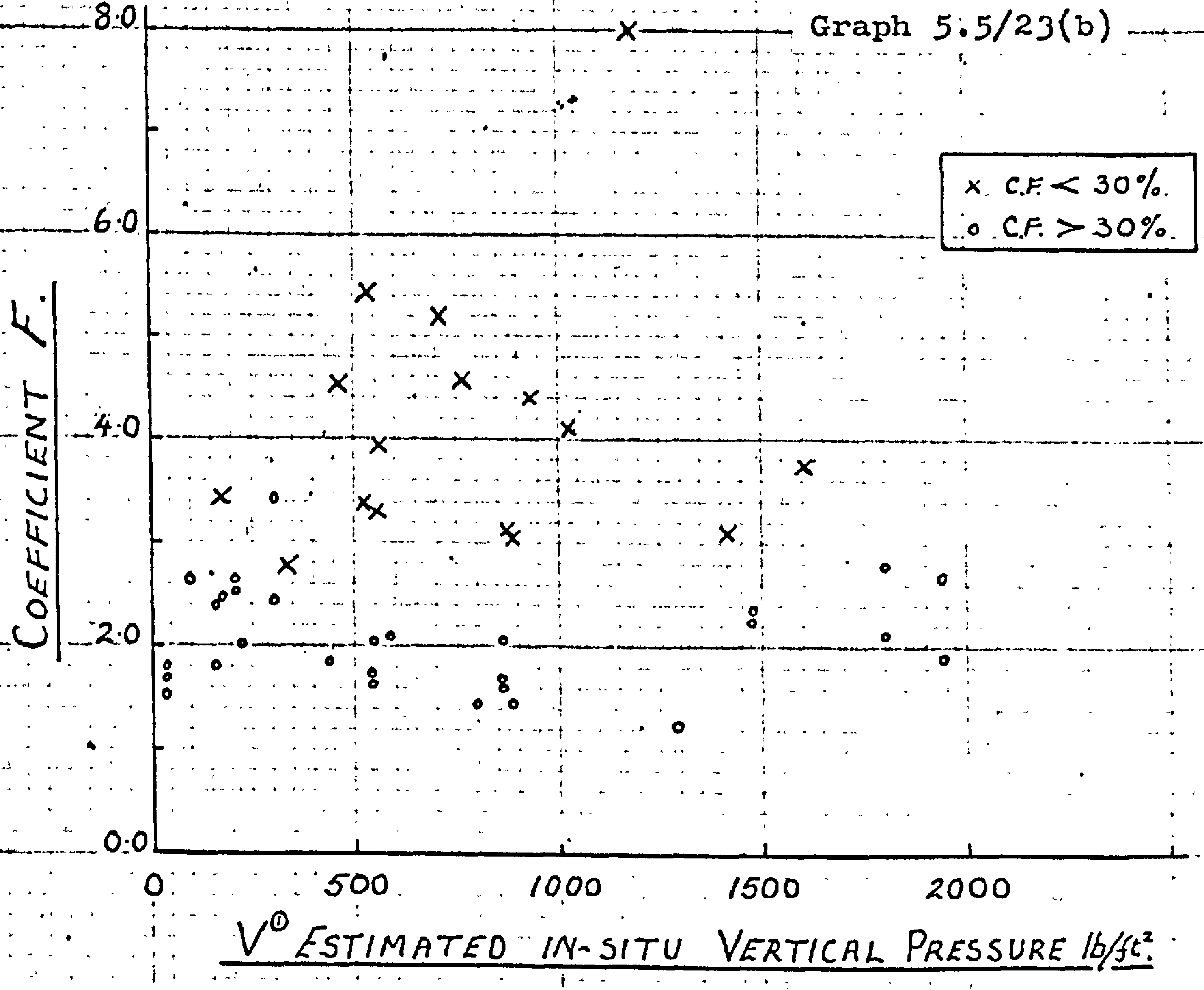
In Graph 5.5/24 of E and F against after test C.F., the Glantlees samples (which were individually analysed) are indicated by circles while the Bridgets results (for which only the range of possible analyses were known) are shown as horizontal lines. Reading Graph 5.5/24 in conjunction with Graphs 5.5/23 and 5.5/27, it appears that the E values tend to be slightly higher for young material than for mature samples but the vertical pressure effect tends to mask this. The F value is markedly higher with

Graph 5.5/23(a)

EFFECT OF IN-SITU VERTICAL PRESSURE V^0 ON E AND F, FOR SILAGE SAMPLES.



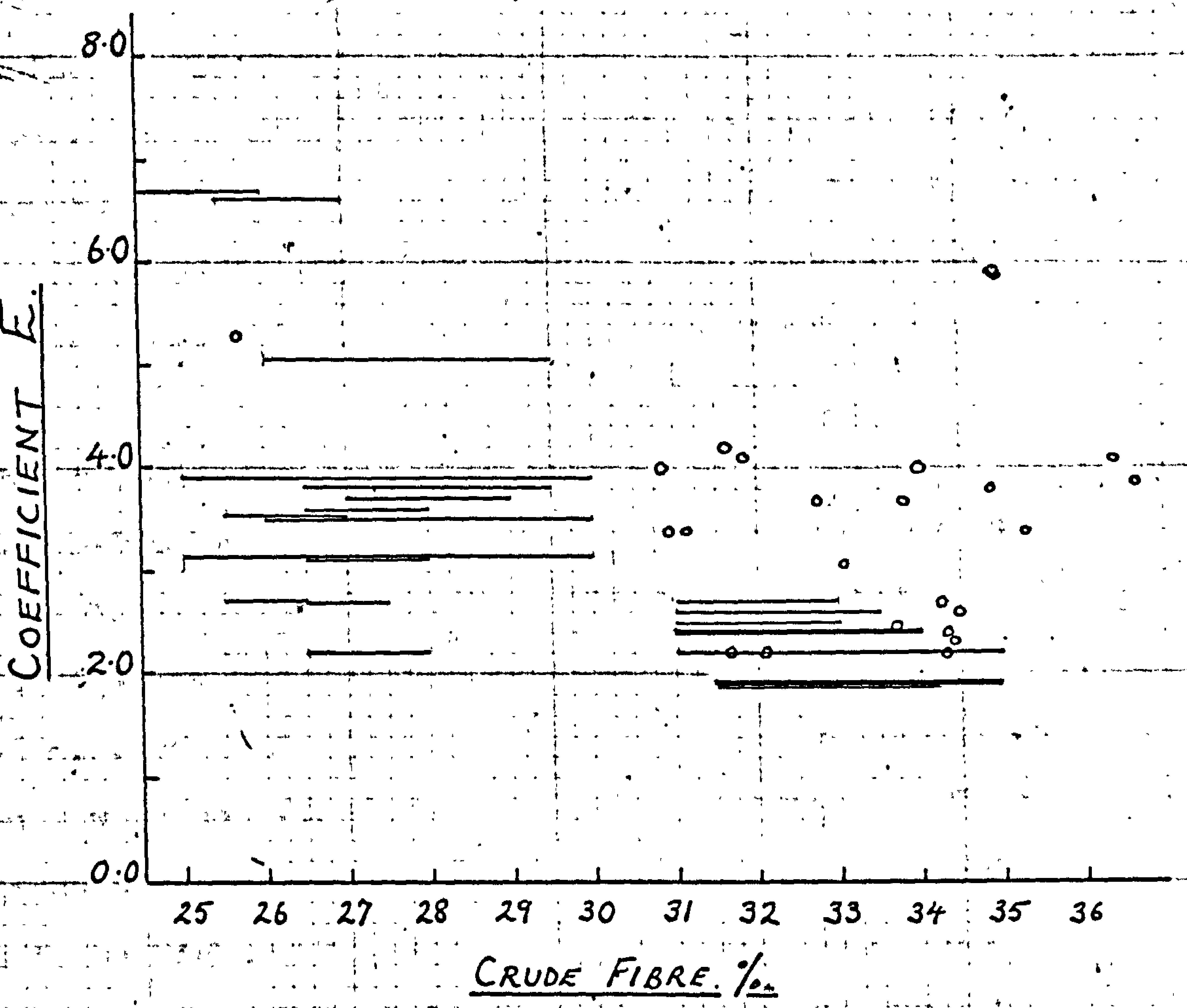
Graph 5.5/23(b)



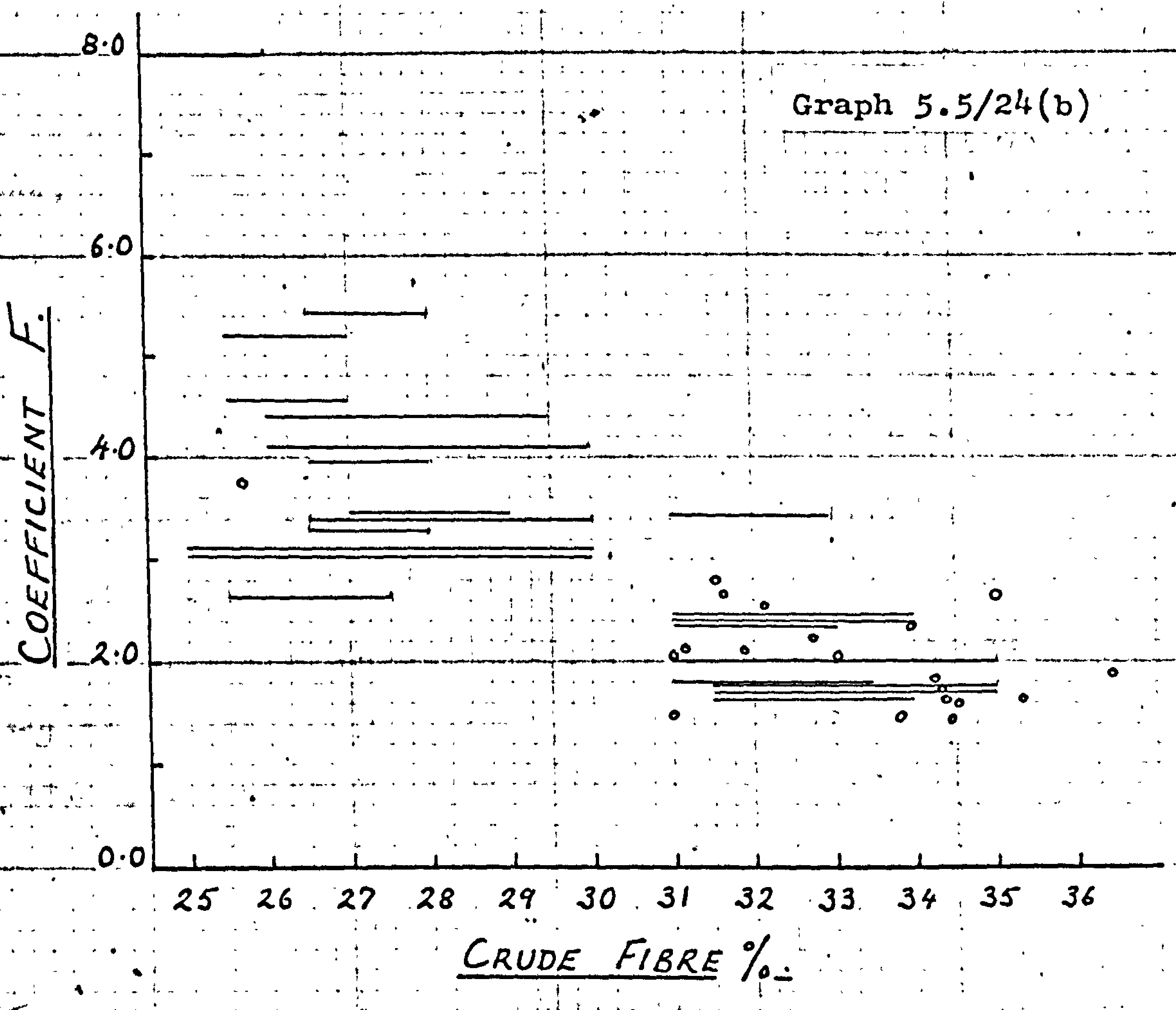
Graph 5.5/24(a)

EFFECT OF CRUDE FIBRE ON E AND F.

FOR SILAGE SAMPLES.



Graph 5.5/24(b)



less mature material the mean value being about 4.0 at 27% C.F. and 2.0 at 33% C.F.

Considering Graphs 5.5/25 and 5.5/26 of Yd' at 1500 lb/ft^2 against Crude Fibre and moisture content for silage samples the maturity effect is clear. The straight line

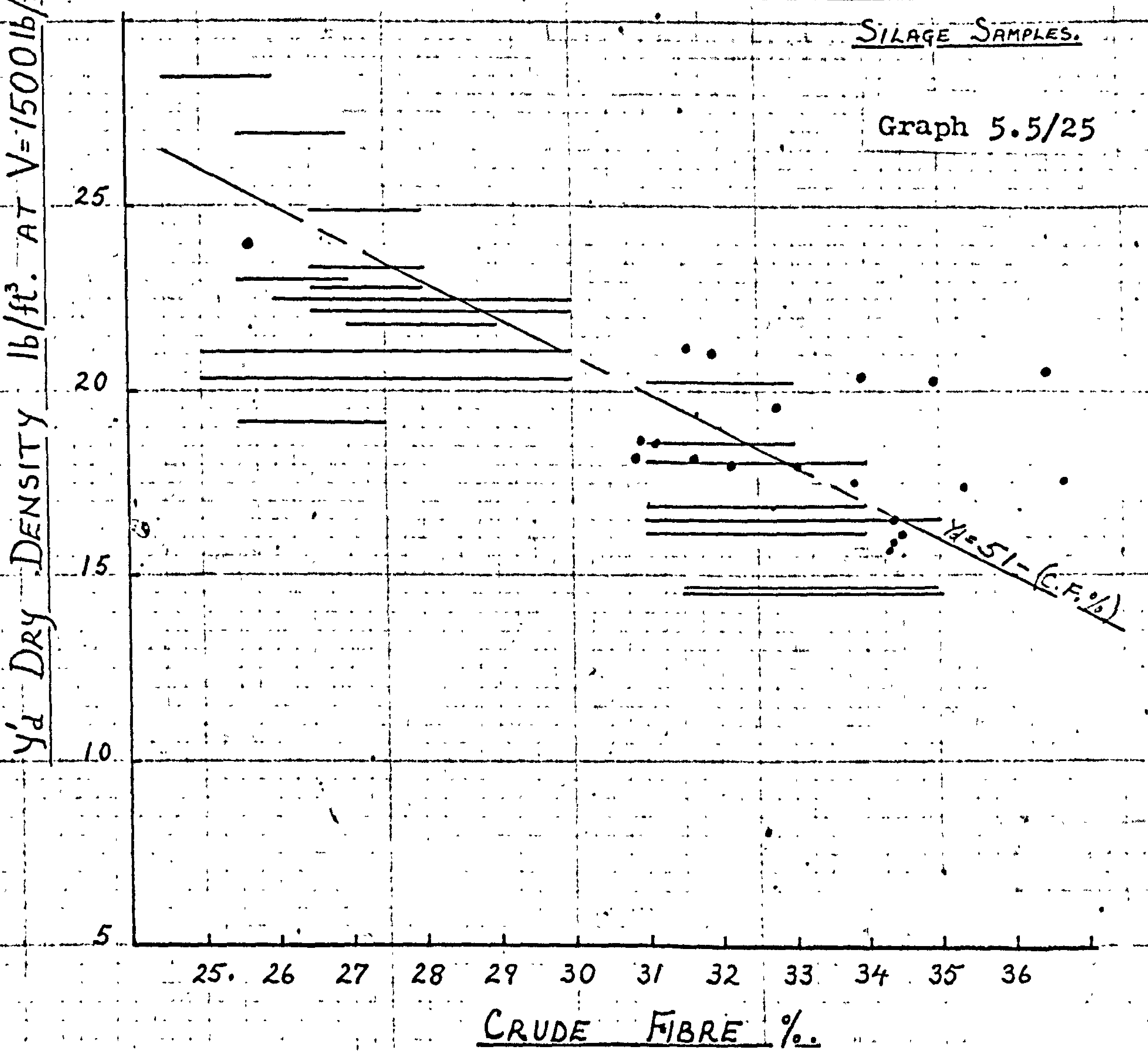
$$Yd' \text{ (at } V = 1500 \text{ lb/ft}^2) \quad 23.03 \text{ Log}_{10}(E + 1.5 F)$$
$$= (51 - C.F.\%) \text{ lb/ft}^3.$$

gives the relationship approximately.

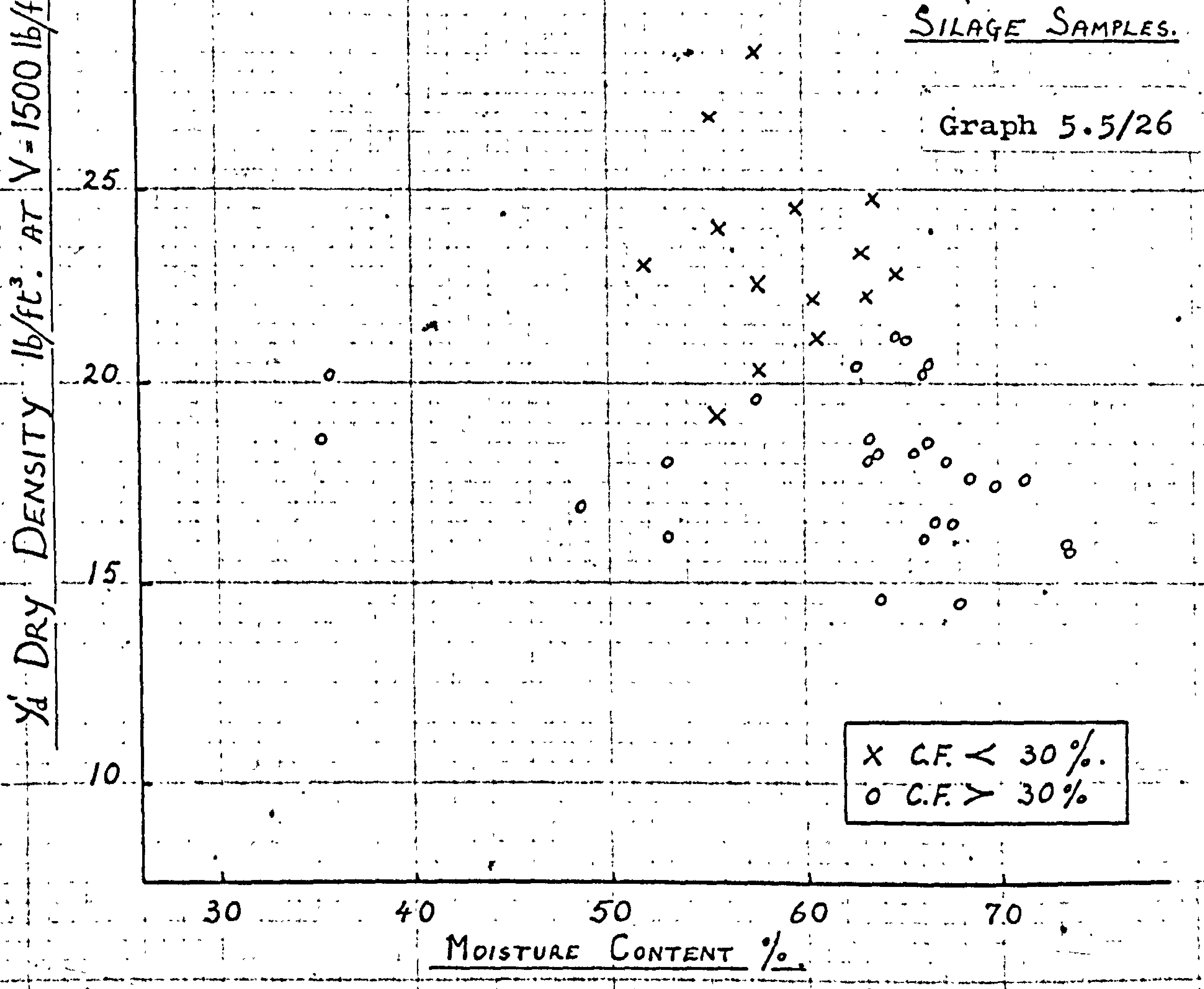
The coefficients E and F are plotted against Moisture content in Graph 5.5/27 for Silage Samples and Graph 5.5/28 for Ensiled Grass and Hay samples from Glantlees. In the 30 - 80% m.c. range for silage in Graph 5.5/27 no significant trend in E with moisture content can be discerned. There is a slight tendency for the F values for the over 30% C.F. samples to be higher at low moisture contents, but there are not enough points at the low moisture content to show if this is significant.

In Graph 5.5/28 of the ensiled grass and hay from Glantlees, all of which was of very similar maturity, the values of E for continuous and after rest samples lie predominately in the range 1.7 to 2.6 at 50 - 80% m.c. While at 18% m.c. the E value is still near 2.0. There appears to be a slight falling off in E towards a value of 1.4 for oven dry material, but more points would be needed to confirm this. While the F values largely lie in the 1.9 - 2.6 range at 50 - 80% m.c. there is a marked reduction at low moisture contents tending downward from 1.5 at 18% m.c. towards 0.90 at oven dry.

EFFECT OF CRUDE FIBRE ON DRY DENSITY.



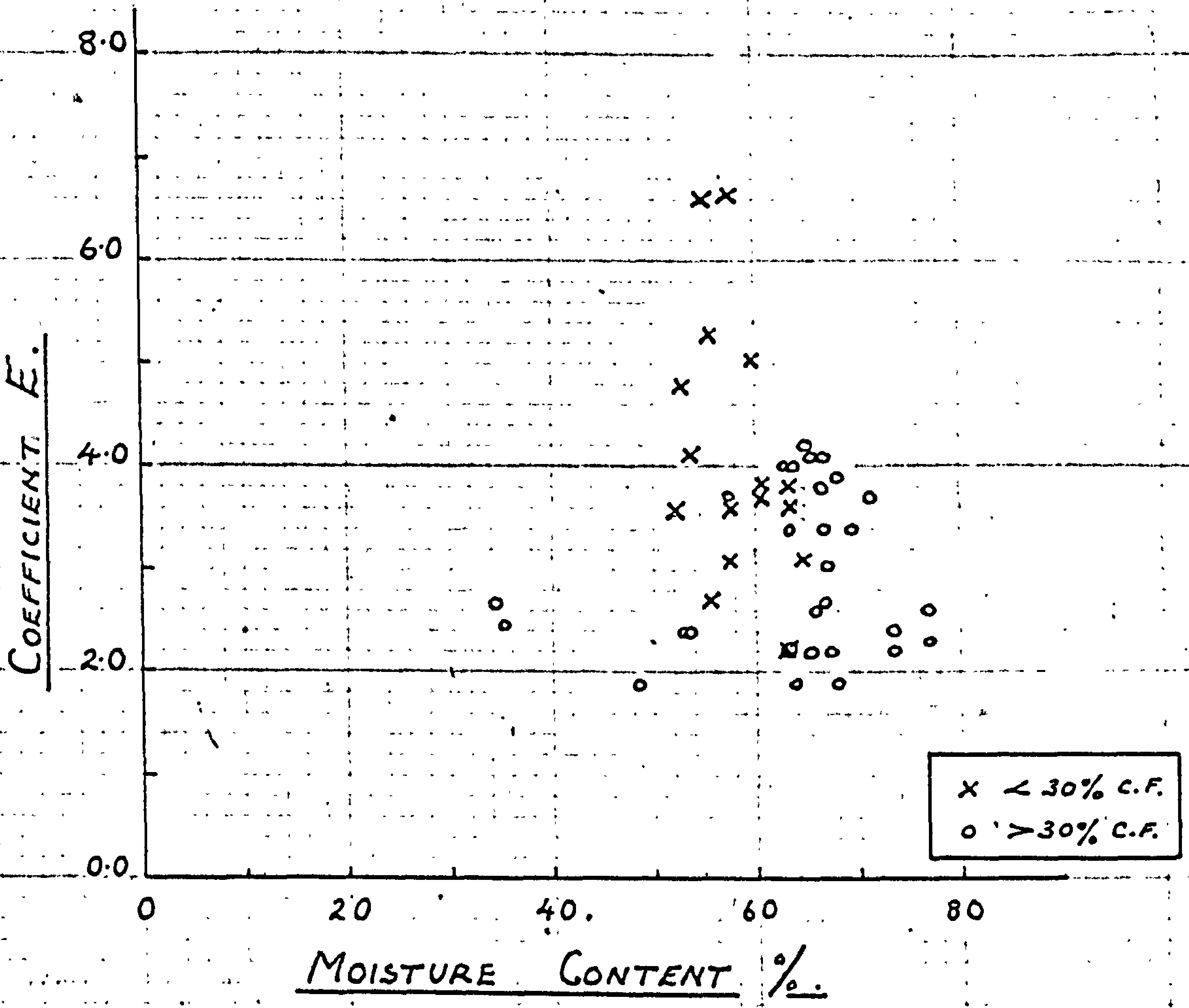
EFFECT OF MOISTURE CONTENT ON DRY DENSITY.

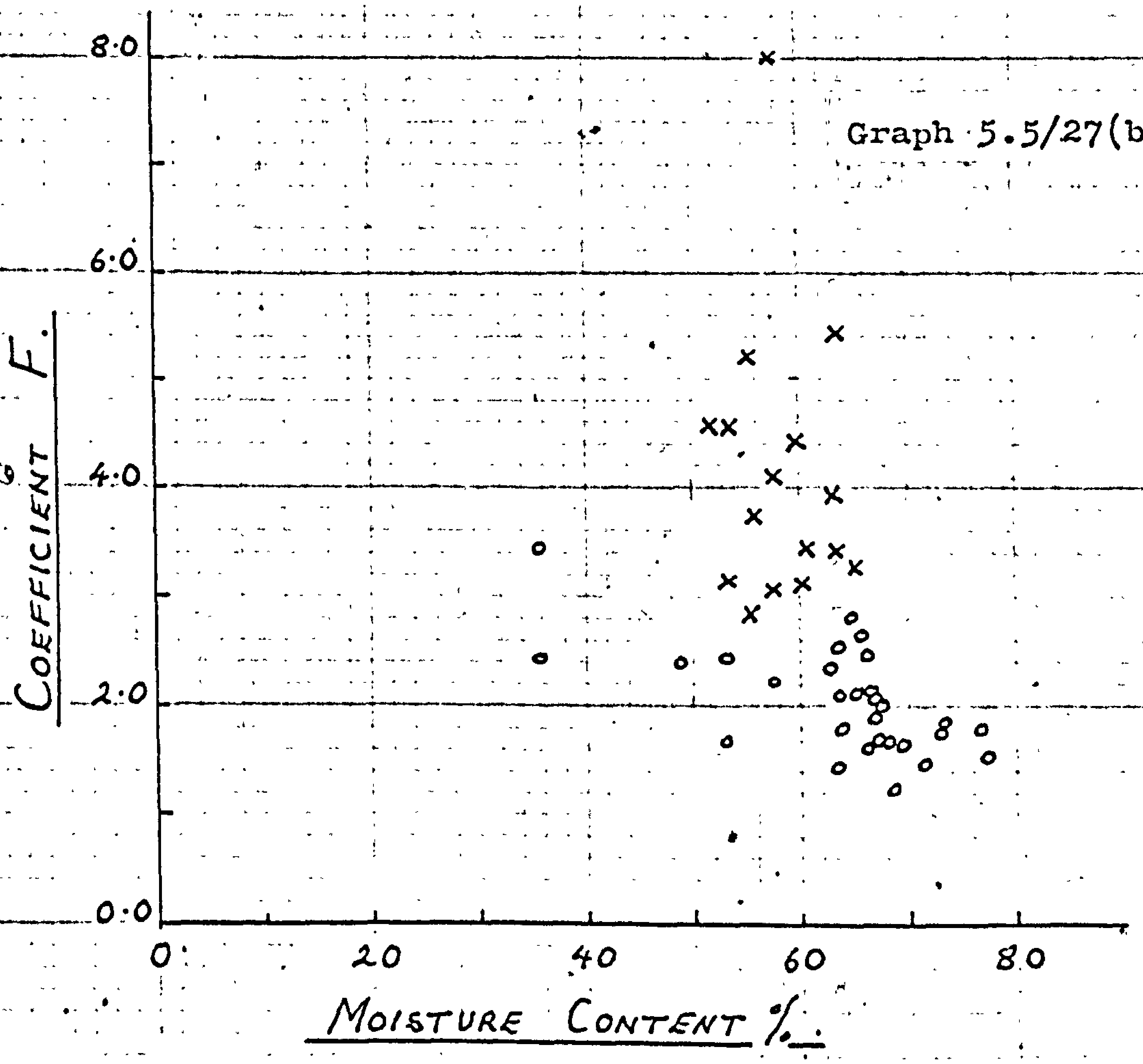


Graph 5.5/27(a)

EFFECT OF MOISTURE CONTENT ON E AND F.

FOR SILAGE SAMPLES.

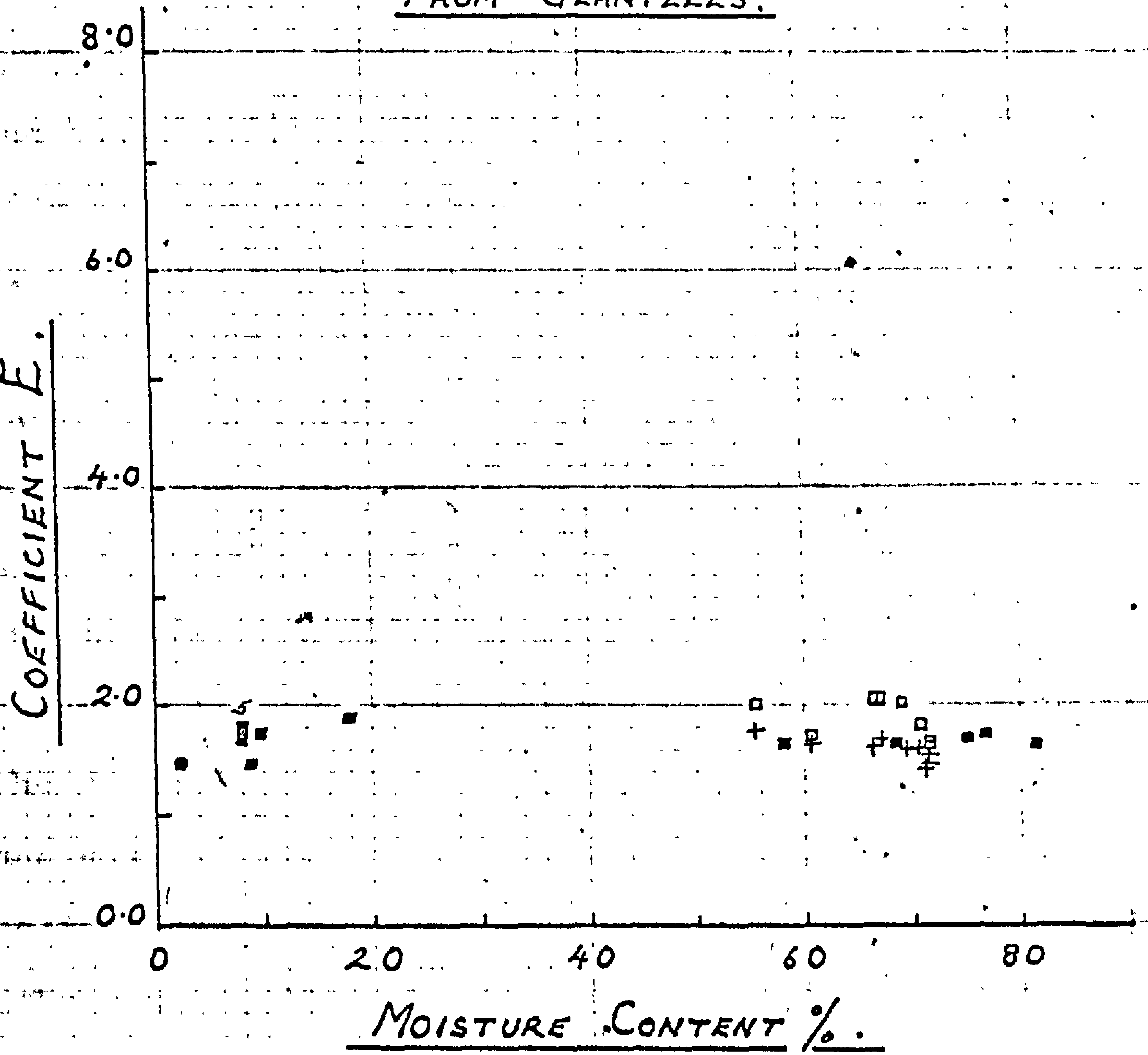


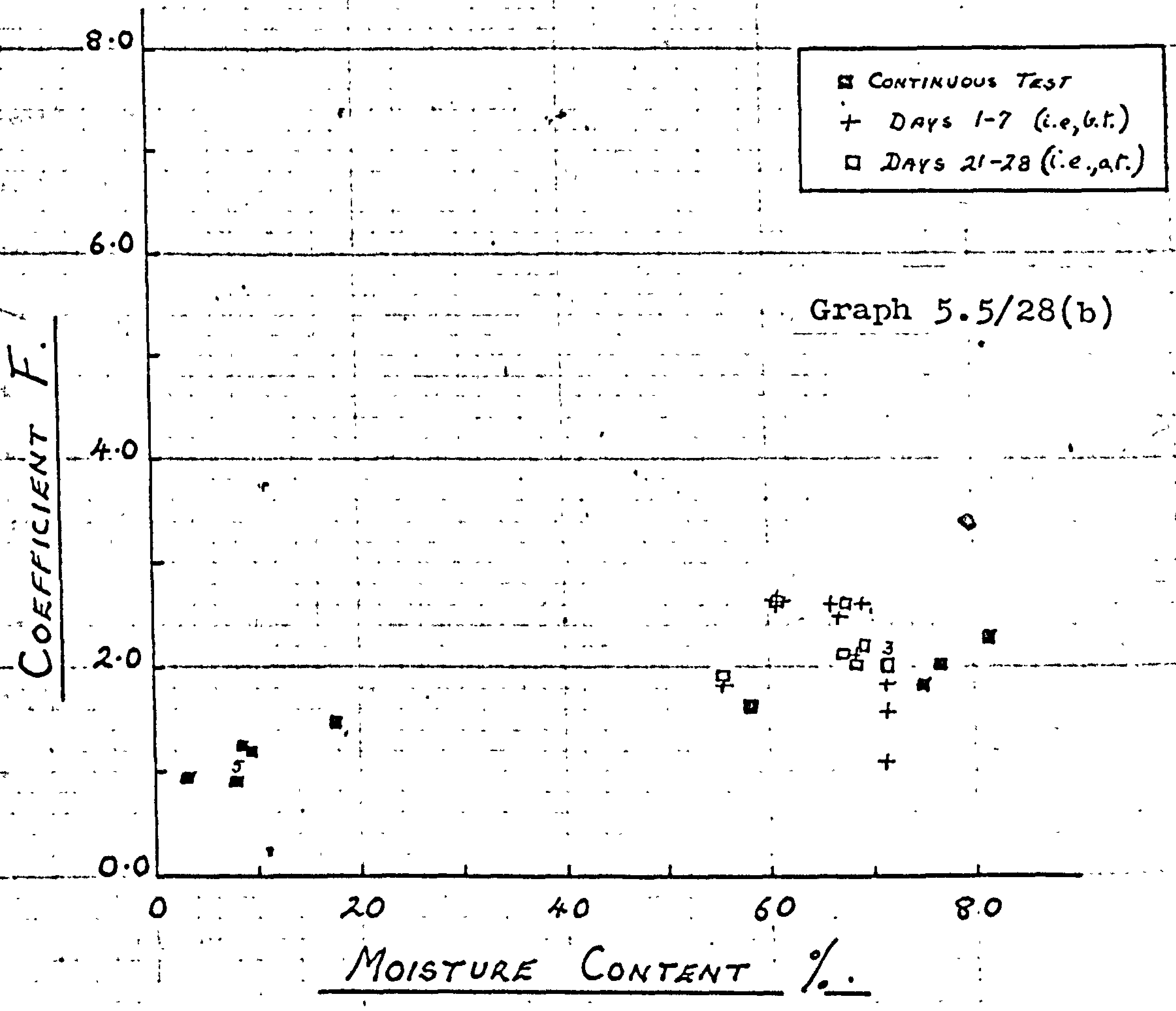


Graph 5.5/27(b)

Graph 5.5/28(a)

EFFECT OF MOISTURE CONTENT ON E AND F.
FOR ENSILED GRASS AND HAY SAMPLES.
FROM GLANTLEES.




Graph 5.5/28(b)

The effect of variety seems, on the comparison chart, Table 5.5/23, to be allied to the maturity effect. Both lucerne and oats, being stemmy by nature, have F values on the low side (1.50) and behave like overmature stemmy rye grass. The E values seem to be similar to those for the grass samples.

The overall pattern for the coefficients E and F considering the above and the data in comparison chart Table 5.5/23 is as follows:-

E. While for silage samples E ranges up to 6.65; for ensiled grass and hay samples it falls entirely in the range 1.4 - 2.1. The high values for the silage samples can be entirely attributed to the prior consolidation of the samples under the in-situ pressure. For the virgin consolidation curve E will be in the 1.4 - 2.1 range. The length of chop has the clearest effect on E (vide GD/Ch/1 - 3/1 - 2). Moisture content reduces E slightly below 20% but does not effect it in the silage range of moisture contents. Maturity has no clear effect on E. For calculating dry densities an E value of 1.8 should be used for all silages until more detailed data is available; this corresponds to a dry density Yd' of 5.9 lb/ft^3 at V = 0 lb/ft^2.

F. The major factor influencing F is maturity and at silage moisture contents it ranges from 1.5 to 9.0. The highest values being for young leafy grass and the lowest for mature stemmy grass, lucerne, or oat forage. No other variable has a clear influence on the F value at silage moisture contents. At below 20% m.c. the F value is reduced and falls below 1.0 with stemmy material and below 1.5 with leafy crops at 7 - 8% m.c.

While the extreme range F is from 1.5 to 9.0 we can cover all but the most exceptional cases by considering three types of silage.

(a) Young leafy grass similar to the youngest material used in the filling of Bridgets with a C.P. of about 20% and C.F. about 25%, as grass. This would have a dry density (Yd') of about 25 lb/ft^3 at 1500 lb/ft^2 and so a coefficient F = 6.5 is used.

(b) Average grass silage with a C.P. of about 12% and C.F. of about 28%, as grass. This would have a dry density (Yd') of about 20 lb/ft^3 at 1500 lb/ft^2 and so a coefficient F = 3.7 is used.

(c) Mature grass silage and stemmy crops with a C.P. of about 8% and a C.F. of about 32%, as grass. This would have dry density (Yd') of about 15 lb/ft^3 at 1500 lb/ft^2 and so a coefficient F = 1.8 is used.

Table 5.5/24 gives values of dry density (Yd') at 1 hour after pressure application for a range of vertical pressure (V) calculated using E = 1.8 and F = 6.5, 3.7 and 1.8 in the expression:-

$$Yd' = 23.03 \text{ Log}_{10} (E + F \times V \times 10^{-3})$$

TABLE 5.5/24

Dry Densities Calculated using $Y'd = 23.03 \log_{10} (E + F \times V \times 10^{-3})$.

			Dry Density, $Y'd$ lb/ft^3 at V lb/ft^2								
Sample Type.	E.	F.	V=0	125	250	500	1000	1500	2000	3000	4000
1. Young Leafy	1.8	6.5	5.90	9.40	12.35	16.1	21.2	24.5	27.0	30.6	33.2
2. Average.	1.8	3.7	5.90	8.15	10.05	12.95	17.5	19.95	22.2	25.6	28.1
3. Mature.	1.8	1.8	5.90	7.05	8.10	9.95	12.8	15.05	16.85	19.75	22.0

In Graph 5.5/29 these values are plotted together with some of the experimental pressure density results for comparison. It will be seen that there is a good agreement between the virgin consolidation curves calculated from the equation and those obtained from the pressure density tests.

5.5.11. Summary on the Equation for Virgin Consolidation Curve for Silage.

Provided the silage has not reached saturation (i.e. effluent produced). The dry density (Yd' lb/ft^3) of a silage 1 hour after the application of a vertical pressure (V lb/ft^2) during its initial consolidation is given by the equation:-

$$Yd' = 23.03 \operatorname{Log}_{10} (E + F \times V \times 10^{-3}) \text{ lb/ft}^3$$

or

$$Yd' = 23 \operatorname{Log}_{10} (E + F \times V \times 10^{-3}) \text{lb/ft}^3$$

where E is a coefficient related to the initial dry density
and F is a coefficient related to the compressibility of the sample.

The density at moisture content ($m\%$) is

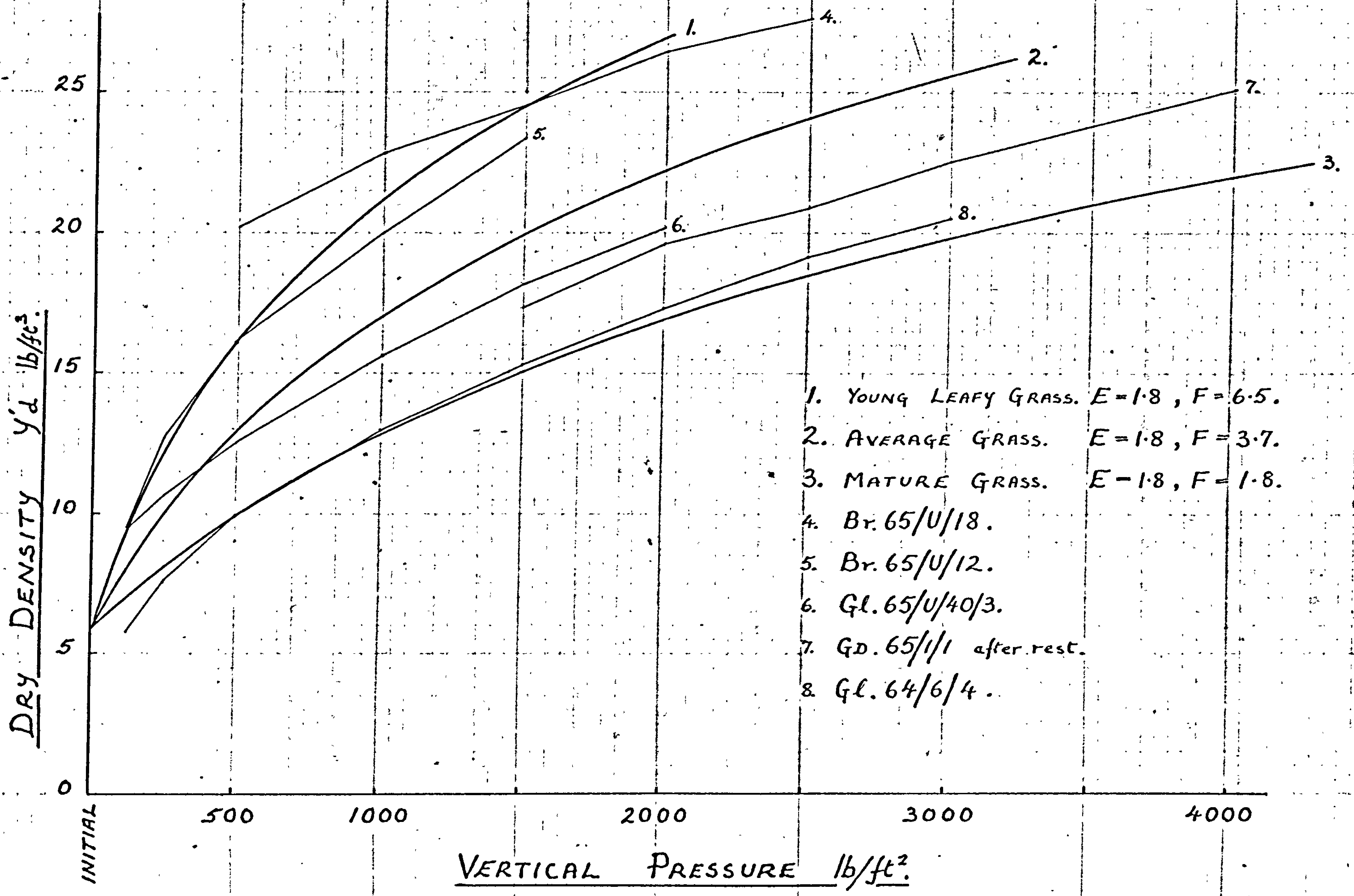
$$Y' = Yd' \left(\frac{100}{100 - m}\right) \text{ lb/ft}^3.$$

While for the virgin consolidation curve for silage E can range between 1.4 and 2.1 and F between 1.5 and 9.0; the normal range of silages can be described by one of the following:-

1. For Young leafy grass (C.P. approx. 20%, C.F. approx. 25%, as grass) use E = 1.8, F = 6.5.

Graph 5.5/29

PRESSURE/DENSITY RELATIONSHIP. COMPARISON OF $\gamma'_d = 23{\cdot}03 \log_{10}\left(E + F.V \times 10^{-3}\right)$ WITH TEST RESULTS.



2. For average maturity grass (C.P. approx. 12%, C.F. approx. 28%, as grass) use $E = 1.8$, $F = 3.7$.

3. For mature grass (C.P. approx. 8%, C.F. approx. 32%, as grass) use $E = 1.8$, $F = 1.8$.

5.5.12. Rate of Increase in Dry Density at Constant Pressure.

In Section 5.5.6. the density time relationship at constant pressure was discussed and the following equations derived:-

$$Y^T = Y' + C' \operatorname{Log}_{10} T \quad \text{lb/ft}^3$$

$$Yd^T = Yd' + Cd' \operatorname{Log}_{10} T \quad \text{lb/ft}^3$$

where:

Y^T and Y' are densities at T hours and 1 hour resp. after the application of pressure.

C' is the rate of increase in density per Log_{10} hours.

Yd^T, Yd' and Cd' are the corresponding dry density terms.

The values of C' at each pressure level, obtained in the pressure density tests are given in Tables 5.5/11 to 5.5/20 with the density and dry density figures. The values of Cd' at each pressure level for each test are given in Table 5.5/25 for silage samples and Table 5.5/26 for ensiled grass and hay samples. The values of Cd' for groups of tests have been averaged at each pressure level and are given in Table 5.5/27. The bracketed values are the values of Cd' at pressures for which there was only one test result in the group.

In Graph 5.5/30 these group average values of Cd' are plotted against Vertical Pressure for the 3 types of samples.

The pattern of variation in Cd' with vertical pressure is similar for all three types of sample. An initial steep rise levelling off at between 0.5 and 1.0. There is no clear indication of the effect of maturity on Cd' for grass as silage or ensiled grass; but it was noted that oat silage samples (7) had a Cd' of only half that for the grass samples. On the whole there is good agreement between the Cd' values of silage and ensiled grass samples.

The hay samples, perhaps because it was easier to determine Cd' accurately for hay, show certain clear trends. Typically the Cd' for hay was only half that for the same material as silage (e.g. GD/65/1-5/1, Ensiled grass (14) compared with GD/65/1-5/2, Hay (15)). Moisture content has a definate effect at hay moisture contents, taking the 1500 lb/ft^2 levels and identical material, Cd' was 0.62 for GD/Ch/1/2, 3/2 (13) at 9% m.c. but only 0.22 for GD/Ch/1/3 (12) at 2.6% m.c.

At the 3% m.c. level maturity appears to effect Cd', this is clearest below 2000 lb/ft^2. At 1500 lb/ft^2 young leafy rye grass (13) had a Cd' of 0.78, the maturer Glantlees hays (11 and 15) had a Cd' of 0.62 and 0.47 while the stemmy lucerne hays had a Cd' of 0.35.

For the calculation of silage densities in tower silos a mathematical expression for Cd' in terms of V is required.

Table 5.5/25

VALUES OF C_d', RATE OF INCREASE IN DRY DENSITY WITH LOG_{10} TIME, FROM PRESSURE/DENSITY TESTS ON SILAGE.

Sample Ref.	m.C %	C_d' lb. dm/ft³/Log_{10} hr at V lb/ft²										
		V. 125	250	500	1000	1500	2000	2500	3000	4000	250	0
Br65ClV1	76·3	C_d' ·08	·17	·30							-·18	-·35
Br65ClV2	60·2	·28	·16	·37	·67	·81		·81			-·87	-1·02
Br65ClV3	67·5	·11	·25	·32	·69	·68	·71				-·27	-1·02
Br64/U1	71·4	·15	·16	·17	·28	·54					-·29	-·45
Br65/U1	64·0	·14	·32	·45	·54	·74	·81	·90	·81		-·61	-1·42
2	68·0	·29	·32	·46	·51	·81	·88	1·00			-·45	-1·36
3	48·3	·21	·33	·72	·91	·93	1·01		1·37	1·05	-·83	-1·80
4	53·0	·21	·35	·61	·78	·75	·80		1·27	·95	-·96	-1·88
5	53·0	·24	·21	·40	·61	·68	·63		1·04	·85	-·56	-1·62
6	35·8	·26	·39	·64	·87	·93	1·03		0·80	·87	-·96	-1·70
7	35·4	·39	·39	·63	·77	·63	·97		·94	·84	-·77	-1·32
8	55·5	·08	·22	·53	·89		·89		·82		-·69	-1·07
9	63·3	·12	·26	·46	·79	·66					-·31	-·61
10	63·4	·26	·37	·61	·88	·92					-·56	-·86
11	64·7	·26	·34	·51	1·02	·65					-·42	-·83
12	63·0	·70	·76	·81	1·22	·96					-·48	-1·01
13	51·9	·24	·34	·48	·72	·67	·96	1·04		1·08	-1·01	-1·82
14	55·1	·43	·34	·50	·45	·49	·63	·67			-·80	-·98
15	57·9	·32	·32	·41	·75	1·04	1·18		1·04		-·67	-1·16
16	60·2	·22	·32	·40	·56	·66	·84				-·40	-·80
17	57·7	·25	·27	·40	·58	·80					-·76	-1·16
18	59·7	·26	·41	·48	·52	·52	·44	·44			-·53	-1·08
Br65/U19	57·7	·275	·41	·43	·71						-·63	-·89

Sample Ref.	m.C. %	C_d' lb. d.m/ft³/Log_{10} hr. at V lb/ft²										
		V. 125	250	500	1000	1500	2000	2500	3000	4000	250	0
Gl65U/4/1	63·4	C_d' ·17	·28	·46	·76	·84	1·15	·92			-·59	-1·43
40/3	65·7	·18	·26	·36	·78	·85	1·02				-·63	-1·10
33/2	73·5	·17	·23	·36	·60	·45					-·18	-·74
30/2	73·4	·16	·17	·29	·52	·63					-·16	-·72
30/3	67·1	·20	·20	·21	·53	·43	·77				-·36	-·95
30/4	69·9	·15	·15	·18	·36	·33	(·54)				-·36	-·51
30/8	66·2	·15	·17	·29	·44	·59	·74				-·40	-·95
24/3	66·8	·17	·17	·23	·40	·57	·76				-·60	-1·03
24/4	63·3	·22	·18	·26	·40	·59	·59	·66	(·66)		-·64	-·99
24/2	66·0	·10	·14	·20	·41	·67	·61	·78	(·68)		-·56	-1·12
13/3	57·5	·15	·23	·25	·36	·47		·74	·70	·89	-1·01	-1·19
13/4	62·8	·24	·26	·39	·52	·46		·71			-·60	-·86
7/3	64·7	·21	·21	·28	·48	·50					-·46	-·92
7/7	65·1	·19	·24	·28	·45	·52					-·37	-·84
5/3	66·5	·10	·20	·22	·30	·40					-·29	-·60
Gl65U 5/7	66·1	·20	·20	·27	·31	·47					-·37	-·75
Ro63U/1	52·8		·18	·39	·57	·60	·72	·47				
Ro63U/2	53·3		·40	·35	·51	·68	·54	·51				
Ro63U/3	55·9		[illegible]	·25	·40	·45	·44	·54	·45			
WeCl63U/1	77·2		·26	·34								
Pe63 U/1	63·7		·18	·13	·26	·25	·31	·33	·51		-·51	-·80
Pe63 U/2	68·3		·18	·18	·25	·33	·38	·47			-·35	-·63

Table 5.5/26

VALUES OF C'_d, RATE OF INCREASE IN DRY DENSITY WITH LOG$_{10}$ TIME, FROM PRESSURE/DENSITY TESTS ON ENSILED GRASS AND HAY.

FOR 1965 ENSILED GRASS; TOP LINE, 1ST WEEK. MIDDLE LINE, AFTER 3 WEEKS.

Sample Ref.	m.c. %	C'_d lb. d.m./ft³/Log$_{10}$ hr. at V lb/ft².										
		V 125	250	500	1000	1500	2000	2500	3000	4000	250	0
Br 1.	68·0	·38	·55	·63 ·38	·85 ·81	·89	—				-·29	-·91
Br 2.	60·15	·21	·37	·58 (·21)	·64 ·62	·78	1·20	·89	—		-·49	-1·02
Br 3.	57·95	·28	·49	·62	·83 (·53)	— ·68	— ·98	1·12	(·63)	1·10	-1·10	-1·22
Br 4/1.	73·9	·06	·14	·23 ·57	·34 1·00	·27 —					-·32	-·54
Br 4/2.	65·4	·29	·32	·44 (·35)	·53 1·02	·67 1·08	1·12				-·57	-·85
Br 5.	69·5	·22	·22	·36 ·42	·36 ·71	·38 ·88					-·66	-·73
Gl 64/6/1.	81·3	·21	·42									-·12
Gl 64/6/2	76·7	·33	·40	·58	·58						-·18	-·58
Gl 64/6/3.	75·0	·35	·43	·51	·80	·54					-·20	-·78
Gl 64/6/4.	68·25	·21	·25	·44	·62	·58	·73	·62	(·60)		-·67	-1·35
Gl 64/6/5.	58·0	·18	(·01)	(·29)	·50	·60	·77	·75	·77	·78	-·42	-1·35
Gl 64/6/6.	17·85	·26	·34	·48	·60	·86	1·03	·74	·71	·90	-·37	-·70
GD Ch 1/1.	71·5	·15	·23	·38 ·14	·52 ·76	— ·82	·81				-·44	-·87
GD Ch 2/1.	71·4	·19	·37	·49 (·07)	·71	·81	—				-·22	-·78
GD Ch 3/1.	70·2	·22	·25	·48 ·11	·57 ·61	·90	·85				-·40	-·92
GD Ch 1/2.	8·45	·11	·18	·30	·50	·70	·73		·82	·85	-·48	-1·05
GD Ch 1/3.	2·65	·09	·05	·17	·13	·22	·29	·29	·32	·31	-·15	-·31
GD Ch 3/2.	9·35	·12	·20	·30	·47	·54	·66		·84	·91	-·45	-·91
HR 1/6.	8·8	·24	·36	·50	·47	·73	·59		·45	1·05	-·73	-110
HR 2/6.	7·55	·26	·39	·55	·55	·60	·55	·74	·83	·83	-·46	-·88
HR 3/6.	8·0	·32	·46	·64	·73	·92	·69		·64	·83	-·46	-·73

Sample Ref.	m.c. %	C'_d lb d.m./ft³/Log$_{10}$ hr. at V lb/ft².										
		V 125	250	500	1000	1500	2000	2500	3000	4000	250	0
GD 65/1/1	60·4	·19	·42	·59 —	·72 (·34)	·99	·86		1·11	1·03	-·97	-1·38
GD 65/2/1	66·95	·22	·43	·67 ~	— ·66	·84	·93		1·03		-·66	-1·03
GD 65/3/1	69·0	·31	·70	·76	·79	·96	·93				-·65	-·90
GD 65/4/1	66·6	·31	·49	·69	·74	·87	·92		—		-·33	-·87
GD 65/5/1	55·5	·21	·31	·50	·66	1·11	— (·53)		1·10	1·11	-·66	-1·60
GD 65/1/2.	8·0	·11	·12	·28	·31	·49	·67		~	·67	-·37	-·85
GD 65/2/2.	8·0	·06	·12	·29	·34	·44	·60		·58	·60	-·34	-·76
GD 65/3/2.	8·4	·175	·175	·30	·34	·51	·46		·64	·48	-·30	-·80
GD 65/4/2.	8·0	·15	·175	·30	·29	·52	·52		·63	·56	-·34	-·80
GD 65/5/2.	7·65	·12	·14	·25	·42	·39	·64	·79	—	·74	-·21	-·78
S23 1/2	9·0	·23	·50	·45	·59	·86	1·05		1·09	1·18	-·73	-1·36
S23 2/4	29·5	·78	·63	·78	1·62	1·27	1·13	·91	1·48	1·27	-·85	-1·27
S23 4/5	14·9	·36	·32	·48	·77	·85	·85	·67	·85	·85	-·30	-·85
HL 3/1	77·3	n.c	n.c.	·38	·27						-·13	-·5
HL 3/2	66·2	·30	·40	·54	·71 (·2)	·71	·74	·81	·25		-·64	-·78
HL 3/3	58·2	·23	·42	·50	·79	·68 ·21	·54	1·0	1·05	1·21	-·5	-·67
HL 3/4	48·3	·33	·49	·57	·75	—	1·19	·62	·72	·88	-·62	-·88
HL 3/6A	8·15	·09	·14	·15	·23	·29	·28	·18	·37	·53	-·40	-·53
HL 3/6B	8·60	·17	·18	·28	·44	·53	·55		·41	·66	-·28	-·73
HL 1/6	8·60	·18	·12	·18	·27	·37	·41	·46		·55	-·32	-·32
HL 2/6.	6·75	·11	·12	·12	·20	·22	·20	·29	·20	·36	-·19	-·20

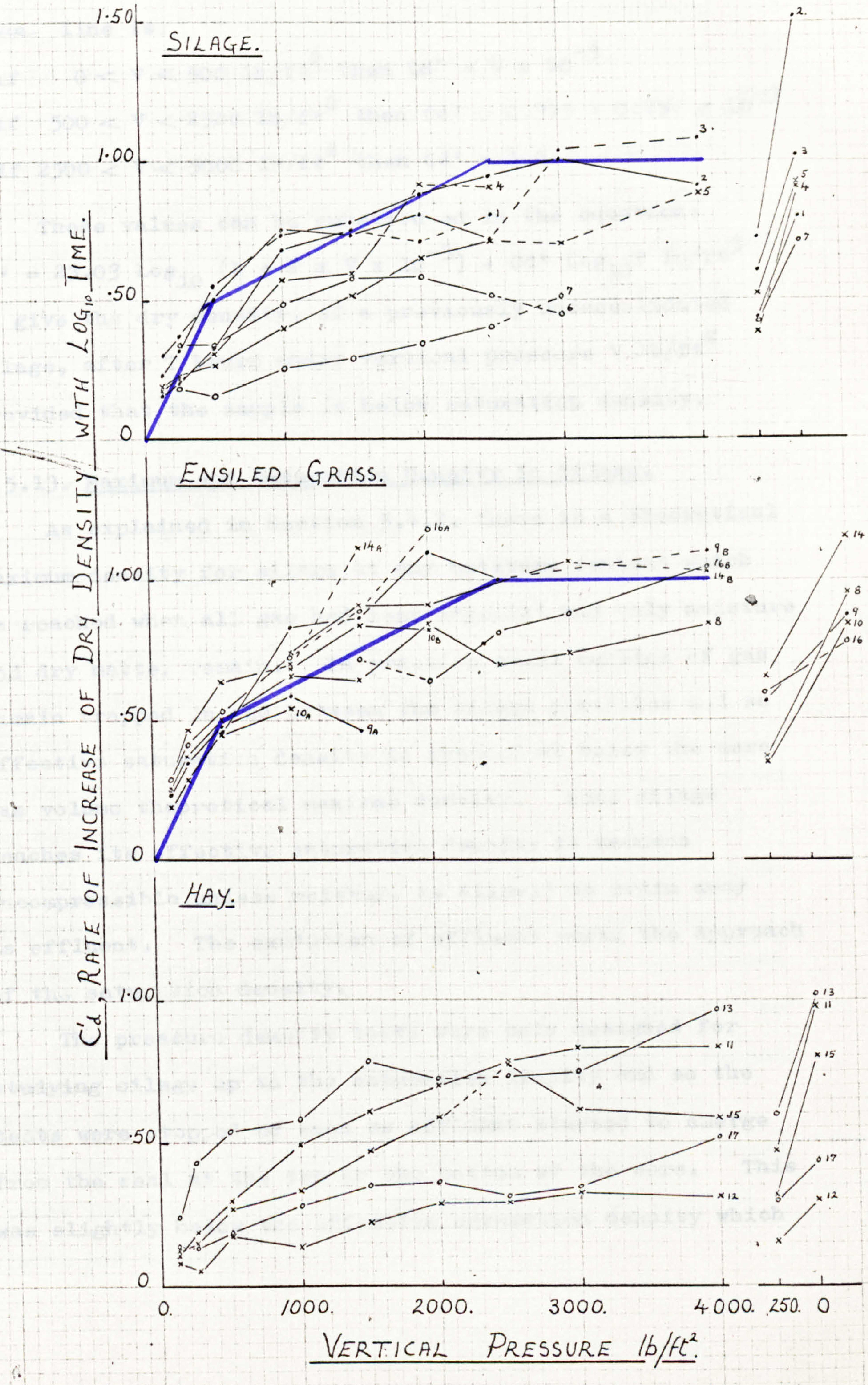
Table 5.5/27

AVERAGE VALUES OF Cd, RATE OF INCREASE OF DRY DENSITY WITH Log_{10} TIME.

GRAPH No.	SAMPLES.		m.c.% range.	Cd lb d.m./ft³/Log_{10} hr at V lb/ft²										
				125	250	500	1000	1500	2000	2500	3000	4000	250	0
1.	Br 65 Cl V1-V3, We 63 Cl U1. [4] CLAMP V^0 0-250	S.	60-77.	·16	·21	·33	·68	·75	(·71)	(·81)			-·44	-·80
2.	Br 65 U1-U8. [3] Top OF TOWER 2ND CUT V^0 0-350	S.	35~68	·23	·32	·55	·73	·78	·88	·95	1·01	·91	-·72	-1·52
3.	Br 65 U9-U19. [11] BOTTOM OF TOWER 1ST CUT V^0 500-1200	S.	52~65	·30	·37	·50	·75	·74	·81	·72	(1·04)	(1·08)	-·60	-1·02
4.	Gl 65 U40, U33, U30. (7) TOP OF TOWER V^0 200-600	S.	63~74	·17	·21	·31	·57	·59	·92	(·92)			-·38	-·91
5.	Gl 65 U24, U13, U7, U5. [9] BOTTOM OF TOWER V^0 600-2000	S.	57~67	·18	·20	·26	·40	·52	·65.	·72	(·70)	(·89)	-·52	-·92
6.	Ro 63 U1-U3. [3] LEAFY RYEGRASS. V^0 500-1600	S	53~56		·34	·33	·49	·57	·57	·51	(·45)			
7.	Pe 63 U1, U2. [2] OATS V^0 900-1300	S	64~68		·18	·15	·25	·29	·34	·40	(·51)		-·43	-·71
8.	Gl 64 6/1-6/6. (6) MATURE RYEGRASS	E.G	17~81	·26	·37	·50	·66	·64	·84	·70	·74	·84	-·37	-·95
9.	Br 1-5. (6) LEAFY RYEGRASS	E.G	58~70	·24	·35	·48 ·46	·59 ·83	·44 ·86	1·10	1·00		(1·10)	-·57	-·87
10.	GD Ch 1/1-3/1. (3) MATURE RYE GRASS	E.G.	70~72	·19	·28	·45	·54 ·69	·84	·83				-·35	-·86
11.	GD Ch 1/2, 3/2. (2) do.	H.	8·5~9·4	·11	·19	·30	·49	[illegible]	·70		·83	·88	-·47	-·98
12.	GD Ch 1/3. (1) do.	H.	2·6	(·09)	(·05)	(·17)	(·13)	(·22)	(·29)	(·29)	(·32)	(·31)	(-·15)	(-·31)
13.	HR 1/6-3/6 + S23 1/2. (4) LEAFY RYEGRASS	H.	7·5~9·0	·24	·43	·53	·58	·78	·72	(74)	·75	·97	-60	-1·02
14.	GD 65 1/1-5/1. (5) MATURE RYEGRASS	E.G.	55~69	·25	·47	·64	·70 ·73	(1·11) ·91	·91		1·07	(1·03)	-·65	-1·15
15.	GD 65 1/2-5/2. (5) MATURE RYEGRASS	H	7·5~8·5	·12	·15	·28	·34	·47	·58	(·79)	·62	·59	-·31	-·80
16.	HL 3/2-3/4. (3) LUCERNE	E.G.	48~77	·29	·44	·54	·74	(·88) (·71)	(1·19) ·64	·81	·88	1·04	-·59	-·78
17.	HL 1/6-3/6B. (4) LUCERNE	H	6·7~8·6	·14	·14	·18	·28	·35	·36	·31	·33	·52	-·30	-·4
18.	S23 2/4. (1) LEAFY RYEGRASS	E.G.	24·5	(·78)	(63)	(·78)	(1·62)	(1·27)	(1·13)	(·91)	(1·48)	(1·25)	(-·85)	(-1·27)

Graph 5.5/30

AVERAGE C'd AGAINST VERTICAL PRESSURE.



The proposed expression, Shown on Graph 5.5/30 as a heavy blue line is:

if $0 < V < 500$ lb/ft^2 then $Cd' = V \times 10^{-3}$

if $500 < V < 2500$ lb/ft^2 then $Cd' = 0.375 + 0.25V \times 10^{-3}$

if $2500 < V < 5000$ lb/ft^2 then $Cd' = 1.0$

These values can be substituted in the equation:

$Yd' = 23.03 \text{ Log}_{10} (E + F \times V \times 10^{-3}) + Cd' \text{ Log}_{10} T$ lb/ft^3

To give the dry density, of a previously unconsolidated silage, after T hours under vertical pressure V lb/ft^2 provided that the sample is below saturation density.

5.5.13. <u>Maximum and Saturation Density in Silage.</u>

As explained in Section 5.4.2. there is a theoretical maximum density for silage at any moisture content which is reached when all gas had been expelled and only moisture and dry matter remain. In practice small bubbles of gas remain trapped in and between the silage particles and so effective saturation density is reached at below the zero gas volume theoretical maximum density. Once silage reaches its effective saturation density it becomes incompressible unless moisture is allowed to drain away as effluent. The exudation of effluent marks the approach of the saturation density.

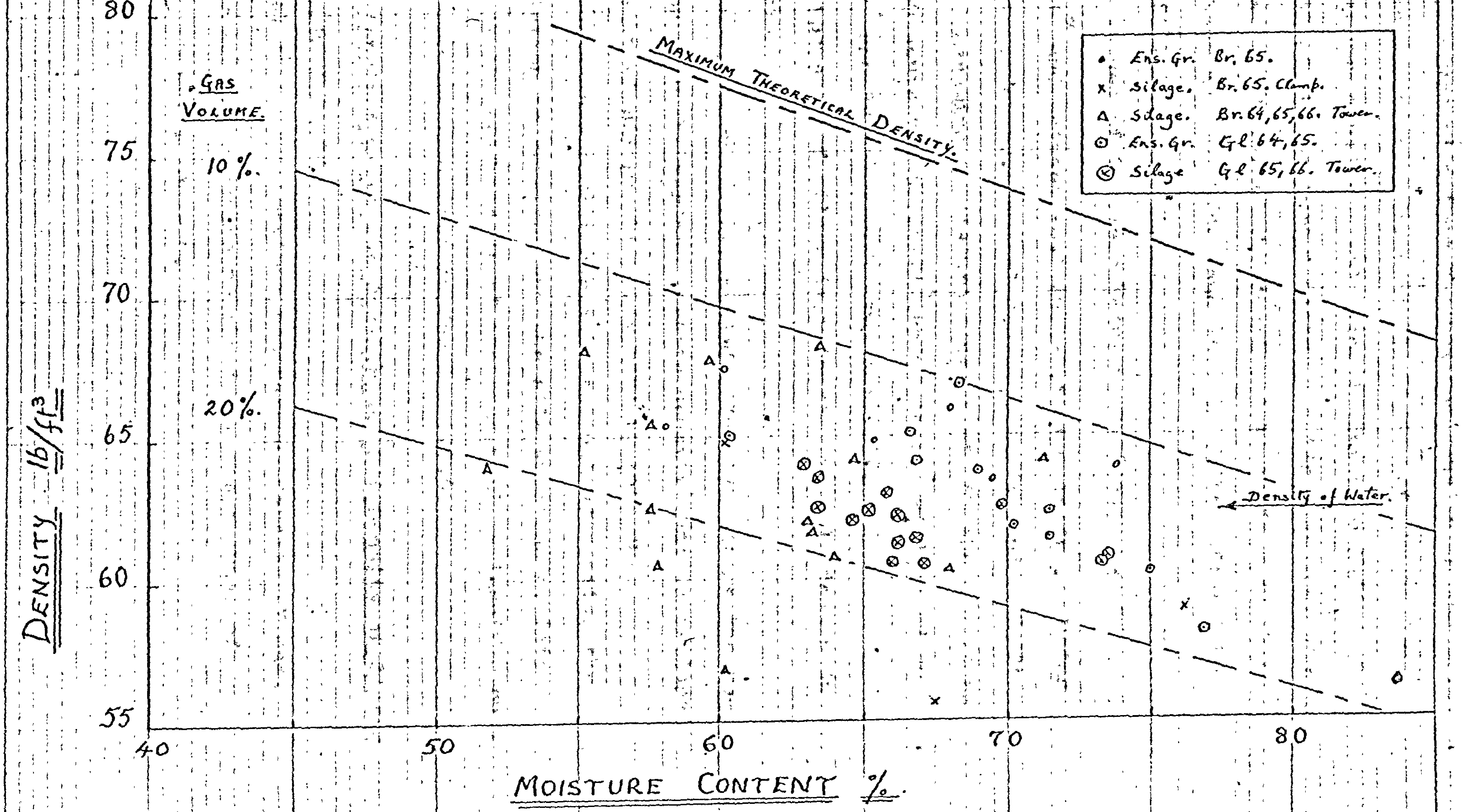
The pressure density tests were only designed for studying silage up to the saturation density and so the tests were stopped as soon as effluent started to emerge from the seal at the top or the bottom of the core. This was slightly below the effective saturation density which would be marked by effluent at both ends. The densities at which effluent appeared are plotted against moisture content in Graph 5.5/31 together with the theoretical maximum density and 10% and 20% gas voids densities. Almost all the results fall in the 10% to 20% gas volume range. From this graph it appears reasonable to take the theoretical 10% gas volume density (calculated on the basis of water at 62.4 lb/ft^3 and dry matter at 100 lb/ft^3) as the effective saturation density for silage in towers. Below this saturation density, silage will consolidate according to the expression $Yd' = 23 \ Log_{10} \ (E + F \times V \times 10^{-5})$. Once silage reaches the saturation density a fluid pore pressure builds up in the silage and further increases in dry density is controlled by the drainage rate of effluent.

5.5.14. Re-expansion of Silage

The re-expansion of the silage on the removal of pressure was measured for all samples and the values of Yd' and Cd' at 250 lb/ft^2 and 0 lb/ft^2 obtained. These values are tabulated and plotted with the corresponding results for the consolidation of silage in Tables 5.5/11 to 5.5/20 and Graphs 5.5/5 to 5.5/19. Because of the friction between the silage and the core wall, discussed in Section 5.5.2.2., the re-expansion observed in these tests will be less than that occuring in unconfined conditions. Because samples re-expanded from different dry densities and, depending on moisture content, different pressures, detail direct comparisons are not possible but certain general trends are clear.

Graph 5.5/31

MAXIMUM DENSITIES IN PRESSURE/DENSITY TEST.



The re-expansion from the maximum density in the test gave a density after 1 hour at 250 lb/ft^2 of 85% to 90% of the maximum density; and after 1 hour at 0 lb/ft^2 of 70% to 80% of the maximum density. So for a typical sample compressed to 65 lb/ft^2 the density fell to 55 - 59 lb/ft^3 after 1 hour at 250 lb/ft^2 and 45 - 52 lb/ft^2 after 1 hour at 0 lb/ft^2.

The values of Cd' were between -0.35 and -0.7 at 250 lb/ft^2 and between -0.7 and -1.5 at 0 lb/ft^2. Using values of Cd' of -0.5 and -1.0 at 250 lb/ft^2 and 0 lb/ft^2 resp. and assuming a moisture content of 66% the densities after 100 hours at 250 lb/ft^3 and 0 lb/ft^2 will be 52 to 56 lb/ft^3 and 39 - 46 lb/ft^3 respectively.

The re-expansion of silage is important in silo design in two ways:-

(a) Unloaders work on re-expanded silage and it is the re-expansion from the maximum in-situ density that determines the density of silage that they have to work on.

(b) As the silage re-expands in a top unloaded silo, the wall friction is reversed and the silo wall can go into tension if the self-weight of the silo wall is insufficient. This is further discussed in Section 6.1.6.

5.5.15. Conclusions on the Density and Dry Density of Silage in Tower Silos.

1. That there is a maximum theoretical density (Y max.) for silage, assuming no remaining gas volume, of:

$$Y\ \max = 100 - 0.376\ m \quad \text{lb/ft}^3$$

and a corresponding maximum theoretical dry density (Yd max.)

$$Yd \max = \left\{\frac{100 - m}{100}\right\} (100 - 0.376\ m)\ lb/ft^3$$

where m is the moisture content (% wet basis).

2. That effective saturation occurs in a silage at the 10% gas volume density (i.e. 90% $Y_{max} = 90 - 0.338\ m$ lb/ft^2). At this effective saturation density fluid pore pressure starts to rise and the rate of increase in dry density is controlled by the rate of effluent drainage.

3. That below the effective saturation density a silage (which has not been previously over-consolidated) will have a dry density (Yd^T) at T hours after the application of a vertical pressure V lb/ft^2 of:

$$Yd^T = 23\ Log_{10}\ (E + F \times V \times 10^{-3}) + Cd'\ Log_{10}T$$

where E is a constant related to dry density at $V = 0\ lb/ft^2$

F is a constant related to the compressibility

Cd' is a constant related to the rate of settlement with time at V lb/ft^2.

The corresponding density (Y^T) at time T is

$$Y^T = \left\{\frac{100}{100 - m}\right\} Yd^T\ lb/ft^3$$

4. For the virgin consolidation of silage

E can range from 1.4 to 2.1

and F can range from 1.5 to 9.0.

The normal range of silages can be described using a value of E of 1.8 and

F = 6.5 for young leafy grass

C.P. approx. 20%, C.F. approx. 25%

F = 3.7 for average maturity grass

C.P. approx. 12%, C.F. approx. 28%,

F = 1.8 for mature grass

C.P. approx. 8%, C.F. approx. 32%.

5. The value of Cd' for all silages can be taken as:-

if $0 < V < 500$ lb/ft^2 then $Cd' = V \times 10^{-3}$

if $500 < V < 2500$ lb/ft^2 then $Cd' = 0.375 + 0.25V \times 10^{-3}$

if $2500 < V < 5000$ lb/ft^2 then $Cd' = 1.0$.

6. Moisture content does not significantly affect silage dry densities at below the saturation density. At moisture contents below approx. 25%, hay gets progressively stronger as it dries out, which reduces dry densities under pressure.

7. Chopping increases dry densities of loose material but the effect is reduced when the crop is compressed and is not of significance at over 500 lb/ft^2.

8. Maturity, for which Crude Protein and Crude Fibre are a convenient but approximate indicator, has the greatest influence on dry density under pressure, but little influence on loose material or at low pressures.

9. Fresh grass has a dry density under pressure which is markedly less than that for the resulting silage. Wilting increases the dry density of grass under pressure towards that for silage. The rise from the grass dry density to the silage dry density occurs at a rate determined by the fermentation and is effectively complete when the silage pH falls below 4.25.

10. Laceration, by increasing the rate of fermentation, speeds the increase in dry density to the silage level and incidentally improves fermentations.

5.5.16. Recommendations for Further Research on the Density of Ensiled Grass and Forage Crops.

The research I have carried out has enabled the broad outlines of a picture of silage density to be drawn. I have proposed in the text several improvements in detail to the present method of carrying out consolidation tests, and the most important of these are:-

1. Reducing the wall friction error in pressure in the sample by:
    - (a) Coating the cores with P.T.F.E.
    - (b) Keeping sample thickness to the minimum consistent with 3a.
    - (c) Correcting for friction if k and u' are known accurately.
2. Improve the accuracy of pressure applied by the consolidation machines by:
    - (a) Re-designing and rebuilding the machine E to reduce friction.
    - (b) Reducing friction in Machines A to D by the use of P.T.F.E. lubricants.
3. Maintaining the accuracy of determination of density by:-
    - (a) Ensuring that the sample thickness at maximum test density does not fall below 1".

4. Reducing moulding in sample by:
    (a) Improving the piston seal (this will probably increase friction between piston and a correction for this would be necessary).
    (b) Where Cd' is not required, or only required at one or two pressure levels, carry out accelerated consolidation tests for only 30 mins. to 1 hour at each pressure level.
5. Improve fermentation in Ensiled grass samples by:
    (a) Reducing the time for ensiling to the start of consolidation.
    (b) Speeding up the initial consolidation to the rest density.
    (c) Lacerating the crop.
    (d) Adding sugar to crop when required.
    (e) Better sealing as 4a.

A major refinement of the apparatus which would enable total control of the ensilage process to be obtained would be to surround the sample core with a controlled environment chamber. The temperature and composition of the gas in this chamber could be controlled. By circulating the gas through the core, instead of sealing the core as at present, the ensilage process could be simulated in every detail.

The technique already developed for the cut sample serves its purpose very well. The repacked sample technique used for Br 65/U12 could well replace the cut sample technique provided that comparitive tests with ensiled grass and cut silage samples showed that:-

(a) that it gave the same consolidation curve above the in situ density as the cut sample on identical silage.

(b) That comparison with the improved ensiled grass tests, described below, shows that the repacked sample and a virgin sample of the same material have the same consolidation curves.

The ensiled grass technique in its present form suffers from two main defects.

(1) That in the 'before rest' period the sample density is rising because of the increases in pressure and the time for which the pressure is held as well as because of the loss of strength in the grass as it ferments into silage. These two effects cannot be separated out.

(2) That the 'after rest' part of the consolidation curve only covers the higher pressure range.

To overcome these two problems a new procedure is suggested using the controlled environment chamber. For each crop sample being tested a number of cores (say 4) would be filled with identical material. Core 1 would be rapidly tested for perhaps 10 mins. at each pressure level up to 500 lb/ft^2 and then left at constant pressure. From this value of Yd' for the fresh crop at up to 500 lb/ft^2 and the density time relationship of the fermenting crop at 500 lb/ft^2 could be obtained. The three other samples would be held unconsolidated in a controlled environment until required. When the fermentation was judged to be one third complete Core 1 would be taken out of the consolidation machine while Core 2 was tested rapidly up to 1000 lb/ft^2 to obtain Yd' for the part fermented material. Core 2 then would be taken out and analysed and Core 1 returned to the consolidation machine for a further period at 500 lb/ft^2. Core 3 would be tested, when the fermentation was two thirds complete in the same way as Core 2. When fermentation was judged complete Core 1 would be tested as for an 'after rest' sample in the present procedure to obtain Yd' and Cd' at pressures above 500 lb/ft^2. Values of Yd' and Cd' for V = 125 to 4000 lb/ft^2 or effluent would then be obtained using Core 4, the completely fermented sample.

This refined technique would obtain, in addition to the data on the densities in the fully fermented settled silage (which we require for the calculation of pressures and capacities) the data on the densities of the top fermenting layers of silage during filling (which we require for the prediction of losses and heat rise in filling).

By controlling temperature and the rate of depletion of oxygen in the sample the fermentation conditions in any type of silo for any type of filling routine can be simulated. The effect of increasing losses (obtained by extending the aerobic period) on density could be studied in this way.

Using the above improved techniques experimental programmes should be devised to study the following:

1. A comparison of the results of the three techniques: cut silage, repacked silage and controlled environment ensiled grass during the fully instrumented filling and unloading of a tower silo.

2. A series controlled environment ensiled grass tests (similar to the Hurley series HL and HR) to obtain density results for a range of moisture contents for a range of maturities on pure swards of first cut rye grass, lucerne and maize and then on typical mixed farm swards.

3. A series of controlled environment ensiled grass tests to determine the effect of increasing losses on the before and after test analyses and the density results.

4. A series of controlled environmental tests to further investigate the effects of chopping and laceration.

5. An extensive series of repacked silage or cut silage tests, using samples from farms, aimed at covering as wide a range of moisture contents, maturities and crop as possible.

6. A series of ensiled grass (Hay) tests to investigate the densities of hays in the 10 - 30% m.c. range.

5.6. OTHER PHYSICAL PROPERTIES

5.6.1. The ratio of Lateral to Vertical Pressure (k).

The use of the ratio of lateral to vertical pressure (k) in the calculation of pressures in silos originated in Janssen's work on grain and it has been discussed in Section 4.5.

With silage a Jansson type approach to the calculation of pressures is valid but the 'constants' of the grain formula must be treated as complex variables in the case of silage, as described in Section 6.1.

There are two conditions to consider in the analysis of filling a silo. With unsaturated silage the lateral pressure of the grass fibres is due to the tendency of the fibres to spread outwards laterally against the walls of a container when compressed by a vertical pressure. Once the silage reaches saturation, it becomes incompressible and a fluid pressure starts to build up in the silage with the application of further vertical pressure. Thus when:-

V is the total vertical pressure,

L is the total lateral pressure,

V_s is the vertical pressure to produce saturation,

$L_f = k \times V$ is the lateral fibre pressure at below saturation,

$L_{fs} = k \times V_s$ is the lateral fibre pressure at saturation,

If $V < V_s$ then $L = L_f = k\ V$,

If $V = V_s$ then $L = L_{fs} = k\ V_s$,

If $V > V_s$ then $L = L_{fs} + (V - V_s)$

$$L = k\ V_s + (V - V_s)$$

L_f cannot increase above the value kV_s, as at above the pressure (V_s) required to produce saturation, there is no further compression of the fibre. All the vertical pressure above V_s is carried by the pore pressure $(V - V_s)$

which exerts an equal lateral pressure. Thus, once saturation is reached the effective value of $k = \frac{L}{V}$ increases from the value $\frac{L_f}{V}$ at below saturation towards unity.

If we consider the extreme case where $V_s = 0$ so that $L_{fs} = 0$, $k = 1$ and $L = V$, we have hydrostatic pressure. This case occurs in practice with manure slurries which have moisture contents of 70% and upwards and consists of the undigested remnant of silage plus water.

Unfortunately there is little by way of experimental data on the value of k for silage. In TAMM's(117) experiments on silage pressure no measurements were taken of the vertical pressures. POMROY and OTIS(95) measured the pressures on the silo floor and on one door 5' up to a 14' x 45' silo. The pressures exerted by silage vary considerably from place to place on the silo wall and floor (e.g. POMROY and OTIS in a later experiment found that the floor pressure in a silo ranged from 1300 lb/ft^2 at the wall to 5800 lb/ft^2 at the centre) and so a value of k calculated from Pomroy's data can only be regarded as approximate. But taking the figures obtained when the first fill stopped on day 3 (when little change in calibration could have occured) we get:-

Average V on floor = 1050 lb/ft^2

L_f on door at 5' = 450 lb/ft^2

The value of V at 5' will have been

1050 - silage density x 5 + wall friction effect lb/ft^2

At this depth the rate of increase in V with depth was probably about 30 lb/ft^2, so we can say that at the 5' level

$$k = \frac{L}{V} = \frac{450}{1050 - 30 \times 5} = \frac{450}{900} = 0.50.$$

YU, BOYD and MENEAR(143) carried out experimental work on the lateral and frictional pressures of corn silage on the walls of a 30' x 60' concrete stave silo. They proposed the use of Janssen's formula (but with the 'constants', density, wall friction and k expressed as functions of depth of silage) for calculating silage pressures. The dangers and short comings of this are discussed in Section 6.2.2.

To obtain a value of k, Yu mounted a 2" cube, fitted with pressure transducers on its top face and on one side, in the silage 4" from the silo wall. From the values of vertical and lateral pressure recorded Yu calculated k. The recorded values of k are not given in the paper but values of k expressed as a function of z the depth of silage are given as polynomials obtained by a computer least squares technique. These values are:-

$$k = f_{31} = 0.463 + 0.434z$$

$$\text{or} \quad k = f_{32} = 0.641 - 0.0149z + 0.000238z^2$$

$$\text{or} \quad k = f_{33} = 0.767 - 0.0336z + 0.000906z^2 - 0.00000678z^3$$

f_{31} appears to be a misprint as it gives k = 4.9 at z = 10 ft

The values of k for f_{32} and f_{33} are:-

at z	=	10'	30'	50'
k = f_{32}	=	0.52	0.41	0.49
k = f_{33}	=	0.52	0.32	0.50

Yu's method using a 2" block almost certainly distorts the value of k, for a solid block in the highly compressible silage would distort the whole pressure pattern in the silage. There is no record of whether effluent occured in this silo.

The pressures recorded at Glantlees, given in Section 2.2.6.2., can only be used to give an approximate assessment of k because of the variations in the pressure measured at different points on the silo floor and silo wall. A value of k in the range 0.2 - 3.0 was obtained from Graphs 2.2/9(a) and (b) of Lateral against Floor Pressures. During filling k was initially 0.65, it then fell to 0.46 (1965 - 66) or 0.2 (1964 - 65) during the final stages of filling and storage and rose to 2.0 to 3.0 as unloading progressed and the silage re-expanded.

The work of DOWNES(36) on the compression of wool is of considerable interest, for wool has a very similar pressure density relationship in compression and re-expansion to silage, the density being about 20 lb/ft^3 at 1500 lb/ft^2. Downes measured the lateral forces exerted by wool when being compressed in a box by vertical pressure. He found that k for wool was almost constant at 0.25 in the 20 to 45 lb/ft^3 density range.

It would seem from the very limited data available that k for unsaturated silage lies in the range 0.25 to 0.65 and is possibly a function of moisture content. Careful research to establish the value of k accurately for silage should be carried out as soon as possible.

5.6.2. The Coefficients of Friction of Silage against Wall Surfaces (u')

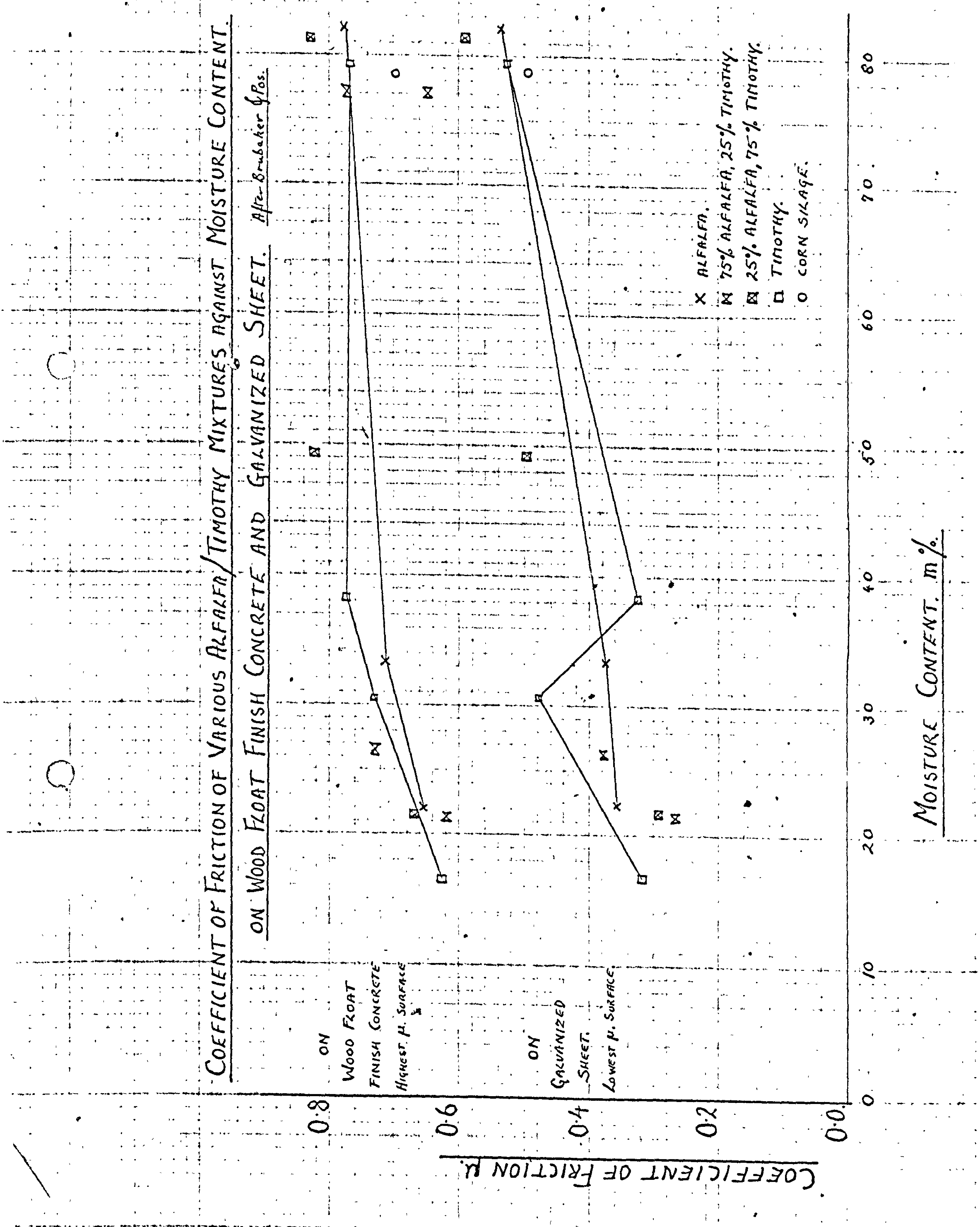
The coefficient of wall friction (u') of silage is important in the calculation of silage pressures and densities and for the design of unloading and handling machinery.

BRUBAKER and POS(20) describe the experimental apparatus they used for the measurement of the static coefficients of friction of grain for a range of m.c., on a number of wall surfaces. This apparatus was also used on silages and the results are given in N.R.C. Farm Building Standards(81). Their results for alfalfa and timothy mixtures are shown on Graph 5.6/1. The coefficient is clearly dependent on two main variables, wall surface and moisture content, and there is some indication that variety may effect it slightly. The range of the coefficient u' for the full range of wall finishes (from Wood float finish concrete to Galvanized steel) and for 80 - 45% m.c. is between 0.8 and 0.45.

RICHTER(104) determined the static and sliding coefficients of friction of silage on galvanized steel and obtained values in the range 0.52 to 0.82.

KLEIS and TOSHITAMI(58) measured the frictional resistance to extrusion of normal and frozen silage from 15" dia. test silos of coated and uncoated concrete and glass coated steel. Unfortunately this carefully done work is of little value as there is no way that the frictional force can be converted to the coefficient of

Graph 5.6/1


COEFFICIENT OF FRICTION OF VARIOUS ALFALFA/TIMOTHY MIXTURES AGAINST MOISTURE CONTENT
ON WOOD FLOAT FINISH CONCRETE AND GALVANIZED SHEET.
After Brubaker & Pos.
ON WOOD FLOAT FINISH CONCRETE HIGHEST μ. SURFACE
ON GALVANIZED SHEET. LOWEST μ. SURFACE
× ALFALFA.
⊠ 75% ALFALFA, 25% TIMOTHY.
⊠ 25% ALFALFA, 75% TIMOTHY.
□ TIMOTHY.
○ CORN SILAGE.
0·8
0·6
0·4
0·2
0·0
COEFFICIENT OF FRICTION μ.
0
10
20
30
40
50
60
70
80
MOISTURE CONTENT. m%.

friction u' as the lateral pressure in the silos was unknown and uncontrolled.

The coefficients of friction between the silage and door panels used for pressure measurement in the experimental work of TAMM(117) and YU et al(140) can be obtained from the ratio of lateral to vertical frictional force on the door (but only so long as the silage remains below saturation).

In Tamm's results the average lateral and vertical frictional pressures for 12' - 14' dia. silos at 15' depth are 150 and 95 lb/ft^2, giving a u' of 0.63. For 16' - 18' dia. silos the corresponding figures are 180 and 100 lb/ft^2, giving a u' of 0.55. The doors were of wood and faced with copper armoured sisalcraft paper so these coefficients cannot be applied to the concrete walls.

Yu determined u' in a similar manner and expressed it as a function of silage depth z in first, second and third order polynomials (f_{21}, f_{22} and f_{23}). These polynomials give the following values of u':-

for z =	10 ft	30 ft.	50 ft.
using f_{21} u' =	0.61	0.50	0.42
using f_{22} u' =	0.62	0.51	0.43
using f_{23} u' =	0.57	0.45	0.39

The door surface is not recorded. The apparent fall in u' with depth, may be due to variations in moisture content or to the total lateral pressure at depth being partly due to pore pressure in saturated silage.

Two workers have concerned themselves with the coefficients of internal friction of silage. This is a rather doubtful concept as it only has meaning in a fibrous material when frictional shearing between lamina of parallel fibres occurs. YAREMENKO(142) who carried out a soil mechanics type shear box test to determine the apparent c and ∅ for 1 cm and 2 - 3 cm chop 'silage material' (this appears to be the wilted crop before ensiling). Converting the apparent ∅ to apparent coefficient of internal friction (u) gives values of u = 0.63 - 0.80 for 1 cm chop and u = 0.83 - 0.87 for 2 - 3 cm chop.

WILLCOCKS(132) gives a value of coefficient of internal friction (u) of 0.4 for 3/8" chop rye grass of 62% m.c. This seems low and on examination it proves to have been calculated on the basis of a false assumption. Willcocks calculated u by dividing the ultimate tensile strength of silage in the direction of the fibres by the estimated internal pressure normal to the fibres. The tensile failure occured when fibres slid over each other, it was not due to fibres breaking.

The correct expression is

$$u = \frac{\text{Total tensile force at failure}}{\text{internal pressure x area of frictional shear.}}$$

Willcocks' expression is only valid if the area of frictional shear is equal to the cross sectional area of the sample. In practice the area of frictional shear is impossible to determine for a fibrous mass like chopped silage.

5.6.3. The Specific Heat of Silage.

The specific heat of silage is the sum of that due to its dry matter (specific heat, s) and that due to its moisture (specific heat 1.0). As with grain, the specific heat of silage can be given in the form:

$$\text{Specific heat} = s + \frac{m}{100}(1 - s) \text{ B.t.u./lb/F}^{\circ} \text{ or cal/g/C}^{\circ}$$

where m is the moisture content%.

There is no precise work on the value of s the specific heat of dry matter in silages. McDONALD et al(65) estimated the specific heat of dried grass to be of the order of 0.45 from calorimetric studies. This seems high in relation to grain as discussed in Section 4.8.2., and other similar substances. The N.R.C. Farm Building Standards(81) give the following values of specific heats for stored products which bear some similarity to grass and silage.

Product	m.c.	Sp.ht.	Sp.ht.of dry matter (s)
Asparagus	93%	0.94	0.14
Corn (green)	75.5%	0.80	0.185
Sauerkraut	89%	0.92	0.27

CHAPTER 6

THE CALCULATION OF THE DENSITIES, CAPACITIES AND PRESSURES IN SILOS AND THE FILLING RATE REQUIRED TO CONTROL HEATING.

Introduction

In the preceding Chapters I have reported the results of experimental work, by myself and others, on the measurement of densities, capacities, pressures, temperatures and losses in silos and on the fundamental physical properties of ensiled crops. In this Chapter I have aimed to draw these two together by proposing a method by which the densities, capacities, pressures, temperatures and losses in silos can be calculated from a knowledge of the physical properties of the ensiled material.

This method of calculation has its roots in Janssen's theory for calculating the pressures in silos by considering the equilibrium of horizontal laminae. With dry grain, for which density (Y) coefficient of wall friction (u') and ratio of lateral to vertical pressure (k) can be considered constant, calculus can be used for integrating to determine the variation of pressure with depth. However, with silage for which Y, u' and k are variables, largely independent of depth, the calculation has to be carried out by representing the ensiled mass in a mathematical model as a stack of finite, plane laminae of specified dry weight. The maturity and moisture content of each lamina must be specified in the form of a function or an array so that Y, u' and k can be calculated. In the simplest form the whole stack of laminae is assumed to have been assembled at one instant and is considered after a specified period of settlement. A more complex dynamic model can be built up from the available data in which the equilibrium of each lamina is considered at finite time intervals as the lamina stack is built up, settles and is unloaded. A further refinement, which would be possible with a better knowledge of the shear strength of silage, is the modeling of the non-uniform distribution case where the laminae are of varying non-uniform thickness and do not remain plane or horizontal.

The applications of this modeling technique are not confined to tower silos filled with silage. It can be used to predict the behaviour in silos, bins, hoppers or clamps of a wide range of stored materials which cannot be considered as fluids or dry grains.

Within the time scale of this research programme it has not been possible to attempt the development of this modeling approach into the computer programs which are essential for carrying out the many calculations involved in this finite lamina technique for the wide range of possible filling combinations. I have confined myself to outlining the principles on which the method is based and using it in a simple form with relatively thick layers of assumed uniform material to illustrate the way it can be applied to calculate densities, pressures, capacities, temperature rises and losses in the silo. The results from these simple models have been compared with field experimental results and existing formulae and a number of important conclusions drawn.

6.1. THE DEVELOPMENT OF A MATHEMATICAL MODEL OF ENSILED MATERIAL IN A TOWER SILO.

6.1.1. The Equilibrium of a Lamina of Silage in a Silo.

The physical behaviour of the whole mass of silage within a silo can be predicted by considering it as a stack of finite laminae. The equilibrium of each lamina is considered in turn from the top downwards, to enable the density and dry density of each lamina and the vertical and lateral pressures exerted by it, to be calculated. Initially I have considered the stack at a fixed time after completion so that all laminae can be assumed to have remained at a constant vertical pressure for a known time. A further necessary initial simplification is the assumption that all laminae are and remain plane and horizontal and exert a uniform vertical pressure on the lamina below.

First I have considered the equilibrium of each lamina in a manner similar to Janssen, except that, with a compressible material, it is more convenient to specify the total weight of dry matter in each layer than its thickness as a measure of lamina size. As the calculations will be carried out on finite elements the dry weight of each lamina may differ provided the weight is specified.

The equilibrium equation of a lamina is:

Area x (Pressure on bottom face - Pressure on top face)

= Weight - Frictional support.

$$(V_b - V_t) \times A = Y \times A \times t - Lfa \times u' \times \pi D \times t$$

$$\delta V \times A = Y \times A \times t - Lfa \times u' \times \pi D \times t$$

$$\delta V = Y \times t - Lfa \times u' \times t \times \frac{4}{D}$$

$$\delta V = t \left(Y - \frac{4Lfa \times u'}{D}\right) \quad \ldots \quad \ldots \quad (1)$$

where D is the diameter of the silo, ft.

V_t is the vertical pressure on the top surface of the lamina, lb/ft^2

V_b is the vertical pressure on the bottom surface of the lamina, lb/ft^2

δV is the increase in Vertical Pressure $(V_b - V_t)$ across lamina, lb/ft^2

Lfa is the average lateral fibre pressure against the silo wall, lb/ft^2

u' is the coefficient of friction of the silage against the silo wall

t is the thickness of the lamina, ft.

Y is the density, lb/ft^3.

The values for substitution in Equation 1 are obtained as follows:-

D Silo internal diameter, ft. Specified for silo under consideration.

u' The coefficient of friction of silage on the silo wall. This has been discussed in Section 5.6.2. As a first approximation it can be expressed as a constant appropriate to the silo wall finish. Ideally it should be expressed as a function of moisture content related to the silo wall finish and be calculated from the moisture content for each lamina. This refinement is most desirable where the moisture content falls below 30% and u' tends to drop sharply.

Lfa Lateral fibre pressure, lb/ft^2. When the average vertical pressure in the lamina (Va) is less than the saturation vertical pressure (Vs), Lfa can be expressed as k x Va. When Va $>$ Vs, Lf = k x Vs. The derivation of this is in Section 5.6.1. with a discussion of values of the ratio of lateral to vertical pressure k. Better data on k for silage is urgently required, but in the interim it is reasonable to consider k as a constant in the range 0.25 to 0.65.

t The lamina thickness, ft. This is calculated from the specified lamina dry weight (W), the dry density (Yd) and the silo diameter (D) using the equation

$$t = \frac{4\,W}{\pi\,D^2 \times Yd} \qquad \ldots \qquad \ldots \qquad (2)$$

Y The silage density lb/ft^3. This is calculated using the following equations which have been derived in Section 5.5.

$$Y = \left(\frac{100}{100 - m}\right) Yd \qquad \ldots \qquad \ldots \qquad (3)$$

Where:-

Yd is the dry density lb/ft^3

m is the moisture content % (wet basis).

$$Yd = 23 \operatorname{Log}_{10} (E + F \times Va \times 10^{-3}) + Cd' \operatorname{Log}_{10} T \qquad \ldots \qquad (4)$$

Where:-

E is a constant related to loose density.

F is a constant primarily dependant on maturity.

Va is the average vertical pressure $(V_t + \frac{\delta V}{2})$ in the lamina.

Cd' is the rate of increase in dry density with Log_{10} time, it is a function of Va.

T is the time in hours from the application the vertical pressure Va.

but Yd cannot exceed $Yd = \left\{\frac{100 - m}{100}\right\} (90 - 0.338m) \ldots (5)$ which is reached when the density becomes constant at saturation (10% gas voids).

The saturation vertical pressure (Vs) which will just produce saturation after T hours is calculated by substituting the appropriate values of m, E, F, T, and Cd' (which is a function of Vs) into the equation:-

$$\left\{\frac{100 - m}{100}\right\} (90 - 0.338m) = 23 \text{ Log}_{10}(E + F \times Vs \times 10^{-3}) + Cd' \text{ Log}_{10}T \quad \ldots \quad \ldots \quad (6)$$

The choice of values of E and F has been discussed in Sections 5.5.10. and 5.5.11. E can normally be taken for silage as a constant 1.8 while F must be specified according to the maturity of each lamina and will normally fall in the range 1.8 to 6.5.

The choice of an expression for Cd' as a function of Va has been discussed in Section 5.5.12. For most silages the following is suitable:-

if $0 < Va < 500$ lb/ft^2 then $Cd' = V \times 10^{-3}$

if $500 < Va < 2500$ lb/ft^2 then $Cd' = 0.375 + 0.25\, Va \times 10^{-3}$

if $2500 < Va < 5000$ lb/ft^2 then $Cd' = 1.0$.

T. The time for which the vertical pressure (Va) has been acting on the lamina must be specified.

To summarise: For calculating the equilibrium of each lamina values must be specified for the following parameters:

D	Silo diameter	ft.
V_t	Vertical pressure on the top of lamina	lb/ft^2
k	The ratio of lateral to vertical pressure	
u'	Coefficient of friction of silage in lamina on silo wall.	
W	Weight of dry matter in lamina.	lb.
m	Moisture content (wet basis)	%
E	Constant in density formula related to loose density.	
F	Constant in density formula related to maturity.	
Cd'	Function of Va in density formulae.	lb/ft^3/Log$_{10}$hrs.
T	Time for which V_t has been applied to lamina.	hrs.

From the calculation of the equilibrium of the lamina the average values of the following in the lamina are obtained.

Yd	The dry density	lb/ft^3
Y	The density	lb/ft^3
t	The thickness	ft.
Lfa	The average lateral fibre pressure on the silo wall.	lb/ft^2

La	The average total lateral pressure on the silo wall.	lb/ft^2
Va	The average vertical pressure.	lb/ft^2
Vs	The vertical pressure which will just produce saturation.	lb/ft^2
V_b	The vertical pressure on the bottom of the lamina.	lb/ft^2

(Va - Vs) = (La - Lfa), the pore pressure in saturated silage, lb/ft^2.

In order to calculate these values Equation 1 to 5 must be solved simultaneously or by successive approximations. The latter approach seems most satisfactory, particularly when a computer is used for the computational work.

The procedure is:

Step 1 Calculate saturation value of Yd using Equation 5.

Step 2 Calculate Vs using Equation 6.

Step 3 Make Va_1 (the first trial value of Va) equal to V_t.

Step 4 If $Va_1 > Vs$ then Yd equals the saturation value from Step 1, go to Step 6.

Step 5 If $Va_1 < Vs$ then Yd_1 (the first trial value of Yd) is obtained by using Va_1 in Equation 4 directly and in the Cd' term.

Step 6 Yd_1 is used in Equation 2 to obtain t_1.

Step 7 Y_1 is obtained by using Yd_1 and m in Equation 3.

Step 8 δV_1 is obtained by using Y_1 and t_1 in Equation 1 and using Lfa = k x Va_1 if $Va_1 \leq Vs$ and Lfa = k x Vs if $Va_1 > Vs$.

Step 9 Make Va_2 (the second trial value of Va) equal to $V_t + \frac{\delta V_1}{2}$

Step 10 Repeat steps 4 to 8.

Step 11 If $\delta V_2 - \delta V_1 >$ accuracy required, then $Va_3 = V_t + \frac{\delta V_2}{2}$ and repeat steps 4 to 8.

Step 12 This process is continued until $\delta V_{(n+1)} - \delta V_n$. is sufficiently small to give the accuracy required. The final values of Y, Yd, t, Lfa, La, Vs, V_b and (Va - Vs) are then calculated.

6.1.2. The Calculation of the Physical Behaviour of a Stack of Laminae in a silo.

Provided that the values of the required parameters are specified for each lamina, the physical behaviour of the stack may be calculated by solving the equilibrium equation for each lamina in succession from the top downwards. The value of V_t for the top lamina is specified as 0 lb/ft^2 if the grass was just blown in or 50 lb/ft^2 if it was walked over thoroughly and sheeted. V_b from the first lamina becomes V_t for the next lamina and so on down the silo.

In the fixed time model, using the lamina equilibrium equation derived in the previous section, the parameters u', k, W, m, E, F and Cd may vary from lamina to lamina. Initially I have considered them all as constants in an example of a silo filled with material of uniform moisture content and maturity, before embarking on the analysis of the more complex fillings found in practice.

The accuracy of analysis improves with the reduction in thickness of the laminae. With computer calculation very thin laminae can be considered but in the examples that follow I have aimed at considering the silo as about 10 relatively thick laminae.

To illustrate the modelling technique for a silo filled with uniform material I have considered as Case A an 18'6"dia. silo, similar to that at Bridgets, filled with 80 tons dry matter at 75% moisture content. It has been divided into 10 laminae each of W = 17,920 lbs. dry matter.

The values of the parameters used in the calculation of Case A are as follows:

$D = 18.5$ ft.

Surface $V_t = 50$ lb/ft^2

$k = 0.5$

$u' = 0.7$

$W = 17,920$ lb.

$m = 75\%$

$E = 1.8$

$F = 6.5$

Cd' if $0 < Va < 500$, $Cd' = Va \times 10^{-3}$

if $500 < Va < 2500$, $Cd' = 0.375 + 0.25V \times 10^{-3}$

if $2500 < Va < 5000$, $Cd' = 1.0$

$T = 3160$ hours (130 days).

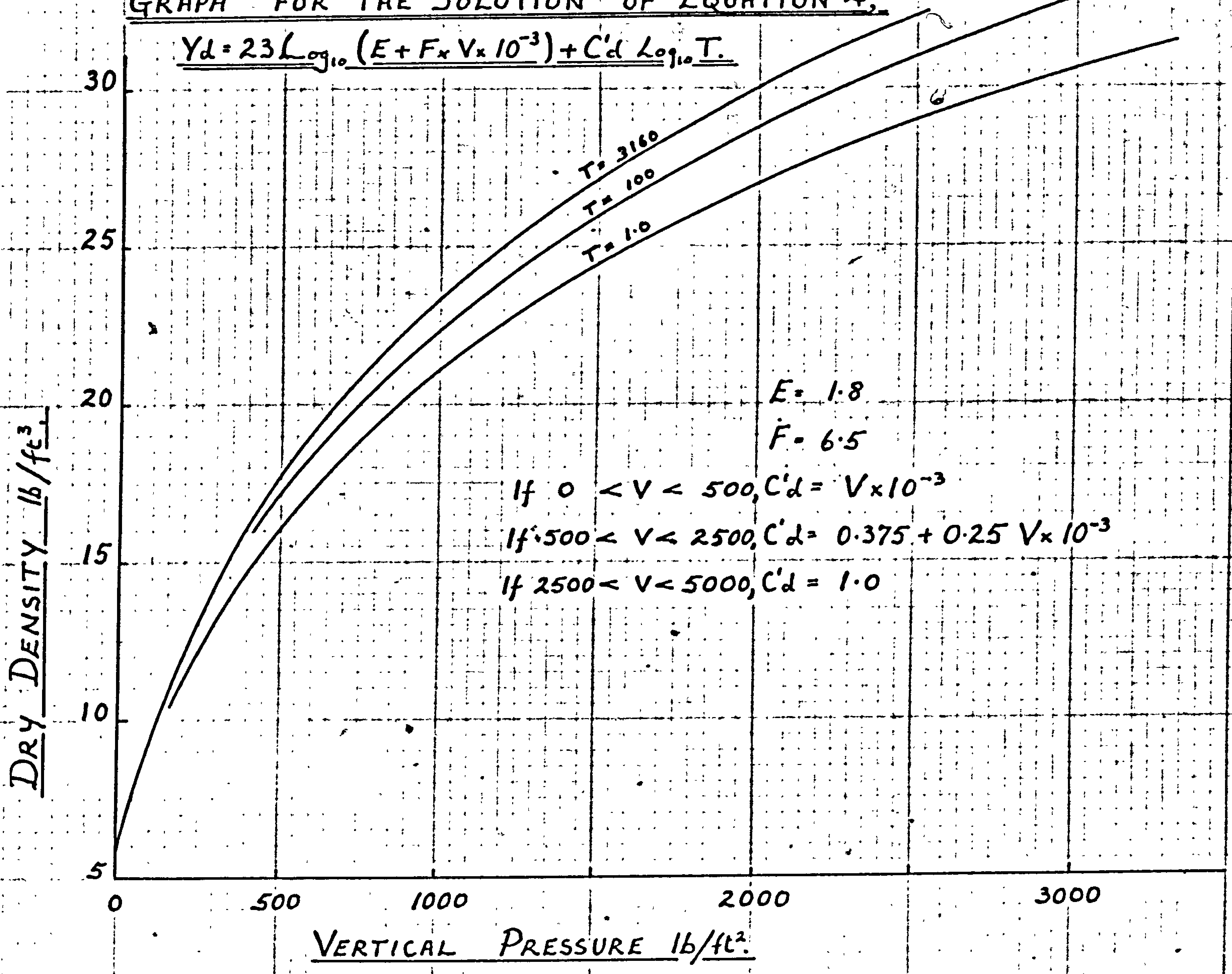
The value of Vs and the saturation value of Yd will be the same for all laminae in this uniformly filled silo.

For the solution of Equation 4 and 6 for all laminae Graph 6.1/1 of Yd against V has been drawn using values of

Graph 6,1/1

GRAPH FOR THE SOLUTION OF EQUATION 4,

$\gamma_d = 23 \log_{10}(E + F \times V \times 10^{-3}) + C'_d \log_{10} T.$



$E = 1.8$

$F = 6.5$

If $0 < V < 500$, $C'_d = V \times 10^{-3}$

If $500 < V < 2500$, $C'_d = 0.375 + 0.25\, V \times 10^{-3}$

If $2500 < V < 5000$, $C'_d = 1.0$

$E = 1.8$, $F = 6.5$ and $T = 3160$ hours in Equation 4. The curves for $T = 1.0$ and $T = 100$ hours are also shown.

Case A.

For all Laminae.

Step 1 Using Equation 5

$$\text{At saturation } Yd = \frac{100 - m}{100} (90 - 0.338\ m)$$

$$= \frac{25}{100} (90 - 25.4)$$

$$= 0.25 \times 64.6$$

at saturation $Yd = 16.15\ lb/ft^3$ $Y = 64.6\ lb/ft^3$.

Step 2 Solving Equation 6 using Graph 6.1/1.

$Vs = 400\ lb/ft^2$ at 3160 hours.

For Lamina 1:

Step 3 $Va_1 = V_t = 50\ lb/ft^2$

Step 4 $Va_1 < Vs$ so go to Step 5.

Step 5 Solving Equation 4 using Graph 6.1/1.

$Yd_1 = 7.6\ lb/ft^2$.

Step 6 $$t_1 = \frac{4W}{\pi D^2\ Yd_1} = \frac{4 \times 17920}{\pi \times 18.5^2 \times Yd_1}$$

$$= \frac{66.8}{Yd_1} = 8.8\ ft.$$

Step 7 $$Y_1 = \left\{\frac{100}{100 - m}\right\} Yd_1 = 30.4\ lb/ft^3$$

Step 8 $\delta V_1 = t\ (Y - \frac{4 Lfa \text{ x } u'}{D})$. As $Va_1 < Vs$, $Lfa = k \text{ x } Va_1$.

$$\delta V_1 = t\ (Y - \frac{4 \text{ x } 0.5\ Va_1 \text{ x } 0.7}{18.5}) = t\ (Y - 0.0757\ Va_1)$$

$$\delta V_1 = 8.8\ (30.4 - 0.0757 \text{ x } 50)$$

$$\delta V_1 = 268 - 33 = 235 \text{ lb/ft}^2$$

Step 9 $Va_2 = V_t + \frac{\delta V_1}{2} = 50 + \frac{235}{2}$

$= 167.5 \text{ lb/ft}^2$.

Step 10 go to Step 4. $Va_2 < Vs$ so go to Step 5.

Step 5 $Yd_2 = 11.2$ Step 6 $t_2 = 5.96$

Step 7 $Y_2 = 44.8$ Step 8 $\delta V_2 = 268 - 75.5$

$= 192.5$

Step 11 $\delta V_2 - \delta V_1 = 42.5$ Repeat from Step 4.

$Va_3 = 50 + \frac{192.5}{2} = 146 \text{ lb/ft}^2$

Step 5 $Yd_3 = 10.6$ Step 6 $t_3 = 6.3$

Step 7 $Y_3 = 42.4$ Step 8 $\delta V_3 = 268 - 69.5$

$= 198.5$

Step 11 $\delta V_3 - \delta V_2 = 6$ Repeat from Step 4.

$Va_4 = 50 + 99.25 = 149 \text{ lb/ft}^2$

Step 5 $Yd_4 = 10.7$ Step 6 $t_4 = 6.25$

Step 7 $Y_4 = 42.8$ Step 8 $\delta V_4 = 268 - 70.5$

$= 197.5$

Step 11 $\delta V_4 - \delta V_3 = 1$ go to Step 12.

Step 12 Final values for laminae 1 are:-

$Yd = 10.7$ lb/ft^3 $Y = 42.8$ lb/ft^3

$t = 6.25$ ft. $\delta V = 197.5$ lb/ft^2

$Va = 149$ lb/ft^2 $V_b = 247.5$ lb/ft^2

$Lfa = La = 75$ lb/ft^2.

For Lamina 2:

The step by step calculations gives:

$Yd = 14.7$ lb/ft^3 $Y = 58.8$ lb/ft^3

$t = 4.55$ ft. $\delta V = 155.5$ lb/ft^2

$Va = 325$ lb/ft^2 $V_b = 403$ lb/ft^2

$Lfa = La = 162.5$ lb/ft^2

For Lamina 3:

Step 3 $Va_1 = V_t = 403$ lb/ft^2

Step 4 $Va_1 > Vs$

$403 > 400$ so silage has reached saturation

$Yd = 16.15$

go to Step 6.

Step 6 $t_1 = 4.14$ Step 7 $Y = 64.6$

Step 8 $\delta V_1 = t\ (Y - \frac{4Lfa \times u'}{D})$

As $Va_1 > Vs$. $Lfa = kVs$

$\therefore \delta V_1 = 268 - 125.5 = 142.5$.

As the silage has reached saturation and become effectively incompressible the values of Yd, Y, t and δV have become constant and are independent of Va so no further iteration is necessary.

The values for lamina 3 are:

Yd = 16.15 lb/ft^3 Y = 64.6 lb/ft^3
t = 4.14 ft. δV = 142.5
Va = 474 lb/ft^2 V_b = 545.5
Lfa = kVs = 200 lb/ft^2 Va - Vs = 74 lb/ft^2
La = Lfa + (Va - Vs) = 274 lb/ft^2

As we are considering a silo filled with uniform material the equilibrium equations for Laminae 4 to 10 will be identical to that for Laminae 3 as with the silage saturated Yd, Y, t, δV and Lfa remain constant while Va, V_b, Va - Vs, and La increase linearly with increasing depth. The values for Laminae 4 - 10 are:

Yd = 16.15 lb/ft^3 Y = 64.6 lb/ft^3
t = 4.14 ft. δV = 142.5 lb/ft^2
Lfa = 200 lb/ft^2

and for Lamina n, where n is between 4 and 10

Va = 474 + 142.5 (n - 3) V_b = 545.5 + 142.5 (n - 3)
Va-Vs = 74 + 142.5 (n - 3) La = 274 + 142.5 (n - 3)

This rate of increase in Vertical Pressure (Va and V_b). Pore Pressure (Va - Vs) and Lateral Pressure (La) is at a rate of 34.5 lb/ft^2 per foot depth of silage. The remaining part of the silage weight 30.1 lb/ft^2 per ft. depth is carried by wall friction.

The full results for all 10 laminae in Case A are given in Table 6.1/1.

In this case high lateral pressures are exerted due to the build up in pore pressure in the saturated silage.

TABLE 6.1/1 Case A

Pressures and Densities in an 18'6" diameter silo filled at 75% m.c.

Calculated as 10 laminae of 8 tons d.m.: k = 0.5, u = 0.7, E = 1.8, F = 6.5, T = 3160.

Lamina	Density lb/ft^3		Depths ft.		Pressures lb/ft^2				
	Yd	Y	t	ha	δV	Va	Lfa	La	Va-Vs
1	10.7	42.8	6.25	3.1	197	149	75	75	0
2	14.7	58.8	4.55	8.5	156	325	162	162	0
3	16.15	64.6	4.14	12.9	142	474	200	274	74
4	15.15	64.6	4.14	17.0	142	616	200	416	216
5	16.15	64.6	4.14	21.1	142	759	200	559	359
6	16.15	64.6	4.14	25.3	142	901	200	701	501
7	16.15	64.6	4.14	29.4	142	1044	200	844	644
8	16.15	64.6	4.14	33.6	142	1186	200	986	786
9	16.15	64.6	4.14	37.7	142	1329	200	1129	929
10	16.15	64.6	4.14	41.8	142	1471	200	1271	1070

Vs = 400 lb/ft^2. Total depth for 80 tons d.m. 43.9 ft.

The dry density and hence the capacity of the silo is reduced as the saturation of the lower laminae prevents their dry density increasing above 16.15 lb/ft^2.

Next I have considered as Case B, the same silo filled with identical material under identical conditions but at a uniform moisture content of 50%.

Case B.

For all Laminae

Step 1 At saturation Yd $= \frac{50}{100}(90 - 16.9)$

$= 36.55$

At saturation Yd $=$ 36.55 lb/ft^3 Y = 73.1 lb/ft^3

Step 2 Vs $>$ 3000 lb/ft^2 so saturation cannot occur in the silo.

The iterative calculation of the equilibrium of each lamina has been carried out as for the last example, and the results for Case B are shown in Table 6.1/2.

In Case B a condition similar to that in grain silos occurs with the lateral and vertical pressures tending to a maximum value at which the wall friction totally supports the weight of each lamina, (i.e. $Y = \frac{4\ Lfa\ u'}{D}$).

Another feature of this filling is the low dry densities and densities, even at the bottom of the silo. Yd only reached 15.85 lb/ft^3 in the bottom lamina, this is only 43.5% of the saturation dry density. In the 75% m.c. filling Yd had reached 16.15 lb/ft^3, by the third lamina but could not increase because this wet silage had reached

TABLE 6.1/2. Case B

Pressures and Densities in an 18'6" diameter silo filled at 50% m.c.

Calculated as 10 laminae of 8 tons d.m.: $k = 0.5$, $u' = 0.7$, $\Xi = 1.8$, $F = 6.5$, $T = 3160$

	Densities lb/ft^3		Depth ft.		Pressures lb/ft^2				
Lamina	Yd	Y	t	ha	δV	Va	Lfa	La	Va-Vs
1	9.1	18.2	7.35	3.7	83	91	46	46	0
2	11.2	22.4	5.95	10.3	61	163	82	82	0
3	12.4	24.8	5.38	16.0	46	217	108	108	0
4	13.4	26.8	4.99	21.2	36	258	129	129	0
5	14.0	28.0	4.78	26.1	29	290	145	145	0
6	14.5	29.0	4.60	30.8	24	317	158	158	0
7	15.0	30.0	4.45	35.3	19	339	170	170	0
8	15.3	30.6	4.36	39.2	16	357	178	178	0
9	15.7	31.4	4.25	44.0	14	372	186	186	0
10	15.85	31.7	4.21	48.2	11	385	192	192	0

Total depth for 80 tons d.m. 50.3 ft.

saturation. The 80 tons dry matter of 75% m.c. fully settled only occupied 43.9 ft. compared with 50.3 ft. for the 50% m.c. material.

Between these two extremes of filling moisture content which I have chosen to illustrate the two types of pressure behaviour there is an optimum moisture content distribution which will produce silage just below saturation density in each lamina. In this way a high dry density is achieved without any build up of pore pressure (Va - Vs). As an example, Case C, of this optimum filling technique let us consider the same silo, filled as before, but we will determine, by iteration, for each layer the moisture content which will give a density of 90% of saturation density. The maximum moisture content we will set at 75% because of the practical problems of fermentation control above this.

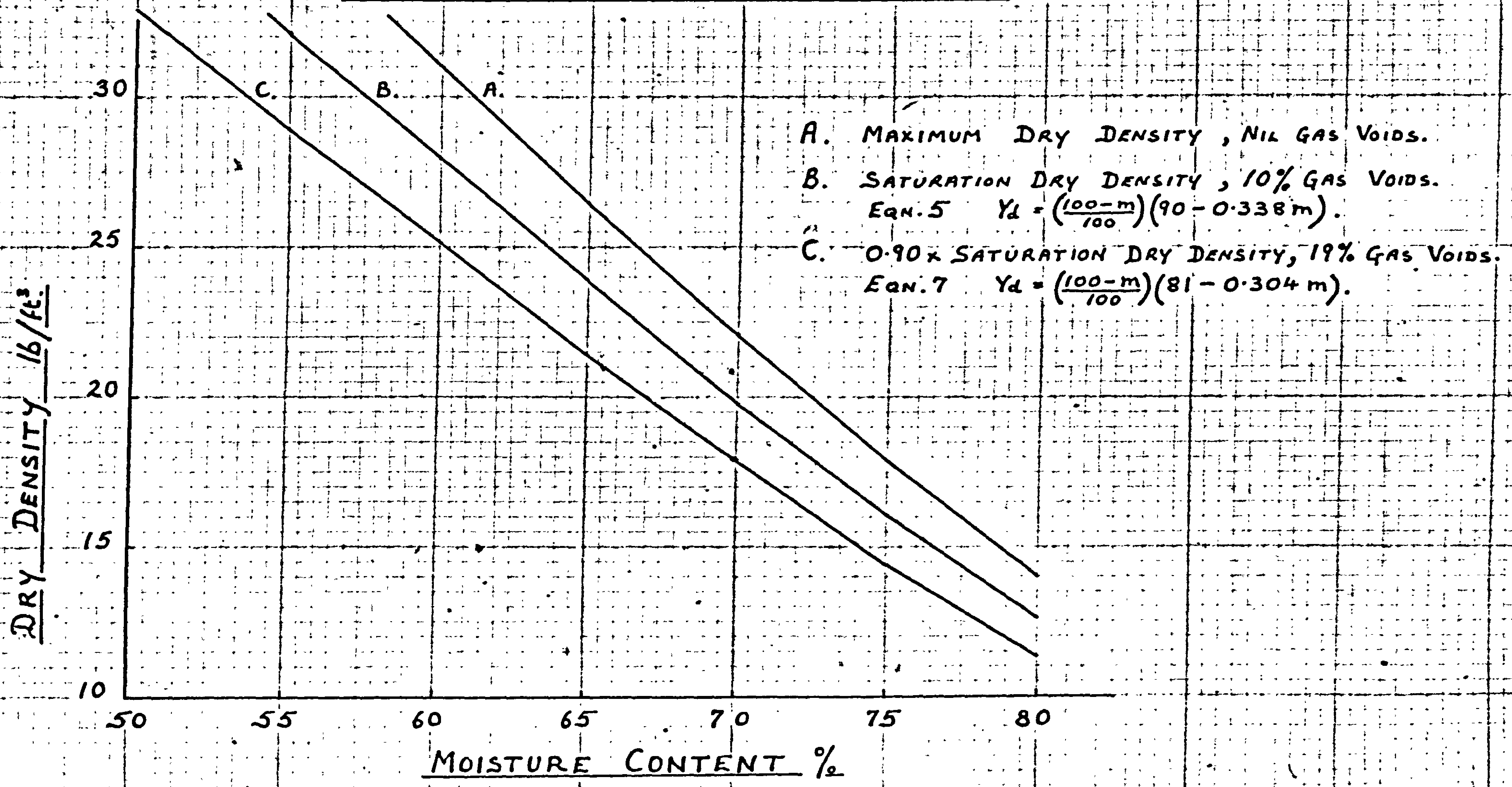
As the density will not exceed 90% saturation density we can dispense with Steps 1, 2 and 4 of the calculation routine. As m is unknown it must be determined before Step 7. The relationship between m and Yd at 90% saturation density is given by the following equation:-

$$\text{At } 90\% \text{ saturation } Yd = \frac{100 - m}{100}(81 - 0.304\ m) \qquad (7)$$

This may be solved using Graph 6.1/2 to determine the value of m_n from the value of Yd_n from Step 5 of the calculation routine on each cycle of iteration. This value of m_n is only used if it is less than 75%, because of the 75% maximum limit on m.

Graph 6.1/2

CALCULATED DRY DENSITY AGAINST MOISTURE CONTENT
FOR THE SOLUTION OF EQUATIONS 5 AND 7.



A. MAXIMUM DRY DENSITY, NIL GAS VOIDS.

B. SATURATION DRY DENSITY, 10% GAS VOIDS.
EQN. 5 $\gamma_d = \left(\frac{100-m}{100}\right)(90-0.338\,m)$.

C. 0.90 x SATURATION DRY DENSITY, 19% GAS VOIDS.
EQN. 7 $\gamma_d = \left(\frac{100-m}{100}\right)(81-0.304\,m)$.

For Lamina 1:

As for Lamina 1 of constant 75% m.c. case

Yd = 10.7 lb/ft^3 Y = 42.8 lb/ft^3
t = 6.25 ft. δV = 197.5 lb/ft^2
Va = 149 lb/ft^2 V_b = 247.5 lb/ft^2
m = 75%.

For Lamina 2:

Take values from Lamina 2 of constant 75% m.c. case as initial values.

Step 5 Yd = 14.7 Step 6 t = 4.55
m = 74.5 from Graph 6.1/2.
Step 7 Y = 57.6
Step 8 V = 4.55 (57.6 - 0.0757 x 325)
V = 150.

This compares with V = 155 at 75% m.c.

So final values are:

Yd = 14.7 lb/ft^3 Y = 57.6 lb/ft^3
t = 4.55 ft. δV = 150 lb/ft^2
Va = 322.5 lb/ft^2 V_b = 397.5 lb/ft^2
Lfa = La = 161 lb/ft^2
m = 74.5%

The values for Laminae 3 to 10 have to be calculated in a similar manner and the results are shown in Table 6.1/3.

The values of dry density (Yd) and density (Y) for all three cases have been plotted against silage depth in Graph 6.1/3 for comparison. The values of lateral

TABLE 6.1/3 Case C

Pressures, Densities and Moisture Contents in an 18'6" diameter silo filled to 90% Saturation Density.

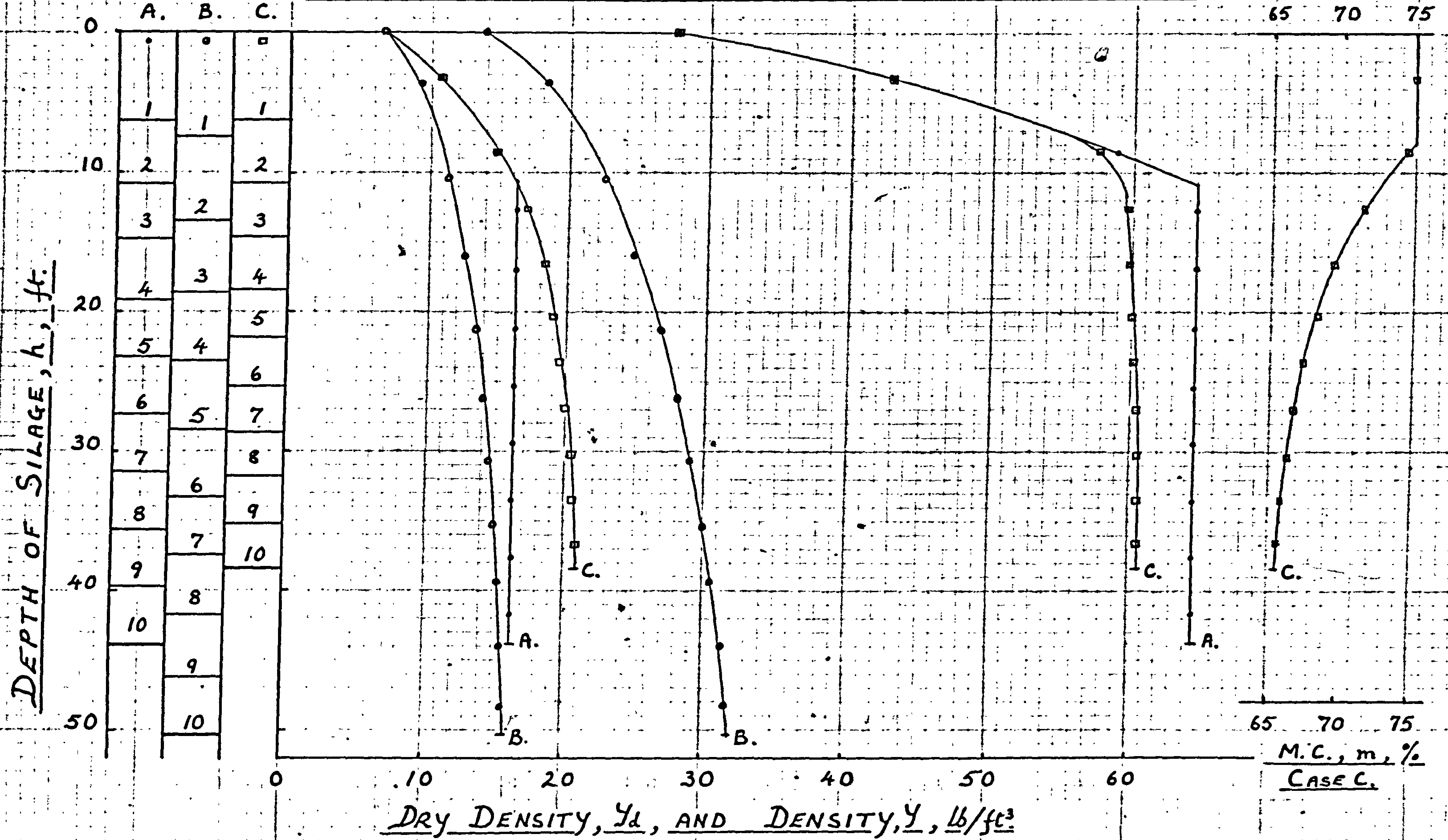
Calculated as 10 laminae of 8 tons d.m.; k = 0.5, u = 0.7, E = 1.8, F = 6.5, T = 3160

Lamina	Densities lb/ft^3		Depths ft.		Pressures lb/ft^2					m.c.%
	Yd	Y	t	ha	δV	Va	Lfa	La	Va-Vs	m
1	10.7	42.8	6.25	3.1	197	149	75	75	0	75.0
2	14.7	57.6	4.55	8.5	150	322	161	161	0	74.5
3	17.0	59.6	3.93	12.8	100	447	224	224	0	71.5
4	18.25	59.9	3.66	16.62	71	533	266	266	0	69.5
5	19.0	60.0	3.52	20.2	53	595	297	297	0	68.3
6	19.6	60.1	3.40	23.6	40	641	320	320	0	67.4
7	20.0	60.4	3.34	27.0	31	676	338	338	0	66.9
8	20.4	60.6	3.27	30.3	24	704	352	352	0	66.4
9	20.6	60.7	3.24	33.5	19	726	363	363	0	66.0
10	20.8	60.7	3.21	36.8	14	742	371	371	0	65.7

The total depth for 80 tons d.m. 38.4 ft.

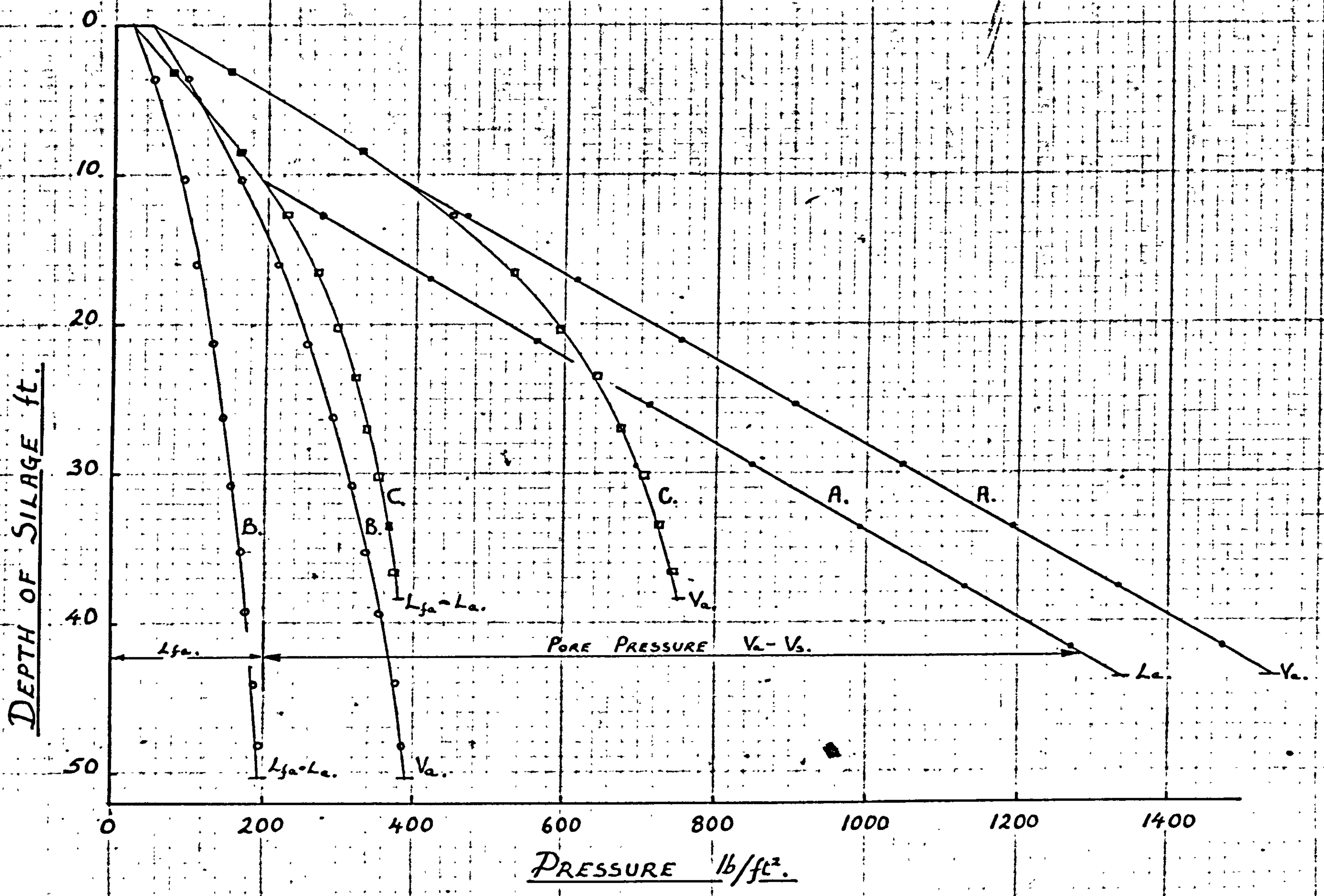
Graph 6.1/3

DENSITIES IN SILOS, FOR FILLING CASES A, B AND C.



Graph 6.1/4

Pressures in Silos, for Filling Cases A, B and C.



pressure (Lfa and La) and vertical pressure (Va) have been plotted against silage depth for all three cases on Graph 6.1/4.

The dry density in Case C was higher than in cases A and B. The effect of this on capacity can be shown in terms of settled depth of 80 tons d.m. which were:-

38.4 ft. in Case C at 90% saturation density.

43.9 ft. in Case A at 75% m.c.

50.3 ft. in Case B at 50% m.c.

If we consider the filling of an 18'6" diameter silo of height 42.5 ft. to allow for settlement to 38.4 ft. it would hold:-

80 tons d.m. in Case C at 90% saturation density

69.3 tons d.m. in Case A at 75% m.c.

58.5 tons d.m. in Case B at 50% m.c.

By filling at 66% rising to 75% m.c. to obtain 90% saturation density a 37% increase in capacity can be obtained compared with filling at 50% m.c.

The need for high densities to minimise the permeability and gas voids in the silage so as to avoid nutrient loss during storage in the silo has been discussed in previous chapters. Both Case A and C are satisfactory in this respect with densities of over 55 lb/ft^3 in all but the uppermost layers. In case B at 50% m.c. where the density rises slowly from about 20 lb/ft^3 to 32 lb/ft^3 at the very bottom, the silage is easily penetrated by air and is much more susceptible to dry matter losses in storage than the wetter silage.

The lateral pressures are by far the lowest in Case B at 50% m.c. reaching 170 lb/ft^3 with 30 ft. depth. Case C in which the silage is kept 10% below saturation density, to avoid the build up of pore pressure, the lateral pressures reached 370 lb/ft^2 at 35 feet depth. However, at 75% moisture content Case A, the lateral pressure reached 1040 lb/ft^3 at 35 ft. depth. These three examples have been chosen to illustrate the calculation technique, the two extreme conditions and the optimum filling condition in one particular silo filled in a particular manner. These calculated results will be compared with experimental results obtained in the field in Section 6.2.

These examples have been used to illustrate the calculation method and cannot be applied to the field situations where different values of any of the parameters are applicable. In particular the values of k and u' used in these examples seem from the results of Section 6.2. to be considerably higher than those found in the field.

6.1.3. The Influence of Each Parameter on the Densities, and Pressures in a Uniformly Filled Silo, Calculated using the Finite Lamina Method.

6.1.3.1. Introduction. In the previous Section I have considered a lamina stack in two cases in which all the parameters have been held constant for the whole silo, and one case in which moisture content was adjusted in each lamina to give a maximum density of 90% saturation in all laminae. In this Section we will consider the effect of varying the paramoters, but keeping them constant for all laminae, on the pressures and densities in the whole silo.

In the last section three clear types of filling behaviour were demonstrated:-

Type A. The silage reaches saturation and thereafter Yd, Y, t and Lfa remain constant while Va, Va - Vs and La increase linearly with depth at a rate dependant on the difference between

$$Y \text{ and } \frac{4k \times Vs \times u'}{D} \qquad \text{(from Equation (1))}$$

This condition gives very high lateral pressures (mostly due to pore pressure), a high density and a reduced dry density.

Type B. The silage tends to a constant level of Yd, Y, t, Lfa, La, Va, where Va > Vs and Lfa = La. This is reached when $\delta V = 0$; i.e. weight of each lamina is totally supported by the frictional force on the lamina. That is:-

$$t \times Y = \frac{t \times 4k \times Va \times u'}{D}$$

$$\text{or } Y = \frac{4k \times Va \times u'}{D} \qquad \text{(from Equation (1))}$$

This condition gives a low density and dry density and low lateral pressures.

Type C. The silage in each lamina is maintained at the moisture content which gives 90% saturation density. This optimum filling gives near maximum dry density, high densities, moderate lateral pressures and a margin of safety against the build up of pore pressure.

We will consider the effect of varying the parameters on these three types of behaviour.

6.1.3.2. Diameter D. The diameter of the silo does not directly effect the density and moisture content. (Equations 3, 4, 5, 6 and 7). Its influence in Equation 2 only effects the thickness of the lamina under consideration which should not significantly influence the results. In Equation 1, which determines the rate of increase in pore pressure in Type A and the maximum density in the Type B situation, D has a significant effect on the value of the $\frac{4Lfa \times u'}{D}$ term. The greater the silo diameter the less the wall friction per unit area and vice versa.

In the Type A situation an increase in diameter will (all other parameters remaining constant) increase all pressures in three ways.

1. Above the saturation level the rate of increase in vertical pressure (δV) will be higher.
2. The saturation vertical pressure will be reached at a shallower depth.
3. The rate of increase in pore pressure (δV) below the saturation level will be increased (e.g. In Case A with 18'6" dia. silo $\frac{\delta V}{t}$ = 34.5 lb/ft^2/ft, but for a 24' dia. silo $\frac{\delta V}{t}$ = 41.3 lb/ft^2/ft).

The dry density and density remain limited by saturation in the lower part of the silo and are only fractionally increased above the saturation level.

In a Type B situation an increase in diameter will make δV larger for each lamina. This will increase the pressure on the next lamina which will increase the Y term in Equation 1 in addition to the direct effect of D on the $\frac{4Lfa \times u'}{D}$ term. These two effects will increase the rate at which pressures and densities increase and the limiting values which are reached when $Y = \frac{4k \times Va \times u'}{D}$. In a marginal case it would turn a Type B case into a Type A case where the increase in vertical pressure took it to above Vs.

The Type C condition will be effected by increased diameter in the same way as the Type B case. To keep the density down to 90% saturation the moisture content would have to be lowered. The dry density would be increased by this and the density fractionally increased. The pressures would increase slightly but by lowering the moisture content pore pressures would still be avoided.

To summarise, increased diameter increases pressures and, except in Type A situation, increases the dry density in the silo. Lower filling moisture contents are required to maintain the Type C condition of 90% saturation density.

6.1.3.3. <u>Ratio of Lateral to Vertical Pressure, k and Coefficient of Wall Friction u'</u>. The effect of changes in k and u' on the pressures and densities is identical as they both appear on the top line of the expression $\frac{4Lfa \times u'}{D}$ in Equation 1. k is contained in the Lfa term which is:-

Lfa = k x Va below saturation.

Lfa = k x Vs above saturation.

The effect of k and u' will be the inverse of that of D so on the same basis as the previous Section on D we can write:-

Decreased values of k or u' will increase vertical pressures and (except in the Type A situation) increase dry density in the silo. Lower moisture contents will be required to maintain the Type C condition of 90% saturation density. A reduction in k will also decrease the values of Lfa and La directly in addition to its effect on Va, when it is below Vs.

6.1.3.4. <u>Moisture Content, m.</u> Cases A, B and C have partially illustrated the effect of moisture content on densities and pressures. The major effects come from:-

Y in Equation 1 which is calculated from Equation 3.

$$Y = Yd \left\{\frac{100}{100 - m}\right\}$$

Vs which is influenced by m in Equation 6.

In the Type A situation an increase in m will increase pressures by increasing δV in the top laminae due to the higher value of Y in Equation 1. Vs will be lower and the rate of increase in pressure thereafter will be at a rate

$$\delta V = t \left(Y - \frac{4kVs\ u'}{D}\right)$$

The Y term (the saturation density) falls very slightly with increasing m, but Vs term will be markedly reduced with an increase in m, so the net effect is an increase in δV with increasing m. For example, with conditions as in Case A:

m %	Y lb/ft^3	Yd lb/ft^3	Vs lb/ft^2	$\frac{\delta V}{t}$ $lb/ft^2/ft$
75	64.6	16.1	400	34.5
78	63.6	14.0	285	42.0
81	62.6	12.0	200	47.4

For the 6% increase in m from 75% to 81% the depth at which saturation takes place, rises from 10.5 ft. to 4.5 ft. and the lateral pressure at 45 depth increases 46% from 1390 lb/ft^2 to 2020 lb/ft^2 while the dry density in the saturated silage is reduced by 25% from 16.1 lb/ft^3 to 12.0 lb/ft^3.

In the Type B situation an increase in moisture content increases density directly in each lamina as

$$Y = \left\{\frac{100}{100 - m}\right\} Yd$$

It will also increase the density and dry density of the lower laminae by increasing the vertical pressure on them. This is because δV is increased by the increase in the Y term with increasing moisture content. The increase in δV increases Va, Lfa and La. These effects continue until Vs is reached and the Type A condition prevails.

Moisture content has an indirect effect on the other parameters particularly if the m falls below 40% into the hay range in which u' falls, F falls, Cd' falls and k possibly falls. However, within the silage range with m between 50% and 80% u', F and Cd' are reasonably constant, and k is possibly constant. Further data on this, particularly for k, is urgently required.

6.1.3.5. E and F, Constants in Density Equation. The effects on these two constants are similar in type but not degree, as they, together determine the relationship between vertical pressure and dry density in Equations 4 and 6.

E is relatively constant and is only influenced to any marked degree by a finer chop, which increases it. Its main influence is on the dry density and density of the top laminae and its influence declines as Va increases, so except at high moisture content the influece of a change in E on Vs is slight.

F normally lies in the range 1.8 - 6.5 and is very sensitive to changes in the maturity of the crop. It falls with increasing maturity. Except in the top laminae F has the dominent effect on Yd.

In Cases A, B and C, F was set at a high value. A lower value of F or to a lesser extent a lower value of E will have three main direct effects.

1. The value of Vs required to compress the samples to saturation will be increased.
2. The value of Yd and Y at any level of V will be reduced.
3. The δV will be reduced because in Equation 1 the value of Y will be lower for any given value of Va.

All these effects will reduce the density and dry density, the lateral and vertical pressures, and the possibility of pore pressures developing. For the type C condition m will have to be increased to maintain Y at 90% saturation as E and F are reduced.

6.1.3.6. Cd' and T, the Time Effect on Density. The density and dry density both increase with increasing time T and the rate Cd' is a function of V. An increase in T or Cd' will have the same effect on density and dry density as an increase in F. So on the same basis as in the previous section we can say that an increase in Cd', or the time T for which the silage has been settling, will increase the density and dry density, lateral and vertical pressures and the possibility of pore pressures developing.

The longer the period of storage T and the higher the value of Cd' the lower must m be to maintain Y at 90% saturation.

6.1.4. The Effects of Variation in the Values of Parameters from Lamina to Lamina.

The simple conditions we have been considering in the previous sections, in which the parameters remain constant for the whole filling, are rarely encountered in practice. Graphs 1.4/1 and 2 and 1.5/1 of the fillings of Glantlees and Bridgets show the wide range and almost random pattern of variation of moisture content and maturity encountered in practice.

Provided the values of the parameters are specified for each lamina the pressures and densities can be calculated using the methods described in the previous section.

In practice the most important variations in parameters from lamina to lamina are in the moisture content, m, and the maturity dependant constant, F. The other parameters may vary slightly but our knowledge is not, as yet, sufficiently refined to quantify these variations.

The random variations in m and F can produce very wide fluctuations in density and lateral pressure with depth. To illustrate this I have recalculated the densities and pressures for laminae 7 - 10 of Case C for different moisture contents and maturities. The average moisture content for the whole silo has not been significantly changed but laminae 7 and 8 are now 75% m.c. while laminae 9 and 10 are 50% m.c. Laminae 8 and 9 have been considered as average maturity grass (F = 3.7) in contrast with the young grass (F = 6.5) in all other laminae.

The values of densities and pressures for laminae 5 - 10 are given in Table 6.1/4 and plotted for comparison with Case C in Graph 6.1/5. The uniform pattern of steadily increasing Yd, Y, L and V found in Case C (shown as a dashed line) is completely disrupted. Despite the fact that the average m.c. is virtually unchanged the lateral pressure is increased to 605 lb/ft^2 at the bottom of lamina 7 and 545 lb/ft^2 at the bottom of lamina 8 compared with a maximum of 375 lb/ft^2 in Case C. This is due to the saturation of laminae 7 and 8 with the development of pore pressures. The more mature crop in lamina 8 had a Vs of 650 lb. which reduces the pore pressure and total pressure compared with the younger material in lamina 7.

The reduction in wall friction in the saturated laminae 7 and 8 and their slightly higher density causes a faster

TABLE 6.14

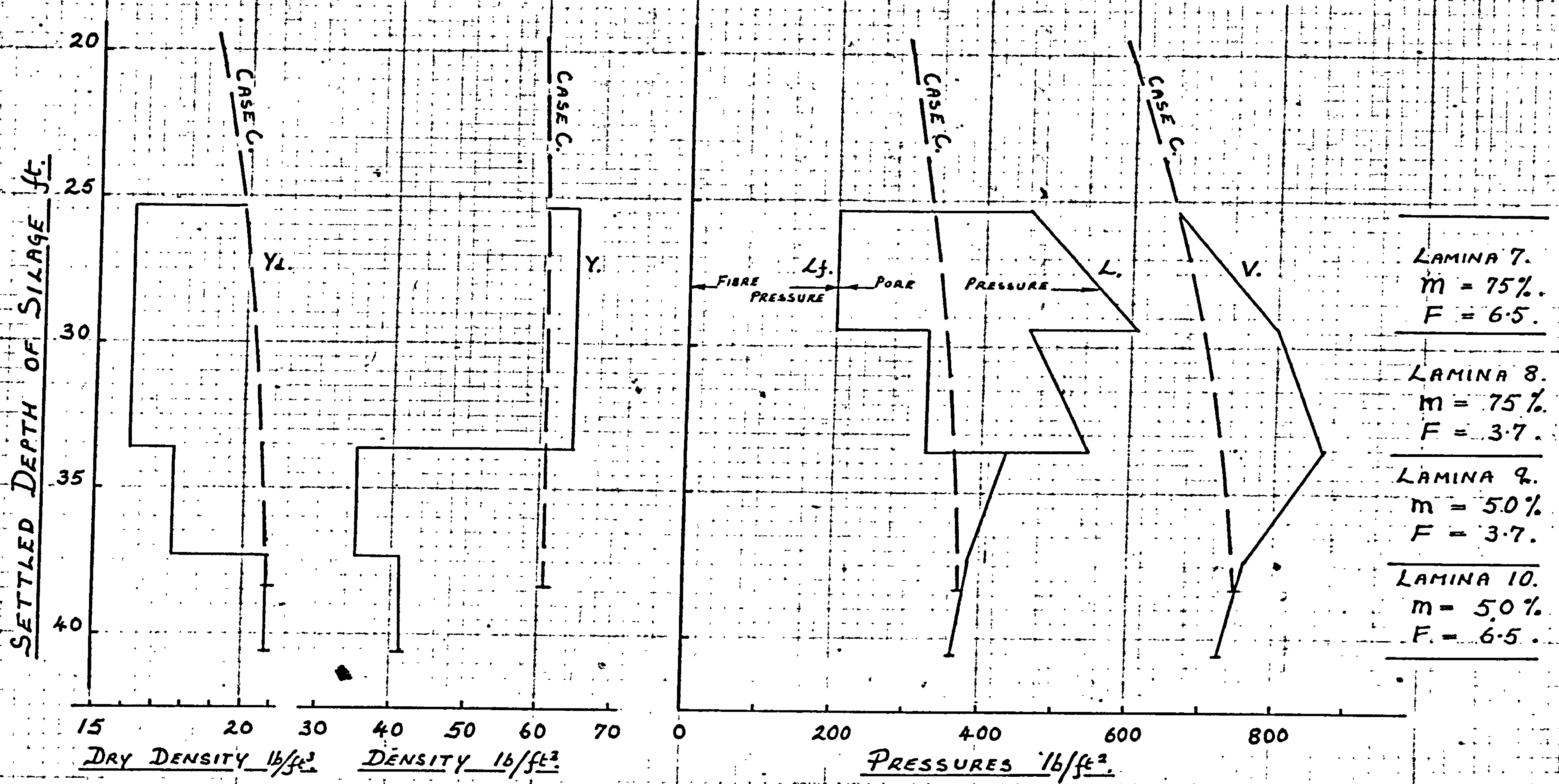
Pressures and Densities in an 18'6" diameter silo filled as Case C for Laminae 1 - 6

Moisture Content and Maturity Varied in Laminae 7 - 10

Lamina	Parameters		Densities lb/ft^3		Depths ft.			Pressures lb/ft^2			
	m%	F	Yd	Y	t	ha	δV	Va	Lfa	La	Va-Vs
5	68.3	6.5	19.0	60.0	3.52	20.2	53	595	297	297	0
6	67.4	6.5	19.6	60.1	3.40	23.6	40	641	320	320	0
7	75	6.5	16.15	64.6	4.14	27.4	142	732	200	532	332
8	75	3.7	16.15	64.6	4.14	31.5	64	835	325	510	185
9	50	3.7	17.6	35.2	3.80	35.5	-100	817	408	408	0
10	50	6.5	20.7	41.2	3.24	39.0	-48	743	371	371	0

Graph 6.1/5

THE EFFECT ON DENSITIES AND PRESSURES OF VARYING m AND F, IN LAMINAE 7–10 OF CASE C.



increase in vertical pressure than in Case C. In laminae 9 and 10 in which the lower m.c. reduces density and in which the wall friction is higher than in Case C, the vertical falls with depth. The limiting effect of saturation on dry density in laminae 7 and 8 and the reduction in dry density due to the increased maturity in lamina 9 (which is partly offset by the higher vertical pressure on this lamina) together increase the total depth required for 80 tons d.m. to 40.6 ft. (38.4 ft. for Case C).

This example has shown how variations in moisture content and maturity between laminae can cause pressures and densities to vary widely up and down with increasing depth. It explains the pressure and density variations with depth that have confused many research workers. The fact that the variations shown in this example were obtained without altering the average moisture content from that in Case C, makes clear why attempts by American workers to correlate lateral pressures and silo capacities with average moisture contents in the silo have not been successful.

6.1.5. Calculation of the Variation in Densities and Pressures with Time during Filling and Storage.

So far the densities and pressures have been calculated on the assumption that all the material in each lamina had been subject to a steady vertical pressure, Va, for a uniform time T. While this is adequate for calculating the behaviour of the silage after a long storage period a slightly different approach is needed for calculating the behaviour during filling and the first weeks of the storage period.

The pressures and densities are calculated for the whole silo at the end of each of a finite number of time periods, (e.g. every 24 hours during filling, every week during storage). All additional material placed in the silo is assumed to be added at the first instant of a time period.

Two refinements must be made to the method of determining the dry density and its rate of increase with time. Equation 4 stated that:

$$Yd = 23 \text{ Log}_{10} (E + F \times Va \times 10^{-3}) + Cd' \text{ Log}_{10} T.$$

where T is the time from the application of pressure Va. This, as has been explained in Section 5.5.6. only holds true for the virgin consolidation of a fully fermented silage. If the silage has reached (due to the application of a slightly lower pressure for a period of time) a dry density, before the vertical pressure Va was applied, which would have taken T_1 hours to reach on the virgin consolidation curve for pressure Va, then the subsequent consolidation gives a dry density which can be determined by Equation 4a.

$$Yd = 23 \text{ Log}_{10} (E + F \times V \times 10^{-3}) + Cd' \text{ Log}_{10}(T + T_1) \quad (4a)$$

So before calculating the value of Yd at the end of any time period the value of Yd at the beginning of that period (i.e. at end of previous period) must be used to calculate T_1.

In the earliest stages of ensiling, particularly with unwilted or slightly wilted grass, the dry density will be lower than that given by Equation 4, because of the strength due to osmotic pressure in the cells. Once the pH falls below 4.25 (this takes between 1 and 10 days) Equation 4 holds true. This effect can be ignored unless a particular study of the initial consolidation of grass is being made. In a detailed study of initial consolidation E and F can be considered as a function of elapsed time from ensiling and the rate of fermentation.

6.1.6. The Equilibrium of Laminae during Top Unloading.

During top unloading the vertical pressure on any lamina falls as the superimposed load is removed. When the pressure falls the silage starts to expand as described in Section 5.5.14. The re-expansion of the silage is resisted by the wall friction force which is reversed, and tends to put the silo wall into tension.

In the work on density reported in this thesis I have made no detailed study of the form of the pressure density relationship during re-expansion. However, further tests I made following the occurance of a series of tensile failures of concrete silo walls, described in (139) and (140), showed that significant re-expansion starts when the vertical pressure on the fibres (Va) has fallen to approximately 75% of the maximum vertical fibre pressure.

We can divide the silo into two zones.

Zone 1. This includes all the re-expanding silage and the frictional force on any lamina will be tending to resist re-expansion. Thus in Equation 1 Lfa is negative and so the $\frac{\delta V}{t}$ will be equal to the sum of the density, Y, and the frictional force per unit area of lamina, $\frac{4Lfa \times u'}{D}$, instead of the difference as in the filling and storage situation. As Va falls Lfa remains constant until Lfa = $\frac{V}{k'}$ i.e. there is a change from an active pressure condition to a passive pressure condition. The exact relationship between Yd and V for a falling V requires defining, as that the pressures and densities can be calculated using the same technique as for the filling case.

Zone 2. This includes all the laminae where Va remains greater than 75% maximum fibre vertical pressure. The pressures and densities in this zone can only be calculated when more data is available on the depth of the transition zone between the re-expanding silage and the still settling silage. However, the pressures and densities will be equal to or less than those calculated for these lamina on the basis that the silage had not yet been unloaded (i.e. assuming an extension of storage period).

Until more precise data on the pressure density relationship is available an exact analysis cannot be carried out but a simpler analysis in which Zone 1 is considered as a single thick lamina is useful.

In its simplest form the calculation is as follows: If we consider the bottom four laminae (7-10) of the 18'6" dia. silo in Case C then at the start of unloading the average values of

V, Lfa and Y can be taken as approximately:

$V = 730 \text{ lb/ft}^2$

$Lfa = 365 \text{ lb/ft}^2$

$Y = 60.5 \text{ lb/ft}^2$

Now using Equation 1 to obtain the equilibrium of Zone 1.

$$\delta V = 0.75 \times 730 \text{ lb/ft}^2$$

$$Lfa = \text{say } 300 \text{ lb/ft}^2 \text{ (allowing for fall in top 2 feet)}$$

$$Y = \text{say } 58 \text{ lb/ft}^3 \text{ (allowing for slight expansion)}$$

So

$$0.75 \times 730 = t\left(58 + \frac{4 \times 300 \times 0.7}{18.5}\right)$$

$$t = 5.3 \text{ ft.}$$

So the maximum total upward force per ft. run of circumference due to the re-expanding silage is t x Lfa = 1590 lb/ft.

A more detailed analysis of the re-expansion effect shows that the maximum upward friction force on the silo wall increases as the square of the diameter and so particular attention must be paid to this when silo diameters are increased.

6.1.7. The Equilibrium of Laminae during Bottom Unloading.

In dealing with top unloading uniform removal of the top surface can be assumed in all cases. With bottom unloading the removal of material is not necessarily uniform.

The effect of uniform unloading from the bottom of a silo is to reduce the vertical pressure on the bottom face to zero. The silage then expands and/or slides down in the silo to fill the gap left by the material removed until equilibrium is re-established. It is possible to calculate pressures and densities during uniform bottom unloading by considering the equilibrium of laminae from both ends of the silo. Generally pressures will be reduced during uniform bottom unloading except the total load taken by the silo wall which can be slightly increased.

The effects of uneven bottom unloading (as in the Simplex Hoy Silo) on pressures and densities is too complex for accurate solution with available information, particularly as it must also be considered in conjunction with the effects of uneven filling. However the data and methods outlined in this thesis will enable reasonable estimates to be made of the likely behaviour of the silage and the eccentricities in the pressure distribution that can develop in field.

6.1.8. The Refinement of the Model to allow for the Drainage of Effluent.

In previous sections each lamina has been considered to be isolated from its neighbours except for the vertical pressures at the interfaces. When a pore pressure develops in one lamina there will be a tendancy for the moisture in the silage to flow vertically into adjacent laminae with lower pore pressure, or horizontally out through leaks in the silo wall, or to drain into unloading flues.

The effluent is a combination of water, fermentation products and suspended solids. As it drains out of a lamina it will reduce both the weight of moisture and the weight of dry matter in that lamina, but the net effect will be to reduce the percentage moisture content m. This will increase Vs and the density will remain at the saturation level while the dry density rises. The pore pressure (V - Vs) will fall.

The rate of migration of effluent is governed by Darcy's Law, i.e. it is proportional to the pore pressure gradient x the permeability of the silage. The model already gives details of the pore pressure gradients within the silage. There is no published data on the permeability of silage to liquids but it would seem reasonable to assume that the resistance to flow is a function of dry density and is higher normal to the plane of grass fibre laminae than within that plane. From observation of the amount of moisture migration in silos it appears that this resistance to flow is high.

With the availability of data on the permeability of silage and the silo wall, the iterative technique for calculating pressures and densities can be elaborated to cover the drainage of effluent.

As pore pressures are only developed when laminae become saturated the drainage of effluent need not be considered in circumstances (such as Cases B and C) in which no pore pressures are developed and the moisture is retained in the silage by capilarity. In Case A when very high pore pressures were developed there would have been a downward flow of effluent because pore pressure gradient is less than the hydrostatic gradient. This would tend to cause a slow increase in pore pressure in the lower part of the silo and a reduction of pore pressure (with suction developing) in the upper saturated laminae. In cases, such as that considered in Section 6.1.4., in which dry, low density laminae are adjacent to saturated laminae with pore pressures the drainage into the drier laminae will result in a fall in the peak pore pressures.

When very thin laminae (i.e. less than 3" thick in settled silage) of alternate wet and dry material are placed in the silo it is unlikely that significant pore pressures will develop in the wetter laminae until the dryer laminae are approaching saturation. Some further work is required on the effect on the pressure density relationship of adding moisture to silage. Except with very dry material (less than 25% m.c.) there does not seem to be any reason to expect swelling of the type that occurs with grain. A check on this is required for the calculation of the pressures developed when large quantities of water are used to fight fires in tower silos as well as for the case of alternate wet and dry laminae.

When the silo wall is permeable (e.g. concrete stave silos when the pressure in the silo reaches a level at which the joints open and to a lesser extent bolted steel plate silos which leak at strained joints at high pore pressures) there can be a partial or complete relief of the pore pressures adjacent to the silo wall with a consequent reduction in total lateral pressure. This venting action is an important safety mechanism in the design of stave silos.

6.1.9. The Effect of Uneven Distribution during Filling on the Uniformity of Laminae.

In developing the mathematical model, laminae have been considered to start and remain plane horizontal laminae of uniform thickness, density and quality. Those conditions are most nearly met in the Big Jim type installation (like that at Glantlees) in which the grass is spread out in uniform laminae during filling. Observations of fibre orientation during unloading have indicated that these laminae tend to become slightly turned up around the edges but otherwise remain plane and horizontal. But even with this filling method there is a variation in vertical pressure (and consequently dry density) between the centre of the silo and the silo wall.

Three other types of initial distribution are encountered in practice and these may be modified by hand spreading. They are:-

1. Central filling. In which the blower pipe discharges centrally and vertically and the crop tends to form a high pile in the centre of the silo from which the grass has to be spread out by hand. This method of filling tends to give a dense core with looser material round the silo wall. The variation of density tends to be symmetrical about the silo axis. The variation in density from centre to the wall depends on the frequency with which levelling is carried out.
2. Automatic distribution. In which a rotating board or an articulated spout is used to spread the crop out towards the silo wall. This tends to pile the material highest in a ring round the wall from where it tumbles into the centre.

Some times some hand spreading is carried out to even out the surface by filling the central hollow. Again the density variation is symmetrical about the silo axis but in this case densities are highest near the wall and lowest in the centre.

3. Unsymmetrical distribution. This includes all other cases for example:
   (a) when the silage is blown in from by the eaves diagonally across to the opposite wall at the base of the silo; this forms a dense diagonal column in the silo.
   (b) when an automatic distributor malfunctions and the crop is spread predominately in one part of the silo.
   (c) when the crop is filled centrally but not evenly distributed out.

The full analysis of these non uniform laminae becomes highly complex. For the symmetrical cases the lamina can be divided into a number of concentric rings of uniform material while the non symmetrical case requires these rings to be further subdivided into elements. The equilibrium of each element or ring can be determined from an analysis of the forces on the element. This requires a knowledge of the shear displacement characteristics of the silage mass which is not yet available.

Without getting involved in the full analysis there is one useful adaptation of the step by step calculation method which enables the case of non uniform but symmetrical distribution to be calculated more accurately than in the uniform lamina analysis.

The laminae are assumed to remain plane but the dry density within the lamina varies radially according to the distribution. The vertical pressure will vary radially according to the dry density from a maximum in the densest areas to a minimum in looser material. In this approximate analysis we can assume that, provided that none of the silage has reached saturation, the average dry density is that due to the average vertical pressure determined according to Equation 4.

If saturation occurs in the high density area this will become saturated and incompressible and the proportion of the vertical load on this saturated area will increase as the other areas tend to continue to settle, which make the laminae non-planer. This will cause the moisture to flow slowly into the less dense areas until eventually the whole lamina becomes saturated as a result of moisture migration and additional consolidation.

If we know the initial radial distribution of dry density in a lamina which remains plane and assume that the average dry density in that lamina is determined by the average vertical pressure on it in accordance with Equation 4 then we can calculate the radial variation in dry density in the lamina. By substituting values from this radial dry density distribution in Equation 4, we can calculate the vertical pressure distribution across the lamina. The two important values of vertical pressure are the maximum (Vm) and the value at the wall, (Vw) and we can express them as functions of the average vertical pressure Va. So that

$$Vm = fm \times Va$$

$$Vw = fw \times Va.$$

Provided that none of the silage is saturated (i.e. ($Vm = fm \times Va < Vs$) then the only alteration to the calculation method is that $Lfa = k \times Vw = k \times fw \times Va$.

So fw will have a similar influence on the pressures and densities in a silo as k and u'. Provided the silage remains unsaturated, central distribution will reduce lateral pressures and the wall friction at any level. In consequence, when compared with uniform laminae, the average vertical pressure and dry density will reach a higher value before the equilibrium between lamina weight and wall friction is reached. The converse applies, with automatic distribution round the silo wall, the lateral pressure at any level is increased and the average vertical pressures and dry densities are reduced compared with uniform distribution.

When saturation starts to occur in the maximum density area (which may be at the centre of the silo or the wall), the position becomes much more complex as the lamina is distorted and much depends on the permeability of the silage to the effluent.

The relative effects of central filling and filling to the wall compared with uniform laminae are not easily established for partially or fully saturated laminae without detail investigation, as they depend on the balance of the following factors:-

(1) The change in the average vertical pressure with depth which is influenced by wall friction.

(2) The ratio of average vertical pressure, Va, vertical pressure at the wall, Vw.

(3) The permeability of the silage and the time available for pore pressures to have been relieved by drainage within the layer.

For central filling the increase in Va due to lower wall friction is offset by the Vw being less than Va.

6.1.10. The Effect of Ensilage Losses on the Calculation of Pressures and Densities in Silos.

As a lamina of grass ensiles into silage complex changes take place. These changes have been described in detail in previous chapters. Normally between 5% and 20% (exceptionally over 50%) of the original dry matter is converted into acids, gasses and water. These respiration and fermentation changes are usually substantially complete within a few days of a lamina being placed in the silo.

For most cases these changes can be allowed for by calculating the dry matter weight (w) and the moisture content (m) of each lamina of silage from the initial dry matter weight and moisture content of the grass as filled and estimates of the losses likely to occur.

For example, a lamina of grass at 70% m.c. with an initial dry matter weight of 10,000 lb. with assumed losses of 10% dry matter (oven dry basis) and 2% loss of total weight as gas. The drainage losses of effluent are considered separately as described in Section 6.1.8.

	Grass	Silage
Wt. of d.m. in lamina	10,000 lb.	9,000 lb.
Total wt. of lamina	33,333 lb.	32,600 lb.
Wt. of moisture in lamina	23,333 lb.	23,600 lb.
% moisture content	70%	72.4%

The moisture content (m), the dry matter weight (w) and the dry density (Yd) used for the calculation of densities and pressures are all based on oven drying for 24 hours. Using this method 'moisture' is water plus some volatile acids and 'dry matter' is the residue. For more precise work involving losses of dry matter, the true dry matter content (obtained by toluene distillation) should be used.

For a detailed analysis of the densities, pressures and losses in the upper laminae during filling, the whole relationship between the ensilage process, the dry matter loss and the pressure density relationship would have to be studied in more detail. With quantitative data on the inter-relation of these factors the finite lamina method I have outlined can be developed to enable the whole ensilage process to be simulated.

6.2. COMPARISON OF THE AUTHOR'S CALCULATION METHOD WITH FIELD RESULTS AND PUBLISHED EQUATIONS.

6.2.1. Introduction.

The full check on the validity of the method of calculation proposed in the first part of this chapter requires further research on the values of the parameters and a detailed and accurate record of the operation of fully instrumented silos as recommended in Section 2.2.8. Even in its simple thick lamina form using approximate and assumed values for some of the parameters, the calculation method predicts pressures and densities very similar to those recorded in my own field work and the published work of others. In this section I give examples of those comparisons and examine briefly and critically the differences between my calculation method and those currently used.

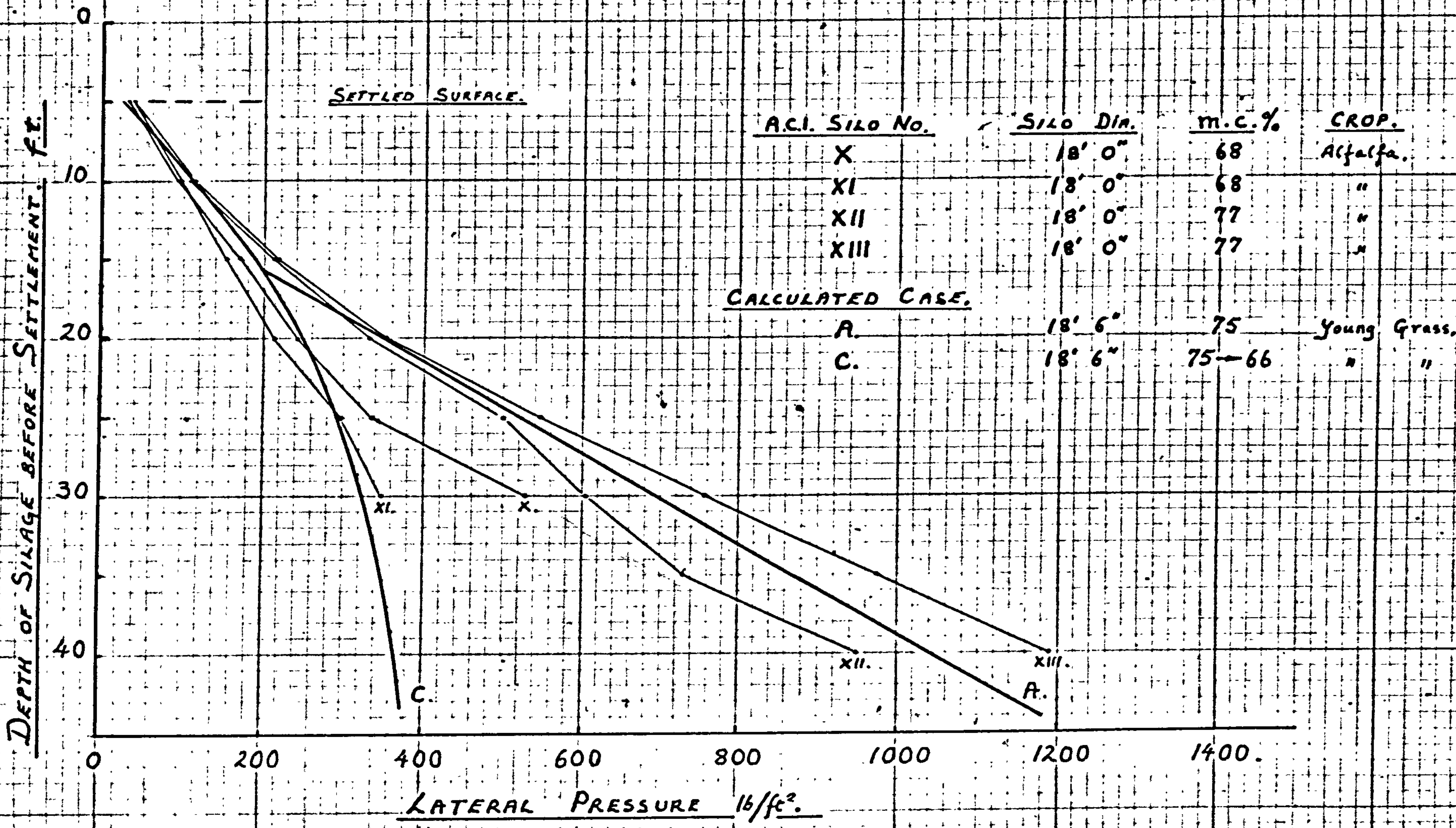
6.2.2. Variation of Lateral Pressure with Depth.

The basis of the most widely used silage pressure formulae is the experimental results of McCALMONT et al(62) and TAMM(117) which have been discussed in Section 2.1.1. In Graph 6.2/1 I have plotted the lateral pressure against depth of silage before settlement (i.e. in the form given by McCalmont, Tamm and A.C.I.714(1)) for two duplicated fillings of 18' diameter silos with Alfalfa. These silos BE4 and BE5 were both filled with 68% average m.c. alfalfa in 1939 and 77% average m.c. alfalfa in 1940. For comparison I have plotted the lateral pressures for Case A (75% m.c.) and Case C (75% - 66% m.c.) for 18'6" diameter silos as calculated in Section 6.1.2. This confirms that the two types of variation in lateral pressure with depth predicted in Section 6.1.2. are encountered in practice.

YU et al's(143) records of pressures in a 30' dia. x 60' corn silo in 1960 (68% average m.c.) give a maximum

Graph 6.2/1

LATERAL PRESSURES IN SILOS, COMPARISON OF FILLING CASES A AND C, WITH EXPERIMENTAL VALUES REPORTED IN A.C.I. 714.



lateral pressure of 700 lb/ft^2. In 1961 uneven filling is given as the cause of the lower lateral pressure of 400 lb/ft^2 at 50 ft. and 300 lb/ft^2 at 60' with 66% average m.c. corn. In 1962 the maximum recorded lateral pressure was 640 lb/ft^2 at 58 ft. depth with unspecified average m.c. corn. From the available plots of pressure against depth it is clear that these pressures are a Type B or C condition tending to a maximum lateral fibre pressure (with little or no pore pressure),

$$\text{where } Y = \frac{4\ Lfa \times u'}{D}$$

$$\text{So for } Y = 60\ lb/ft^2, \quad u' = 0.7 \text{ and } D = 30 \text{ ft.}$$

$$\text{Max. } Lfa = 640\ lb/ft^2$$

$$\text{for } Y = 65\ lb/ft^2, \quad u' = 0.5 \text{ and } D = 30 \text{ ft.}$$

$$\text{Max. } Lfa = 975\ lb/ft^2.$$

So my theory is consistent with the pressures recorded by YU et al.

The A.C.I. and Neubauer formulae for calculating lateral pressures (set out in Section 2.1.1) were derived by curve fitting to the McCalmont and Tamm pressure records. The A.C.I. formulae within its limits (for corn and alfalfa silages of less than 75% m.c., for silos up to 18' dia. 42' deep) is a good empirical formula. It checks well with the Type A condition.

Neubauer's attempt at elaborating and extrapolating the A.C.I. formula using curve fitting techniques is falsely based. The curve that he attempted to fit an equation to is a transition between two different physical equilibrium conditions (type A and type B). The shapes of the curves is further distorted as the average moisture content is made up of a wide range of moisture contents varying more or less at random from lamina to lamina. A comparison of Silos No.7 and No.13 in Graph 2.1/1 illustrates this well.

Neubauer's consideration of moisture and diameter is also over simple to a fault. For moisture content and diameter effect the whole shape of the curve and simple scaling of the type he uses is inadequate and has no theoretical foundation. A simple check on Neubauer's two formulae by substituting in values of the silos height (h) and diameter (D) and moisture content (m) within his range limits gives the following values of lateral pressure L.

$$L_1 = 0.0133\, h^{3/2} (d - 6) (m - 50) \text{ lb/ft}^2$$

$$L_2 = 0.70\, h^{3/2} \times d \times \left(\frac{m}{100}\right)^4 \text{ lb/ft}^2.$$

		m=80, d=20.	m=75, d=30.	m=90, d=30.
for h = 50	L_1 =	1970	2820	4510
for h = 70	L_1 =	3280	4750	7500
average increase in L_1 per foot depth		65	96	150
For h = 50	L_2 =	2000	2350	4850
for h = 70	L_2 =	3320	3900	8060
average increase in L_2 per foot depth		66	77	160

The full hydrostatic pressure of water at 62.4 lb/ft^3 is

for h = 50 L = 3120 lb/ft^2

for h = 70 L = 4360 lb/ft^2

In all these cases both Neubauer's equations show rates of increase of lateral pressure with depth exceeding that of full hydrostatic water pressure by a factor of between 1.04 and 2.56. While in the extreme case a very short chopped, well lacerated, very wet silage would tend to give pressures equal to those of a fluid slurry of equal density, this could not exceed 1.10 x hydrostatic water pressure. Thus the validity of Neubauer's equations beyond the limited range of the data on which they are based must be totally discounted.

McCalmont's formulae for lateral pressure for silage of less than 74% m.c. have similar short comings to Neubauer's if they are extrapolated.

SAARMAN's(105) results for lateral pressure in aluminium silos are consistent with the Type A condition predicted by my theory.

6.2.3. The Filling and Unloading of Glantlees 1965-66.

The record of filling and unloading the Glantlees silos in 1965 is set out in detail in Section 1.1. to 1.4. The results of the pressure density tests on samples from Glantlees are set out in Section 5.5. The records of pressures recorded are in Section 2.2.

I have set out in Table 6.2/1 the values of pressures and densities in the silo calculated using the method described in the earlier sections of this chapter. The values of the parameters used were as follows:

$D = 23.6$ ft.

$V_t = 50$ lb/ft^2

The value of $\frac{4\ Lfa\ u'}{D}$ was taken as 0.02 Va.

That is Lfa x u' = k x fw x u' = 0.118.

fw = 0.75 (from floor pressures recorded, see Table 2.2/4)

Two combinations of k and u' were considered.

for Lfa (1) k = 0.5 u' = 0.315

for Lfa (2) k = 0.3 u' = 0.525

Values of W and m for the silage were obtained from the filling records of grass weights and moisture contents. The filling has been divided into 12 laminae of similar moisture content material. To convert the grass dry matter weights and moisture contents into estimated silage weights a 10% d.m. loss and 2% loss of weight as gas were assumed.

The silage samples taken for pressure density tests during the unloading of the silos were preconsolidated so the E values were higher and F values lower than for virgin consolidation. The E value used for this simulation is 1.8. The F value used is 2.8, which gives a Yd' of 17.9 lb/ft^3 at 1500 lb/ft^2. This was selected to represent the average material in the silo. The Yd' values at 1500 lb/ft^2 of the silage samples tested are given in Table 5.5/21 and range from 15.7 lb/ft^3 to 21.25 lb/ft^3.

The first calculation was made using u' = 0.7, k = 0.5 and fw = 0.75, but the total depth was too high and the floor pressure too low by comparison with the measured values. A reduction in u' to 0.55 still gave a total depth of 48.1 ft. and floor pressure of 1075 lb/ft^2 compared with 42.9 ft. and 1640 lb/ft^2 measured. The further reduction of k x u' to 0.157 (i.e. for k = 0.5, u' = 0.315) gave a total depth of 45.1 ft. and average floor pressure of 1425 lb/ft^2 as shown in Table 6.2.1.

This highlights the need for further data on k and u' for use in this calculation method. The relationship between total depth, dry densities and vertical pressure is good. A further iterative reduction of k and u' would probably enable calculated results coincident with the field results, to be obtained. But this would require either a low value of k (which would give lower than the recorded lateral pressures) or a lower value of u', than those obtained in the laboratory by Brubaker and Pos.

In Graph 6.2/2 the calculated densities and dry densities for the twelve laminae have been plotted against depth for comparison with the dry densities for 5 thick laminae, the thickness of which were recorded during unloading and the dry matter weights of which were obtained from the filling records and corrected for 10% d.m. loss. This shows a good correspondence between calculated and measured values. An even better fit would have been obtained with a lower k x u' value in the calculation, which would have increased the vertical pressure, hence the dry

TABLE 6.2/1

Pressures and Densities Calculated for Glantlees Filling 1965-66

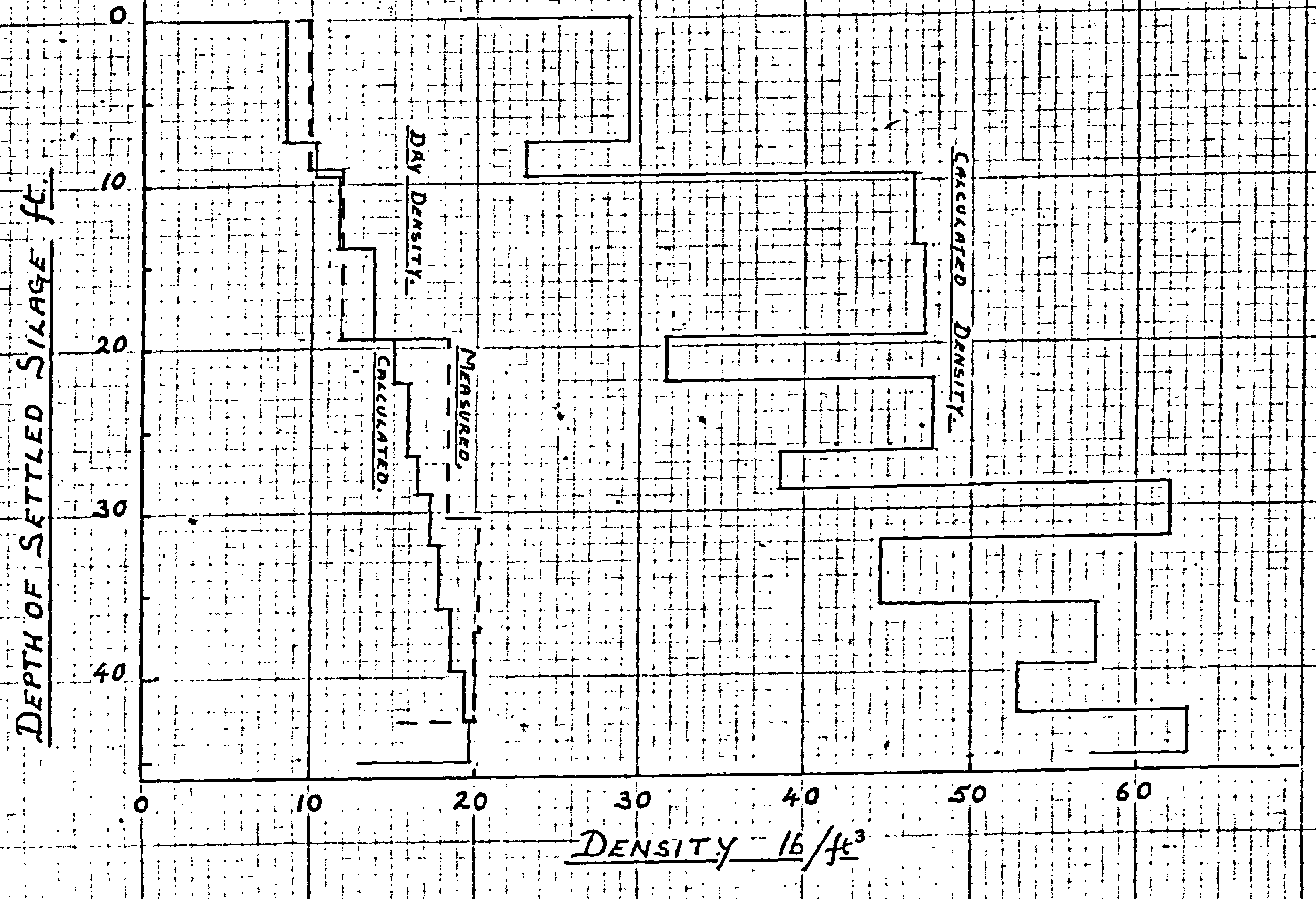
Parameters as stated in Text

Lamina		Parameters		Densities lb/ft^3		Depths ft.		Pressures lb/ft^2			
No.	Loads	W lb.	m%	Yd	Y	t	ha	δV	Va	Lfa(1)	Lfa(2)
1	218-239	27,000	71.4	8.4	29.4	7.35	3.7	196	148	55	33
2	209-217	10,350	55.7	10.2	23.0	2.32	8.5	40	266	100	60
3	183-208	22,350	74.8	11.75	46.6	4.35	11.8	170	373	140	84
4	148-182	33,400	70.8	13.8	47.2	5.55	16.8	200	557	209	125
5	137-147	16,100	52.9	15.0	31.8	2.46	20.8	45	679	254	153
6	109-136	30,500	67.1	15.75	47.9	4.44	24.3	144	774	290	174
7	97-108	16,750	57.3	16.5	38.7	2.32	27.6	50	871	327	196
8	76- 96	23,700	72.3	17.2	62.1	3.16	30.4	136	963	361	216
9	54 - 75	29,500	60.2	17.8	44.6	3.79	33.9	88	1076	392	242
10	31- 53	31,300	67.7	18.6	57.6	3.85	37.7	131	1185	433	266
11	16- 30	24,400	63.5	19.3	52.9	2.89	41.0	78	1290	470	290
12	1- 15	23,100	68.7	19.8	63.2	2.67	43.8	95	1376	502	310
Floor							45.1		1425	520	320

Graph 6.2/2

COMPARISON OF CALCULATED AND MEASURED DRY DENSITY.

GLANTLEGS SILO 1965-66. ASSUMED 10% D.M. LOSS, 2% GAS LOSS.



densities in the lower part of the silo to the levels recorded in the field.

The lateral pressures were calculated using fw = 0.75 and k = 0.5 for Lfa (1) in Table 6.2/1 and using fw = 0.75 and k = 0.3 for Lfa (2). Although no pore pressures occur in the whole laminae there were wetter loads in laminae 8 and 12 which would have definately caused a localised band of pore pressure before it was relieved by drainage. For example loads 77 to 82 in lamina 8 had an average filling moisture content as grass of 74.2% which would become 76.8% as silage. This would give a pore pressure of 240 lb/ft^2 and an average total lateral pressure of 600 lb/ft^2 in this part of lamina 8 and locally peaking higher.

Similarly loads of 69.1%, 71.3%, 67.8% cut on the 11.6.65. would have reached saturation in lamina 12. This checks with the observed peaking of pressure on Cell 15 discussed in Section 2.2.6.3. Loads of grass younger than the F = 2.8 material considered probably occured in the earlier stages of filling and this would increase the chance of other thin saturated zones giving local high pressures in the bottom laminae.

The calculated range of lateral pressure in the bottom laminae is from 350 - 520 lb/ft^2 (for Lfa (1)) or 200 - 320 lb/ft^2 (for Lfa (2)) with the probability of thin zones of saturated silage giving local pore pressure with total pressures of up to 700 - 800 lb/ft^2 in laminae 8 and 12 and to a lesser extent in laminae 10. These are of the same order as but slightly lower than those recorded for the settled silage which were

on Cell 14; 650 lb/ft^2 (see Graph 2.2/6).

on Cell 16; 500-800 lb/ft^2 (see Graph 2.2/7).

The maximum total upward wall friction load recorded during unloading at Glantlees in 1965-66 was 2420 lb/ft run of circumference (see Table 2.2/4). The maximum upward wall friction load calculated on the basis of a single thick lamina as explained in Section 6.1.6. is as follows:-

V max = 1640 lb/ft^2 (from Table 2.2/4).

Lfa = 600 lb/ft^2 (from Graphs 2.2/6 & 2.2/7)

Y = 56 lb/ft^2 (average for laminae 8-12. Table 6.2/1)

u' = 0.315 (as for Lfa (1)).

u' = 0.525 (as for Lfa (2)).

D = 23.6 ft.

$$V = 0.75 \text{ V max} = t\left(Y + \frac{4 \text{ Lfa} \times u'}{D}\right)$$

for u' = 0.315

$$0.75 \times 1640 = t\left(56 + \frac{4 \times 600 \times 0.315}{23.6}\right)$$

$\therefore$ t = 14.0 ft.

$\therefore$ Max. upward wall friction load = t x Lfa x u' = 2650 lb/ft. run.

for u' = 0.525

t = 11.3 ft.

$\therefore$ Max. upward wall friction load = 3560 lb/ft run.

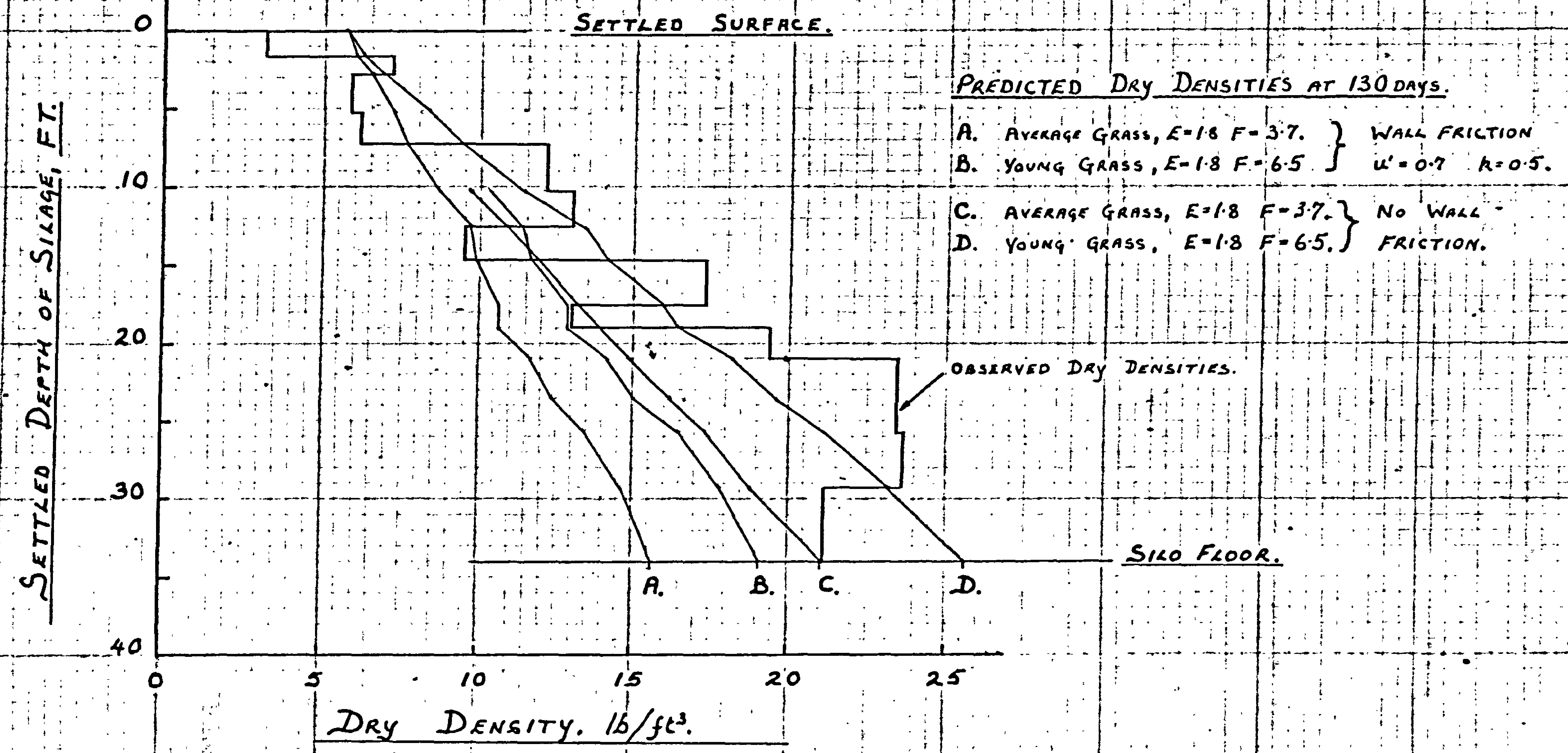
So in general the correlation between the calculated and recorded densities and pressures at Glantlees was good. However, there is clearly a need for more accurate values of the parameters.

6.2.4. Dry Densities in the Bridgets E.H.F.Silo.

In Graph 6.2/3 the observed dry densities of laminae, obtained from the filling and unloading records for 1965-66 reported in Section 1.5, have been plotted against settled depth. The dry densities, calculated using the method outlined previously in this chapter, have been plotted using 4 sets of parameter values A, B, C and D. For A and B k = 0.5 and u' = 0.7 while for C and D wall friction was neglected (i.e. k x u' = 0). The basis for A and C was an average maturity grass (Yd' = 19.95 lb/ft^3 at 1500 lb/ft^2) with E = 1.8 and F = 3.7 while for B and D a young grass (Yd' = 24.5 lb/ft^3 at 1500 lb/ft^2) with E = 1.8 and F = 6.5 was used for the calculation of dry densities. The weights and moisture contents of laminae are those recorded during unloading. The actual maturities of the grass in the silo can be gauged from the Yd' at 1500 lb/ft^2 figures in Table 5.5/21 which ranged from 14.7 lb/ft^3 for some of the second cut material at the top to 28.5 lb/ft^3 in the youngest grass in some of the bottom laminae. The 4 calculated dry density plots (A, B, C and D) aim to show the probable range of dry densities for maximum and minimum possible wall friction and for two levels of maturity. As all the average maturity grass in the second cut material was in the top of the silo it is the B and D plots which should

COMPARISON OF OBSERVED DRY DENSITIES, BRIDGET'S E.H.F. 1965-66.

WITH PREDICTED DRY DENSITIES.



Graph 6.2/3

give the dry densities of the younger grass in the bottom 20 ft. of silage. Bearing in mind that the actual maturity of first cut ranged on either side of the F = 6.5 grass there is a very good fit between the D plot (i.e. non wall friction) and the observed dry densities. This shows, like the Glantlees results, that the wall friction factor k x fw x u' is low in the field. At Bridgets the vitreous enamel wall and dryish material would have lowered u' to perhaps 0.5 on the basis of the Brubaker and Pos results. The central filling with levelling at the end of the day would give a low value of fw (which was 0.75 with the relatively even filling at Glantlees).

The Bridgets results like those from Glantlees confirm the general validity of my calculation method but highlight the need for more data on k, u' and fw.

6.2.5. Density and Capacity formulae.

The published data on densities in and capacities of silos has been discussed in Section 5.4. Maize (corn) and lucerne (alfalfa) are relatively more consistent and less compressible than grass. The variation in dry density and capacity will be less under the conditions for which the N.S.A. and Aldrich Capacity tables are based than with the grass normally ensiled in the U.K., for which capacities can vary by a factor 2 (or more) with moisture and maturity variations.

While the N.S.A. and Aldrich capacity tables have been a useful rule of thumb method of determining capacities of small silos for maize and lucerne, their extrapolation to larger size silos and to other crops has increased the errors that arise from their use considerably. The assumption of constant dry matter capacity regardless of moisture content is patently false as has been demonstrated by the increases in capacity with improved filling at Bridgets and by the calculated examples in the Section 6.1.2. and 6.1.4.

Using my calculation method the capacity of any silo can be calculated provided the parameters and details of filling are specified. Various general rules applicable to filling can be concluded as follows:-

1. The maximum dry matter capacity obtainable in a silo for a given crop is achieved by adjusting the moisture content in each lamina so that it is just saturated.
2. To provide a factor of safety against pore pressures and effluent and to improve the fermentation in the top laminae while still obtaining a high dry matter capacity. A farmer should wilt to give a moisture content (not exceeding 75%) which will give a density of 80% to 90% saturation in each lamina in the manner of Case C.
3. Filling with material wetter than in 1 or drier than in 2 will reduce the dry matter capacity considerably. In particular over-wilting of the top laminae and insufficient wilting of the bottom laminae can seriously reduce the capacity. The dry matter capacity of a silo varies not only with the average moisture content but with the distribution of moisture content in the silo.
4. The d.m. capacity of a silo filled with average maturity grass in accordance with 3 can be given approximately

as follows:-

The dry density (Yd) in the silo at h below the settled surface can be taken as:

$$Yd = 140 + 14.4\ h \quad kg/m^3$$ where h is in metres.

This is the form I have proposed for the Draft B.S. on Tower silos.

In Imperial Units it is:

$$Yd = 8.75 \times 0.262\ h \quad lb/ft^3$$ where h is in feet.

If h, the settled depth of silage, is 90% of hu the utilised height of the silo (i.e. max. depth before settlement) then the standard dry matter capacity (C) of a silo of diameter D can be given as

$$C = \frac{\pi D^2}{4} (0.126\ hu + 0.0058\ hu^2)$$ tons, in S.I.units:

that is:

$$C = \frac{\pi D^2}{4} \times 10^{-3} (3.6\ hu + 0.050\ hu^2)$$ tons, in Imperial units.

This provides a simple standard method of determining silo capacities for farmers and salesmen. For young grass a 25% increase in d.m. capacity can be expected and for mature grass a 20% reduction in d.m. capacity will occur.

6.3. THE CALCULATION OF THE FILLING RATE REQUIRED TO CONTROL HEATING.

6.3.1. Introduction.

So far in this chapter I have been primarily concerned with the pressures and densities in the mass of silage during storage. In this section I deal with the densities in the top laminae during filling, which has an important but previously only sketchily studied, influence on the heat rise and losses in silage.

Firstly, I have outlined the principles involved in heating and the consequences of it. Next I have established from field results the rate of consolidation required to limit heating to a tolerable level. These consolidation rates are then expressed in terms of the required output for field machinery for silos of given diameters filled with a crop of average maturity for a range of moisture contents.

6.3.2. The Physical and Chemical Process Governing the Heating of Silage.

In Section 4.9.8. the respiration heating of grain was described. The same principles apply to the respiration of silage. The heating is predominately due to the oxidation of carbohydrates. The process can be considered as being the oxidation of glucose that is:-

$$180\text{g } C_5H_{12}O_6 + 192\text{g } O_2 \rightarrow 264\text{g } CO_2 + 108\text{g } H_2O + 677 \text{ k Cal.}$$

As with grain the heat rise of a silage due to the oxygen in the air of a 'sealed' sample (i.e. all the gas in the voids is initially air, no further oxygen enters the sample and there is no loss of heat energy from the sample) of specified density, moisture content and specific heat can be calculated.

I have calculated these values of heat rise for a range of densities, at 40%, 60% and 80% moisture content and with a specific heat of dry matter assumed as 0.45. The results are plotted on Graph 6.3/1. The range of dry matter losses as glucose calculated for the same cases was:-

0.68% loss of d.m. at 80% m.c. 10 lb/ft^3
0.15% loss of d.m. at 80% m.c. 30 lb/ft^3
0.25% loss of d.m. at 40% m.c. 10 lb/ft^3
0.05% loss of d.m. at 40% m.c. 30 lb/ft^3

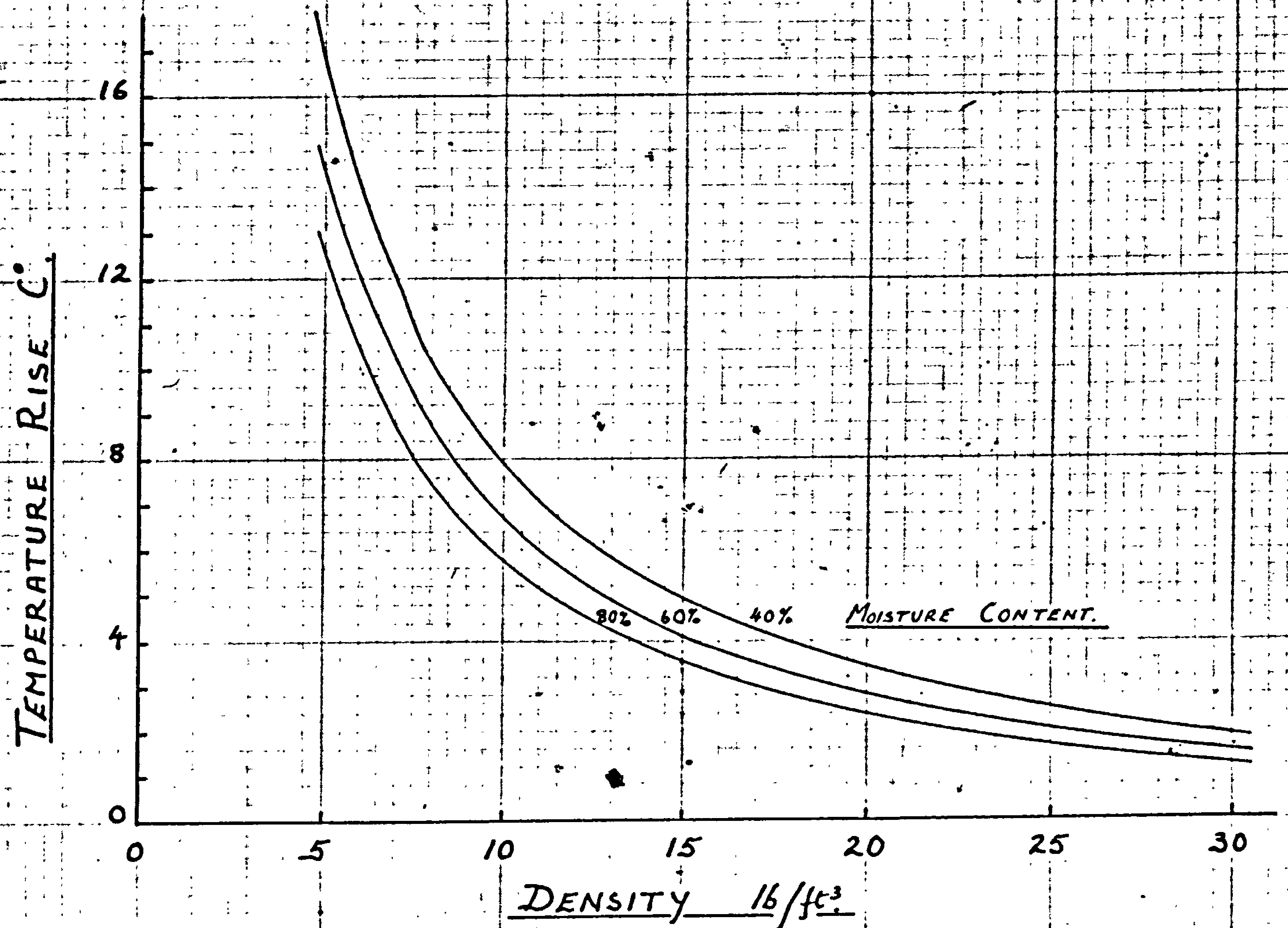
The dry density of the top laminae of ensiling grass in a silo can range from 2 lb/ft^3 to 6 lb/ft^3 depending on the method of distribution, moisture content and length of chop. This gives a density range of 3.3 - 10 lb/ft^3 at 40% m.c. and 10 lb/ft^3 to 30 lb/ft^3 at 80% m.c. So except with the driest loosest material, the heat rise due to oxygen initially within the lamina will not exceed 10°C.

Temperature rises several times greater than those predicted on the 'sealed' silage basis are encountered in practice. For this to happen the volume of oxygen in the lamina must be utilised and replaced several times. The dominant gas movements effects in the top laminae are:-

1. The convection currents within the silage and the air above.
2. The blast of air downwards from the end of the blower pipe, particularly when the silo is getting nearly full.
3. The upward movement of gas (mostly oxygen free) from the lower laminae as they are consolidated.

Graph 6.3/1

CALCULATED HEAT RISE IN 'SEALED' SILAGE.



The first two effects could both cause several gas changes in a lamina before it was sufficiently covered and consolidated by the succeeding laminae to be isolated from the air. The rising oxygen free gas tends to reduce the heating in the lamina, but this effect does not occur where an unloading flue provides an alternative escape route. As with grain, any zone with a higher than average respiration rate within a 'sealed' lamina will have a greater than average total oxygen consumption. This will cause hot spots in these zones. The control of temperature rise basically depends on controlling the supply of oxygen to the lamina. This can be achieved by:-

1. Reducing the gas volume in the lamina to a minimum, by consolidating and avoiding over-wilting so as to maximise the density of the lamina.
2. Providing the maximum resistance to the flow of gas into the lamina by maximising the thickness and reducing the permeability of the superincumbant layers.
3. Eliminating external causes of gas movement in the silage mass.

It follows that the initial temperature rise is largely controlled by the density and dry density of the top laminae during the first few days after ensiling.

From the temperature records at Glantlees it is clear that the initial heat rise is substantially complete within the first three days of ensiling the lamina. So I have used as a measure of the rate of filling the density and dry density achieved in a lamina 3 days and 6 days after ensiling and related this to the measured heat rise and overheating effects.

6.3.3. The Consequences of Overheating.

The energy from oxidised carbohydrates which heats the silage is from the most digestible part of the grass which should be preserved to provide energy in the animals diet. The glucose required to heat the silage mass a given amount can be calculated using the equation in the previous section. On the basis that 1 lb. glucose lost in heating must be replaced in the animals diet by 1.27 lb. barley (as suggested by ARMSTRONG(11)) the replacement cost of the lost nutrients can be calculated using the formula:-

$$B = 0.76\ W \times T \times S$$

where B is the loss of feed value, in lbs. barley required to replace loss.

W is the weight of silage in tons.

T is the temperature rise in C°.

S is the Specific heat of silage.

So if we consider the case of a farmer conserving 100 tons dry matter at 60% m.c. in a tower silo the barley replacement required per 10°C heat rise is:-

$W = 250$ $S = 0.78$ $T = 10$

$$B = 0.76 \times 250 \times 0.78 \times 10 = 1480 \text{ lbs.}$$

With barley at say £22 per ton the cost of overheating is:-

£14. 10s. 0d. per 10°C per 100 tons d.m. at 60% m.c.

The corresponding figure for clamp silage at 80% m.c. is

£33. 0. 0d. per 10°C per 100 tons d.m. at 80% m.c.

When expressed as the weight of glucose lost, as a percentage of total dry matter, the losses per 10°C heat rise are 0.53% in a tower at 60% m.c. and 1.19% in a clamp at 80% m.c.

There are two other serious adverse consequences of heating. The utilization of sugar for aerobic respiration reduces the supply of sugars for the acidification of the silage and increases the risks of an unsatisfactory butyric fermentation. At above about 30°C there is a slight tendancy for the proteins, in the presence of oxygen to become indigestible, above 40°C this loss of protein digestibility becomes serious. These effects are fully dealt with by McDONALD et al(65) and by WIERINGA et al(128). In correspondance WEIRINGA(129) has suggested that 40°C should be regarded as the maximum tolerable temperature in wilted silage. The value of protein is much higher than starch and a 10% loss of protein equivalent can be valued, at replacement cost as:-

£84 per 100 tons d.m. for 12% Crude Protein (P.E.8.4.) grass.

6.3.4. Correlation of 3 Day Density with Heating.

In Section 2.4.4. the initial temperature rise in the silage in 1963, 64 and 65 has been plotted against the density and dry density achieved after 3 days and the 6 day density. From this limited data the best correlation seems to be with 3 day density (Y_3). The maximum temperature T max. was found to be:-

$$T \text{ max.} = 70 - 1.2\, Y_3 \ C^\circ.$$

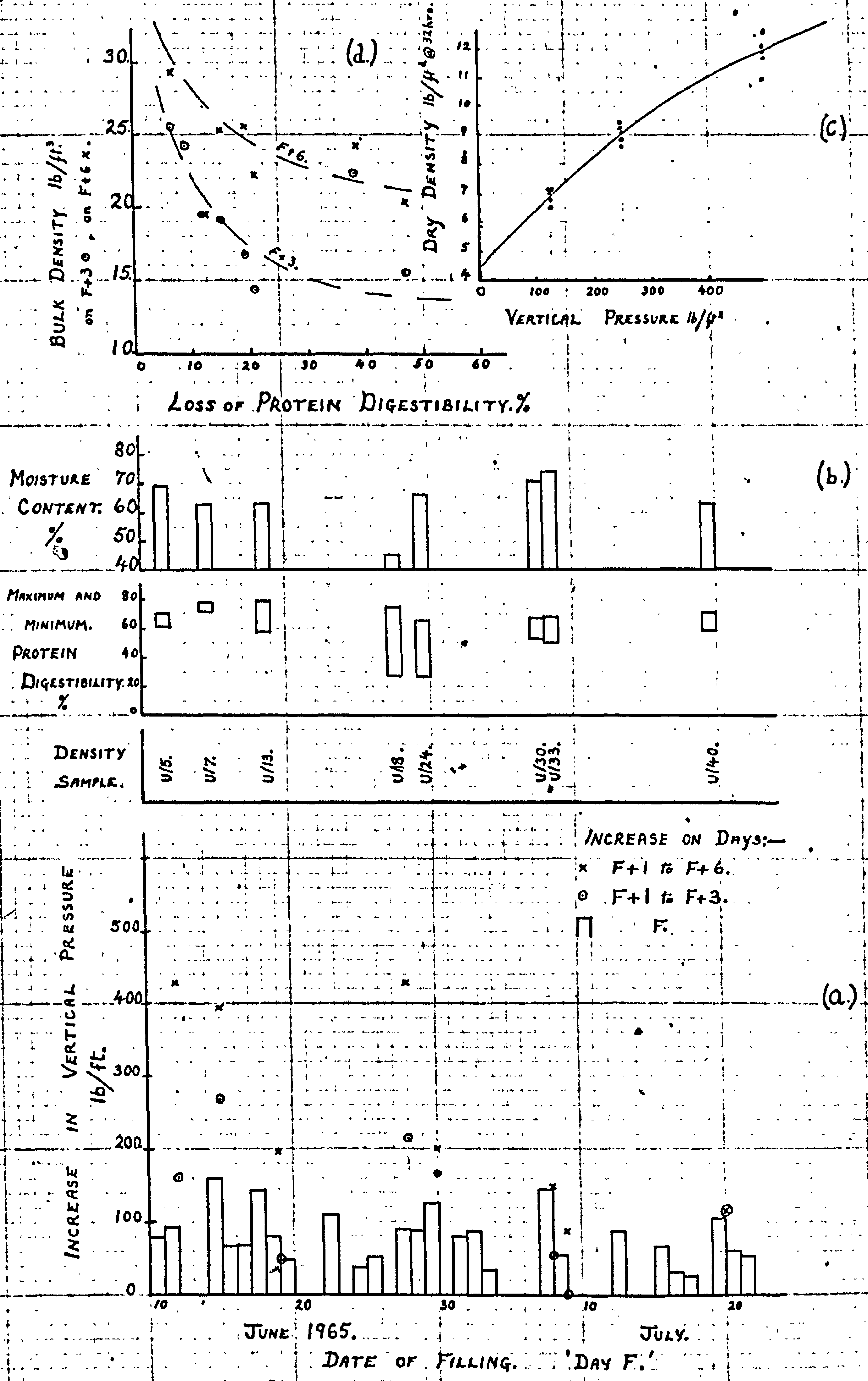
This occurs as a uniform initial heating across the whole silo and is applicable to silos both with and without flues. To keep the temperature to 40°C (i.e. 20°-25°C heat rise) a 25 lb/ft^3 density must be achieved within 3 days. To keep the temperature down to below 30°C a 3 day density of 33 lb/ft^3 is required.

To establish the relationship between loss of protein digestibility and filling rate I have used Graph 6.3/2. At the bottom (a) the daily filling rate, in terms of daily rate of increase in vertical pressure (i.e. total weight ensiled per day ÷ top surface area of silo) has been plotted against date of filling, for the filling of Glantlees 1965. For the surface laminae the effect of wall friction is negligable so that the vertical pressure 3 days after filling on the material filled on any day, F, can be calculated approximately as the sum of the increases of vertical pressure on days F + 1 to F + 3. The values of the vertical pressures after 3 and 6 days have been plotted for the dates of filling of the analysed unloading samples. The moisture contents and the maximum and minimum protein digestibility of the silage (from Graphs 1.4/8 and 1.4/9) have been plotted (b) for each of the analysed unloading sample levels U/5 to U/40. The dry density and density of each sample was then calculated at 3 and 6 days using the graph (c) of dry density against vertical pressure. This is based on pressure density tests during ensiling (i.e. before rest) on samples GD/65/1-5/1 as reported in Section 5.5.8.3.

Graph 6.3/2

RELATION OF PROTEIN DIGESTIBILITY LOSS FROM OVERHEATING TO RATE OF FILL AND DENSITY.

GLANTLEES, 1965.



These densities at F + 3 and F + 6 have been plotted against loss of protein digestibility % (i.e. maximum protein digestibility % minus the minimum protein digestibility %) on Graph 6.3/2(d). Graph 6.3/3 also shows the 1965 values of density at F + 3 and F + 6 plotted separately against protein digestibility loss and the 1964 filling values have been added. A tentative curve fitted to the points is shown. The relationship seems clearest with density at F + 3. The 23% drop in protein digestibility of U/10 1964 despite its relatively high 3 and 6 day density was probably due to the serious overheating and charring of the layer above which was left exposed during a two week break in filling, see Graph 1.4/1.

Further experimental data is needed before the relationship between protein digestibility loss due to overheating in flue type silos and filling rate (expressed as density at F + 3 or in a more refined manner) can be closely defined. Similar data is also required for silos without flues. However, serious protein digestibility loss occurs at a density of less than 20 lb/ft^3 at F + 3 and noticeable protein digestibility loss occurs at densities of up to 25 lb/ft^3 at F + 3 in flue type silos.

On the above evidence, I recommend minimum values for density at F + 3 of 25 lb/ft^3 for normal silos and 30 lb/ft^3 for flue type silos, if losses are to be kept to a tolerable level.

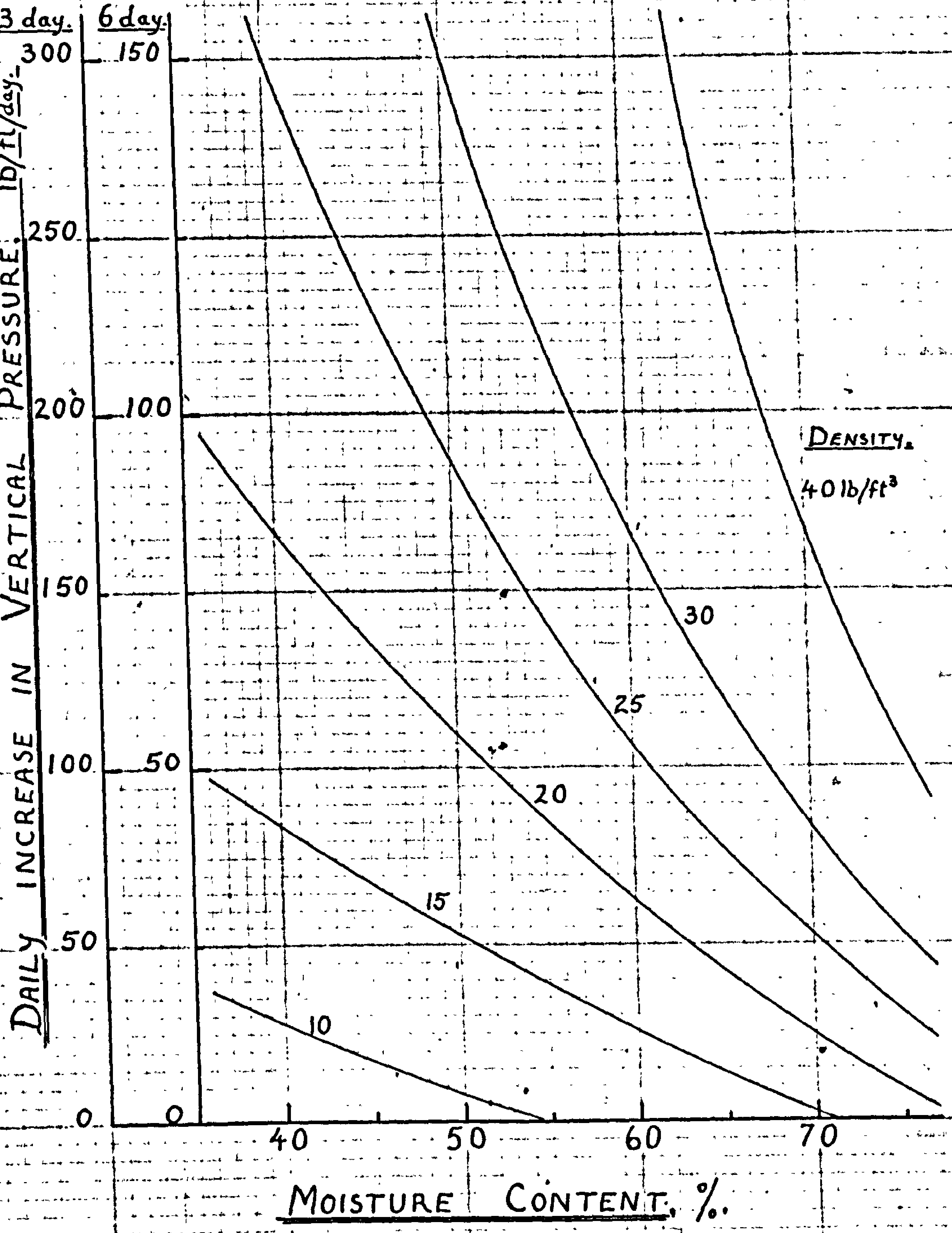
6.3.5. Filling Rate Required to Limit Overheating.

Graph 6.3/4 shows the daily rate of increase in vertical pressure required to obtain densities at F + 3 and F + 6 of 10 to 40 lb/ft^3, plotted against moisture content. I have calculated it on the basis of a rye grass of 30% C.F. approx. The pressure density relationship used is that shown in Graph 6.3/2(c) which is based on the mean of the ensiling (before rest) pressure density relationships of samples GD/65/1-5/1.

The relationship between the day's fill and the daily rate of increase in vertical pressure is shown on Graph 6.3/5 for 16', 20' and 24' diameter silos. The day's fill is expressed as gross tons and also for 75%, 60% and 40% m.c. in terms of loads per day and acres per day. The load weights are based on the average of those recorded at Glantlees in 1964, see Section 1.4.8. The yield per acre is estimated at 30 cwt/acre. Combining Graphs 6.3/4 and 6.3/5 I have obtained the figures for Graph 6.3/6 of the average daily fill required to obtain a density of 25 lb/ft^3 in 3 days. This is expressed in terms of loads per day, acres per day, tons dry matter per day and gross tons per day. The equivalent figures for obtaining 30 lb/ft^3 after 3 days may be obtained approximately by multiplying the figures in Graph 6.3/6 by 1.5.

This Graph clearly illustrates the effect of moisture content and silo diameter on the filling rate required. It is important to realise that it gives the average filling rate required. The field machinery output required to

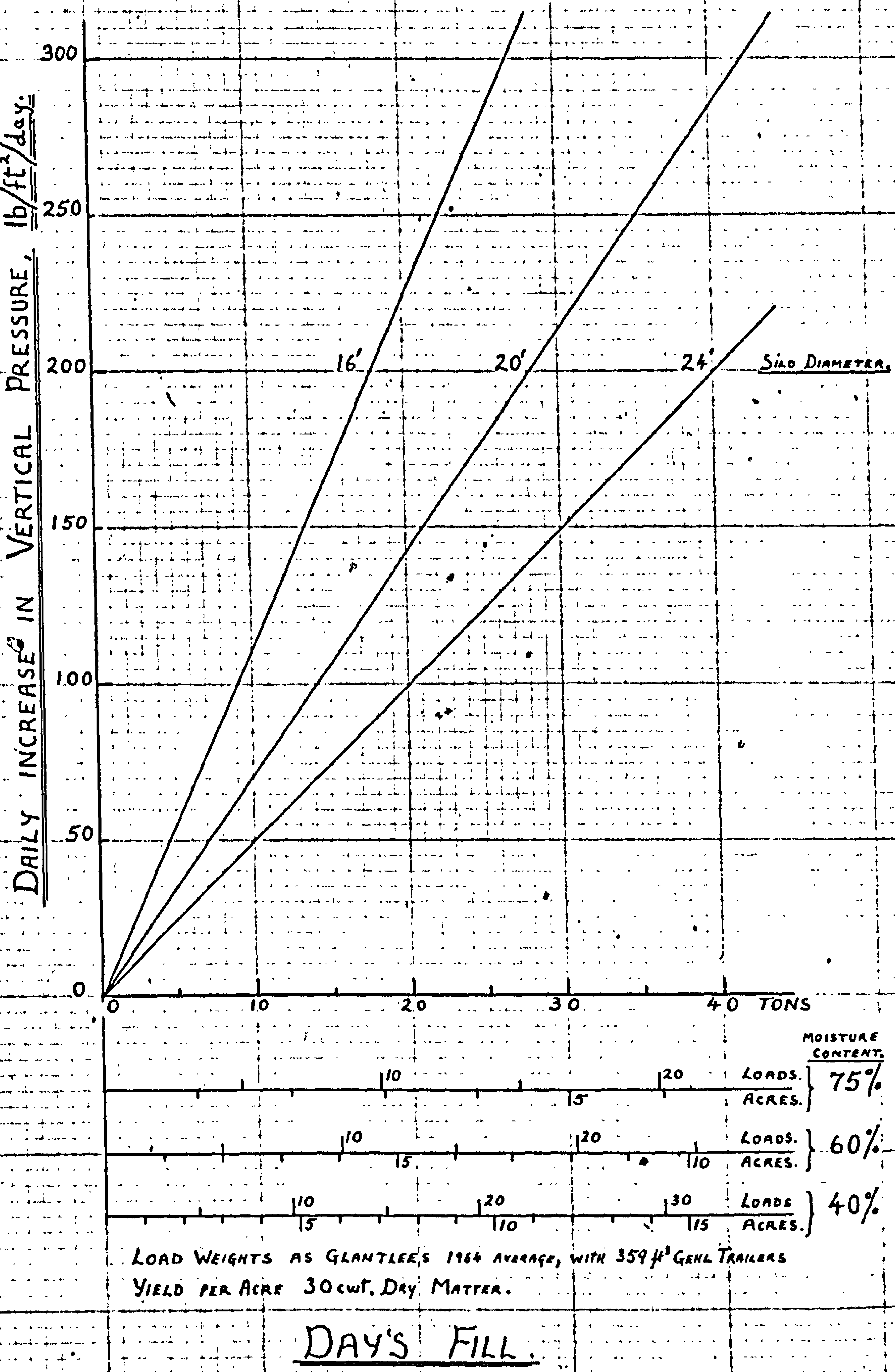
Graph 6.3/4



SILAGE DENSITY, 3 AND 6 DAYS AFTER FILLING.

[FOR RYEGRASS C.F. 30% APPROX.]

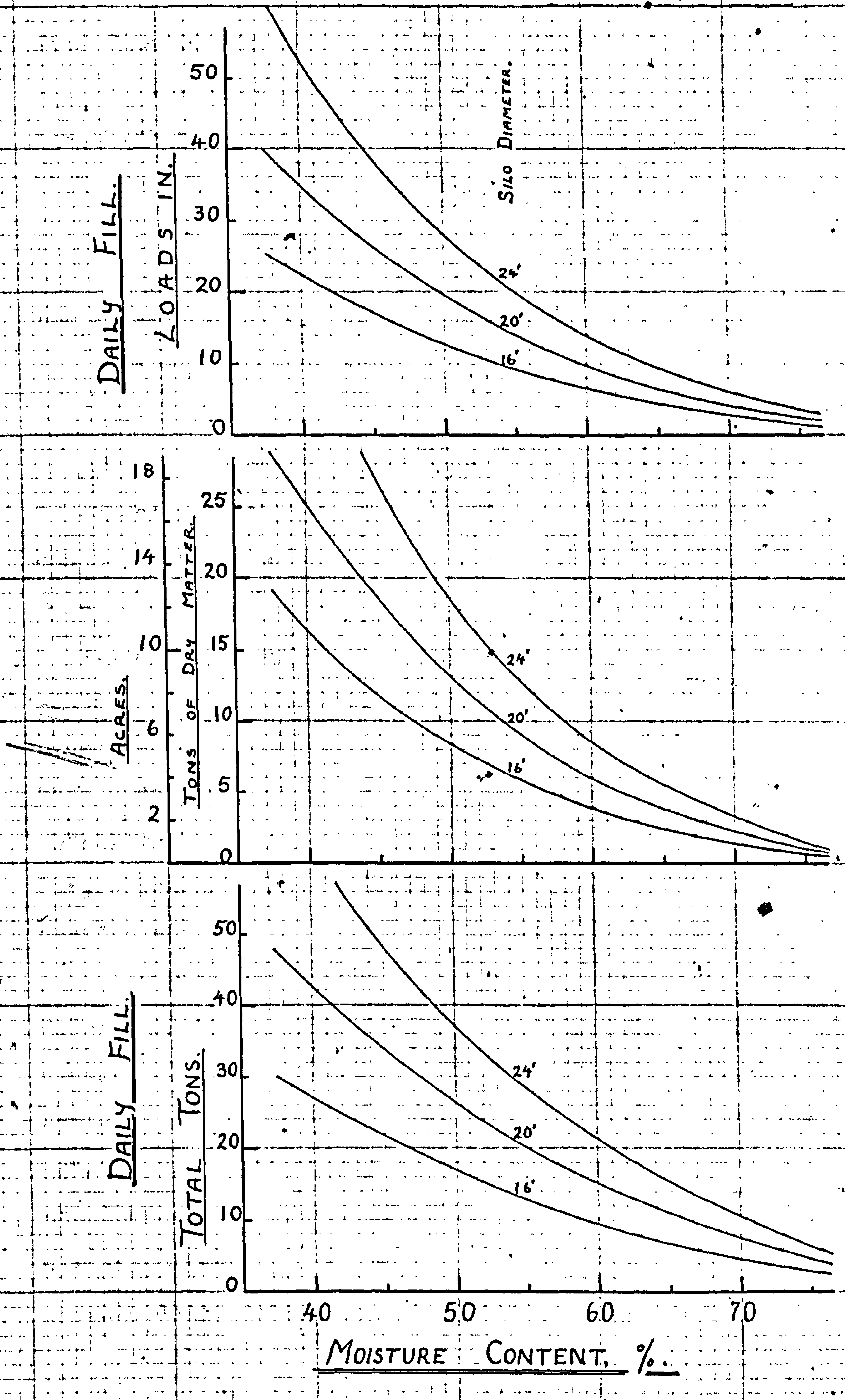
SILO FILLING RATE.



LOAD WEIGHTS AS GLANTLEE'S 1964 AVERAGE, WITH 359 ft³ GEHL TRAILERS
YIELD PER ACRE 30 cwt. DRY MATTER.

Graph 6.3/6

AVERAGE DAILY FILL REQUIRED
TO OBTAIN 25 lb/ft³ DENSITY IN 3 DAYS.



maintain this average output will be considerably greater than this average.

At Glantlees the maximum daily rate of fill achieved was 12.15 tons d.m. in 15 loads between 9.30 and 7.30 on 14.6.65. The average total fill per working day was:-

5.3 tons d.m. in 1964
5.5 tons d.m. in 1965

The average total fill per day of filling period

4.0 tons d.m. in 1964 (excluding long break 27.6-13.7)
3.4 tons d.m. in 1965.

With the best machinery and transport system working to capacity a filling rate of 3 to 4 tons d.m. per hour can be obtained which at 8 working hours per day gives 24 - 32 tons d.m. per working day. Because of delays due to weather, breakdowns and breakages the three day average filling rate will normally be 1/3rd to 1/2 that obtainable under perfect weather and reliability conditions. The best 3 day average of the daily filling rate that can be consistently obtained will be in the range 6 - 16 tons d.m. per day, depending on the management expertise and the equipment available.

The moisture content for filling a silo is largely determined by the requirements of obtaining the maximum density possible without undue risk of saturation and effluent, as in Case C in Section 6.12. This requires moisture contents, for average maturity grass, of about 55% ± 5% in the bottom of the silo. A farmer must select his silo diameter and field machinery so that the 3 day average daily fill rate of the machinery enables him to obtain 25 lb/ft^3 at 3 days even when filling at 50% m.c.

Table 6.3/1 gives the required filling rates for silos with and without flues for minimum moisture content levels of 50% m.c. and 55% m.c. for three silo diameters.

TABLE 6.3/1

REQUIRED FILLING RATES

Tons d.m./day, 3 day average.

min.m.c.%	Flue	Diameter 16'	20'	24'
50	Yes	12.5	20	29
55	Yes	9	14	20
50	No	8	13	18.5
55	No	6	9	13

It is not desirable for a farmer to aim ensile at a minimum moisture content of 55% to avoid overheating, as it would inevitably increase the risk of effluent damage to an unacceptable level. Comparing the figures with the rates of fill that can be achieved in practice it is clear that 16' and 20' diameter silos without flues are the only ones that a farmer can reasonably expect to fill without undue heating and consequent losses.

The example I have given is based on average maturity grass; a similar calculation can be carried out for other maturities when the pressure density relationship of the ensiling grass is known. The more compressible young material will require a lower filling rate to obtain the desired density in 3 days at any moisture content level.

As it has to be ensiled at a lower moisture content to give the same factor of safety against effluent the actual rate of fill required for a given silo will not be greatly effected by maturity.

In this section I have aimed to establish the relation between filling rate, moisture content, silo diameter and the heating and losses in the silo. The filling rates I have specified will give a good working guide for silo design. A detailed research programme into the physical and thermo-chemical processes and economic factors involved would enable a more elaborate and precise design study to be made so that the total system cost per ton dry matter stored of the filling machinery, the silo and the replacement cost of nutrient lost could be minimised.

7. SUMMARY OF MAIN CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

The most important conclusions are summarised below. Detailed conclusions will be found at appropriate points in the main text.

7.1.1. Chapter 1, Filling and Unloading Records.

The filling and unloading records show wide variations in the maturity and moisture content of the silage within silos: see Graphs 1.4/1, 1.4/2 and 1.5/1.

In-situ density and dry densities were measured for comparison with calculated values in Chapter 6.

The measured dry densities of the first and second cut grass silage in twin clamp silos at Bridgets E.H.F. clearly showed the reduction in dry density with the more mature grass, see Table 1.5/3.

It was found that the average load dry matter weight increased with wilting while the average load total weight decreased. The average in trailer density was found to be $3.44 + 0.101\ m\ lb/ft^3$, where m is % of moisture content (wet basis). See Graphs 1.4/3 and 1.4/4.

The radial sampling and analysis of silage at 8 levels revealed a marked fall in protein digestibility, particularly near the flue, when overheating occured.

7.1.2. Chapter 2, Pressure, Strain and Temperature Measurement

The Maihak pressure cells used are not ideal for field work in their present form because of their sensitivity to temperature and shock. A refined version of the McCalmont-

Tamm type pressure panel would be more suitable for the measurement of pressures on silo walls in most instances: see Section 2.1.1. and 2.2.2.

The 9" x 26" pressure plate which I developed for measuring floor pressures worked satisfactorily; see Section 2.2.3.

The lateral pressures recorded at Glantlees were of the same order as those predicted by the A.C.I. formula. The high pressures associated with underwilted material and effluent, which must be considered in design, were not encountered with the properly wilted crop at Glantlees. The settling of layers of varying moisture content past the pressure cells caused pressures to rise and fall markedly. See Section 2.2.7.

The measurement of vertical pressure at 4 points on the silo floor showed that even with the even spreading of the 'Big Jim' there was a marked variation in vertical pressure on the floor between the wall and the centre. In 1965-66 Pressures were highest at the centre during filling but this pattern was reversed during unloading: see Table 2.2/4.

The wall load due to friction between the setting and re-expanding silage was found (from the difference between total weight in the silo and the average floor pressure) to be as great as 2610 lb/ft run in compression during filling and storage and 2570 lb/ft run in tension during unloading: see Table 2.2/4 and Section 2.2.7.

The moisture movements of the concrete staves caused large (over 300×10^{-6} in/in) strains in the silo wall which can markedly increase or reduce the prestress of silo; see 2.3.4.4.

The silo wall was found to behave in accordance with theory, with lateral pressures in the silo causing relatively small strains in the silo wall up to the critical pressure at which the prestress is overcome, further increases in pressure were accompanied by large increases in hoop strain as the joints opened: see Graph 2.3/5 and Section 2.3.4.4.

The complexity of wall strains revealed in this work due to the combined effects of moisture and temperature effects and secondary bending stresses in the silo wall and hoops requires more detailed instrumentation before it can be fully unravelled and accurate determinations of prestress made: see Section 2.3.4.4.

The initial steep rise in the silage temperature was complete within 3 days of filling and followed by steady cooling of the outer part of the silage. The central part of the silage round the flue tended to increase in temperature if (a) the initial heat rise was large and (b) the silage remained at a low density: see Graph 2.4/1 - 4.

A good correlation was found between the calculated density of silage three days after filling (Y_3 lb/ft^3) and the temperature after the initial heat rise (T C^o) where $T = 70 - 1.2\ Y_3$: see Section 2.4.4. and Graph 2.4/5 b.

7.1.3. Chapter 3. Concrete Silo Staves

Three grades of silo stave are desirable to meet the needs of silage silos, large grain and industrial silos and small outdoor silos respectively. Flexural strength and 24 hour absorption at 28 days are the best measure of the quality required: see Section 3.1.3. to 3.1.6.

Saturated Stave Density was found to be a good non-destructive measure of the stave quality that can be used for production quality control tests shortly after casting. Graphs 3.1/1 and 3.1/2 show the relationship between stave density and the primary quality measures, flexural strength and absorption.

The moisture and temperature movements of a typical stave were accurately measured: see Graphs 3.1/3 and 3.1/4 and Section 3.2.8.

7.1.4. Chapter 4. Properties of Ensiled Grain

Janssen's theory and recent elaborations of it, all consider density (Y), coefficient of friction between grain and silo wall (u') and ratio of lateral to vertical pressure (k) as constants. Many of the widely quoted values for these 'constants' appear to be erroneous, e.g. bushel weight (by definition the minimum density) is often used as the basis of density instead of the compacted density which may well occur in the silo: see Section 4.4.17.

While the assumption of constant values of Y, u' and k is reasonable for clean dry grain, it can lead to errors with moist grain of varying moisture content.

I have found (see Section 4.4.17) that the dry density of grain (Yd^T lb/ft^3) of moisture content (m%) at Time (T hours) after the application of a Vertical Pressure (V lb/ft^2) can be expressed in the form:

$$Yd^T = A - B \times m + Cd' \times \text{Log}_{10}T$$

and the density $Y^T = \left\{\frac{100}{100 - m}\right\} Yd^T$

where A and B are functions of V,

and Cd' is a function of m.

For Barley $A = 43.0 + 0.154\ V^{0.37}$

$$B = 0.448 - 0.074\ V \times 10^{-3}$$

$$Cd' = \frac{m}{100}$$

Using this equation it is possible to calculate the pressure rise that will occur when grain increases in moisture content while confined at constant volume within a silo: see Section 4.4.16.

The survey of the other physical and biological properties of grain shows major gaps in current knowledge: see Section 4.5 to 4.12.

7.1.5. Chapter 5, The Properties of Ensiled Grass and Forage Crops

There are serious shortcomings in the currently used methods of calculating density in silos. In particular some values quoted in the U.K. suffer from multiple misquotations: see Section 5.4.3.

I have found that the dry density (Yd^{T} lb/ft^3) of silage can be accurately calculated, for any specified crop of moisture content (m%) at time (T hours) after the application of vertical pressure (V lb/ft^2) as the lower of the following two values.

(a) the effective saturation dry density

$$Yd^{T} = \frac{100 - m}{100} (90 - 0.338m) \text{ lb/ft}^3$$

or

(b) the dry density at below saturation

$$Yd^{T} = 23 \text{ Log}_{10} (E + F \times V \times 10^{-3}) + Cd' \text{ Log}_{10} T$$

where E is a constant related to dry density when V = 0 lb/ft^2.

F is constant related to compressibility

Cd is a constant related to the rate of settlement with time at V lb/ft^2.

The detailed conclusions on the density of silage are given in full in Section 5.5.15.

There is an urgent need for more data on the value of k the ratio of lateral to vertical pressure in unsaturated silage.

When silage reaches saturation an increase in vertical pressure will increase the pore pressure and cause an equal increase in lateral pressure: see Section 5.6.1.

The coefficient of friction of silage on the silo wall (u') is a function of moisture content and wall surface. There is a great need for further information on its value, particularly in the 50% - 75% m.c. range: see Section 5.6.2.

The specific heat of silage can be given in the form

Specific heat = $s + \frac{m}{100}(1 - s)$ B.t.u/lb/F^{o} or Cal/g/C^{o}.

where s is the specific heat of dry matter. The only reasonable quoted figure for s is 0.45. This requires checking.

7.1.6. Chapter 6, Calculation of Physical Behaviour of Ensiled Crops

Using the finite lamina technique, described in Section 6.1., the densities in and pressures exerted by the material in each lamina in a silo filled with specified material of a wide range of moisture contents and maturities can be calculated.

The comparisons, in Section 6.2. between my own and published records of the densities in and pressures on silos and the values of densities and pressures calculated using my finite lamina method confirm the validity of the method but highlight the need for further data on the physical properties of the crop.

The currently used empirical pressure formulae for silage all have serious shortcomings when extrapolated: see Section 6.2.2.

The optimum filling technique which gives the maximum dry matter capacity consistent with reducing the risk of effluent and high pressures to an acceptable level, can be determined using the finite lamina technique: see Section 6.1.2.

The capacity (C ton d.m.) of a silo filled using a standard filling procedure with average maturity grass can be given approximately as

$$C = \frac{\pi D^2}{4} \times 10^{-3} (3.6\ h_u + 0.050\ hu^2) \text{ tons d.m.}$$

where d is the silo diameter in feet

hu is the utilised height before settlement in feet.

This should provide the basis of comparison of silo capacities in place of cubic capacity, the highly misleading measure currently used: see Section 6.2.5.

To limit the initial heat rise and consequent losses in silos to an acceptable level the filling procedure must ensure that the density of silage reaches at least 25 lb/ft^3 in normal silos, and 30 lb/ft^3 in silos with unloading flues, within three days of ensiling. With existing field equipment only silos of 20' diameter and less, without flues, can be filled fast enough to achieve this consistently at the recommended filling moisture contents: see Section 6.3.5.

The annual cost of replacing the energy, used in raising the temperature of silage, by barley is

£14. 10. 0d. per 10°C per 100 tons d.m. at 60% m.c.

and £33. 0. 0d. per 10°C per 100 tons d.m. at 80% m.c.

If the temperature rises above 40°C and there is a loss of protein digestibility in addition to the loss of energy this will cost

£84. 0. 0d. per 10% loss in Protein Equivalent per 100 tons d.m. for grass at 12% C.P. (P.E. 8.4.): see Section 6.3.4.

7.2. RECOMMENDATIONS

7.2.1. Improvements in Agricultural Practice

Silo design is currently based on the extrapolation of existing empirical formulae. This has lead to a number of structural and operational failures in silos (see frontispiece). The main practical conclusions of this thesis have been incorporated in the Draft for a British Standard (138). This standard should be applied to check existing silo designs and to produce new more satisfactory designs.

The methods of calculating the optimum filling moisture contents and filling rates is set out in Chapter 6 and the Draft B.S. This should be used as the basis for advice to farmers on the choice and method of operation of silage conservation systems.

7.2.2. Further Research

Further research should be carried out as a major co-ordinated research programme on ensilage to include:

(a) the incorporation of the calculation technique developed in Chapter 6 into a computor programme, which would calculate the physical behaviour of silage for the whole filling and unloading cycle.

(b) the monitoring of filling and unloading, pressure, stresses, densities and temperatures in full size silos as suggested in Sections 2.2.8. and 2.3.4.6., to provide a check on the validity of the calculation technique.

(c) the further study of the Physical Properties of Ensiled crops, as recommended in Sections 5.5.16 and 5.6., to provide the basic information for the calculation technique.

Similar programmes could be undertaken to study the behaviour of other agricultural and industrial materials stored in silos.

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