An Investigation into the Production and Performance of Low-Technology Ceramic Filters for Point-of-Use Drinking Water Treatment in Developing Countries

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Abstract:

Lack of access to wholesome water is a significant factor in morbidity and mortality for over one billion people in the developing world. Classical western water treatment technologies are unsuitable, and often unsustainable, interventions due to the lack of infrastructure and the prohibitive cost of installing, operating and maintaining such systems. A locally produced simple filtration system, developed from low-technology ceramics and operated at the point-of-use, represents one of the most promising approaches for an effective and sustainable solution.

Filters fabricated using simple clays, tempered with common waste materials and produced using techniques that are ubiquitous to local artisans were found to be capable of removing bacteria with extremely high efficiency (average removal rates >99.98%).

Considerations for materials (clay and temper), manufacturing (moulding, drying and firing) and operation (duration, regeneration and flow conditions) were made to ensure that the optimum balance of simplicity and performance was achieved.

Simple system adaptations were made to the basic filtration units by incorporating low-technology adsorbents capable of removing other contaminants of concern, such as arsenic and heavy metals.

The end product is a cheap and simple ceramic material, suitable for use in household filtration systems, which allows the effective removal of bacteria, associated pathogens, toxic pollutants and metals from contaminated water, and notably, can be produced and operated without the need for imported skills or materials.

Abbreviations:

AAS,HG	Atomic Adsorption Spectrophotometer, Hydride Generator
APHA	American Public Health Association
As	Arsenic
BAMWSP	Bangladesh Arsenic Mitigation Water Supply Project
BGS	British Geological Survey
CDC	Centre for Disease Control and prevention
CFU	Colony Forming Units
DFID	Department For International Development
DPHE	Department of Public Health Engineering
E. coli	*Escherichia coli*
GWP	Global Water Partnership
HAC	Heat-Activated Charcoal
ICDDR,B	International Centre For Diarrhoeal Disease Research, Bangladesh
IDWSSD	International Drinking Water Supply and Sanitation Decade
LMH	litres per meter squared per hour ($lm^{-2}h^{-1}$)
MDG	Millennium Development Goals
NERC	Natural Environmental Research Council
NGO	Non Governmental Organisation

NTU	Nephelometric Turbidity Units
PFP	Potters for Peace
PHAST	Participatory Hygiene and Sanitation Transformation
PVC	Poly Vinyl Chloride
QUANGO	Quasi Autonomous Non Governmental Organisation
RPM	Revolutions Per Minute
SEM	Scanning Electron Microscope
SEMs	Scanning Electron Micrographs
SODIS	Solar Disinfection System
UN	United Nations
UNEP	United Nations Environment Program
UNICEF	United Nations Children's Fund
USA	United States of America
UV	Ultra Violet
WCW	World Commission on Water for the 21st Century
WHO	World Health Organisation
WSSCC	Water Supply and Sanitation Collaborative Council

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"Access to safe water is a fundamental human need and, therefore, a basic human right. Contaminated water jeopardizes both the physical and social health of all people. It is an affront to human dignity"

Kofi Annan, United Nations Secretary- General

1. Introduction

1.1 Water

Irrespective of wealth, health and social caste, the physiological human need for water, and the importance of the quality and quantity of this water to ensure good health, are universally acknowledged.

The world's growing population is facing a perilous water predicament. Domestic water usage for drinking, washing and cooking, together with industrial and agricultural demands, impose a huge strain on what is a diminishing global resource. In the last century the world's population has tripled, though our water demand has increased sixfold (WHO/UNICEF 2000). This is a long way from being sustainable.

Viewed from space, the Earth appears a blue planet, with water covering 71% of its surface. Closer to the truth, is that fresh water is one of the Earth's most precious finite resources. Water is a commodity that is widely taken for granted. Only 2.5% of the world's water is non saline; of this fresh water two thirds is locked up in the polar ice caps and glacial regions. By the time the volume that is geographically accessible and viable for use is taken, what is left is 0.08% of the world's total water resource available for all domestic industrial and agricultural requirements. (WCW 2000)

Changing global weather systems, receding ice-caps and increasingly common 'extreme' weather events are all affecting the global water cycle. Whilst one corner of the earth suffers deluges, another experiences drought. What is common across these dynamic and diverse regions and climates, is the need for a consistent quality water source to support life.

1.1.1 Health, wealth and development

A child dies every 15 seconds from preventable water-related disease (WHO/UNICEF 2000). There are significant social and economic implications in such pandemic disease. 89% of deaths through communicable disease occur in the developing world (WHO 1999) It is widely recognised that for any significant difference to be made in the life styles of the 2.8 billion people currently living in poverty (less than $2US daily income, World Bank 1999) an improvement in health and well-being is a fundamental prerequisite. Only through a reduction in morbidity and mortality can the economic capacity of both the people and their nation be increased.

To facilitate this reduction in mortality and morbidity, an appreciation of the chief causes and methods of communication of diseases is required. Using an epidemiological model of 'source-pathway-receptor' for the four most significant causes of morbidity in the developing world, water can be identified as the principal pathway accounting for 3.4 million deaths in 1998 (WHO 1999)

Wholesome water is not only vital in the prevention of disease but also in its treatment. Diarrhoea is the primary water-related killer; its most significant physiological effect being dehydration. Wholesome water and re-hydration solutions are the key to effective treatment. At the other end of the spectrum, the treatment of immunological compromised HIV/AIDS patients with antiretroviral drugs is greatly compromised when the patent has not got access to a source of clean wholesome water.

Education, sanitation and water supply are three fundamental factors that have the capacity to most appreciably reduce the burden of disease that is currently causing such a high social and economic encumberment within the developing world. Through a balanced approach to these factors, it has been shown that a real and lasting difference can be made in the wealth and health status of a population and, ultimately, the development standing of a nation (WSSCC 2000, WCW 2000).

1.1.2 Water supply options

Sources of biologically and chemically safe drinking water occur naturally. This so called 'blue water' can be abstracted from aquifers, springs and uncontaminated surface waters. Blue water is fit for consumption untreated; it is also a rare, finite and increasingly scarce resource. (WCW 2000)

Throughout the last century, population growth and rapid urbanisation have outstripped the capacity for key infrastructure development such as sanitary waste removal and treatment facilities. Currently, half the world's population, 3 billion people, live with insufficient sanitary facilities (WHO/UNICEF 2000); this leads to the concentrated deposition of highly contaminated faecal material. Inadequate and poorly managed drainage, and minimal treatment capacity, result in the contamination of vast fresh water resources. The precious clean waters from deep aquifers are also under threat from poorly managed wastewater. Groundwater from as deep as 2.8km has been shown to have detrimental active bacterial fauna (Carter and Tyrrel 2001), making many supplies untenable for direct consumption.

Where a supply of blue water is not available or where the available blue water is insufficient for the needs of the population, wholesome water can be produced from the treatment of a contaminated source. Treatment options are as diverse as the water sources. They range in technical development and scope from centralised industrial treatment systems, run by profit driven utility companies, to home operated systems purifying water at the very point of consumption.

Classically, western systems have evolved to provide household connections and a source of chemically disinfected water supplied from central treatment facilities. Since the initial development of the slow sand filter in Germany in the 1800s, treatment processes have evolved significantly; though the principles remain the same. Ozone, ultraviolet light and various forms of chlorine have all been used to kill pathogens, viruses and bacteria in order to provide a clean and wholesome water source with a residual resilience to bacterial growth. Pressurised delivery networks, with reservoirs to provide sufficient capacity to maintain supplies in times of shortage or technical failure, add to a robust and reliable system (Twort *et al* 1994).

However, the classical western water supply model does not suit all users. The huge infrastructure requirements of such a system make for a very inflexible system entailing high initial costs and little capacity for expansion and adaptation. Transient and rapidly established communities, such as those in many areas of the developing world, have little scope for assimilating heavily infrastructure-based systems; a viable alternative to the western model is the development of point-of-use technologies.

Point-of-use has many advantages. Primarily, that it can provide a quality water source at the point of consumption. Benefits of this are evidenced in the reduction of recontamination incidents, a common problem in the storage and transport of water, especially when using communal water sources or in a delivery network susceptible to loss of pressure and intermittent supply (Sobsey 2002).

Point-of-use technologies shift the responsibility for operation and maintenance to the end user. By installing the treatment system at the point-of-use, the end users are made aware of the importance of hygienic practices and good management of both the treated and untreated water. Point-of-use schemes also offer considerable flexibility. Little hard infrastructure is required to reach large populations and, whilst there is a significant education requirement to ensure a sufficient skill base to effectively manage the treatment system, the costs of such systems are often more manageable and better distributed throughout the life span of the project (Mintz *et al* 2001, Sobsey 2002, WSSCC 2000).

1.2 Aim

To produce a sustainable point-of-use technology to provide a household with adequate wholesome water for their drinking water needs.

1.2.1 Scope

There are a number of effective water treatment systems currently in use, either available as commercially produced units or developed by communities through years of experience. Individuals having the finance or the experience should be able to purchase or produce a water filter that is capable of providing their required daily supply of wholesome water. The aim of this thesis was not to produce another treatment technology but to focus on establishing a sustainable treatment regime capable of providing a wholesome source of drinking water at the point of consumption.

The target of sustainability is the driving force behind this work and defines the reasoning in the development of this thesis. In order to produce a system that is truly self-perpetuating, both social and physical considerations are important. With regard to the instigation of any sustainable point-of-use technology, a primary social consideration relates to whether the end user has the motivation and skills to operate such a system. If there is a social climate that will support the implementation of a point-of-use scheme, then physical factors, such as the availability of materials and consumables, together with other social factors such as skills and education, need to be considered.

1.2.2 Objectives

Whilst developing the proposal and the initial course of study for this research, some key objectives, premised on the underlying philosophy of the project's aims, were established. These objectives, summarised below as they were formulated at the outset of the project, have guided the decision-making process as the work has evolved and developed.

- To develop a robust, low-cost, treatment regime the production of which requires no imported materials or external supervision.

- To establish the skills, knowledge and needs of the end user and reflect these at each stage of the design to ensure feasibility of production and facilitate effective assimilation of the system into the daily routine.

- To assess the performance and possible adaptation of the filter in the removal of non-biological contaminants, specifically the removal of arsenic from groundwater.

- To investigate operation and maintenance regimes, and establish best practice for the handling and regeneration of contaminated filter units.

1.2.3 Approach

Taking into account both physical and social constraints, what is required is a system that, rather than introducing new materials and techniques to the end user, adapts existing practices and skills to produce a new product.

The filtration property of ceramics is well established. Recognised by Henry Doulton as early as 1827 (www.doulton.ca), the application of ceramic filtration has been developed to produce diverse products ranging from candle filters of diatomaceous earth used for water purification to flue gas ceramic scrubbers used to remove particulates from industrial gas streams (Kiely 1998).

The approach taken in this work is to combine the proven filtration capacity of ceramics with the existing craft skills and fabrication techniques for the handling, moulding and firing of ceramics that already exist in many cultures.

Production of a porous ceramic filter is possible by mixing fine clay fractions with a coarse admixture, then firing the material to produce a solid porous matrix (Clasen 2004, Khuntia 2002, Lantagne 2001). This can be achieved with relative ease and, according to the quality of the fabrication, produces a filter with a very fine porous structure capable of removing biological and physical contaminant parameters.

This thesis investigates conditions that allow ceramic filter units to be fabricated in an optimised and sustainable process accessible to even the most technology-limited communities.

1.3 Thesis structure

By way of a guide to this document, what follows is a synopsis of the individual chapters. For the sake of parsimony, only the pertinent processed data are included in the pages of this thesis; lines of investigation that proved unsuccessful or inconclusive have not been included.

1.3.1 Chapter synopses

Chapter one: Introduction

This chapter provides a brief summary of the areas covered in the ensuing work detailing project context and motivation and the design philosophy, together with the project aims, objectives and the approach taken.

Chapter two: Literature review

The background and context of the study are significant if its outcome is to be of value. In Chapter Two, issues of water, health and development are considered, and some practical requirements and limitations for possible solutions are investigated.

Chapter three: Bangladesh

Working on a treatment technology in a university laboratory provides only half the picture. A field visit to Bangladesh, a potential user of the system under consideration, offered an opportunity to take an integrated approach to the design and development of the ideas and techniques. In Chapter Three, specific historical, geographical and social issues relevant to the application of a treatment technology to a specific location are presented and discussed.

Chapter four: Methods

This chapter covers the laboratory work conducted to appraise the production criteria for the fabrication of low-technology tempered ceramics, and to take steps towards optimising the material's filtration capacity.

Chapter five: The design of a household filter unit

Bringing together the literature, the field experience and the laboratory research, this chapter looks at the production of the individual filter units.

Chapter six: Conclusion

A concise summary of the findings of the work and proposals for possible further investigations.

2 Knowledge base

2.1 Chapter abstract

This chapter represents a summary compiled from the reading, meetings, conversations and research undertaken from the point of inception to the conclusion of this work. The background research has been an ongoing process and has covered a wide range of disciplines and source materials. What is reported here is only the background relevant to the work contained in this thesis. Using the power of hindsight, it is laid out to support the rest of this document rather than to indicate a chronological order of the work.

The introductory chapter outlined the initial motivation for this study in order to support the course of action that followed and create an impression of the way in which the work has evolved. In this second chapter, issues and options pertinent to international development and the development of a treatment regime are investigated. These issues range from politics and policy through to the importance of, and threats to, wholesome water, and the difficulties, prejudices and practicalities associated with domestic-scale water filtration schemes.

2.2 The Development

2.2.1 Understanding the indefinable

To start with a definition of 'development' would reduce the ambiguity surrounding what is meant by this contentious term in this context. Development is, however, a subjective and indistinct concept that means different things to different people, so the temptation to offer a single semantic definition is resisted. As a discipline, development encompasses a broad spectrum of people from the world's poor to the World Bank, and geographical regions from Newcastle to New Guinea. Likewise, this thesis has delved into many disparate disciplines. Therefore, to take one semantic definition of the subject would not do justice to the magnitude or significance of the concepts it embodies.

In place of an exclusive definition, a scope for what is implied by the concept of 'development' can be constructed. There is an initial and significant ambiguity in defining the parameters of a process such as development; the continuum that development represents having no fixed limits or way points. In outlining a scope for development it is imperative, at the outset, to consider some of the pitfalls of 'prescriptive' development. As a process, a 'top down' view of the developing world as simply a developing market, is one that is questioned by Ivan Illich (1997). His view that, "Rich nations now benevolently impose a straight jacket of traffic jams, hospital confinements and classrooms on the poor nations, and by international agreement call this development", represents an interesting interpretation of the motivation behind development policies popular amongst some major financial agencies. Such policies advocate 'capacity building', focused primarily on establishing financial strength, allowing the infrastructure and services to the poor to be dragged along by increasing economic ability.

Economists need to quantify current situations, and assess change, in numeric terms and so rely on economic indicators to represent social situations. Whilst this is a good place to start formulating an understanding of where on the development continuum a nation lies, these indicators are of questionable value for assessing subjective and intangible factors such as quality of life. Although it may be possible to infer what social conditions may be like from economic statistics, it is important to bear in mind that the economic indicators measured, and on which the success of an intervention is assessed, are not necessarily the quality of life factors that development processes aspire to influence.

The value of economic indicators for social situations has been the subject of debate in social and economic science. It has been claimed that "there is not enough money in the world for development to succeed in a way that is measured by the terms adopted by those who make development policy "(Illich 1997). Nevertheless, it is important to recognise that this does not mean that there is insufficient finance to invest in the process, but rather that development is concerned with more than money. Arturo Escobar (1997) observes, "The signifiers of 'poverty', 'illiteracy', 'hunger' and so forth have already achieved a fixity as signifiers of 'underdevelopment' which seems impossible to sunder". With this observation, he captures many of the salient issues that can be ignored when development is assessed on an economic and financial scale. However, development is not solely concerned with investment, it is also a social process aiming for dignity, respect and independence.

In its 'Vision 21' report, the Water Supply and Sanitation Collaborative Council (WSSCC) (2000) offers an insight into their perception of development as: "The process of strengthening human capabilities to make and exercise choices towards a decent standard of living". Whilst significantly more progressive in its outlook and intentions, this is still a contentious view, as it assumes that a state of hindered development results from a lack of ability. It thus fails to recognise that skills and abilities are often present but suppressed by ill-health and economic factors, often resulting from exploitation by the more developed world. Vision 21 (WSSCC 2000) does, however, recognise that change will only result from having both a will and a capacity to change.

A prescriptive approach to the 'application' of development projects, can perpetuate the stigmas of colonialism and inhibit, rather than assist, independence. The risk of Western intervention in development is to impose the view that development is a commodity that can be given by those more advanced on the development continuum, to those who are struggling. Escobar (1997) concludes, "The ploughs of the rich can do as much harm as their swords" and agrees with the theory that so called 'Coca-colonialism' is as destructive to prospects, dignity and independence as the waves of empires and slavery that were the scourge of the African and Asian continent in past centuries.

The importance of industrial, agricultural and financial stability, and a fair world arena in which to trade, are vital elements for successful development. Yet for nations to be in a position to take these political and global opportunities, should they arise, there are significant health and quality of life issues that require addressing on a grass roots level.

2.2.2 Healthy development

"Improving sanitation and water supply brings valuable benefits to both social and economic development", (WHO/UNICEF 2000).

A sustainable and significant step needs to be taken in addressing the global imbalance of wealth, health and discrepancies in quality of life. The principal obstacles that are preventing development are cited as: poverty, corruption, disease and war (UN Department of Public Information 2002). The importance of hygienic living conditions is implicit in all of these factors.

Improved health and hygiene are a crucial step in the alleviation of poverty. 98% of communicable disease deaths occur in the lower to middle income bracket (WHO/UNICEF 2000). Increasing the economic prosperity of a population on both a micro economic scale, via increased working capacity through good health, and a macro scale, by increasing international investment and industrial development, will go a long way towards improving the health, wealth and ultimately development status, for millions of people in the developing world (WSSCC 2000).

The need for hygienic conditions is recognised by all parties as an 'entry point' to human development and, hence, poverty alleviation. Groundwork, conducted by the WSSCC (2000) found that communities cited the need for improved hygiene as one of the key obstacles in the route to continued development. This view is reflected all the way to the top, with Dr Gro Harlem Brundtland, director general of the World health Organisation (WHO), citing access to water as: "One of the most fundamental conditions of human development" (WHO 2003a).

2.3 Water

Since Dr John Snow removed the pump handle from a contaminated London well in 1854 and locally contained a cholera epidemic, the link between contaminated water and disease has become better recognised by modern science. Many indigenous cultures across the world have prospered for generations due, in no small part, to a respect for the clarity and quality of their drinking water. The great civilisations of the Incas, the Romans and the Greeks all valued highly water and water infrastructure.

2.3.1 The development 'initiative'

As the gap between the rich and poor has grown, and the cumbersome wheels of international politics turn to attempt to rectify this situation, the vital role of water, and its part in achieving health, wealth and development, has received increasing recognition.

There is increasing awareness that we all share and influence the same natural environmental system, irrespective of political boundaries. Further, that fresh water is, in its own right, a finite global resource (Dublin Principles 1992 cited in WSSCC 2000). This awareness, rather than more altruistic motives, may lie behind the slow shift to a more long-sighted policy in the management of human impact on our limited fresh water resources.

Development initiatives range in scale. The UN's 1980 'International Drinking Water Supply and Sanitation Decade' (IDWSSD), aspired to water and sanitation provision for all. While international conferences, such as the earth summits of Rio and Johannesburg, have led to the UN's more realistic Millennium Development Goals (MDG) contained within the UN's Millennium Declaration (2000) aimed at reducing by half those without access to water and sanitation by the year 2015. Development is also on the agenda at G8 meetings, and, aptly, the 2003 G8 was held in the French spa town of Evian.

Quangos, such as the Water Supply and Sanitation Collaborative Council (WSSCC), together with the World Water Vision Commission Report (WCW 2000), have advocated a community-centred sustainable approach towards development. The focus of such an approach being the empowerment of populations to contribute to change, and the addressing of issues such as gender, poverty and the importance of health and education.

At the other end of the scale, yet with a similar focus, are non-governmental organisations, trusts and charities working with small-scale community schemes through to household level.

2.3.2 Developing successfully?

International attempts to redress the water supply imbalance have had some success, with the view of water as a shared global resource gaining acceptance, and a more holistic approach to catchments as international commodities gaining precedence. The WCW Report (2000) has highlighted some of the more pertinent aspects of water management and the need for a holistic global approach to water use and conservation.

During the IDWSSD, 1600 million people were serviced with improved water supplies (WHO/UNICEF 2000). This represented a considerable increase in funding and a shift in attitude toward the development sector. In real terms however, even this effort struggled to make a significant impact on the health status of the poor as this decade also saw the population of the developing world grow by 800 million (WHO/ UNICEF 2000). Though some successes were recorded during the IDWSSD, much of the work was insufficient and some ineffective. However, valuable experience has been gained from this drive for service provision and many important factors reflecting the sustainability of various infrastructure systems have come to light.

Water supply needs to be provided to 280,000 additional people a day for the next 12 years to meet the UN's 2015 target (Mintz *et al* 2001). At the current rate of provision, coupled with the non-committal approach of many of the world's major financial players, and the shift of aid focus from water and sanitation provision to a more economically driven focus on capacity building, there is little hope of achieving this. The Johannesburg Earth Summit in August 2002 saw international ratification of the millennium development goals; the Johannesburg summit also cost £56 million pounds to host in a country where 57% of the population live in poverty.

The year 2003 was designated the 'year of fresh water' by the WHO, yet government funding for all aid projects rose by £1.5 bn whilst defence spending rose by £3.5 bn (BBC news archive 2003) Hence although developed countries put time and resources into the promotion of water, health and hygiene, their achievements in these fields often fall short of expectations.

2.3.3 Water- elixir of life and root of all evil

"Contaminated water jeopardizes both the physical and social health of all people. It is an affront to human dignity" Kofi Annan (2003), United Nations Secretary-General.

Water is of interest to the public health and development engineer (if it is indeed possible to 'engineer development') in two guises. It is of interest as clean water for consumption, and then as foul water for treatment and disposal. It is not possible to consider drinking water and the provision of safe water for consumption without regard for the rest of the network into which it fits (Figure 1)

A number of studies have assessed the importance, and impact, of water supply in isolation; similarly, the role of sanitation in improving hygiene has been well researched (summarised in Sobsey 2002). A more interesting approach is the assessment of the symbiotic roles of water supply, sanitation, drainage and education (Cairncross and Feachem 1993; Esrey 1996a; Esrey 1996b). In some circumstances combined interventions have been seen to yield greater benefits than the sum of their parts.

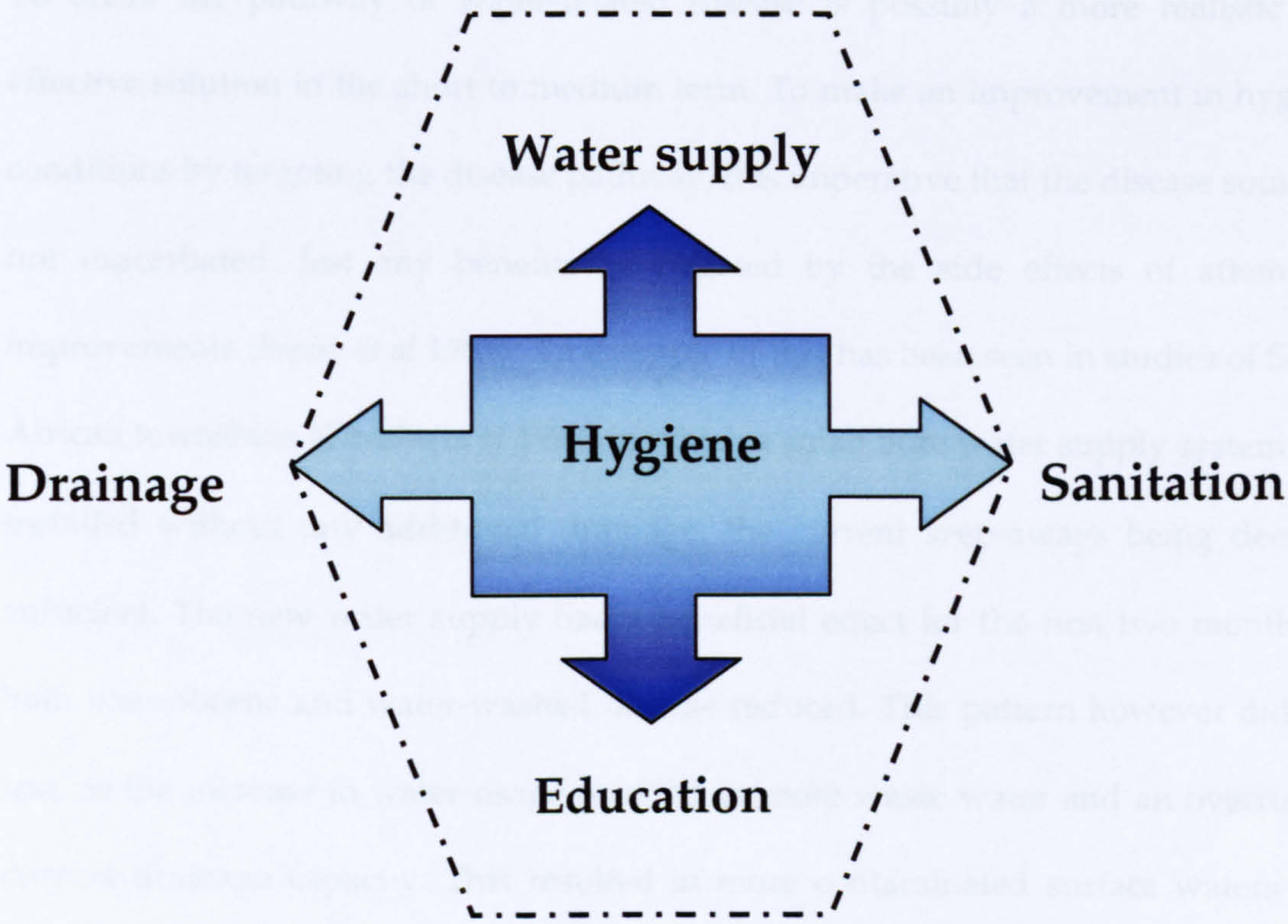


Figure 1: The tools associated with hygiene promotion (dashed line contains those within the scope of this project.)

The basic source-pathway-receptor model introduced in Section 1.1.1 highlights the two options for reducing the scale of water-borne disease; either stop the source or break the pathway. High density poor populations, often in illegal settlements, frequently have no capacity to dispose of their waste. Similarly, it is not economically viable to collect and treat the waste from small disparate rural populations. To combat this, waste-minimising and self-composting sanitation facilities are being installed, though the current rates are far from sufficient. Even if the UN's MDG targets are met, there will still be one billion people without adequate sanitation; add to this the contaminants sourced from agriculture and livestock, and it is evident that it is not possible to eliminate the source of disease.

To break the pathway of water-related disease is possibly a more realistic and effective solution in the short to medium term. To make an improvement in hygiene conditions by targeting the disease pathway, it is imperative that the disease source is not exacerbated, lest any benefits be negated by the side effects of attempted improvements (Esrey *et al* 1985). An example of this has been seen in studies of South African townships (Genthe *et al* 1997) in which a small bore water supply system was installed without any additional drainage, the current seep-aways being deemed sufficient. The new water supply had a beneficial effect for the first two months as both water-borne and water-washed disease reduced. This pattern however did not last, as the increase in water usage resulted in more waste water and an overrun of current drainage capacity. This resulted in more contaminated surface waters and ultimately, greater exposure to water-borne disease, and deterioration in health.

2.3.4 Water: the risks

Water, whilst essential to human life, is also a potential source of disease. All manner of hazardous material is present in water, both naturally occurring and deposited through human action. Health hazards can be in the form of deposits of hazardous material or elements, or innate, using water for a stage in its life cycle.

Classifying diseases by causative agent, such as microbe type, has a value in terms of understanding the etiology of infection. However, a definition based on the mode of transmission can be of more relevance in understanding, and taking action against disease. Whilst not mutually exclusive, Bradley (cited in Feachem *et al* 1986) suggest the following four groups:

water-borne or faecal oral - caused through consumption of contaminated water (for instance diarrhoeal diseases, infectious hepatitis, typhoid, guinea worm).

water-washed - caused through the use of inadequate volumes for personal hygiene (for instance diarrhoeal disease, infectious hepatitis, typhoid, trachoma, skin and eye infections).

water-based - where an intermediate aquatic host is required (for instance guinea worm, schistosomiasis, giardia).

water-related vector - spread through insect vectors associated with water (for instance malaria, dengue fever).

"Adaptations to this classification system, replacing the waterborne category with 'faecal-oral' (to reflect multiple routes of transmission), and the restriction of the water-washed diseases to only those skin and eye infections that solely relate to the quantity of water used for hygiene, have been suggested" (Cairncross and Feachem, 1993).

Addressing the water quality issue at source is principally concerned with reducing the concentrations of hazardous biological and non-biological pollutants. The reduction, removal or inactivation of the contaminant load requires an understanding of the contaminant's source and morphology, or similarly chemical state, and life cycle.

2.3.4.1 Quality or quantity?

Water can be hazardous to health both in its quality and in quantity. Beyond the required minimum consumption (1 – 4.5 litres a day according to climate and activity, Howard and Bartrum 2003), water is required for maintaining health through good hygiene. Keeping utensils clean and bathing are both vital to maintaining good health. The importance of hand washing, especially when handling small children and food, has been shown to be a significant potential health intervention. Hand washing with soap has the potential to reduce the incidences of life threatening diarrhoea by more than a half, as well as reducing acute respiratory infection (Cairncross 2003).

Promoting the use of water to encourage better hygiene behaviour, requires ensuring access to a low-cost wholesome source (Siddique *et al* 1995). High cost water sources have been seen to encourage elasticity in source selection rather than to influence the quantity of water used (Cairncross and Kinnear 1992; The Economist 2000). This elasticity will lead to using water that ranges in potability, potentially exposing the users to a greater risk through a wider range of contaminants.

2.3.4.2 Biological contaminants

Pathogenic biological contaminants are invasive parasites with the capacity to cause illness in a human host. Such pathogenic parasites are often in the form of opportunistic, facultatnive parasites, such as bacteria. Whilst capable of completing their life cycle outside a host, they will colonise the human body, primarily the digestive system, though potentially the skin, organs and blood as well. Alternatively, parasites can be of an obligate form, such as viruses and helminths. These parasites require the support of another organism to develop, in the case of human host the infection can result in extensive illness.

There are billions of bacteria in our bodies yet the introduction of minute populations of foreign parasites can be enough to make us seriously ill. To effectively protect against the agents of disease, it is necessary to understand a little about them. In ascending size order, the principal water-related biological agents of concern are:

Viruses: size 2-200 nanometres - from the common cold to SARS and HIV, the severity and contagiousness of viruses is highly variable. Viruses are very small and whilst susceptible to chlorine, ozone and high dose UV, can be highly persistent. Hepatitis and polio are two of the more common viruses associated with poor hygiene (Davis 2001)

Bacteria: size 0.1-10 micrometers - opportunistic organisms able to colonise a wide range of environments. Short generation times lead to the ability to adapt quickly. Bacterial infections associated with insufficient and ineffective water supply are typhoid, dysentery, leptosperosis and cholera (Mc Feters 1990).

Protozoa and metazoa: 2-100 micrometers - larger, more complex and predatory to bacteria. Whilst still single cellular organisms, protozoa are the most abundant animals in the world, and can cause Malaria, Giardiasis and sleeping sickness, dysentery and Cryptosporidiosis (Mc Feters 1990).

Plankton: 20-200 micrometers - whilst not specifically pathogenic, are larger organisms. Zoo, and phyto-plankton are often associated with supporting high concentrations of bacteria. Single Copepods have been shown to harbour up to 10^6 bacterial cells, a sufficiently large dose to induce symptoms of cholera in a susceptible host (Mc Feters 1990). They are "seen as playing a major role in the multiplication, survival and potential transmission of cholera" (Huq *et al* 1996).

Helminths: 100+ micrometers- more complex multi cellular organisms, the eggs and larvae of worms and flukes colonise a carrier to incubate or procreate. Helminth infections, whilst often non-fatal, affect an enormous population, estimated to number 2 billion people (WHO/UNICEF 2000). Common infections are pin worm, round worm, hook worm and scistosomiasis, all of which are commonly associated with water supply concerns.

Identifying the presence of any of the above pathogenic organisms can be complicated. The specific growth conditions and relatively small populations of individual organisms can make finding them, successfully culturing them and subsequently identifying them, difficult. The use of common and readily-cultured indicator organisms is common practice in assessing the suitability of water sources for drinking. Faecal coliforms, such as *E. coli* and *streptococcus*, are both robust and relatively safe to handle. They also occur in significant numbers where faecal contamination exists, making them ideal indicators of the possible contamination with pathogens.

2.3.4.3 Non-biological contaminants

Not all hazards are living organisms. The litany of years of poorly regulated industrial activity and increasingly intensive agriculture, combined with large-scale industrial accidents (notably, Bhopal and Chernobyl), and corporate environmental abuse, have led to the application and dumping of millions of tonnes of metals, pesticides, chemical wastes and other non-biological contaminants. Ultimately, a major sink for all of this contamination is ground and surface water. Combined with the less preventable, but equally damaging, leaching of natural sources of toxic minerals and metals, there is additional risk to health from non-biological factors. This risk often presents as chronic symptoms and cancers, rather than the more apparent and easily recognised acute responses, and is a real concern in the development of water courses. The British Geological Survey, (BGS) in their water quality fact sheet (BGS 2001), specify inorganic ions, principally arsenic and fluoride, as the greatest problem of all.

Non-biological factors present an enduring and not necessarily obvious hazard. The bio-accumulation of even minuscule concentrations of toxic compounds can have significant long-term health effects. Whilst there are standards that set targets for the maximum allowable concentrations, it is worth considering the reasoning behind the setting of these standards. Detection limits for the available test procedures often dictate the level at which the standards are set, whereas if a purely risk-based approach was taken, the level may be even lower.

Through improved regulation of hazardous substances, and the potential for less chemical-dependent agriculture (due to genetic engineering), the use of toxic non-biological hazards may diminish. This will not however reduce hazardous sources of a natural origin, nor will it remedy the situation as it is at present.

2.3.5 Rights

"Access to safe water is a fundamental human need and, therefore, a basic human right." Kofi Annan, United Nations Secretary-General (cited in WHO 2003a)

As a key element in the founding charter of the United Nations (UN), and an explicit clause in the UN Convention on the Rights of the Child (UN 1989), access to an 'adequate supply of wholesome water' is recognised as a fundamental right for all children. 2003 saw the adoption of General Comment 15 as part of the Economic, Social and Cultural Rights (cited in WHO 2003a), and made water not only a public good but a human right. Yet, access to wholesome water is a right not enjoyed by 1 in 6 of the world's population. Wholesome water is not just a human right, it is a prerequisite for the development and care of present and future livelihoods and generations. A lack of access and a poor quality of water are key factors preventing the progress of the 2.6 billion people who currently live in a state of abject poverty (less than US$2 per day) (World Bank 1999).

2.3.6 Human costs - the triple burden

Water-related disease, including malaria and diarrhoea, is the developing world's single largest killer (WHO/UNICEF 2000). There is a significant triple burden on resources, finance and time involved in dealing with pandemic disease. Diarrhoea resulting from inadequate and unhygienic water claims the life of a child every 15 seconds (WHO/UNICEF 2000).

It is not just the life expectancy impact that is an important issue for communities striving to develop. Disease is a cause of morbidity as well as mortality. In the developing world there are over 4 billion diarrhoeal episodes annually (WWC 2000). Individual illness, care for the sick, as well as the effort and hazards of collecting water from distant, often polluted sources, must all feature in the health burden and costs that are incurred due to a lack of access to an adequate water supply (Schutte 2001).

A supply of wholesome water is vital to treating illness as well as preventing it. The quality of the water is especially important in treating immune-compromised patients, such as those with helminth infections or Aids/ HIV (Trevett 2002), the very young and the aged. Estimates of the extent of the impact of HIV/AIDS on the populations of the developing world vary considerably. What is beyond doubt is that the Aids epidemic is bringing countries to their knees, and its impact is still spreading. Life expectancy in the kingdom of Lesotho has dropped to 33 and is set to reach 27 in the next decade, whilst in Burundi it has fallen from 69 to 39 in both cases Aids and HIV have been cited as the primary factor (WHO/UNICEF 2000).

Furthermore, the use of anti-retroviral drugs to treat second generation Aids victims requires that infants are not breast-fed; the alternatives such as formula milk require safe water to prepare them. In its absence, contaminated water is used exposing some of the most vulnerable individuals to water-borne diseases. What is now being found is that a lack of quality water is leading to an increase in mortality amongst this immune-compromised population.

The decimation of populations due to pandemic disease leads to an unsustainable family structure. The capacity for education for the young and economic activity for the principal family providers is frequently curtailed due to illness and care of the infirm. This can result in generations of children missing out on available schooling. Education is a significant facilitator of improved health. An awareness of germ theory and the roots of infection, as well as good hygiene habits, are only going to be developed through attendance at basic schooling. Sadly, those most in need of this are those who are hardest to reach, as the pressure of poor health reduces the available time for earning, schooling and care for the family; so, the cycle is perpetuated.

2.3.7 Access

The Millennium Development Goals set targets for water supply in terms of a population with 'access to safe water'. The use of the word 'access' introduces an unhelpful ambiguity in achieving a successful increase in standards of living through the supply of safe water.

There are currently one billion people recognised as living without access to safe water. Yet many more live with severely restricted access to, what is frequently, insufficient or an untenable supply. These people are not included in the statistics despite their need for improved supply, and consequently the published data are probably a substantial underestimate of the true extent of the problem.

Insufficient access can result from a poor understanding and recognition of the available water, as seasonal changes can render supplies unsafe, or poor maintenance and sampling can result in so called safe sources being designated as of poor quality. A number of studies have found shortfalls in what are classed as safe water supply systems. 86% of wells in Khatmandu have been found to contain *E. coli*, whilst 58% have been found to be contaminated to unsafe levels, with more affected during the rainy season (Bolt 1999). Moreover, 8% of 'safe' tube-wells in Bangladesh are in fact microbiologically unsafe (Chemistry in Britain 2003).

The African and Asian urban populations are expected to double over the next 25 years; despite this, coverage for urban water supplies has decreased during the 1990s (WHO/UNICEF 2000). The reliance on water vendors to provide access to water for the ever increasing urban populations has left the important regulation of quality and access down to poorly managed local cartels, themselves a target for corruption and poor supply quality.

The importance of improving access to safe water is not only to reduce the burden of disease but also to free people from the encumbrance of collecting water, increasing their time available for family care, education and economic activity. Currently, water collection requires the expenditure of 10 million person years annually, with 40 billion working hours lost to water carrying each year in Africa (Mintz *et al* 2001). This burden is typically borne by the women and female children of households. Injuries from carrying weights at a young age, vulnerability to attack, potential for damage to the spine, the early onset of arthritic diseases and risk of hip damage, could all be reduced through improved access to water (WHO 2000).

Storage of small quantities of water for daily needs and stockpiling of water to see out dry times are necessary procedures where access to water is intermittent or limited. Improved access to water supply systems reduces the need to store water in the home, a known point of contamination (Sobsey 2002). Outbreaks of Dengue fever have been common in India and are linked to the practice of domestic water stockpiling.

2.3.8 At what cost?

The need to pay for what some see as a 'God-given gift', is well-established and evidenced by western consumption of 'designer' bottled water (at up to £6 per litre in a recent London heatwave), and in the developing world where people spend up to 40% of their income on so called 'safe water' (UNICEF 1995).

Successful water supply is inextricably linked to the financial constraints of cost, price and value (Hulton 1980). It has been said that you can filter anything from water if it is filtered through enough money (Van Dyke 1986). For both the provider and the consumer, finance is inextricably linked to success. Somebody has to fund the initial outlay, somebody has to pay the ongoing costs of operation and maintenance and, ultimately, the project needs to bring about a reduction in ill health and an increase in economic activity to ensure that 'value' is achieved, and the investment is considered profitable.

Now recognised as a key element in poverty alleviation, and development through improved economic capacity, the links between water supply and its economic results are becoming increasingly apparent. As improved water leads to improved health, so improved health leads to improved micro-economic capacity (Mintz 2002, Sobsey 2002, WSSCC 2000). There are also savings to be made through improved water provision on a macro-economic scale for the end users. A study in Karachi (WHO 2003a) found that people living in areas without adequate sanitation or hygiene education spent six times more on medical treatments than people who had such services. While, on a macro-scale, Peru suffered a massive cholera outbreak in 1991 in which nearly 3000 people died. In ten weeks Peru lost an estimated US$1billion in trade and tourism, more than three times what had been spent on sanitation in the preceding decade (WSSCC 2000).

There is uncertainty about how much money is required to improve this global situation, and controversy over where the finance is to come from. Meeting the MDGs will certainly take a sizeable investment, but there is no agreement about how much is needed. In 2000, a group under the auspices of the World Water Council (WWC) and the Global Water Partnership (GWP), two large international quangos, estimated that investment in water in poor countries was running at about US$ 75 billion - 80 billion a year, and suggested that this would have to be raised to some US$ 180 billion (WWC 2000).

WaterAid, a respected British charity, suggests that an extra US$ 35 billion a year would be a sufficient investment. Its planning director, Stephen Turner, has observed that appropriate provision often means standpipes in villages, not piped water to every home. The Water Supply and Sanitation Collaborative Council (WSSCC 2000) note that if low-technology solutions were to be properly implemented, coverage of water and sanitation could be achieved at one tenth of the US$ 110 billion price-tag the World Bank has earmarked.

Regarding where the money is to come from, opinions differ. Whether it is more effective to achieve universal water supply through private, profit-making industry, or through public, subsidised, provision, is unclear. Essentially, as a profit-driven service, water, paid for at a full market value, should be a relatively economically-sustainable process. The ongoing costs are taken into account in the price, and profits are only made after the principal initial costs have been recovered. There are down sides to the private approach. The rural poor are often overlooked, as they are not as cost effective to connect as their urban counterparts. Furthermore, the scope for corruption and the development of so called 'Water Mafia', can result in the costs of water supply being borne disproportionately by the poorest people; people for whom the purchase of water can equate to 40% of their annual income. Securing the capital to invest in water quality improvements can be a major hurdle for the poorest people. The Grameen bank lends money to 2 million landless Bangladeshis; as an alternative to traditional collateral, the credit reputation of local groups is staked against loans to fund water supply systems. In 1993 it lent US$ 16 million at 20% interest (WSSCC 2000). Such approaches to total cost recovery can however price out the poorest people.

The principal alternative to the private sector remains the public sector, supported by aid and charity. The scale of the water and sanitation shortfall and its significance is one problem that cannot be remedied through charity alone; it is a time for policy to take a commanding role (Short 2000). Well-intentioned projects funded by short term aid are recipes for constant failure (Short 2000); so it is unfortunate that Britain's development ministry cut the share of its aid going to water from 5% in 1997, to 3.5% in 2003, as this further reduces long-term aid to those in need.

The way to manage and fund water provision is through good governance and sound financial practice. It is apparent that only through an equitable total cost recovery structure can a sustainable system be achieved (US Department of Energy 2002). It is imperative that there are transparent and clear payment routes and minimal reliance on corruptible influences. Experiences gained through a number of projects have shown that without clear and reliable cash-flow paths, corruption is rife and confidence wanes (The Economist 2000).

The Chilean economist Jorge de Ahumada (cited in Illich 1997), writing on the costs and choices facing developing nations, said that of his own Latin America, "every dollar spent on doctors and hospitals cost one hundred lives, had not each dollar been spent on providing a safe drinking water supply".

2.4 Research Gap

The field of water treatment and supply systems is highly developed and represents a significant international industry, with an average annual value of £2.7 billion in the UK alone (www.statistics.gov.uk). Consequently, there is a growing body of research into novel technologies. Allied to this, the level of expertise and understanding in the field of physical and chemical treatment technologies, is not only well-established but continually growing. However, despite the scale and depth of this sector, no satisfactory method for ensuring adequate access to wholesome water across the developing world has yet been devised.

In an attempt to address the current lack of sustainable low-cost water supply solutions, it is important to consider whether the classic western water supply model represents the most appropriate and achievable solution, and whether there is a viable alternative.

2.4.1 The western model

Western treatment technologies and supply systems are based on a centralised treatment facility processing a combination of surface waters, abstracted from rivers, lakes and reservoirs, and groundwaters. This water is treated to reduce bacteria, pathogens and certain chemical constituents to acceptable levels; it is then disinfected with chlorine, or other disinfectants, to provide a residual resistance to contamination. Water is then supplied to individual homes via a pressurised supply network. This approach has been seen as the target to which developing countries should aspire. However, in practice the costly nature of intensively infrastructure based systems is not always an option. There are however alternative methods that offer a simpler, cheaper and more flexible solution, capable of achieving a more sustainable and far reaching water supply system.

Rapid urbanisation, a feature common across low income countries, puts huge pressure on land, resulting in high density urban settlements. Often squatted rather than legally settled, the illegal status of these settlements precludes them from receiving infrastructure support. Where support and finance are available for retrofitting infrastructure to an existing community, there are some very significant obstacles to be overcome.

If a western approach is taken, aiming to provide household or street corner pressurised connections from a central treatment facility, there are both physical and social constraints that need to be considered. The housing density and lack of road and vehicular access preclude the option of digging trenches in which to lay pipes. Alternative systems using surface-laid flexible pipes are possible, but these, whilst increasingly popular, are far from ideal; they are open to sabotage, in terms of illegal connections, and hence potential sources of contamination (Cairncross and Feachem 1993). Furthermore, such systems face topographical limitations. The land that is typically settled, being of little financial value, is often steep or prone to flooding, making it difficult to provide a system with even-distribution pressure, thus increasing the chances of leaks or contaminated water ingress (Twort *et al* 1994). Complexities in the nature of the distribution network, coupled with the difficulties of continually operating a treatment facility, lead to pressure irregularities. These fluctuations further increase the likelihood of leakages, dead ends and groundwater ingress; all of which are potential sources of contamination. In addition, the provision of a water supply without a suitable drainage facility, an infrastructure requirement that can be more complicated than a supply system, but is just as important, is likely to have a negative effect on public health.

Adopting a centralised system for the provision of water to more remote low-density rural communities is equally difficult. The costs of installing long pipe runs and managing a large delivery system are prohibitive. The operation of large delivery networks relies on pumping stations and the associated infrastructure, which may not be economic for the scale of populations served (Twort *et al* 1994)

2.4.1.1 Adequate treatment - when is enough, enough?

There is a difference between reducing water-borne contamination and reducing disease. Western standards for adequate treatment have evolved with the detection limits of the techniques used to enforce them. If standards were to be developed on a risk basis, considering infective doses, they are likely to be more complicated to interpret than current guideline levels.

Dr Richard Feachem in a letter to the Lancet (1980) suggested that even the WHO guideline for total coliforms suggested at that date, for un-chlorinated water, of 10 $CFU.100ml^{-1}$ was too stringent and that flexible standards of up to 50 $CFU.100ml^{-1}$ would offer significant benefits, both as achievable standards and as a health gain when populations regularly consume water with in excess of 1000 $CFU.100ml^{-1}$.

The adoption of highly stringent standards is not the key to improving water quality;

achievable standards that improve the quality of water whilst ensuring that the providers strive to continually improve their performance, are a better solution for both users and suppliers (Feachem 1980).

Furthermore, it is important to recognise that not all water has to be of the same quality. Water Aid's director, Stephen Turner, has commented that "when resources are scarce, there is little point in treating all water to drinking quality, since much of it is used for cleaning or washing" (The Economist 2003). For this reason, the judicious application of standards is a more powerful system than the blanket enforcement of an unattainable target.

An ethical dilemma faces treatment interventions; is it enough to promote a technique that achieves a treatment standard less than you accept yourself? Is it enough to take a small step forward knowing that you are reducing the risk, not totally removing the hazard?

2.4.2 Point-of-use: a practical alternative

"For many people in the world today, the goal of providing access to water at home will not be realised in the short or even medium-term. Practical, achievable interim goals are therefore a priority" (WHO 2003a)

Whilst this prognosis may appear negative, it serves to highlight the importance of achieving manageable small scale tasks, even if they are only stop-gap measures and play little part in the ultimate solution.

A new approach to an old problem is required. In much the same way that developing nations have assimilated modern telecommunications systems, moving straight in to the cellular networks, so domestic service providers must consider their strategies. As highly cumbersome, infrastructure-intensive wire-based telephone systems are unsuitable and becoming obsolete, so developing nations are taking on newer wireless technologies. Uganda despite the lack of basic sanitation needs already has a mobile phone network that covers the entire country. Similarly, other domestic service providers must consider whether their aim is to follow a pattern of westernisation, or assist in a process of development.

Point-of-use water treatment systems make the end user the treatment operator. By equipping the individual households or users with the necessary skills and materials to treat their own water, it is intended that the consumer can make decisions about how to best serve their individual needs and protect their own water supply. The hardware required in point-of-use systems can be kept simple to operate and made suitable for both rural and urban applications. Similarly, in disaster relief situations, where large populations can be mobilised and relocated more quickly than the speed at which the necessary infrastructure can be installed, a point-of-use system can offer a realistic and practical treatment solution.

Point-of-use water treatment technologies therefore do not follow the western model of a developed, centralised water supply system. They do, however, provide considerable advantages in their flexibility and application, one of the most significant factors being their reduced hard infrastructure needs, leading to quicker assimilation and significantly reduced start up costs.

Whilst being a non-traditional approach, point-of-use systems are receiving increasing support as the only viable system that will serve the world's poor in the short to medium term (Denny 2003; Sobsey 2002). Point-of-use is a new approach, but it is not unproven (Colwell *et al* 2003). There are a number of studies that have shown that in both developed and developing countries water-borne diseases can be reduced by appropriate treatment and storage in a domestic setting. Although figures vary according to the technology used and the situation in which it is instigated, reductions in water-borne disease ranging from 6% - 90% have been achieved using point-of-use systems (Sobsey 2002). "Point-of-use water treatment merits far greater priority for achieving a meaningful rate of implementation" (Mintz *et al* 2001).

Recontamination is a risk associated with shared community water supplies. A street corner connection, even if of a high quality, can still be the source of significant contamination resulting from poor practices during water collection and storage, or a lack of responsibility for the upkeep of the community supply. By treating water in the home, point-of-use systems address the recontamination risks associated with shared water supplies. In addition, the 'in-house' nature of point-of-use systems reduces the possibility for contamination with external pathogens, increasing the likelihood of immunity to any lasting contamination (Musa *et al* 1999).

"The only way to reverse the disastrous trend to increasing underdevelopment, hard as it is , is to learn to laugh at the accepted solutions in order to change the demands which make them necessary" (Illich 1997).

2.4.2.1 Concerns with point-of-use

By their nature, point-of-use systems require both significant motivation on behalf of the end users and good educational and social support to ensure a smooth and effective uptake by the target communities. It is imperative that, in promoting the uptake of point-of-use systems, the correct user group is supported. In many societies, traditionally, water collection is a woman's work, whilst education is a man's domain. Ensuring the hygiene message is heard by those to whom it is most relevant is vital.

Point-of-use treatment systems are not water supply systems; they rely on the availability of ground or surface waters. Whilst they do not provide an increase in the volume of water available within a domestic setting, they do provide households with the capacity and flexibility to produce wholesome water from a contaminated source. This can reduce water collection times, as more local, lower quality, sources can be used. Point-of-use systems target water quality, not quantity. Though it has been shown that increasing water quantity can be a highly effective tool in the reduction of water-borne disease, through improved hygiene practices, improved access to higher quality drinking water has the capacity to bring about great improvements in health standards in developing countries (Cairncross and Cliff 1985; Sobsey 2002; WHO/UNICEF 2000).

As point-of-use systems generally operate as a batch process, there is an additional requirement for a suitable storage reservoir for treated water to protect against the possible introduction of contamination.

Previously, point-of-use systems have not gained the unequivocal support of the World Bank (Denney 2003; Sobsey 2002). This is due to the intangible nature of the costs associated with such schemes. For example, the costs of community support and education, have proved harder to account for than capital investment. Additionally, a larger repayment structure is required as the loan is less well secured than in heavily infrastructure based systems.

2.4.3 Technological approaches to point-of-use systems

There is nothing new about point-of-use systems (Heuvel 1932); indeed water treatment almost certainly started on a point-of-use scale. As such, there are many systems both commercially available and developed through years of experience. Existing point-of-use schemes can be divided in to three categories

2.4.3.1 Heat and UV

Classically, this approach has involved boiling water using solid fuels. Whilst highly effective against disease, killing bacteria, protozoa, helminths and viruses, boiling is hugely energy intensive and without safe storage facilities, only offers a brief respite from contamination. The use of solid fuels in homes has been linked to a range of respiratory illnesses. Furthermore, the deforestation associated with the collection of firewood has been cited as instrumental to increasing erosion, reducing slope stability and putting lives at risk from increased flood risk and run-off (Fu 2003).

United Nations guidelines for the treatment of water by heating, suggest a rolling boil for 5 minutes to ensure adequate disinfection (WHO/UNICEF 2000). Whilst this is an effective guideline, as a rolling boil offers a visual guide, there is no need to expose the majority of biological contaminants to this level of heat. Pasteurisation at temperatures as low as 55 °C is capable of killing the bulk of biological contaminants, given adequate exposure time. In this respect, solar reflectors have been shown to achieve water temperatures of 65 °C, and such temperatures are capable of effective pasteurisation in a matter of hours (Burch and Thomas 1998; Safpour and Metcalf 1999; Sobsey 2002).

In addition to heat, sunlight provides a source of germicidal UV radiation. Intervention studies amongst Kenyan villages have shown reduction in disease to be achievable by storing water in transparent plastic bottles in direct sunlight (Burch and Thomas 1998). UV-a exposure of small quantities of water in discarded plastic drink bottles has been shown to significantly reduce the bacteria and viral contamination of water. SODIS is a solar disinfection system developed as an optimisation of this process, ensuring a minimum initial turbidity and incorporating periodic oxygenation to achieve the maximum effect from UV exposure (Joyce *et al* 1996).

Heat and UV systems whilst cost effective and simple, do have shortcomings. A reliance on solid fuel or bright sunshine, reduced efficacy in turbid waters, and the difficulty of treating large quantities, all detract from the suitability of these systems for domestic-scale implication in all geographical locations.

2.4.3.2 Chemical systems

Chemical water treatment provides the final quality assurance stage in western water systems. Coagulation, precipitation, adsorption and disinfection are all physico-chemical processes that can be effectively operated in the home. By definition, chemical systems rely on a supply of reagents; these can be supplied at full cost, subsidised by government or charitable initiatives, or produced locally at minimal cost. Chemical systems have the ability to remove biological and non-biological contaminants.

Removing contaminants from water by the formation, and extraction, of larger flocculated particles is the mechanism behind coagulation and precipitation treatment systems. Using simple chemicals it is possible to destabilise both biological and non-biological colloidal contaminants in water to form a dense floc that can be settled out or removed by simple filtration or gravity (Twort *et al* 1994). Iron, alum, seed extracts and dried clay have all been used as coagulation aids capable of achieving removal rates for biological contaminants in excess of 99% (Sobsey 2002). Coagulation systems require a well-controlled pH and can also be affected by other chemical water parameters. The addition of chemicals to drinking water also requires a good level of understanding to ensure they are used effectively and safely. Furthermore, residual levels of chemicals will be left in the water and these may be toxic, for example the commonly used coagulant alum.

An alternative to removing the biological contaminants is killing them *in situ*. Disinfection can be achieved using a variety of oxidising chemicals such as ozone or chlorine (Twort *et al* 1994). Disinfection with chlorine is a viable point-of-use technique. Chlorine has the benefit of providing residual bacteriological resistance but does entail some hazards related to the health effects of by-products of organic material and chlorine, namely carcinogenic trihalomethanes (Twort *et al* 1994).

Chlorine can be produced locally and cheaply using salt, water and a hypochloride generator, or available as sodium hypochlorite, or imported as the caustic and dangerous calcium hypochlorite powder. Used in conjunction with a suitable water container, the dosing of chlorine is a simple and low-cost domestic treatment option but as with all chemical systems relies on a continual and affordable source of reagents, education and a relatively high degree of operator skill.

2.4.3.3 Physical systems

Using no material or energy addition, physical systems use gravity and straining to remove suspended particles from water. Settlement or simple sedimentation is a highly effective method for removing excessive suspended matter from water. Settlement is also effective against helminths, though few other discreet biological contaminants are sufficiently large to settle due to gravity (Rushton *et al* 2000). Clumped or aggregated cells and those associated with larger organisms, such as plankton, will settle effectively under gravity. Pathogen removal rates of up to 90% have been achieved through settlement over multi-day durations (Sobsey 2002).

The principal disadvantages to sedimentation systems are that they require long durations to remove small particles and large clean vessels, and furthermore sedimentation concentrates rather than removes or inactivates contaminants. This leads to the need to carefully extract the clean supernatant water to avoid the concentrated sediments, and then to safely dispose of the bulky wet wastes.

The aim of filtration is to separate the components in a suspension by allowing the permeation of the 'solvent' while restricting the flow of foreign bodies carried therein. Filtration, in the form of physical separation, uses a fixed porous structure of sufficiently small apertures (in the case of bacteria typically requiring a pore size less than 1 microns), so that the bacteria are retained but the water permeates. Alternatively, granular media filters work by a process of surface adsorption. Surface adsorption works by using a medium that has a large surface area and a higher affinity for the contaminants than the carrier water, so restricting the permeation of the bacteria, metals and other contaminants (Hwang and Redner 2001).

Rapid-flow granular-media filters, using simple materials such as sand and carbon or more complex charge altered media, can be produced using buckets or barrels to suit small-scale applications (Skinner and Shaw 1999). The need for good operator control, coupled with relatively short filter runs between cleaning cycles, makes granular-media more suited to community-scale application. Similarly, slow sand-filters (Twort *et al* 1994), due to their delicate operation and low flow rates, whilst having been implemented at domestic levels, are better suited to a larger scale application.

Fixed media filters, utilising a membrane of porous material, offer a robust treatment system, and can be specified to treat waters to the highest standards. In their coarsest forms, fixed media filters can use woven materials such as sari material or nylon mesh. Multiple layers of these cheap materials are highly effective against druncitis and many of the larger infectious agents (eggs, ooccysts and protozoa) and aggregated forms of smaller contaminants (bacteria and viruses). Studies on filters made from folded sari material showed that a 2 log reduction of *Vibrio cholerae* was achieved from two layers of material (Huq *et al* 1996). However to achieve an appreciable removal of free suspended bacteria and viruses takes a much finer filter, and can not be achieved efficiently with coarse woven materials.

Fixed media filters made from porous rock and ceramics are both highly effective and applicable at a point-of-use level. Ceramic fixed media filters are capable of achieving sub micron pore sizes that have been shown to achieve 99.9999% removal rates for bacteria (Sobsey 2002). Typically formed as candles, such ceramic elements are capable of removing many of the smallest biological pathogens. The use of ceramics has been investigated as both an export market opportunity for companies such as Doulton (www.doultonceramics.co.uk) and for local low-cost production by Potters for Peace (PFP) (www.potpaz.com).

Ceramic filters manufactured from high quality materials in closely controlled environments are available for use in developing countries, both for in-house and during disaster relief efforts. However, the cost of such units restricts their applicability. A more perspicacious approach is the local production of filters from abundant materials. PFP have developed and field-trialled a locally-made coarse ceramic filter that is impregnated with silver to act as a bacteriostatic agent (Lantagne 2001). These units have worked well in limited laboratory-scale trials showing only minimal bacteriological breakthrough with minor bacteriological pathogens, such as *Aeromonas* and *Pseudomonas* and minimal silver leaching, a significant potential health hazard (Lantagne 2001). What is unclear however is the importance of the silver in achieving bacteriological removal. The extent to which silver alone inactivates microbes in water is limited, bacteria may also develop a resistance to the silver and many microbes such as viruses, ooccysts, protozoan cysts and bacterial spores are not affected by silver (Sobsey 2002). This fact, combined with the cost of producing colloidal silver with which to impregnate the filters, brings into question the validity of using silver within ceramic filters.

2.5 The proposed solution

A filter, produced using locally-sourced skills and materials, capable of removing biological as well as non-biological contaminants, whilst being robust and simple enough to be operated in the home, would be a significant intervention in the process of development.

As alluded to in Section 1.2.3, low-cost and universal usage, combined with good mechanical strength and filtration properties, make ceramics ideally suited for use in a domestic filtration system. Many communities are already using basic ceramic vessels for water collection and storage and the production of ceramic vessels is common practice in even the poorest of countries. "(One of) the most promising and accessible of the technologies for household water treatment is filtration with ceramic filters" (Sobsey 2002).

As outlined in Section 2.3.4.3 hazardous non-biological contaminants pose a significant health risk. Low-cost simple systems could be readily produced to remove such hazards, and combining the filtration capacity of ceramics with a non-biological treatment phase would result in a multi-barrier water treatment regime. Such a unit could be capable of achieving robust high performance point-of-use filtration. Coupled with good unit design and the right educational support system, this filter could constitute part of a viable hygiene management regime (as already exemplified in Figure 1. Consequently, this thesis will focus on some of the key issues concerned with the development and definition of such a multi-barrier system.

2.5.1 Ceramics

One of the oldest and most universal building materials, used for shelter, tools, storage and ornaments, ceramics have been found dating back to the earliest of civilisations, 30,000 years B.C. (Rice 1996)

Ceramics are a matrix of clay, water and temper, which, having been exposed to heat, irreversibly form a cohesive and stiff solid. The diversity of ceramic properties has made them suitable for a wide range of applications; from the coating surface of space crafts to the humble flower pot, the uses of ceramics are as diverse as their users.

2.5.1.1 Clay

Clay is an ambiguous term. The range of definitions of the materials commonly referred to as clay highlights the variability of the materials and its potential sources and uses. Clay is generally defined as:

- a dry powder that becomes plastic when wet,
- a specific group of minerals, encompassing rocks and soils in which these minerals predominate,
- a range of particles of specific size

Clay is the end product of weathering of silicate minerals. It is found as either primary deposits local to the parent rocks, or as secondary deposits remote from the rocks of origin, typically as a fluvial deposit. These secondary clays are the principal sources used by potters for their finer more homogenous characteristics and ease of extraction. 'Clogs' of clay can be removed directly from river banks or flood plains often at no cost.

Silica and alumina are the two constituents of rock most resistant to weathering, and as such form the basis of most clays. According to the conditions of weathering and the presence of other minerals and metals, clays can vary to include iron, manganese and other common impurities, though the basic formula is ostensibly the same,

$AL_{1.67}\,Mg_{0.33}\,Si_4\,O_{10}\,(OH)_2$ (for a basic ball or hyplas clay) (Potclays, UK).

Implicit in the principle of using low-technology ceramics, is the importance of using locally sourced materials. As such, the clays that are available in any given situation are unlikely to be well-refined or of high purity. This does not however mean that the clays are of poor quality. Due to the well-established nature of ceramic production, there is often much experience available relating to the selection and blending of clays to produce a good workable material. This selection process is based on the characteristics that the physical and chemical properties of the clay yield, rather than an exact understanding for the mineralogy and particle size.

2.5.1.2 Temper

Tempers are used by potters to influence the wet, dry and fired properties of clays.

Through an understanding of the properties of a temper, and how it will respond in the wet clay, as well as during the drying and firing processes, it is possible to influence the density, porosity, strength and appearance of final fired ceramics. Very few ceramics are found or used in an un-tempered state.

Light tempers, for example paper, perlite and vermiculite can reduce density; hydrophobic tempers, e.g. silicate, can reduce water contents and increase drying rates. Conversely, hydrophilic tempers, such as sawdust and cellulose, increase water content, slow drying and increase heat transfer; long fibrous tempers e.g. glass and nylon fibres, can improve the mechanical strength of both wet and fired ceramics (Rice 1996).

To produce a strong and porous vessel, with a uniform cross-section, necessary for ensuring an even flow path, and hence filtration performance, it is essential to use a fine and well-graded temper to promote strength and porosity.

Cellulose is a temper that is particularly suitable for producing filter elements (Gault 1999). Cellulose fibres are very fine tubes that will, in a well-refined form, increase the porosity of the fired structure, speed up the drying process and reduce the density without significantly reducing strength. Cellulose is abundant in many common materials such as wood and various plants, and in a more refined and readily available form in paper and wood pulp. Sawdust is an unrefined source of cellulose. Sawdust is hydrophilic, so slows drying, reduces plasticity and increases heat transfer (Gault 1999). There are numerous other sources of cellulose often available as agricultural waste such as rice and corn husks.

2.5.1.3 Manufacturing

The fabrication of ceramic units consists of two key phases; shaping and then drying. There are many ways to shape ceramics. The two methods best suited to producing smooth-walled vessels with a uniform cross-section and the fewest possible voids are moulding and throwing.

Moulding can be in the form of press moulding where stiff clay is forced under pressure in to a strong, usually metal, mould. This system ensures uniform density and wall thickness and is relatively rapid. The disadvantage being that in order to produce a mould that can withstand the pressure required to form and compact the clay, normally in the order of thousands of kpa, the moulds are very expensive. A lower cost method of moulding involves producing a loose clay slip that can be poured into much lighter weight moulds. Such moulds are often made of plaster, and as such are fragile but cheap. Slip-casting, as this method is known, is a viable low-cost production method. However, producing a slip requires the addition of much water which increases the drying time extensively; and, as such is better suited to thin section vessels and fine china rather than heavier, stronger products (Rice 1996, www.Potpaz.com).

The pottery wheel, in its many incarnations, offers the most viable and reliable way to produce ceramic filter vessels. Throwing pots on basic pottery wheels is a well-established skill and applicable in even the most basic of potteries.

Figure 2: Three examples of basic pottery wheels found in Dhaka Bangladesh

To produce a vessel on a pottery wheel involves starting with a relatively stiff clay containing only the minimum amount of water to make it workable. The clay is then raised and knocked back to exclude any trapped air so reducing the chances of cracking during firing. Thrown vessels are not going to be as uniform in size and shape as moulded vessels, though using basic quality control guides and skilled operatives, it should be possible to regulate production to within acceptable limits.

Having shaped the clay, the vessels must be dried to ensure there is no excess inter-pore water in the clay matrix. The run-out of water during firing can increase porosity, and, where this water cannot escape, the expansion of water to steam will cause cracking. Drying must be monitored to ensure that the 'green' vessels do not slump and deform, and that the rate of drying is not so great as to cause deformations (Rice 1996).

2.5.1.4 Firing

2.5.1.4.1 Benefits of firing

Firing is the irreversible process in which plastic, malleable clay is converted to a sintered, brittle solid. Ceramics, once fired, increase in mechanical strength and whilst still porous are unaffected by the ingress of water. Firing will result in weight loss and shrinkage of the work-piece, both factors dependent on the nature of the clay and its tempers.

Firing is not a uniform or predetermined process; it is possible to manipulate the properties of a ceramic through controlling its firing conditions. Earthenware, 900-

1200 ^{0}C, stoneware, 1200-1350 ^{0}C and porcelains 1400 ^{0}C and over, vary in their finished characteristics, mainly due to their firing conditions (Rice 1996).

2.5.1.4.2 Principle of firing

During firing, the application of heat removes chemically bound water and melts and realigns the silicates and tempers in the clay body. Changes in ceramic structure start to occur quickly as heat is applied. Surface and free pore water is driven off, then burning-off of organic materials and tempers in the clay occurs. This all happens between 100 ^{0}C and 500 ^{0}C. The burning-off of available carbon results in surface deposition as the carbon migrates from the inner structure to the surface and a more oxidising environment. Surface carbon residues are removed as the temperature continues to rise. The minimum temperature to produce an irreversible change in the clay, and to produce a vitrified solid, is approximately 550 ^{0}C (Rice 1996). From this temperature upwards, the realignment and change in the mineral structure starts to dominate. Vitrification may occur over a temperature range of 200 ^{0}C influenced by conditions such as atmosphere and soak. Porous characteristics start to develop as pores open, and they increase as temperatures rise to 800 ^{0}C as volatiles burn off. At 1000 ^{0}C vitrification, a process whereby the silicates melt and form a fused solid, takes over and seals the open pores, and firing shrinkage occurs.

2.5.1.4.3 Methods of firing

The techniques and technology for firing are diverse. From computer controlled kilns to open fires, they all achieve the same task of applying heat to the clay vessels in a controlled process. To achieve this consistently, and to minimise wastage through cracking and thermal shock, and to manipulate the properties such as porosity of the end product, it is necessary to understand and control some of the conditions that occur during firing.

Three parameters are principally responsible for the outcome of ceramic firings (Rice 1996):

- Temperature: both as maximum temperature achieved during firing and rate of change of temperature.

- Duration: the overall time for the firing as well as periods of 'soak' at set temperatures.

- Atmosphere: the availability of oxygen during firing.

As discussed previously, the maximum temperature achieved during firing will influence the properties of the final ceramic; as a rule of thumb, hotter firings produce a harder finished. The rate of heating will subject the workpieces to significant thermal stresses as the chemically combined water is released and the silicates melt. The soak period, or period for which the maximum temperatures are sustained, is also significant as the migration of volatiles through the clay body can be slow and the realignment of crystals is not instantaneous (Rice 1996).

At its most basic, a kiln is just an open fire. Vessels are placed amongst the fuel and are fired during combustion. This is a poorly controlled practice as vessels are exposed to great temperature variations. Heat gradients will exist across ceramic sections and from side to side on individual vessels; minimal soaking time at peak temperatures and the variability of the fuel, stoking and aeration of the kilns all add to the variations in firing conditions and ultimately the finished ceramic properties.

Figure 3: Basic open firing

One characteristic of open firings is the very rapid temperature rise. Open firings, using a combustible and resin filled soft wood could reach temperatures in excess of 900 °C in under twenty minutes; typical temperatures achieved in open firings are lower, in the range of 600 °C to 850 °C (Rice 1996). When firing in the open air, drafts and wind can increase the temperature variations. Kiln fuel and its relative combustion rates are parameters that will control the ultimate temperature and heating profile of an open firing. As a rule of thumb, the density of a fuel is a good indicator of the rate at which it will burn; denser fuels offering a longer burn duration and lighter fuels a higher faster temperature change (Rice 1996).

The progression from an open firing is the use of a pit kiln. Basic pit kilns feature in all but the most primitive of ceramics industries. In pit kilns, a fire is stoked in a pit underneath a low walled pen. The material to be fired is placed in the pen with layers of straw or other light fuel and then the whole stack is capped in rough soil. By heating the kiln from beneath, a more even heat profile is achieved and localised hotspots are better distributed; ventilation and stoking are also more easily controlled. The presence of top fuel preheats the pots, reducing stress in the vessels, and leaving a layer of ash, which further insulate the kiln. Using this configuration, the heat of the fuel is retained longer. This can lead to greater temperatures in the firing, and, due to the better insulated environment, result in a more uniform and efficient heating profile and longer period of soak (Rice 1996).

Solid fuel kilns come in more highly evolved forms and are popular with Western potters for their natural temperature and atmosphere fluctuations. Solid fuel kilns, being neither totally reducing nor oxidising, can provide unique finishes to glazed wares. Using a more developed solid fuel kiln it is possible to make better use of the heat by improving the insulation and recycling the heat through multiple chambers as in oriental climbing kilns. Efficiency of a kiln is an important consideration in keeping the manufacturing cost to a minimum. In Bangladesh, solid fuel pit kilns use ratios of wood to clay of between 2:1 and 3:1, being notably more efficient than the Staffordshire kilns of the nineteen hundreds which used 3:1 coal to clay (personal communications, Dhaka potters 2003). Fuel for pottery firing is often the potter's most significant financial cost (Rice 1996). The use of solid fuels has caused extensive deforestation in many developing countries which could add to a risk of exacerbating erosion and flooding.

2.5.2 Low-cost non-biological contaminant removal

2.5.2.1 Metals removal

The removal of toxic metals, arsenic being of primary concern in many deltaic regions, is an area of research that has recognised the value simple point-of-use systems can offer as a quick and effective way of reaching a large and significantly poor sector of society, (Jiang 2001; Lehimas *et al* 2001; Petrusevski *et al* 2002). Domestic arsenic removal has been achieved, and deemed viable, using two different approaches.

2.5.2.2 Coagulation/co-precipitation

The use of reagents such as alum or ferric chloride has fortuitously removed arsenic from contaminated waters as a part of the coagulation stage of conventional treatment processes (Gregor 2001). This has offered protection to those in developed countries, for example areas of America and New Zealand, at risk from high arsenic ground waters. Recently it has been shown that it is possible to recreate this coagulation/co-precipitation step in a domestic situation without the need for expensive reagents or materials. Using 2 g sachets of ferric and hypochlorite, it is possible to precipitate the arsenic from 20 litre batches of contaminated Bangladeshi tube-well water; subsequently removing the precipitate with a simple sand filter, produces safe water at a chemical cost of 0.02 cents (U.S.) per litre (Meng *et al* 2001).

There are a number of drawbacks to the use of coagulation and co-precipitation at the household level. The complex nature of the process can be easily affected by fluctuations in pH. In addition, other variable water parameters, such as elevated phosphate and silicate concentrations, common in deltaic groundwaters, can lead to a dramatic reduction in the removal efficiency (Meng *et al* 2001). A minimum water volume is required for pre-measured chemical doses; 20 litres is regularly used as it equates to standard jerry can capacities. This volume may be unavailable, or unwieldy to collect and store safely in the home; factors which could affect the way that the sachets are diluted and their ultimate efficacy. Furthermore coagulation and co-precipitation produce wet bulky wastes which need further treatment for safe disposal to ensure no leaching of the contaminants present in the precipitated solids.

Despite their drawbacks, pre-packaged solutions that use this technology are currently being marketed by Proctor and Gamble®, under the brand name PuR®. This product contains slow release chlorine residues that offer an extended protection from recontamination. The PuR® system is a well-tested and possibly highly effective water treatment solution, but significantly the marketing models on which it is based have failed to emphasise the basic education requirements necessary to ensure its effective assimilation. There is a need for a good communication chain and educational support, to ensure the correct and safe use of the chemicals. Filtration, operation and cleaning are important and long-term elements that need to be considered when costing options based on co-precipitation and coagulation.

2.5.2.3 Adsorption

One promising method for arsenic removal appears to be adsorption from solution

(Elizalde-Gonzalez *et al* 2001). Adsorption has proven to be a very efficient method to control the mobility and bioavailability of arsenic (Pattanayak *et al* 2000). Adsorption is possible on a range of media, including activated alumina, iron-coated sand, carbon (activated and non) and clays such as kaolinite and bentonite (Elizalde-Gonzalez *et al* 2001; Sobsey 2002; Petruneski *et al* 2002).

Arsenic adsorption systems have been implemented to great effect using carbon-based media in treatment plants in the U.S. Such plants have achieved 99% arsenic removal even at very low initial arsenic concentrations (Van Dyke 1986). A further benefit of carbon adsorption is its ability to remove trihalomethanes and other potentially carcinogenic contaminants. These plants operate by optimising the conditions for adsorption and utilising an adsorbent that is most suitable to the characteristics of the waters. In doing this, it is possible to achieve removal rates in excess of 90 mg arsenic/gram adsorbent (Anstiss *et al* 2001).

In a low-technology setting, this kind of optimisation is not practical as the chemicals, monitoring and plant required to control the chemical and physical water characteristics that influence adsorption, such as temperature and pH, (Manju *et al* 1998) would be prohibitively expensive and require technical knowledge that is not always available. However, there is a chance that adsorption systems could be operated at a much more basic level whilst retaining their beneficial effect.

There are numerous cost-effective carbon sources available as potential adsorbents. Whilst the majority of activated carbon used in the western world is a coal derivative (Bradley 2001), carbon from wood, bone, coconut, pecan and almond shells and other agricultural wastes have all be successfully turned into effective carbon adsorbents (Elizalde-Gonzalez *et al* 2001; Manju *et al* 1998).

Carbon adsorbs metals by providing a surface with polar or acidic surface groups to bind metal ions (Navarro and Alguacil 2002) The term activated refers to a method of preparing the carbon in which it is either acid washed or heat-treated to open the structure and provide a large internal surface area, so facilitating significant removal capacity gram for gram. Almond shell carbon, activated by staged heating, has been shown to achieve a surface area exceeding $1200m^2g^{-1}$, however non-activated carbon can also be an effective adsorbent (Pattanayak *et al* 2000). Whilst it is not directly comparable to its activated counterpart, non-activated carbon, especially when ground into small particles, still possesses a significant surface area and characteristics that will make it an effective adsorbent. Adsorption on simple carbon can be operated effectively on a low-technology level, since As(III) sorption is practically independent of pH over the range of pH values of interest in groundwaters (pH6-9) (BGS and DPHE 2001).

2.5.2.4 Conclusion

This chapter has explored the definition and politics of development, and has considered the role of water within the process of development. It has identified and discussed a number of issues related to the accessibility of wholesome water, and has acknowledged the need for further research and a new approach to water treatment. Further development of approaches focused on a low-cost, locally-sourced, point-of-use ceramic water filter that is robust, simple to operate and capable of removing biological as well as non-biological contaminants has been highlighted. It has discussed practical issues related to the proposed materials and processes involved in the manufacture of such a filter, and represents the groundwork for the chapters that follow.

3 Field study /context

3.1 Chapter abstract

There is no single geographical location, climate or topography that dominates in the developing world. Arid areas and those that are deluged by monsoons struggle alike to find sufficient fresh water. Whilst the objective of this work is to produce a water treatment system that is applicable to a broad range of locations, climates and users, it is important to recognise that all situations differ and all environments and communities have their own specific requirements. To ensure that this work is founded on a realistic view of what is practical and practicable, both for production and use of the water treatment system, it is imperative to consider the context of its intended application. To this end, a field visit was conducted to Bangladesh and the issues raised during this visit are summarised in this chapter, and Bangladesh's history and specific water-related issues are presented as a case study.

3.2 Field visit to Bangladesh

Bangladesh presents a diverse array of water-related issues, and has a history of well-established public health and social motivation projects. Generous contacts in the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B), provided the opportunity to discuss with users, producers and health workers the needs and requirements of potential point-of-use treatment systems.

Through conversations, using an interpreter, with local artisans and practitioners it was possible to record views regarding what was practical for production and what would be desirable in a marketed solution. From this discussion it became evident that consideration of the history and predicament of the population is an important element in producing an acceptable and sustainable solution. Consideration of the wealth, mobility and structure of communities is also imperative as is a sound understanding of the life span and long-term support, in both production and use, of any intervention that is proposed.

3.3 Bangladesh

Figure 4: Map of Bangladesh.

Bangladesh occupies a small, highly fertile, but very poor, corner of Southeast Asia (see Figure 4). Sitting at the northern end of the bay of Bengal, and ranking 139th out of 173 on the UN's development index (www.UNDP.org/hdr2003), Bangladesh's population of 130 million is growing at a rate of approximately 2 million a year, making Bangladesh the most densely populated country in the world (with the exception of principality states). Of the 130 million people in Bangladesh, 70 million live below the poverty level with an estimated 20 million living in 'extreme' poverty (Alam *et al* 2002).

Beset by war and beleaguered by natural disasters Bangladesh has struggled to get itself started on the road to meeting the development goals prescribed by the west. Bangladesh is a country born into controversy and hardship. In a short but brutal war it gained independence from Pakistan in 1971, and the eleven years that followed saw seven heads of state, including three military coups. Times of unrest and brutal pogroms against the educated classes, predominantly Hindu, followed independence; campaigns of strikes or 'Hartals' called by opposition parties are still an accepted and occasionally brutal occurrence. Bangladesh remains a young, and often frenzied, political hot-bed.

Bangladesh is no stranger to natural disasters. In 1787 a flood killed one third of the population, and cyclones in 1970 killed half a million (Nizamuddin and Chakraborty 2001). The subtropical monsoon climate sees the majority of its 2000 mm of annual rainfall arrive in just the four months from June to September; normal monsoon conditions see 70% of the country underwater. Cyclones and floods, and subsequent ferry disasters, landslides and building collapses, are still an all too regular occurrence. A large and late monsoon in 2003 led to the annual appearance of press coverage detailing disasters, death and damage, further perpetuating the meagre image of this ancient, diverse and culturally-rich nation.

Borders with India surround three sides of Bangladesh, whilst the entire south of the country spreads out into a mass of islands to form the world's largest delta. With the exception of the hill tracks of the Chitagong, bordering Mayanmar in the south-eastern corner, Bangladesh is ostensibly flat; 90% of Bangladesh is within 10 m of sea level. Braided by the many river channels that cover the land, being predominantly a delta fed by the mighty Padma (Ganges), Jamuna (Brahmaputra) and Meghana

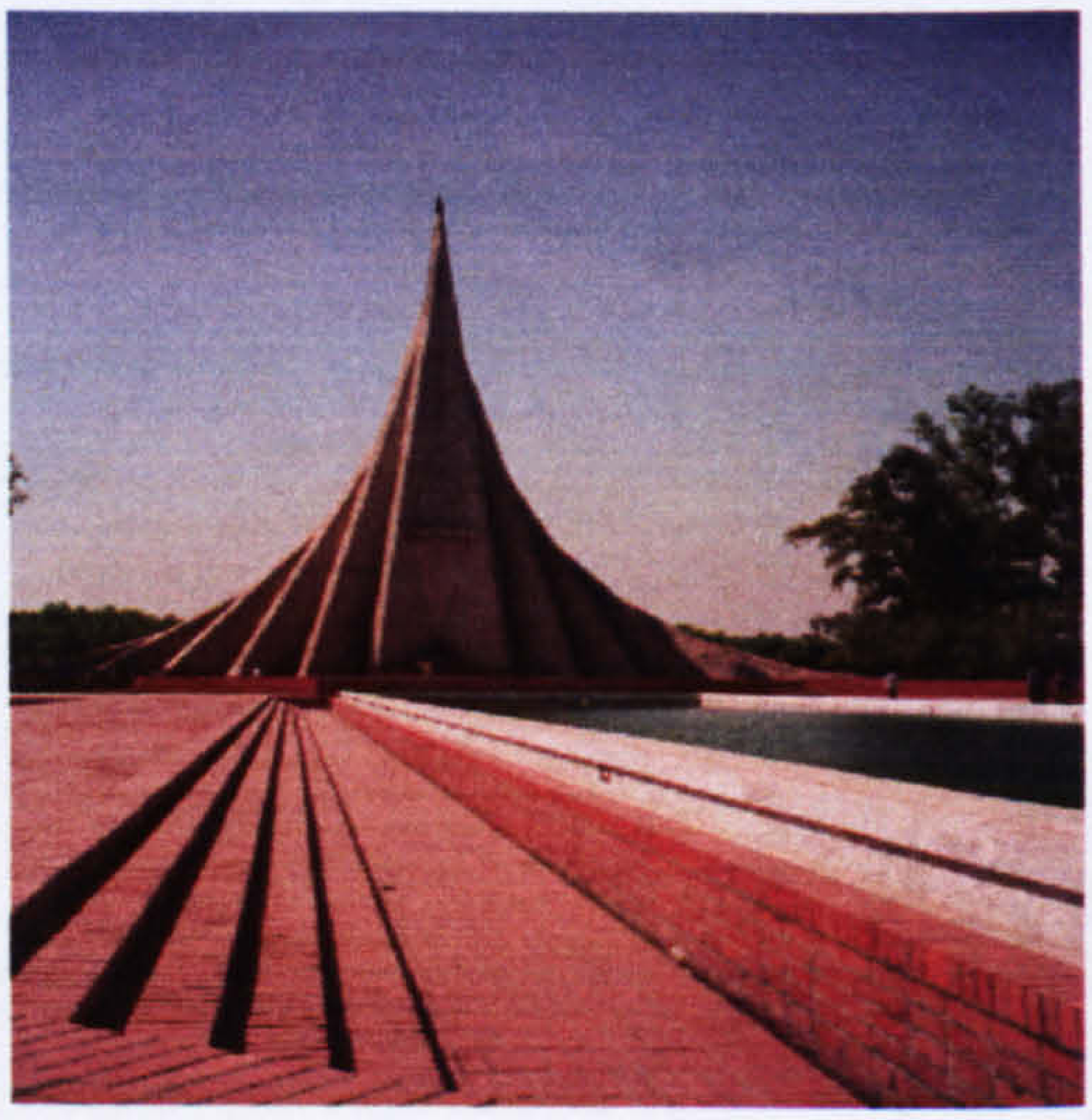


Figure 5: The national monument of Bangladesh, built to commemorate those who died fighting for freedom.

Rivers, the lowlands of Bangladesh are fed annually by the monsoons and sediments that wash down from Northern India and the Himalayas. 240 million tonnes of sediment are deposited annually across 85% of Bangladesh's surface (Alam *et al* 2002). Whilst it has the same land area as England and Wales, annually as much water flows through Bangladesh as flows through the whole of Europe. Hence there is no shortage of water but the seasonal deposition, and poor qualities of this water are major concerns.

Despite its fertile soils (73% of land use is arable) and a hard working population, it has yet to realise its economic potential and the classic economic and quality of life indicators remain low (Table 1). Life expectancy in Bangladesh remains less than the government's recommended retirement age from the civil service.

Table 1: Table of economic indicators for Bangladesh, summary of statistics from (www. Adb.org).

GDP per capita, US$	Infant mortality /1000 live births	Adult literacy rate%		Life expectancy years
		male	Female	
253	73	59	43	60

3.3.1 Water quality in Bangladesh

Bangladesh has achieved an ability to live with pandemic disease and to cope with the decimation brought about by frequent disasters. Through organisations such as the International Centre for Diarrhoeal Disease Research, Bangladesh (ICDDR,B), efforts are being made to understand the implications of water-borne diseases such as epidemic cholera, and devise to form strategies that will protect the population.

The broad spectrum of water-related disease (see 2.3.4) is not Bangladesh's only water-related concern. A programme of well instillation throughout the 1970s led to the population being served with groundwater from a network of many millions of predominantly hand pumped, shallow tube-wells. This project, funded and backed by various international organisations, governments and charities, aimed to reduce the rates of disease by providing a supposedly high quality supply of fresh water. However, supplying groundwater has not proved to be the panacea that was envisaged. In reality, the quality of the water found in the shallow aquifers, and the contamination resulting from poor well placements and unhygienic collection and storage practices, has failed to provide the wholesome water that was anticipated (Islam *et al* 2001).

Since 1993, a more sinister and equally significant water quality concern has emerged. The groundwater, initially considered a good source of microbial-safe drinking water, has come to be recognised as containing dangerously high levels of arsenic. Estimates of the concentrations and distribution of the arsenic vary, however it likely that over 40 million people are exposed to arsenic concentrations up to one hundred times the WHO drinking water guidelines (Alam *et al* 2002).

3.4 Arsenic

3.4.1 What is arsenic

Arsenic is one of the most toxic and carcinogenic substances present in ground and surface waters (Jiang 2001), yet it is ubiquitous to the earth's crust, comprising approximately 1% of all rocks, coals and soils, and significantly more in areas of alluvial deposit (Alam *et al* 2002).

Once revered for it medicinal benefits, and previously used as an ingredient in many cosmetics, arsenic causes chronic incurable exposure effects. Hyperpigmentation, depigmentation, keratosis and peripheral vascular disorders are the most common symptoms of chronic arsenic exposure; skin cancers can also result, as can cardio-vascular and neurological disease (Kabir 1999). Arsenic is also suspected as a causal factor in Haff's disease, internal cancers (lung, bladder, liver, prostate and kidney), hepatic disease and diabetes mellitus (BGS 2001).

The principal cause of concern, and the most toxic form of arsenic, is the inorganic arsenic found in groundwaters, (Elizalde-Gonzalez *et al* 2001). Inorganic arsenic, bonded with oxygen, chlorine and sulphur in a trivalent and pentavalent state such as arsenite (As_{-3}) and arsenate (As_{-4}) respectively, is the most common and lethal form. Organic arsenic, present in foods, is of less concern as its toxicity to humans is minimal (, BGS and DPHE 2001; Petrusevski *et al* 2002); (Table 2).

Table 2: The toxicology of various forms of Arsenic (data from Elizalde-Gonzalez *et al* 2001)

Arsenic specification	Median lethal dose, LD50, mg/kg
Organic: dimethylarsinic	1200
Inorganic: arsenate	14
Inorganic: arsinite	4.5

3.4.2 Extent of human risk

Estimates for the exact population at risk vary according to the subjective interpretation of what level of contamination constitutes a risk, and whether the WHO guideline or the Bangladeshi government's permitted concentrations are adhered to. The highly variable nature of the contamination, with localised 'hotspots' and wells that rapidly deteriorate, make it hard to gauge accurately the magnitude of the hazard. Furthermore, most estimates are based on data produced during the 1997 WHO, UNICEF and World Bank sampling programme; these data have subsequently been shown to be misleading due to poor detection limits of the field test kits used to gather the data (BGS and DPHE 2001).

However, even a most conservative estimate for the at-risk population is in the region of 40 million (Alam *et al* 2002; Kabir 1999). Other estimates vary suggesting between 25 and 40 million, (Jiang 2001), 70 million, (BGS 2001; Meng 2001), and up to 75 million, (Khuda 2001) are at risk. The at-risk population estimate rises to 150 million if the neighbouring areas of West Bengal are included; with yet more vulnerable populations living in Nepal, Thailand, Cambodia and Laos (BGS 2001).

3.4.3 Source of arsenic

With regard to the source of the arsenic, opinions converge on this being of a natural, geological origin. Despite the wide spread use of arsenic in industrial and mining applications, pesticides and fertilizer manufacture, and some theories pointing to the Farakka barrage that controls the low-level flows of the Ganges (Nizamuddin and Chakraborty 2001), the nature and depth of the deposits found in the sediments and groundwater of Bangladesh suggest that most arsenic originates from natural sources. The passage of the arsenic from the ground into the water is still an issue with connotations for potential liability groups and as such is causing considerable debate.

Two hypotheses regarding the transition of the arsenic from the ground to the water have been proposed so far; both of these cite the origin of the arsenic as a deposit of arsenic-enriched sediments in the subsurface soils formed by years of alluvial deposits. The two theories are, however, not compatible.

The two key hypotheses are the 'iron oxide reduction' hypothesis proposed by DAS *et al* (1996), also supported by the British Geological Survey, and the alternative 'pyrite oxidation, draw-down' hypothesis supported by Bagler and Kaiser (1996) and favoured by West Bengal's scientists.

Iron oxide reduction hypothesis

This hypothesis postulates that naturally occurring iron in the sediments that form the Bengal delta, have scoured the arsenic from the fluvial loads. Subsequently, these arsenic rich sediments have been buried under more than 70 m of dense sediments. The increase in flooded agriculture, coupled with the layers of dense sediments, produce an oxygen deficient atmosphere in the subsurface soils; a situation confirmed by the BGS in their investigations of 1992. In these strongly reducing groundwater conditions, the arsenic is released to the groundwater through processes of dissolution and desorption as the iron oxide is reduced.

Pyrite oxidation draw-down hypothesis

This hypothesis suggests that large-scale irrigation during the dry season, an action supported by the BGS in 1992, and the existing six million or more domestic tube-wells, result in significant draw-down of the water table during the dry season. As oxygen permeates the ground, arsenopyrite is oxidized releasing arsenic to the ground. Subsequently, as the water table rebounds during wetter months, arsenic dissolves into solution.

Evidence found in studies such as the Hatkopa village investigation (Nizamuddin and Chakraborty 2001) support the draw-down theory. Here, wells were found to develop arsenic contamination as they aged. Yet the spatial dispersion and density of contaminated wells, and the lack of correlation between arsenic contamination and the absence of high sulphate concentrations in the groundwaters of arsenic affected areas, lends more credibility to the iron reduction theory. Currently, the ambiguities in the source and mechanisms of transport of arsenic into the groundwater make it impossible to determine the origin of the problem, and as such makes the possibility of point of origin mitigation unfeasible.

3.4.4 Possible solutions to arsenic contamination

In 1998 the Bangladesh Arsenic Mitigation Water Supply Project, BAMWSP, was established with a US$44 million loan from the World Bank; though it is estimated that US$275 million will be required in the next 10 years to make any significant progress (Kabir 1999). The focus of the BAMWSP so far has been to assess the magnitude of the situation, and as yet little has been done to develop a strategy that deals with the mounting disaster.

Figure 6: Tube-well marked with green paint to indicate no arsenic contamination.

With no realistic option for treatment at source, one option to avoid the arsenic rich waters is to drill deeper wells. This though is not always possible, and at a cost of £10,000 for each well has limited appeal. Furthermore, the risk of increasing the draw-down and possibly raising other contaminants cannot be ignored.

Another option is to treat the contaminated waters; however, the absence of a piped centralised treatment system makes large-scale treatment plants impractical. Household level treatment schemes are being investigated using various adsorption media, such as sand, gravel, clay and brick chips, and co-precipitation with iron and aluminium. In the absence of effective groundwater treatment, reverting to the use of surface waters, and the associated disease risk, may be the only option.

As for the current sufferers of arsenosis, there are not many options. Advanced and clinical symptoms are mostly incurable; although some may go into remission provided arsenic-free water is supplied at an early stage (BGS 2001). There are also significant social stigma that result in the ostracising of arsenosis sufferers, with arsenosis sufferers often being dismissed from work and social groupings as the symptoms are frequently mistaken for leprosy. Young children can be excluded from school, and for females and the parents of female children, the need to provide a dowry becomes even more significant.

3.4.5 The legal implications of arsenic contamination

Where the arsenic has come from, and who is responsible for the exposure of such a vast population, are issues that are currently, and rather counter-productively, consuming time and finances. The World Health Organisation describes the situation as "The world's largest mass poisoning of a population in history" (Smith *et al* 2000). Equally dramatically, the American news network CBS cited the 'disaster' as being the world's largest man-made risk, drawing similes with the Bhopal and Chernobyl contamination incidents (cited in Khuda 2001).

So far, blame has been apportioned to UNICEF and the British Geological Survey. In 1999, UNICEF reported "at the time most of the wells were installed, arsenic was not recognised as a problem in water supplies, and therefore standard water testing procedures did not test for arsenic". More recently, Jan Willem Rosenboom, arsenic project officer in Dhaka for UNICEF, has said that "The UN has been identified right from the start as having something to do with it. We put the message across to sink these wells. We advised the government and now we are blamed. Yes, we do have a responsibility" (The Guardian 2003). The liability of the Natural Environmental Research Council, NERC, and its sister organisation the BGS, is currently under scrutiny. 750 Bangladeshis have been granted a right to take the BGS to trial to see if they have any liability for failing to test for arsenic in the water toxicology survey which they conducted in 1992 and which gave the groundwater a clean bill of health. The trial started in late 2003[1] and has implications for the many millions of arsenosis sufferers in Bangladesh.

3.5 Conclusion

The field visit to Bangladesh indicated that there is a need for a water treatment system with the ability to treat water containing both biological and non-biological hazards. It also made apparent that the country has the capacity to incorporate a low-cost point-of-use treatment regime, both as a potential industry and a sustainable health intervention. The flexibility that a non infrastructure based treatment system could offer being a significant advantage in a country that suffers political and financial instabilities and relatively frequent extreme weather events.

[1] The Court of Appeal rejected the appeal in April 2004, stating that the link between the individual and the BGS was too remote for a 'duty of care' to be upheld

The experiments described in the following chapter, address the issues highlighted by the groups of interested parties consulted during the field visit, and detail the development of a suitable low-cost point-of-use filter material.

4 Filter evolution

4.1 Chapter abstract

At the heart of the proposed point-of-use water intervention is a robust and reliable filter element. Community requirements and specific cultural and marketing necessities dictate the appearance and specifications of the final units, but they all have in common the same robust, strong and reliable filtration medium. The specification and production of this filtration medium is covered in this fourth chapter. Focused on the use of laboratory-grade materials, and operation and testing in laboratory conditions, this chapter aims to assess the capacity of low-technology tempered ceramics to remove contaminants, and to take steps towards optimising this process. Evaluation of the key properties of materials and manufacturing processes are considered against set performance criteria.

4.2 Methodology

The objective of this low-cost, point-of-use drinking water treatment regime is to consistently produce suitable quality filters, from abundant local materials. These filters must be capable of reducing water-borne contamination.

Ceramics have a proven history as a filtration medium and their properties are well understood and utilised. What is less well understood is whether these characteristics can be reproduced using low-grade materials and simple manufacturing techniques.

Sample filter elements were produced using a range of basic ceramic materials and appropriate production techniques and their performance was assessed against set criteria. In this way, it was possible to predict how effectively low-technology ceramics could be used against agents of disease. To enable a consistent comparison of variables, the techniques used in preparation, production and testing filter units, were standardised.

The iterative process used in developing this filter is shown in Figure 7:

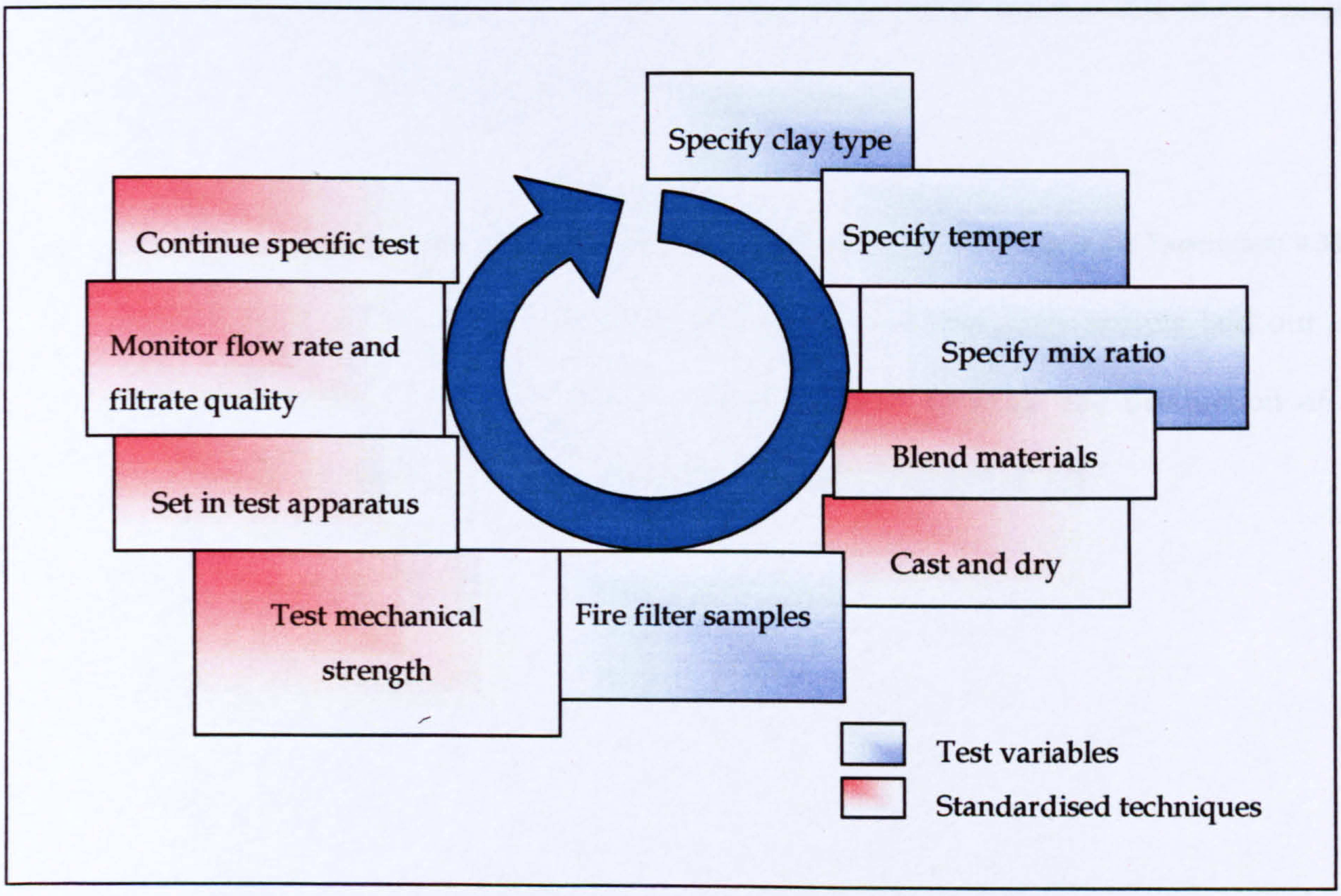


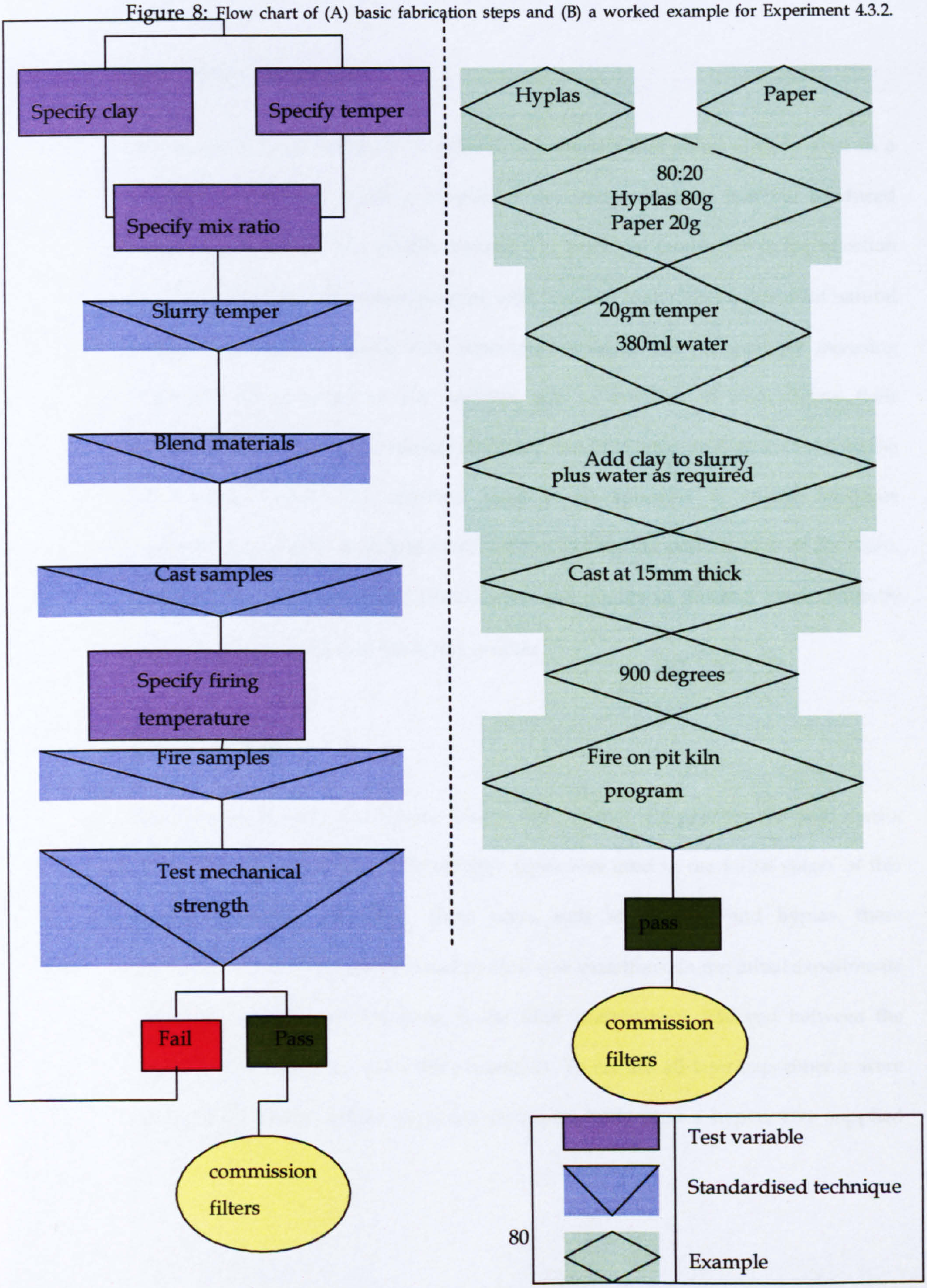
Figure 7: The iterative design process used in the development of the filter material.

'Test variables' are the materials and techniques that represent the parameters of the individual investigations. These materials and techniques are specified based on the potential availability of materials, facilities and skills expected to be available in most basic ceramic industries in developing countries based on observations from the Bangladesh field visit, (Section 3.2). To minimise variations between production runs, every effort was made to use classified and uniform products and materials and laboratory-controlled processes.

'Standardised techniques' (detailed in Section 4.2.2) represent methods developed specifically for the assessment of these filters. These techniques are based on good practice and standard methods, adapted as necessary to suit this specific design process. These techniques were standardised to allow each test variable to be varied individually whilst holding all other variables constant.

Figure 8: Flow chart of (A) basic fabrication steps and (B) a worked example for Experiment 4.3.2. shows the stages for the specification and production of a filter sample laid out in order, this diagram also includes a worked example showing the production of a filter sample for use in one of the later investigations (Section 4.3.2).

Figure 8: Flow chart of (A) basic fabrication steps and (B) a worked example for Experiment 4.3.2.



4.2.1 Test variables

The scope of 'local materials' is defined as materials that either already exist in a plentiful supply and within a reasonable proximity, or those that are produced locally in a consistent and reliable manner. The principal motivation in the selection of suitable local materials was financial: only low-cost materials, i.e. plentiful natural resources or waste products, were considered suitable. The rationale for assessing materials and processes as test variables was to establish to what degree their properties affected the performance of a filter unit. It is imperative to understand the limits within which the materials need to be specified to ensure adequate performance, as there is limited scope for monitoring the performance of the filters when *in situ* and therefore the performance and quality of finished filters is totally reliant on a consistent manufacturing process.

4.2.1.1 Clays

The main constituent of a ceramic filter is the clay that will produce the solid matrix of the filter. A selection of different clay types was used in the initial stages of this project, including ball clays, china clays, buff school clay and hyplas, these representing a range of mineral and particle size variations. In the initial experiments there was no obvious difference in the filter performance achieved between the different clay materials, (data not presented). To ensure all later experiments were comparable, and to reduce variables, all experiments used a hyplas clay supplied from one supplier, 'Potclays'[2] and all clays were provided in a graded powder form.

Whilst hyplas is typical of clay extracted from UK soils, its mineral properties are similar to those found in all fluvial deposits and estuarine deltas, (Table 3).To ensure that hyplas clay was a good model for locally-sourced materials, a sample of clay collected from a potter in Dhaka, Bangladesh was analysed for particle size distribution and mineralogy and compared with the characteristics of the more readily available hyplas. The particle size distribution showed a high degree of uniformity, 90%<0.01 mm, and minimal organic fraction. X-ray diffraction analysis showed the clay to comprise a significant proportion of ilite, with other quartz and kalinite minerals present. All of these are characteristics similar to the hyplas powdered clays used in this study. Details of the clay analysis results are shown in Appendix 1.

Table 3: Mineral composition of clays

Clay	Kalonite	Silica	Carbonaceous material
Hyplas	54-62%	8-12%	2-3%
Bangladeshi clay sample	>30%	>30%	2%

[2] Potclays: Brick kiln lane, Etruria, Stoke-on-Trent ST47BP

4.2.1.2 Tempers

The role of the temper in the filter is to reduce the density of the clay body during mixing and forming; then, during firing, to be burned out leaving small voids or pores that increase the internal surface area and porosity of the fired ceramic.

The seminal work of Gault (1999) focused on the use of macerated paper as a low density temper to influence handling and firing characteristics. During this work, the author noticed an associated increase in permeability. Macerated paper is also assessed in this project along with other more widely available alternatives, including food by-products such as bran and rice husk, together with industrial wastes such as sawdust and ground glass fibres.

All tempers were graded prior to use to ensure uniformity of particle size, and were specified as a dry weight of a specified size range. Grading was performed using standard brass soil sieves in the following size order; 1>0.71>0.5>0.35>0.297 mm

4.2.1.3 Ratios

When preparing filters, all materials were mixed to defined ratios. All mix ratios were specified as a percentage of temper to the total dry weight of material.

4.2.1.4 Firing

The firing process is vital to the quality of the finished ceramics. The temperature, the duration and the heating and cooling profile are all important parameters. Firing in low-technology kilns or open fires is a highly variable process. To simulate the conditions of a low-technology pit kiln, the heating profile expected in such a kiln, using an average density and resin content wood, was reproduced using a computer-controlled electronic kiln, (Falcon FL 3220). Using this kiln, it was possible to specify firing conditions and to control the oxidation environment to best suit the conditions of low-technology kilns.

Through conversations with Bob Park of the Greystoke pottery (one of the few potteries to use a solid fuel kiln in the UK[3]) and visits to low-technology potteries in Bangladesh, it was possible to produce a firing program that would reproduce the temperature profiles and time durations that could be expected in a pit kiln firing. This program was used for all firings throughout this investigation. The temperature profile of this program can be seen in Figure 9

[3] Greystoke potteries is located in Greystoke Gill, Penrith Cumbria, UK

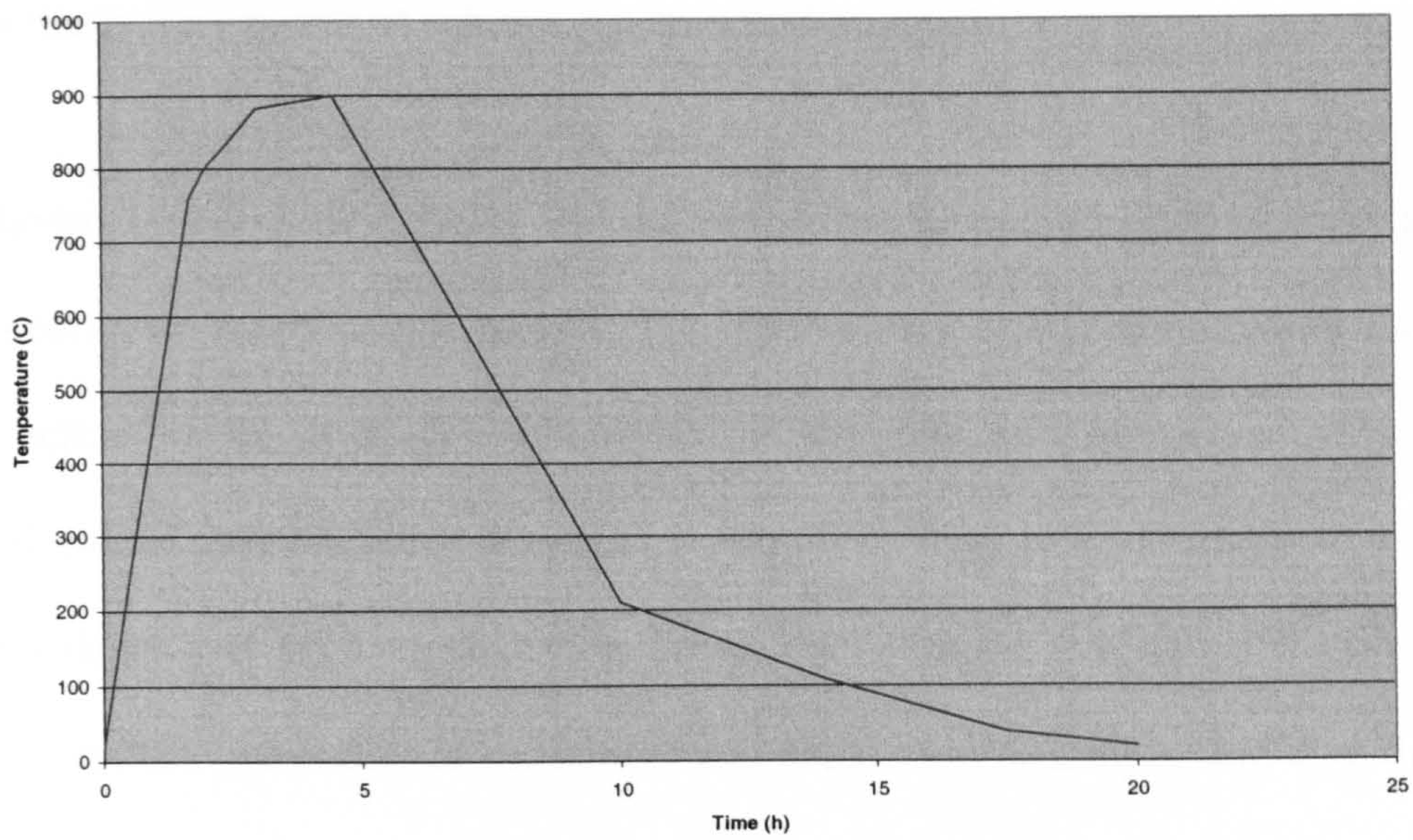


Figure 9: Firing temperature profile for a basic pit kiln.

4.2.2 Standardised techniques

4.2.2.1 Blending materials

Once the required clay and temper have been specified they are mixed to the specified ratio to produce a smooth and uniform mixture, with a workable consistency. To achieve this it is necessary to produce a wet slurry of the temper and then blend this into the dry clay. This technique reduces the tendency for the temper to 'clump'; fibrous tempers are particularly prone to this and care needs to be taken to ensure good mixing of the slurry. It is imperative to ensure a homogenous distribution of the temper in the finished filter to eliminate short circuits caused by voids of cracks resulting from large bodies of temper aligning with the filtration path.

From experience, slurries of temper were prepared at 5% (W/V) in distilled water to facilitate the process of achieving a smooth final mixture.

Having blended the dry clay and the wet slurry, further addition of water is required to produce 'loose' and workable clay. The volume of additional water required is a function of the hydration properties of the clay and temper so will vary with individual specifications, however, it should be kept to a minimum to avoid excess shrinkage and prolonged drying times. Furthermore, a reasonably stiff clay body reduces the possibility of settlement and separation of temper and clay during both preparation and casting of test samples. However, care must be taken as excessively stiff clays will not mould evenly and this can cause large bubbles to be retained in the final piece.

Whilst the exact amount of water required to achieve a loose clay will vary according to the temper and clay minerals, it was found that using 5% (W/V) dry clay to water was effective as an initial approximation.

The process of mixing the clay body can be carried out mechanically, using a food blender or electric mixer. However, this method can result in air being entrained in the final clay, which reduces the density of the final filter and leads to variable filter quality and porosity. In addition to affecting the filtration performance of the final unit, air entrained in the samples can lead to cracking during firing. To eliminate as much of this air as possible the mixed clay should be rested to ensure complete hydration and to allow the air to rise; stirring gently and intermittently helps to allow the air to escape. The clay should be rested for in excess of 24 hours. Ideally, the clay should then be 'wedged' on a coarse wooden surface to ensure as smooth and homogeneous a blend as possible.

4.2.2.2 Casting and drying sample filters

To enable a number of samples to be assessed against identical flow conditions, a standardised test filter is required. To produce test specimens to a standardised specification, an investigation was conducted to identify the most reliable and reproducible method for moulding and forming filter units.

In a preliminary examination of wheel-turned and slip-cast units, wheel-turned units exhibited a pitted and less regular surface due to the effect of long fibres from the temper creating a pulled and uneven surface, whereas the slip-cast sections produced a more level and homogeneous section. Further investigations comparing press moulded and slip-cast sections showed that sections of slip-cast filters contained the least bubbles and maintained the most consistent wall thickness; slip-casting was also the least skill-dependent fabrication method. Therefore, slip-casting was deemed to be the most appropriate fabrication method to produce the standard test filters. (Scanning Electron Micrographs (SEMs) of sections through slip-cast and press moulded sections are included in Appendix 2).

It is acknowledged that slip-casting may not be the most suitable technique for production in small-scale potteries, where throwing vessels on a wheel is likely to yield the most consistent results. However, the skills required to produce a consistent product using this technique were not available during the laboratory phase of the project. Therefore slip-casting was adopted since it has the benefit of requiring minimal physical skills, and has the least specific requirements for material properties, reducing the likelihood of variations between samples. Slip-casting also enables many filters to be made simultaneously.

To produce consistent samples, some basic equipment was prepared and the following technique developed:

Equipment: Moulds were made from plastic rings: diameter 75 mm, depth 18 mm, wall thickness 3 mm, (cut from PVC drain pipe). The use of shallow ring sections made it possible to vary the mould depth according to the shrinkage rate of the clay, so ensuring even final thickness. The plastic had the advantage of not adhering to the clay; so, as the clay shrank from the walls of the mould, there was little stress on the sample, thus reducing the tendency to cracking.

A plaster of Paris slab was used as the base of the moulds to assist even drying through water extraction from the base of the samples (capillary suction).

Plastic sheeting was used to cover the units in order to slow the drying of the samples, to ensure even shrinkage and reduce warping. Furthermore, by wrapping the casting slab in plastic and enclosing an open bowl of water, an ideal drying atmosphere could be maintained.

The technique used to cast the samples was as follows:

Slips were produced to a consistency that would allow the sample to be poured from a 500 ml beaker inclined at 45^{0} below the horizontal. The preferred method for production was for samples to be spooned into the moulds and smoothed flat with the back of a metal spoon; efforts were made at this point to ensure minimal entrainment of air.

After the initial drying period (24h) samples were scored on their upper face with an identification number. After casting, samples were released from the plaster slab only when fully dried, typically 3 days, thus eliminating buckling and ensuring a flat surface for bonding to the test apparatus. The finished samples were then stored at room temperature (22±5 ^{0}C) for a further week to ensure their suitability for firing

4.2.2.3 Pre-selection of sample filters

To ensure that the samples tested were suitable for their intended use, an initial empirical assessment of their mechanical strength was conducted. If a sample could withstand reasonable flexing and compression applied by hand, then it was assumed that it would withstand the hydraulic head from a test rig (detailed in Section 4.2.2.4) and the demands of application. Whilst simple, this test ensured that only suitable materials were subjected to detailed testing. During pre-selection, 1:20 filters failed through defects in production.

4.2.2.4 Filter test apparatus

To achieve a consistent controlled test environment, a specific test apparatus was developed. The rig was devised to enable multiple filter elements to be challenged simultaneously with the same sample water under the same conditions, and to enable the retentate to be collected and stored in sterile conditions, allowing easy monitoring and regular batch sampling. The system set up is shown in Figure 10.

A 20 litre reservoir of water containing the challenge water, spiked with bacteria and other required contaminants was placed on a scissor jack stand, and the water level marked against a fixed reference point. The stand was raised at regular intervals (to coincide with sample collection on a 24 hour basis) to keep the driving head constant as the water level dropped.

A manifold of silicone pipes and polypropylene connectors was attached to the reservoir and a sample port installed in the main delivery pipe upstream of the manifold. Due to the relatively low flow volume, the sampling point was located as close to the filter as possible such that the water sample at the sampling point had a similar detention time to water passing through the filter.

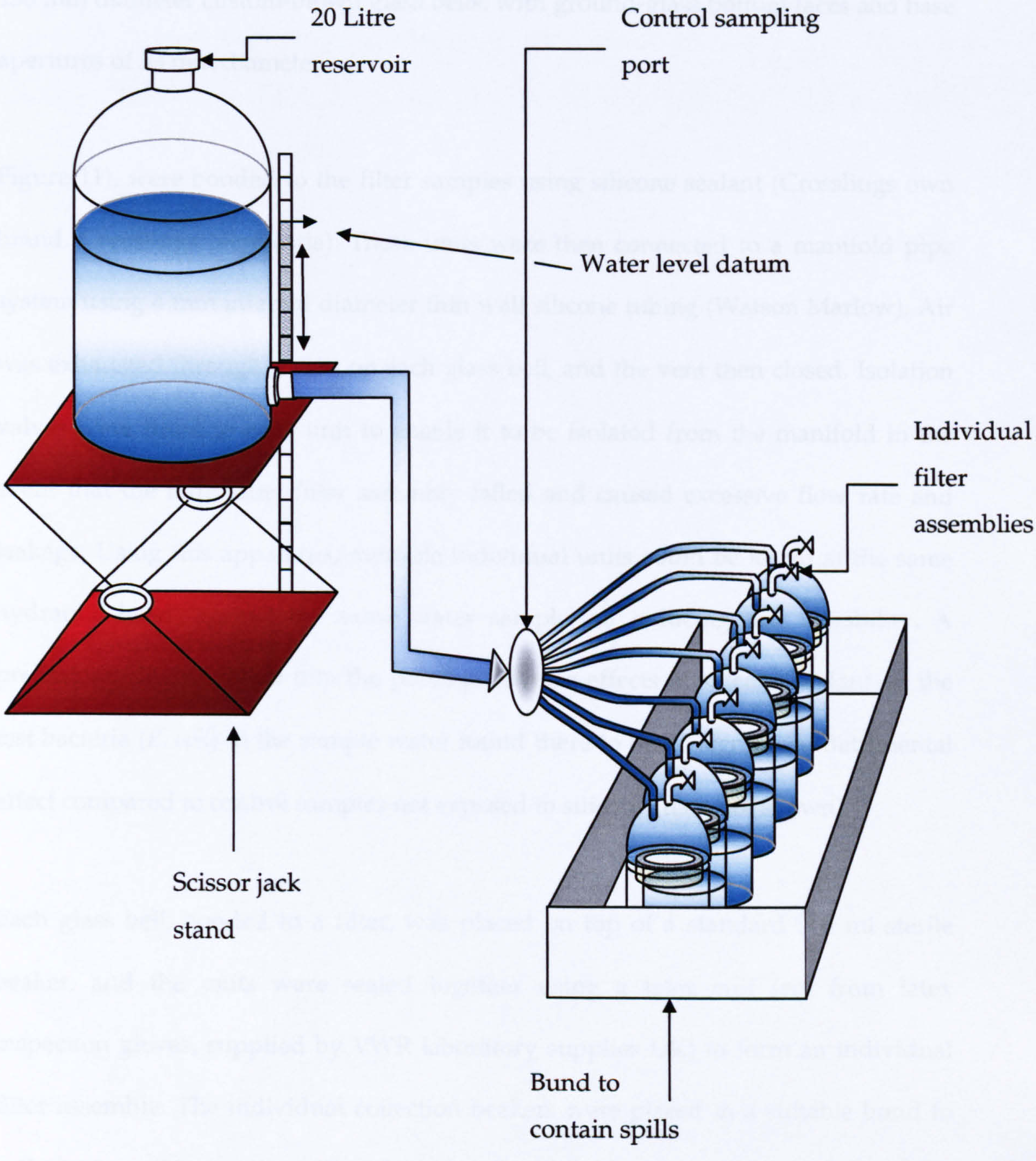


Figure 10: Filter test apparatus; not to scale.

150 mm diameter custom-blown glass bells, with ground-glass bottom faces and base apertures of 53 mm diameter

Figure 11), were bonded to the filter samples using silicone sealant (Crosslings own brand, Crosslings Newcastle). These units were then connected to a manifold pipe system using 4 mm internal diameter thin wall silicone tubing (Watson Marlow). Air was exhausted through a vent on each glass bell, and the vent then closed. Isolation valves were fitted to each unit to enable it to be isolated from the manifold in the event that the individual filter assembly failed and caused excessive flow rate and leakage. Using this apparatus, multiple individual units could be tested at the same hydraulic head, against the same water sample, so reducing test variability. A preliminary investigation into the possible adverse effects of silicone sealant on the test bacteria (*E. coli*) in the sample water found there to be no significant detrimental effect compared to control samples not exposed to silicone (data not shown).

Each glass bell, bonded to a filter, was placed on top of a standard 500 ml sterile beaker, and the units were sealed together using a latex cuff (cut from latex inspection gloves, supplied by VWR laboratory supplies UK) to form an individual filter assembly. The individual collection beakers were placed in a suitable bund to collect any spillages and overflow from failed test filters.

Samples were taken at specified intervals (typically daily) from the control sampling port, and filtrate collection beakers were replaced. Samples of filtrate were transferred to sterile 25 ml universals or 100 ml medical flats (according to flow volume) for bacteriological testing in batches. This testing was conducted within 24 hours of collection. In the interim, all samples were stored at 4 ^{0}C in accordance with Standard Methods (APHA 9222). Filtrate volume was assessed at all sampling intervals.

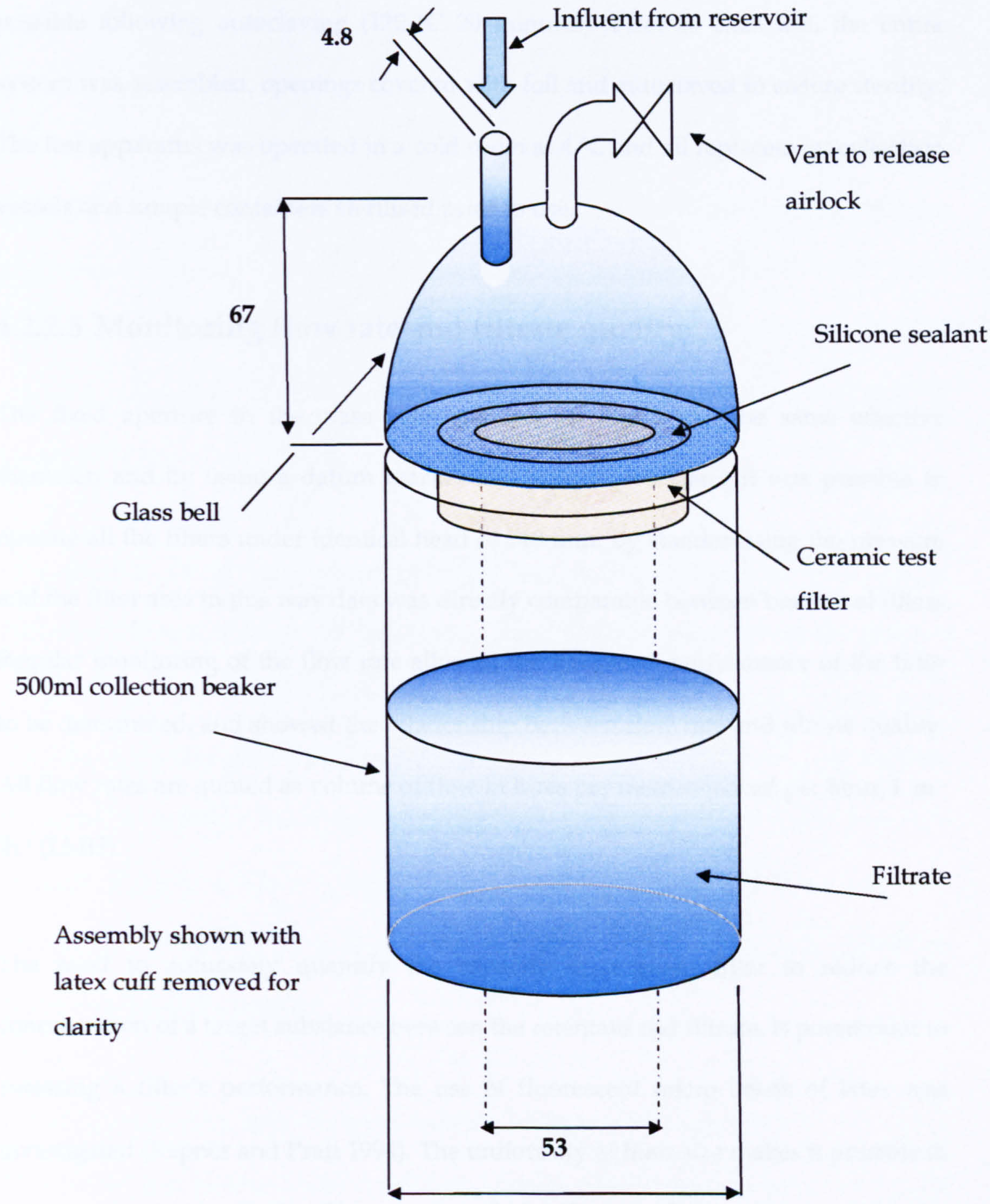


Figure 11: Diagram of individual filter assembly; dimensions in mm.

Using this test apparatus, all materials were either glass or silicone, and reuse was possible following autoclaving (120 ^{0}C 20 minutes). Prior to each test, the entire system was assembled, openings covered with foil and autoclaved to ensure sterility. The test apparatus was operated in a cold room at 4 ^{0}C and all replacement collection vessels and sample containers sterilised prior to use.

4.2.2.5 Monitoring flow rate and filtrate quality

The fixed aperture in the glass bells ensured all filters had the same effective diameter, and by using a datum marker and scissor jack stand it was possible to operate all the filters under identical head of 740 mm. By standardising the pressure and the filter area in this way data was directly comparable between batches of filters. Regular monitoring of the flow rate allowed the long-term performance of the filter to be determined, and showed the relationship between flow rate and filtrate quality. All flow rates are quoted as volume of flow in litres per metre squared per hour, $l.\ m.^{-2}h^{-1}$ (LMH).

The need to accurately quantify the capacity of a given filter to reduce the concentration of a target substance between the retentate and filtrate, is paramount to assessing a filter's performance. The use of fluorescent micro beads of latex was investigated (Kepner and Pratt 1994). The uniformity of their size makes it possible to measure pore size of the filters accurately; and their fluorescence enables the adsorption and bonding sites of the filters to be identified under UV light. However, this approach was abandoned in favour of one using a cheaper and more reliable biological marker. A culture of bacteria (*E. coli*), grown in nutrient enriched broth

(Oxoid nutrient enriched beef broth) provided a cheap and reliable source of indicator organisms of a relatively uniform size with which to challenge a filter. The use of a biological marker, rather than a physical one, provided a more realistic performance indicator as it was a good representation of bacterial pathogens in contaminated drinking water. A biological marker responds to the physical structure and surface charge of the filter and represents the life cycles and potential biofilms that could develop within a ceramic material. The use of a cheaper marker enabled a higher number of tests and the assessment of filter performance under more extreme concentrations.

The selection of an appropriate biological marker for testing filter performance requires that there is no growth, no death and no physical change across the duration of the experiment. A preliminary investigation into the survival of test organisms in the filter assembly showed that under a storage temperature of 4 ^{0}C suspensions prepared in distilled water survived equally well as suspensions prepared in ¼ strength Ringers' solution. Consequently, distilled water suspensions were used throughout this study to achieve realistic representation of bacteria present in contaminated surface waters.

Initial investigations into the most suitable biological markers included the use of *Enterobacter* and *Escherichia coli (E. coli)*, two resilient coliform bacteria that are readily culturable and relatively safe to handle. *E. coli* was selected in preference to *Enterobacter* as it had shorter incubation times and achieved higher cell densities during the preparation of stock cultures. The original *E. coli* culture was prepared from a non-pathogenic, laboratory strain of *E. coli*, and stocks were maintained on agar slopes and checked regularly on agar streak plates before each new experiment. *E. coli* bacteria normally grow as 2 µm long rods and are therefore representative of other water-borne pathogenic bacteria (Lester and Birkett 1999).

To assess the performance of the filter material, cultures of non-pathogenic *E. coli* were grown in 200ml of nutrient broth for 24 h at 37 ^{0}C at 40 rpm in a shaking incubator, to give a final approximate cell density of 10^8 CFU.ml^{-1}. Culture density was measured using a spectrophotometer, (UNICAM 8625) with an absorbance of 1.5 - 1.6 at 600 nm, indicating that the growth of the culture had reached its stationary phase. A 20 litre reservoir of distilled water was then inoculated with this culture to achieve the required cell density for the individual experiment. To ensure that the bacterial cells were dispersed evenly within the challenge water, the volume of pure culture was first added to 1 litre of distilled water and mixed thoroughly. This mixture was then added to a further 5 litres before finally being made up to 14 litres.

Having prepared the challenge water, the reservoir was connected to the filter assembly. Initially, bacteria were enumerated using nutrient agar spread plate techniques (APHA 9215). The microbiological removal performance of the filters was higher than initially anticipated, requiring an improvement in detection levels to 1 CFU.100ml^{-1}. For this level of detection, the 0.5 ml maximum sample volume that could be applied to a spread plate was inappropriate. Consequently, 10-100 ml samples were analysed by membrane filtration (APHA9222) in order to attain a suitable level of sensitivity.

All results reported in this thesis[4] were achieved using membrane filters on membrane laurylsulphate broth at 44 °C for 18-24 h.

4.2.2.6 Further testing of sample filters

Once the initial assessment for performance had been conduced, the sample filters could be decommissioned, autoclaved and stored in sealed bags at room temperature, or taken for further testing. Further testing included analysis of physical structure using scanning electron microscopy (Sections 4.3.3, 4.3.4), and investigation into re-use and regeneration (Section 4.3.6).

[4] All investigations were conducted blind by coding the filters to ensure freedom from bias.

4.3 Experimental assessment of filter performance

Having established a standardised protocol for producing and assessing the performance of simple ceramics, experiments were conducted to characterise the critical factors involved in material selection and filter production. The experiments investigated the following:

Production: methods and materials of filter fabrication

Performance: efficiency, selectivity and duration of operation

Optimisation: achieving the maximum performance and identifying the key constraints

4.3.1 Microbiological performance, bacteriological removal

Objective

The general requirement of the filter material is that it can remove discrete suspended bacterial cells, whilst providing a sufficient flow rate to produce an adequate quantity of wholesome water from an acceptably sized unit.

The initial experiment was designed to define the constituents and parameters of such a simple ceramic material, and to test its filtration performance in challenges with bacteriological concentrations typical of contaminated surface waters.

Method

A pair of filters was produced using the methods detailed in Section 4.2.2. The filters were made using hyplas (Potclays 3407) as a clay body and 3% paper temper (www.paperclay.co.uk 0.06 mm). The filters were fired to 900 ^{0}C using a pit kiln simulation firing.

Challenge water was prepared containing *E. coli*, approximately 10,000 CFU.ml^{-1}, and the filters operated for a period of 5 days. The performance of the filters was monitored over a duration of 8 days to look for any change in performance and to ensure equilibrium flow conditions were achieved.

Samples of the retentate and filtrate were collected periodically (sample intervals shown in Figure 12), and flow volume and bacteriological concentration were assessed using the standardised methods (Section 4.2.2.5).

Results

Figure 12 confirms that the *E. coli* in the challenge water were able to survive the conditions of the test, as markers were relatively stable over the 120 hours of monitoring. During the first 50 hours, the bacterial populations appeared to increase before reaching a more stable concentration at approximately 7.5×10^3 CFU. 100.ml^{-1}. This increase may be an anomaly, being attributable to the change in the physical state of the bacterial culture as the cells break free from aggregated lumps (that would have predominated in the growth media); alternatively, the increase may have occurred after the culture was inoculated into the reservoir due to continued cell growth. A suspension of *E. coli* in 20 ml of nutrient broth would provide a source of carbon supporting the continued growth of the culture, which in turn could account for the observed increase in cell numbers.

The results for the filtrate quality show there was a peak in *E. coli* numbers 50 hours after the retentate reached its maximum, and this was followed by a rapid decrease in concentration. From these experiments, it is unclear whether or not the filtrate peak concentration was connected to the retentate peak concentration. However, it was evident that over the 5 day period the filters were, on average, 99.94% effective at removing the *E. coli* and that this represents a substantial reduction in the bacterial concentration of the challenge water.

The flow rates for the two filters were highly consistent (Figure 13) and very similar over the 5 day duration. Whilst the rates varied slightly throughout the test, the differences reduced progressively as the experiment continued and never exceeded 10%.

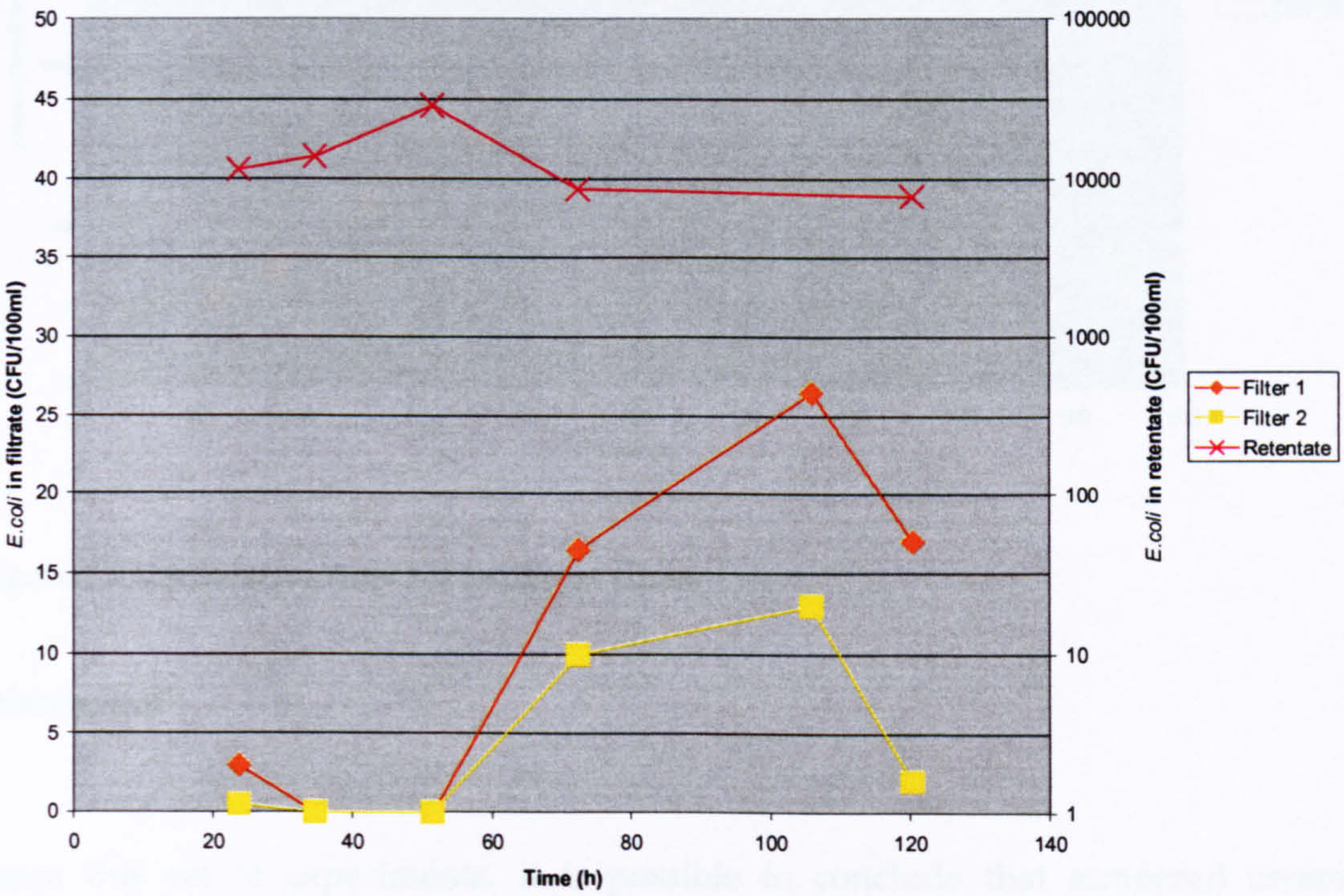


Figure 12: Temporal changes in microbiological quality of filtrate from test filters.

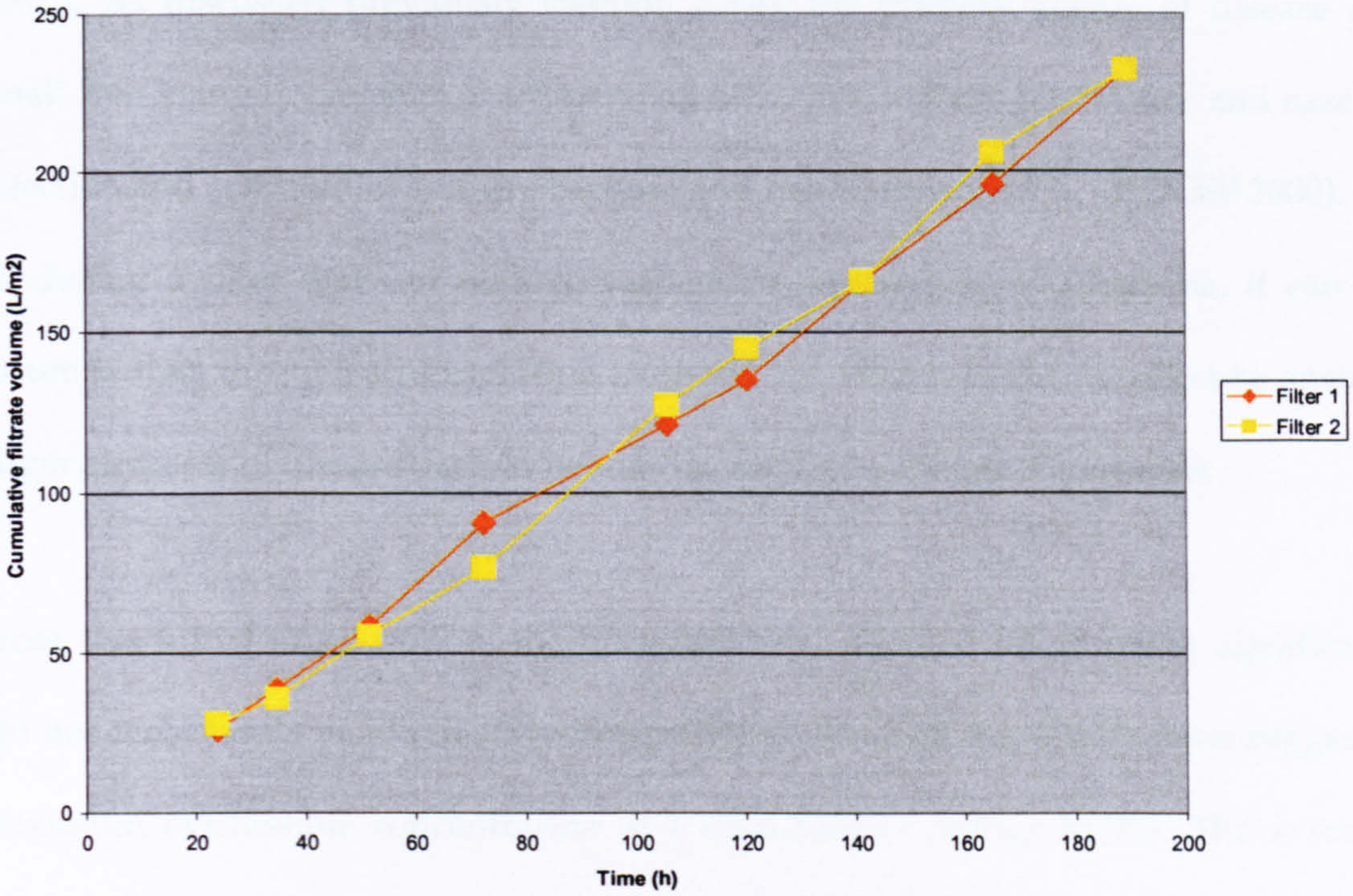


Figure 13: Cumulative flow for basic test filters

Discussion

From this set of experiments, it is possible to conclude that tempered ceramics produced under defined laboratory conditions, without optimisation, are capable of removing suspended bacteria, with an efficiency exceeding 3 log removal. Therefore, these experiments confirmed the proof of principle for the basic method of production and formed the basis for future experiments that would investigate the critical parameters of fabrication.

There is much evidence to suggest that for a point-of-use, low-technology water intervention to be effective in preventing disease, it must be consistently able to reduce the biological contaminants in a given water source (Morgan 1990; Sobsey

2002.). As discussed previously (Section 2.3.4), the primary agents of disease are small free-living organisms; of primary concern, due to their prevalence and ease of infection and communication, are bacteria and helminths, (WHO/ UNICEF 2000). By producing a filter that can remove suspended, non-aggregated bacteria, it can be assumed that, through size-exclusion methods, the filter will also be effective against larger elements of disease such as helminths, protozoa and other parasites.

From this initial investigation, the bacteriological removal rates, whilst significant, did not consistently yield results below guideline levels of the WHO which suggest a maximum permissible concentration of 1 CFU.100ml^{-1} (WHO 2003b). The average concentration throughout the test period was 7 CFU.100ml^{-1}, which, whilst in excess of the levels expected from centralised treatment and disinfection systems in more industrialised nations, nevertheless offers a marked improvement for communities accustomed to consuming untreated supplies.

The microbiological removal capacity of this filter is comparable to the best of the alternative low-technology systems (Table 4), removing a similar order of magnitude of bacteria to chlorination systems, coagulation and precipitation and boiling, and showing similar performance to more complicated centralised systems such as UV lamps and ozonation, (Sobsey 2002).

Table 4: Comparison of bacterial removal rates for different point–of-use systems

Water treatment System	SODIS or sunlight exposure	Chlorination	Simple sedimentation	Boiling
Average removal rates	90%	99%	90%	99%

From the flow rate assessment, it can be seen that porous ceramic materials, whilst offering a high quality of filtrate, do not have particularly high flow rates under the operating conditions within this test. However, the role of the filters is to produce water for consumption, not to meet the greater water needs, approximately 20 l/head/day (World Bank 2004) for washing and other domestic requirements. The recommended level of water for consumption varies, though a range of 1-4.5 l/head /day according to climate and activity has been proposed (Howard and Bartrum 2003). These results show that from a unit of 0.5 m diameter and 0.5 m height it would be possible to treat, over a period of 12 hours, enough water for six adults at an average water consumption level (totalling over 24 l). As such, it is possible to conclude that the filter material is able to produce sufficient water to meet the daily requirements of a family with an acceptably sized filter unit.

4.3.2 Tempers and mix ratios

Objective

The experiment in Section 4.3.1, has confirmed that ceramic vessels could be fabricated with a useful degree of porosity and selectivity. It is common practice to bulk ceramics with temper to influence both the wet and the fired properties. Porosity of ceramics is a property that can be readily influenced by the addition of tempers (Section 2.5.1). The objective for this set of experiments was to determine the ratio and nature of the tempers most suitable for producing a reliable filter with good flow characteristics whilst retaining the capacity to remove suspended bacteria.

The main constraint in defining suitable tempers was that, to ensure sustainability in the production of the filters, the materials must be readily available low-cost materials or waste products in developing countries.

Method

To meet the aims of sustainability whilst providing the required filtration performance, the tempers in Table 5 were selected for assessment[5]; these tempers

[5] Several tempers were assessed; only those found to be readily handled and to provide acceptable flow characteristics were considered for further evaluation.

were selected on the basis that they offered a consistent supply of material at a very low-cost, as a waste product and a food by-product. Whilst some pre-treatment or preparation may be required this could be easily achieved with minimal skills, resources or machinery.

The paper fibre temper was supplied in a relatively uniform ground state ready for use, (www.paperclay.co.uk size 0.06 mm) to prepare the bran and rice husk, or similarly to produce a suitable paper temper, the materials were ground using a pestle and mortar and then sieved, using British Standard soil sieves, to a size range of 1>0.71>0.5>0.35>0.297 mm.

Table 5: Suitable tempers.

Material	Description	Source	Availability
Paper fibre	Fine ground paper, macerated to an average size of 0.06 mm	www.paperclay.co.uk	Produced from newspaper and recycled paper pulp; requiring a mill or grinding apparatus
Rice husk	The woody coating of rice seeds, an inedible agricultural waste .	Bangladeshi farmer.	Readily available in all rice growing nations; no mechanical grinding required.
Bran	The ground husks of wheat	The 'health fair' food shop.	Used in the production of bread and cereals, low value.

These experiments investigated flow rate and filter performance, and the influence of an increasing temper ratio on these parameters.

The first set of filters was prepared in accordance with the standardised methods (Section 4.2.2); the filters were made from hyplas with 0, 0.5, 1, 1.5, 5, 10, 20% paper fibre temper. This range of temper concentrations represents the limits of temper that produce a solid and workable clay body; beyond 20% temper, excess shrinkage, cracking and difficulties in blending the materials made it impractical to handle, and hence unsuitable for application. The filters were made to a thickness of 10 mm±1.5 mm according to the methods reported in Section 4.2.2.2, and were fired at 900 °C on a pit kiln firing program. The filters were then commissioned and monitored for flow rate and filtrate quality in accordance with Section 4.2.2.5.

The second and third sets of filters were produced to the same specification as the first set of filters, with the exception that they were tempered with either bran or rice husk; both at 10 and 20% ratio[6]. A comparison of the performance of these filters with the performance achieved by the filters containing the paper fibres, allowed conclusions to be drawn regarding the performance and suitability of different tempers, and the most appropriate temper to be identified for future experiments.

Results

With the addition of tempers, variations in both their nature and quantity must be considered when defining drying times and handling methods. It was found that to

[6] These concentrations were selected on the basis that they represented the most suitable range for a filter, based on the first phase of experiments.

produce samples with high paper temper ratios (10 - 20%), care had to be taken to reduce the rate of drying as the standardised drying time could cause pronounced warping and cracks to appear. By drying the samples in a slightly moist environment (over 5 days rather than 3 days), rather than open on the bench, a greater success rate was achieved.

Figure 14 and Figure 15 show the performance of the filters containing paper fibre temper when challenged with water containing *E. coli;* these showed a consistent 4 log reduction in bacteria between the retentate and filtrate. The reservoir required replenishing after 220 hours, which explains the slight increase in bacterial concentration of the retentate from 220 hours onwards. Following this refill there was a deterioration in filtrate quality from filters with the three lowest temper ratios; however, the maximum concentration of bacteria in the filtrate still represented a marked reduction (99.6%). Due to the isolated nature of these peaks, consisting of a single data point, and the fact that at 370 hours *E. coli* counts in the filtrate returned to the previous levels, it is possible to conclude that these transient peaks represented contamination incidents rather than a progressive deterioration of filter performance.

With the exception of these transient peaks (330-360 hours), the filters all provided excellent quality filtrate with no obvious difference according to the levels of temper.

The flow rate was, however, noticeably affected by the temper ratio. Whilst the un-tempered sample was porous, there was only a slight increase in flow noticed with the paper fibre ratios of 1.5% and below. However, the 5% temper produced a noticeable increase in flow compared with the 1.5% temper. There appeared to be a linear relationship between flow rate and temper addition for temper ratios between 5% and 20% (Figure 16).

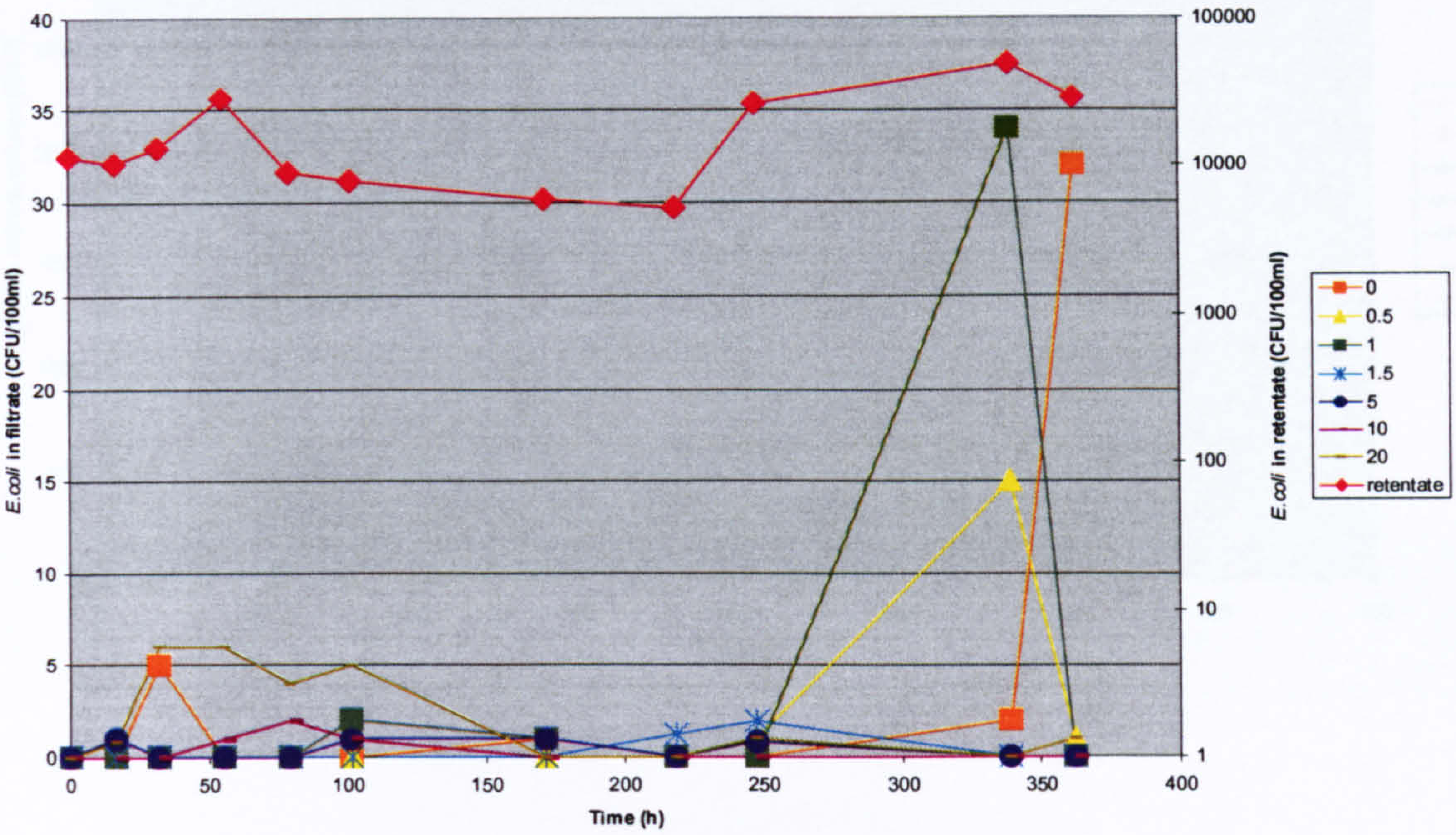


Figure **14: Effect of paper fiber temper ratio on the bacterial removal of ceramic filters.**

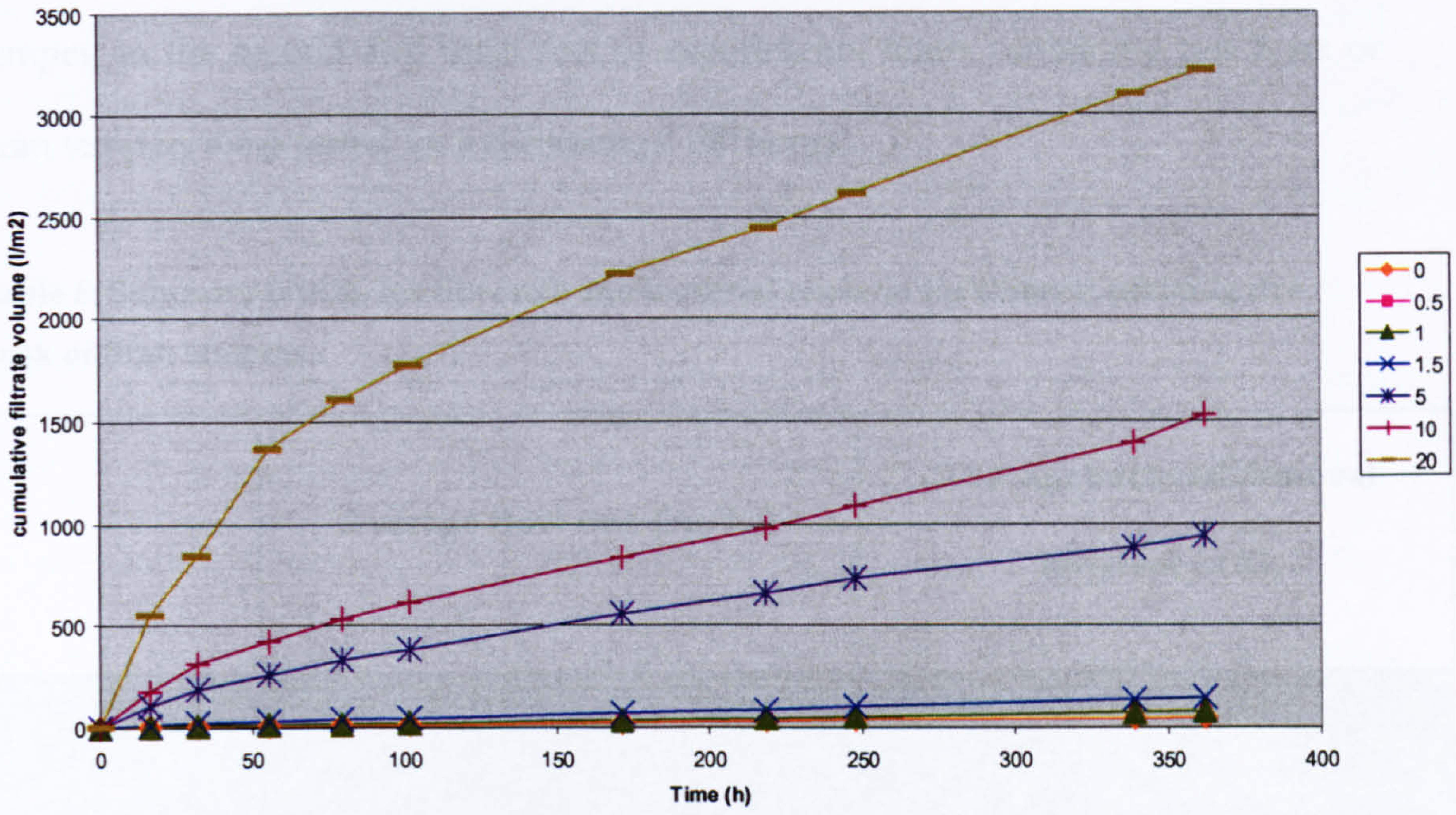


Figure 15: Effect of paper fibre temper ratio on flow rate ceramic filters.

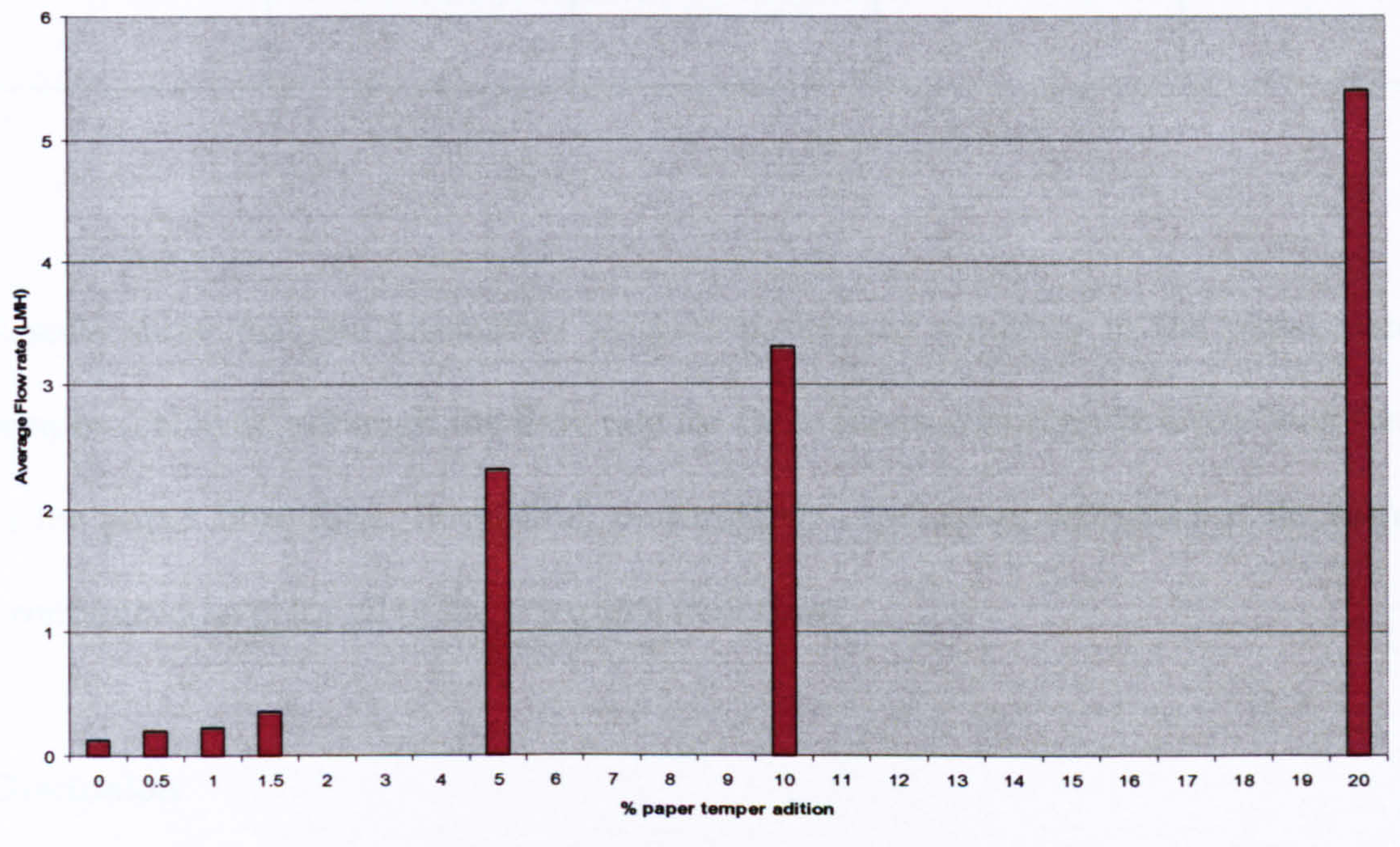


Figure 16: Comparison between average flow rate and percentage paper temper addition.

Having established the performance capabilities of filters produced with paper fibre temper, in the second and third sets of experiments filters containing rice husk or bran tempers were tested for a duration of 190 hours:

Table 6: Summary results for flow rate and bacterial removal for filters containing rice husk or bran tempers

	Average flow rate ($lm^{-2}h^{-1}$)		Average bacterial removal efficiency (%)	
Ratio	10%	20%	10%	20%
Rice husk	3.3	5.4	99.98	>99.99
Bran	3.1	5.3	>99.99	>99.99

Results show that the alternative tempers performed similarly to the paper fibre temper (Table 6), although the flow rate for these filters was slightly lower than that of the paper fibre filter. In general, performance capabilities remained at the same pronounced level for all of these various materials.

Discussion

Filtration performance was high for all permutations of temper investigated in this set of experiments. This indicates that the selection of temper material is not critical in the process of producing a viable ceramic filter. Although the WHO guidelines (2003b) were exceeded with bran and rice husk tempered ceramic filters, with the exception of some of the later results, the average level of CFU in the filtrate was less than 5/100ml, representing substantial removal rates. This represents a high quality of filtrate that would contribute to reducing exposure to, and ultimately infection from, water-borne contaminants. Whilst the bacterial removal efficiency of the filters appears be independent of the level of temper, the flow rate can be manipulated by ranging the temper concentrations. At the 20% temper levels, the material produced is still strong and robust, and the increased flow rate would add considerably to the versatility of this material in its eventual application in a point-of-use filter vessel.

The use of a range of tempers showed that the performance achieved so far with the paper temper can be reproduced, to a high degree, with a range of simple and cheap tempers. Some of these tempers may be cheaper to attain and more simple to process. Filters produced with paper fibre temper consistently achieved the highest flow results which may be due to the more processed nature of the cellulose in this material and its small minimal particle size (30 μm), making the filters slightly more porous.

4.3.3 Thickness and fabrication

Objective

Producing a reliable water filter in low-technology surroundings requires a sound understanding of the key stages in unit production and specification. Consideration of both the performance of the filter and the suitability of the material for fabricating a unit capable of safe sustained operation in the home, are essential. The thickness of a filter section will have a direct bearing on its strength, weight and, potentially, performance. These experiments were conducted to assess the effect of filter thickness on suitability and performance.

From the electron micrographs (Section 4.3.4) the flow path of the filter can be seen as a series of interconnected pores and fissures. The tortuous nature of this flow path, combined with the small dimensions of the pores, likely results in the physical retention of bacteria within the filter matrix. These experiments were conducted in order to assess the relevance of the length of this flow path and determine whether there was any relationship between filter thickness and effective treatment.

Method

A pair of filters containing 10% paper fibre temper was fabricated according to standardised methods of slip casting (Section 4.2.2), using hyplas as a clay body and fired to 900 °C on a pit kiln simulation firing. These filters were produced with two different cross-sectional thickness, one at 5 mm and one at 15 mm. These cross-sections represent the limits of practical production with the slip-casting technique. Below 5 mm the finished filters were physically weak, whereas filters thicker than 15 mm tended to warp and crack during drying.

The filters were tested by the standardised methods, (Section 4.2.2.4), over a period of 408 h.

Results

Owing to the extended duration of this test, the retentate reservoir required refilling after 225 h; this caused a slight increase in strength in the retentate. The 15 mm section filter showed no bacteriological breakthrough prior to the replenishing of the reservoir, although after this point breakthrough was observed. The 5 mm filter sections showed breakthrough at an earlier time point, although measured values of *E. coli* were low, <10 CFU.100ml^{-1}.

As shown in previous experiments, the filters produced at 5 and 15mm thickness performed effectively, and showed an average removal rate of 99.98%. Whilst not achieving the WHO (2003b) guideline (<1 CFU.100ml), a substantial reduction was observed (Figure 18).

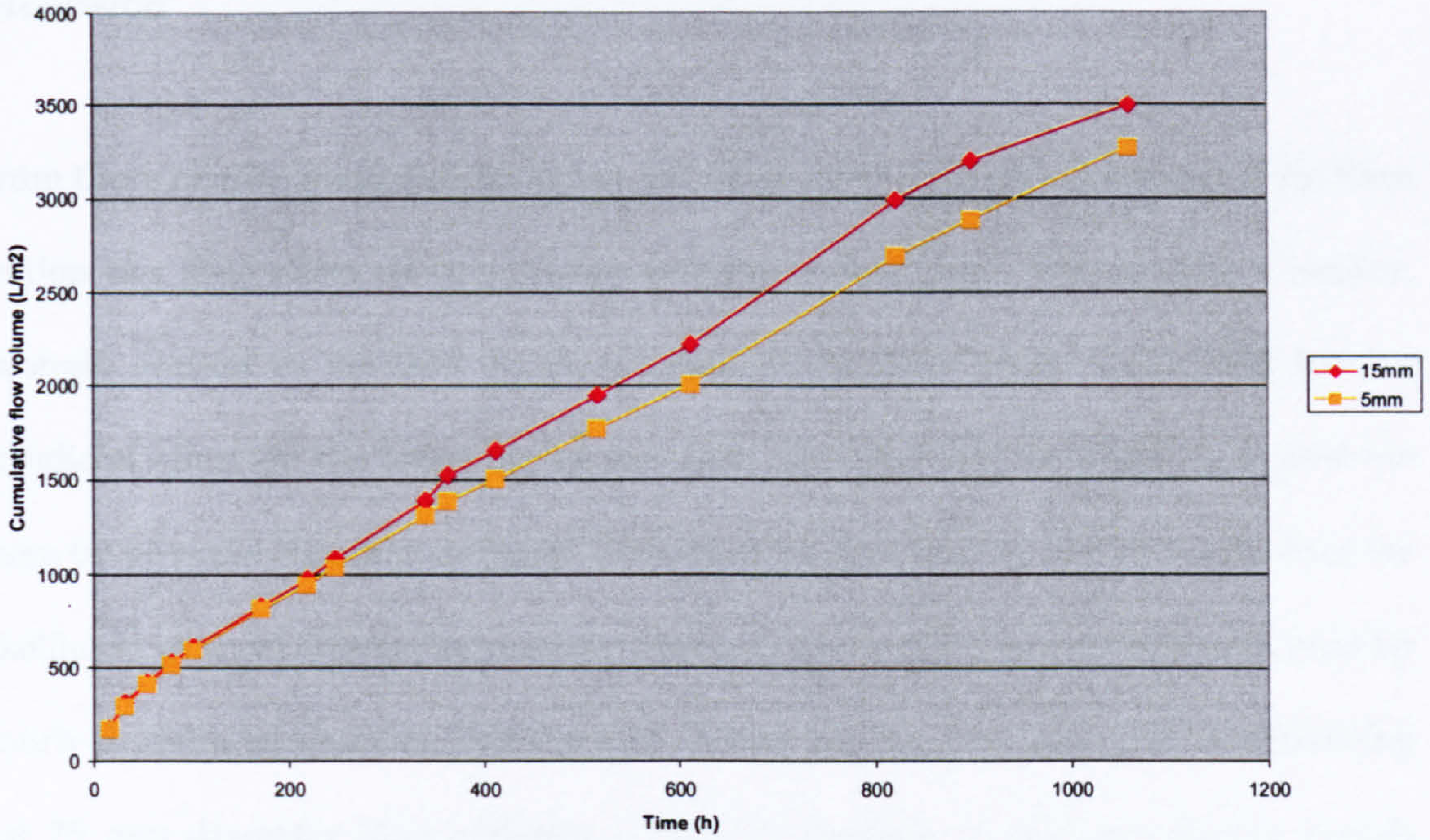


Figure 17: Flow rate comparison between different thickness of filter section.

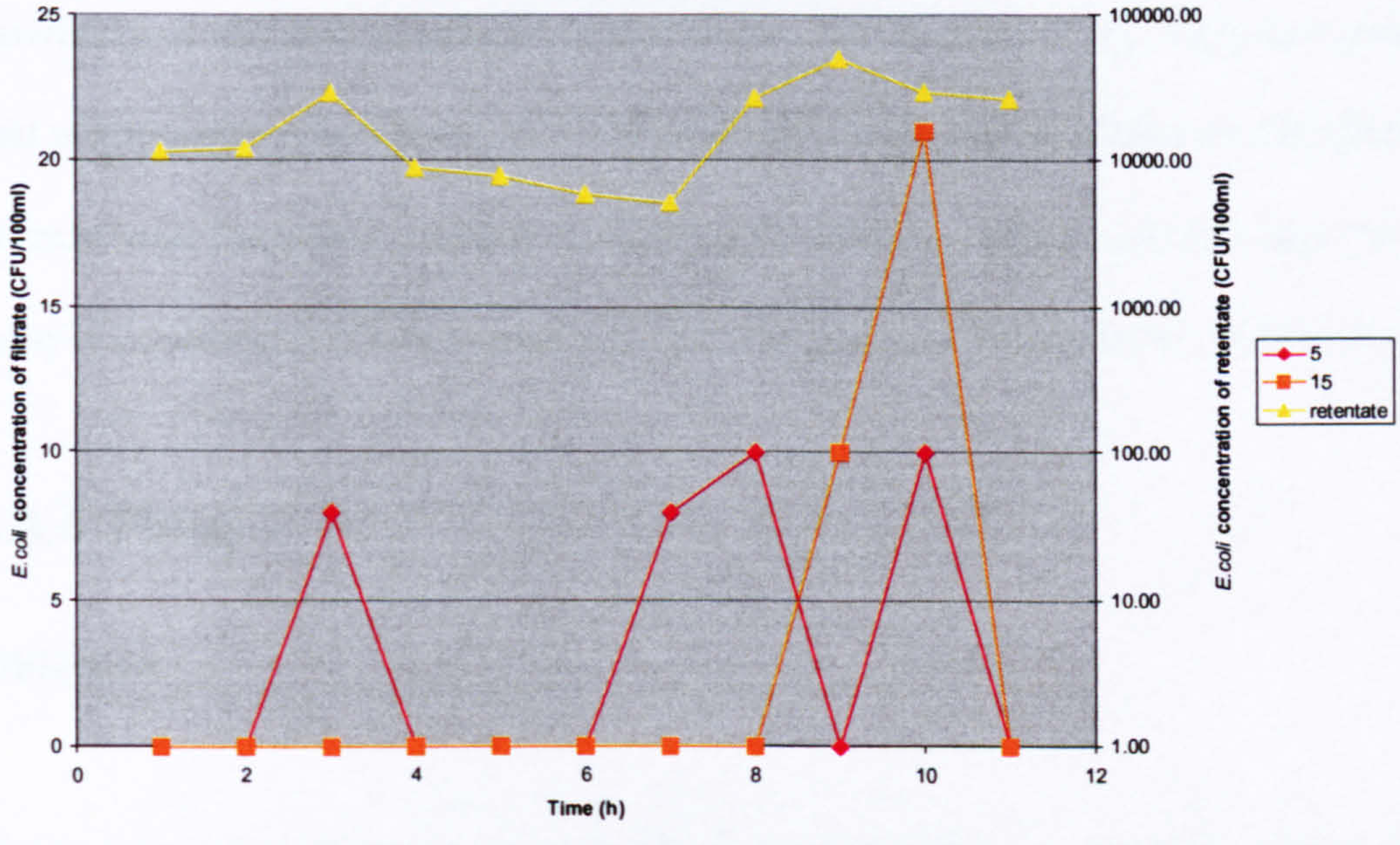


Figure 18: Bacteriological performance comparison between different thickness of filter section.

Discussion

From these results, it appears that over the range 5 to 15 mm the thickness of the filter section has little effect on its porosity and hence flow rate. This enables a thicker, stronger section to be used in the production of filter units, which will have a beneficial effect on the longevity of the units as well as the potential to regenerate them by physical cleaning methods. The use of thicker sections would also reduce the likelihood of short circuits induced by fractures in the filters or by fissures created by poorly distributed tempers. Even though 15 mm was the practical limit for producing flat 75 mm diameter filter samples, it may be possible to produce thicker vessels without distortion by hand throwing or press moulding traditional pot shapes.

In considering the specification of the units it is important to ensure that they are not unwieldy or difficult to operate in the home. The density of the ceramic material on test is approximately 1 tonne m^{-3}. Hence a unit of 300 mm diameter and height with a 10 mm wall thickness, capable of holding 20 litres, would weigh just less than 6 kg (empty), making it viable to produce and transport, and to operate in the home.

4.3.4 Firing

Objective

Firing has a significant impact on the final properties of ceramics. Firing in low-technology kilns is intrinsically a variable and poorly controlled process. In order to produce a high quality filter consistently, experiments were conducted to establish the effect of variations in firing conditions on ceramic filters.

Method

A set of 15 filters was prepared according to standardised methods (Section 4.2.2.2) using hyplas clay and paper temper at 1%. Filters were fired in batches of 5 in separate kiln runs to different maximum temperatures of 600, 800 and 1000 °C. A single filter of average density, and with no obvious visual cracks or flaws, was selected from each firing temperature and attached to the distribution system (Section 4.2.2.4) and monitored for flow and filtrate quality (Section 4.2.2.5) over 408 h. The filters were then decommissioned and fragments of the filters mounted and analysed by Scanning Electron Microscope (SEM) Cambridge S240 stereo scan operated at 8KV.

Results

All of the fired samples all had a notably different texture. The 1000 °C samples were hard and solid to the touch, hard to score and relatively brittle; whereas the 600 °C samples were dusty to the touch, easily scored and friable when fractured.

The SEM images failed to show any notable difference between the crystal structure of the three filters despite the obvious differences in their appearance, physical characteristics, porosity and bacterial removal efficiency (Figure 19 and Figure 20).

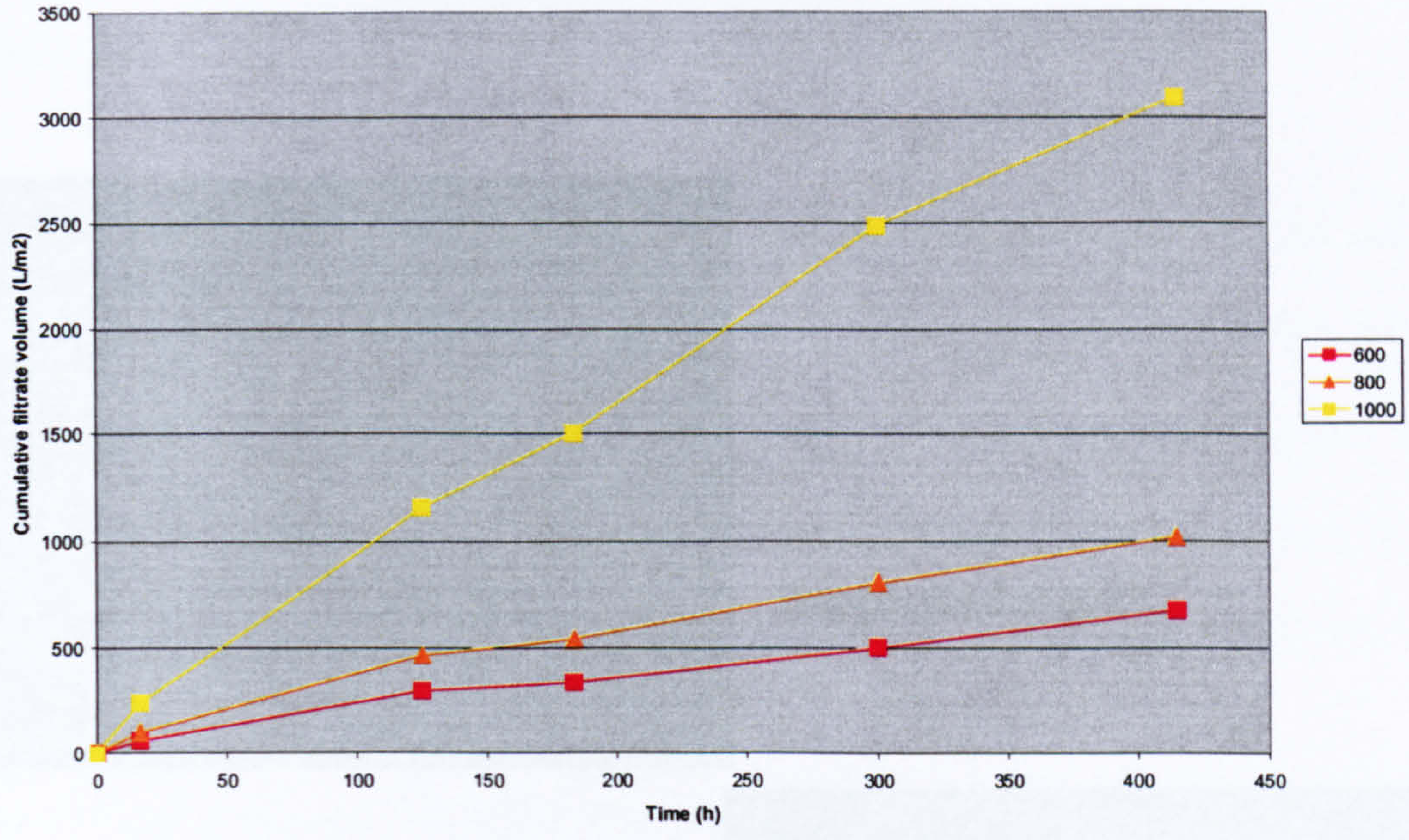


Figure 19: Effects of firing temperature on the flow performance of ceramic filters.

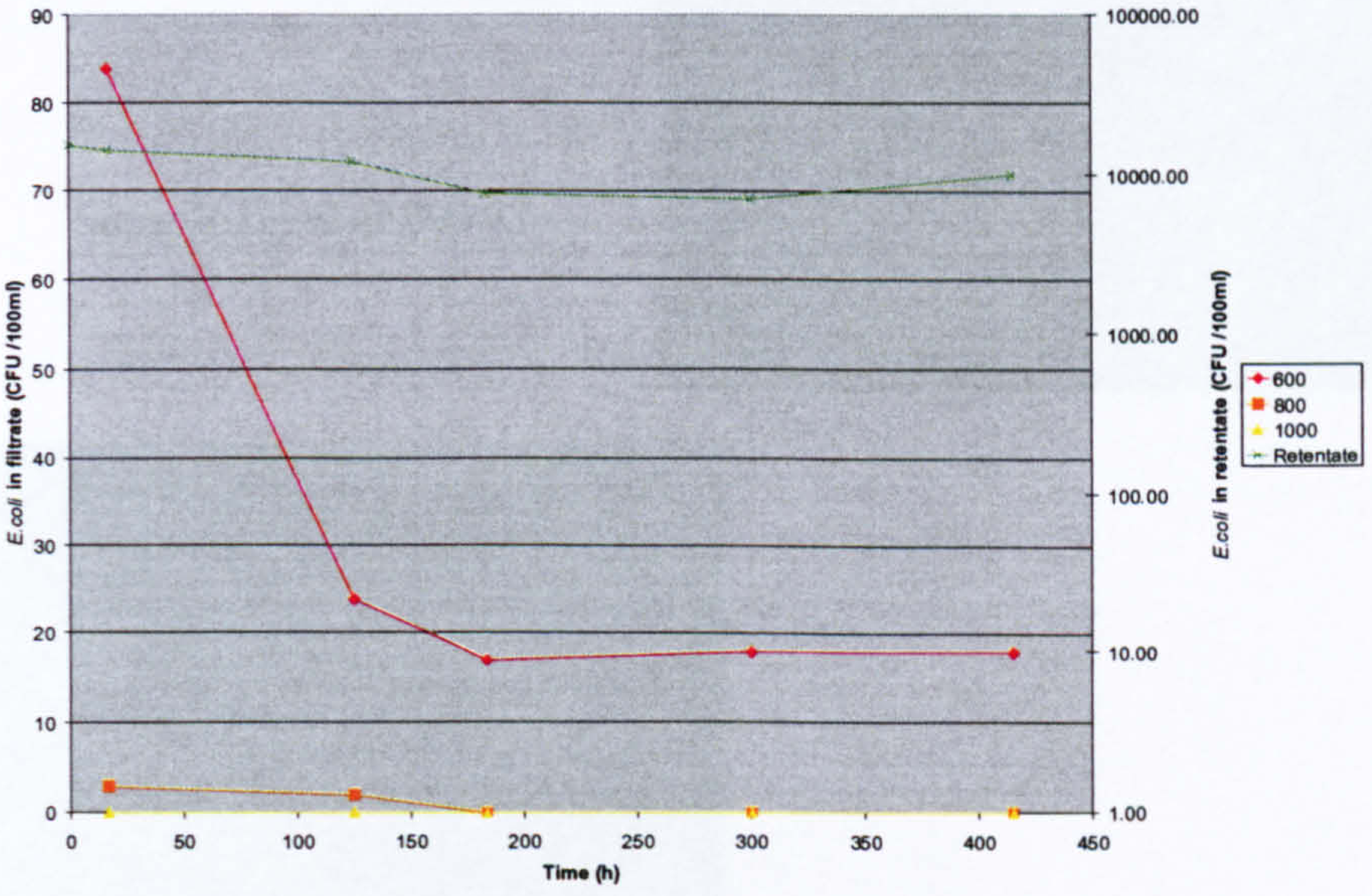
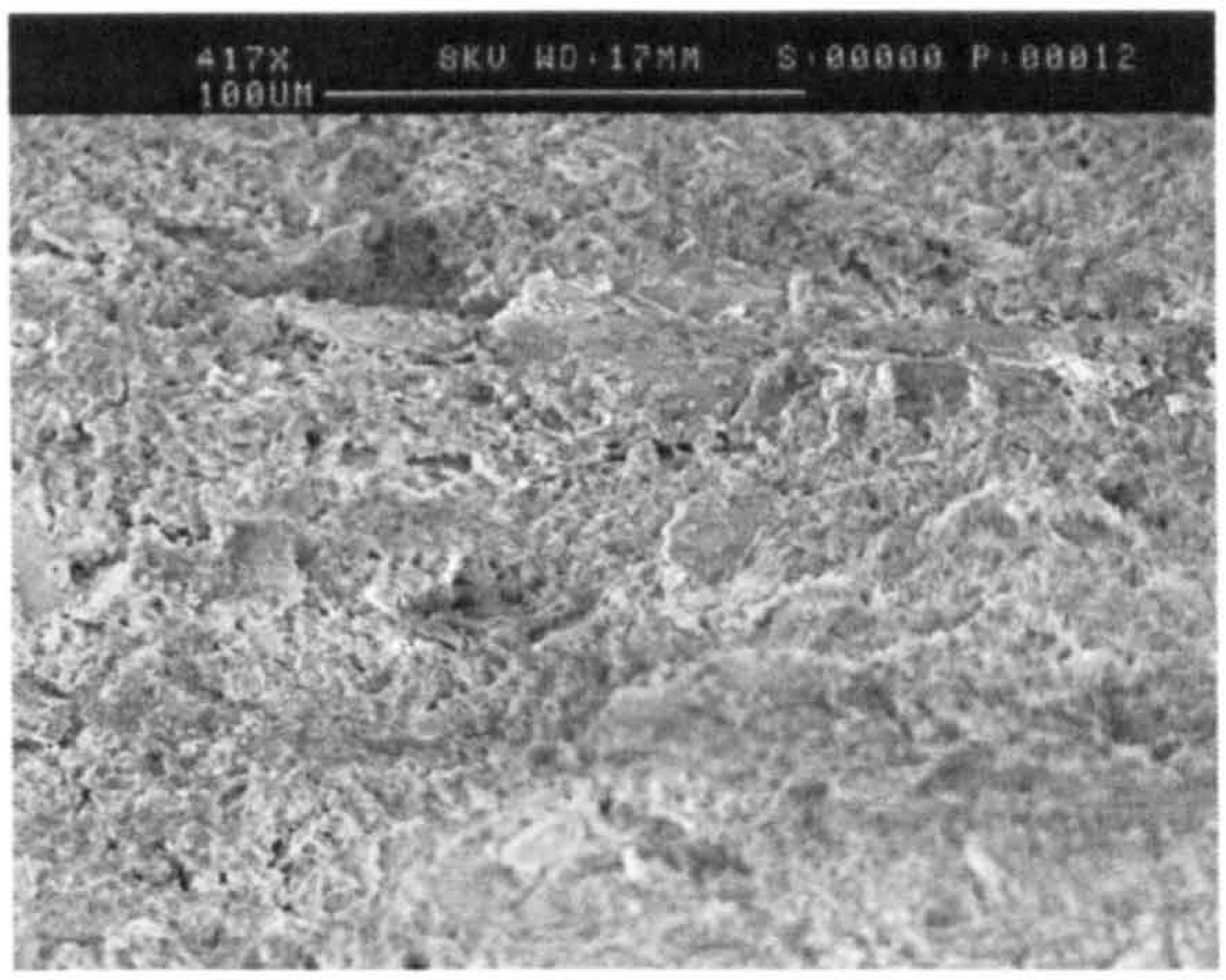
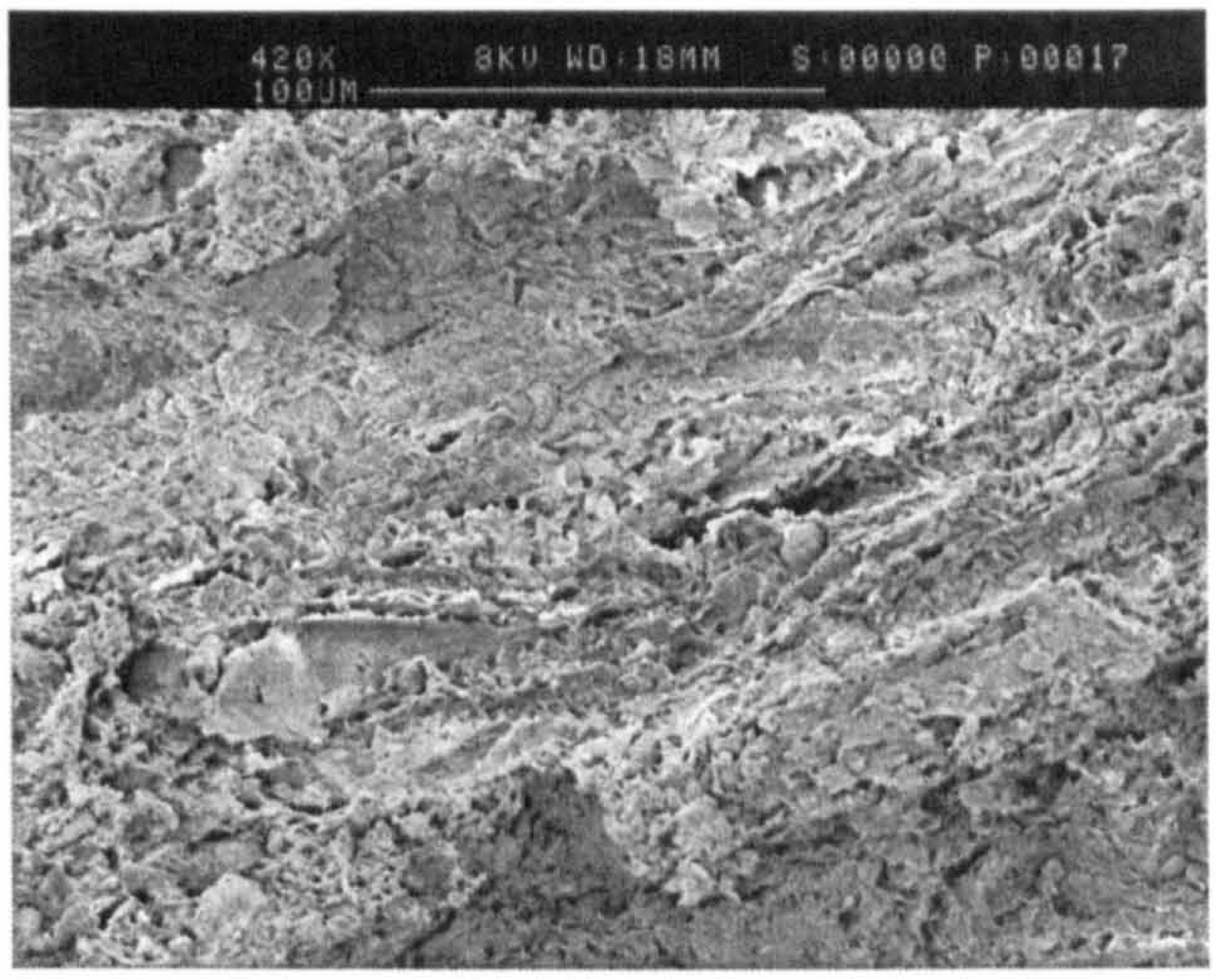


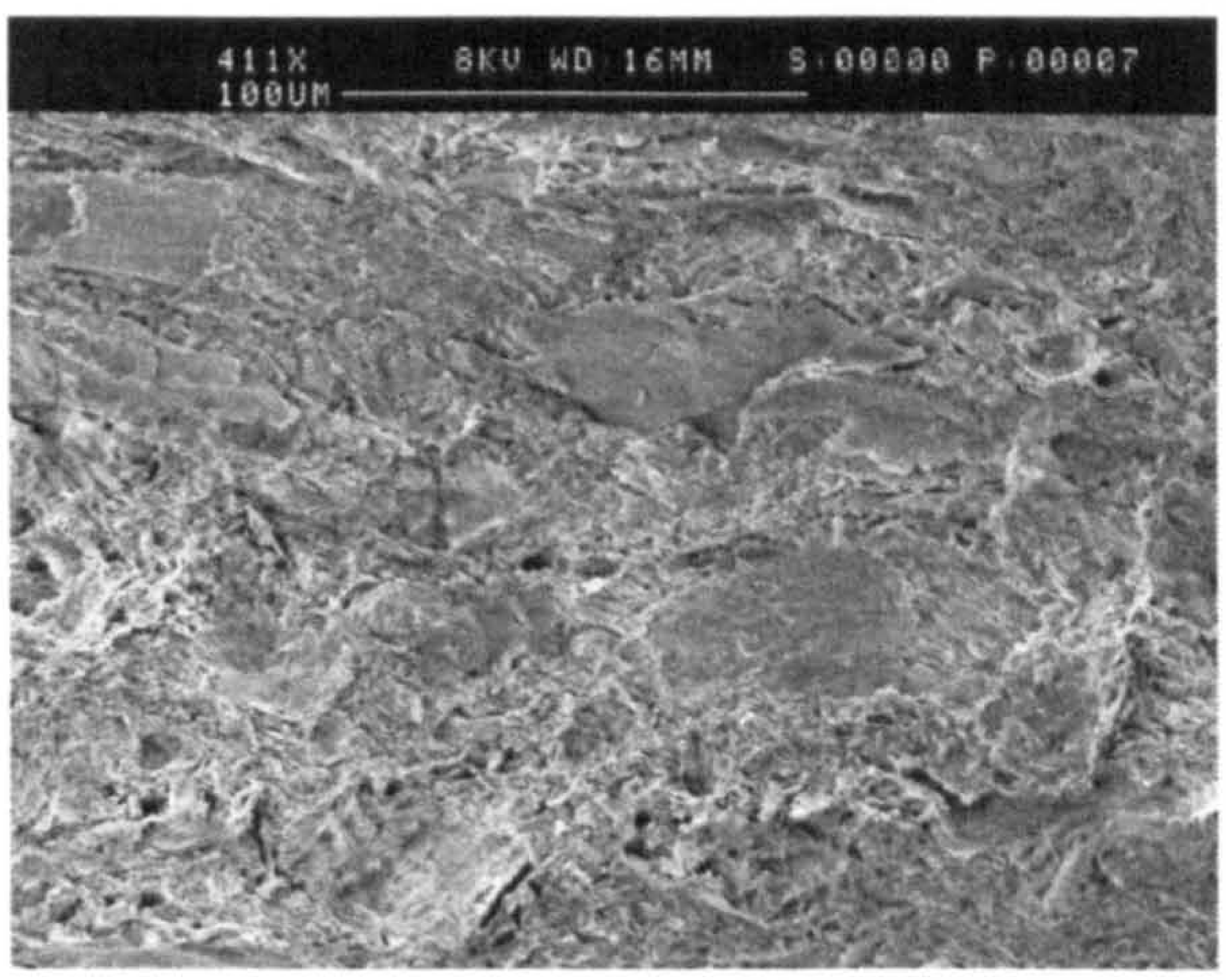
Figure 20: Effects of firing temperature on the bacterial removal performance of ceramic filters.



Sample fired at 600 °C



Sample fired at 800 °C



Sample fired at 1000 °C

Figure 21: SEM images of filter sections

Discussion

From these investigations, it can be seen that the maximum temperature achieved during firing can have an effect on both the flow rate and filtrate quality; with the sample fired at the highest temperature (1000 ^{0}C) performing better in both respects. The temperatures assessed in this test represent the range of temperatures that are readily achievable in basic pit kilns such as those in use in Bangladesh, (Figure 23).

More advanced solid fuel kilns, such as the one in use at the Greystoke potteries, (Figure 22), are capable of higher temperature firings. Techniques used by Greystoke, such as preheating and the use of forced aeration, increase attainable temperatures, and, as suggested by these experiments, increase the filters' potential performance; although a 1350 ^{0}C filter would be likely to become impermeable (due to fusing of the silicates) suggesting there is a limit above 1000 ^{0}C at which improvement would not be gained. However, these experiments confirm that even at the relatively modest temperatures of 800 ^{0}C the fired ceramics work effectively as high quality water filters and are both physically and mechanically robust.

A comparison of two solid fuel kilns showing common features:

Figure 22: A solid fuel kiln, Greystoke Cumbria, UK.

Figure 23: A solid fuel kiln, Dhaka Bangladesh.

Colour and turbidity removal

Objective

The objective of this assessment was to quantify the colour and turbidity removal capacity of simple ceramic filters. These represent water quality parameters that appear in many water quality standards throughout the world and can be monitored simply and cheaply.

A micro-porous filter has the capacity to change the physical properties of a water sample, as well as the biological conditions. Colour and turbidity present in water result from suspensions of very fine particles and dissolved coloured substances, such as humic and fulvic acid. A ceramic filter may remove fine particles, through surface adsorption and physical straining, reducing the colour and turbidity and so reducing its taste and making the water more pleasant to drink. The removal of colour could also be used as a readily assessable indicator of performance, enabling quality assessment to be under taken at a basic level without the need for complex equipment.

Method

A pair of test filters was prepared according to the standardised slip casting methods (Section 4.2.2.2). The filters contained 15% paper clay, had a dried thickness of 15 mm and were fired to 900 ^{0}C on a pit kiln firing program.

A river water sample was collected from the upper reaches of the River Tyne during a period of low flow; this water contained high levels of peat derived colour, but contained only small quantities of coarse suspended matter. The river water sample was inoculated with *E. coli* as a microbiological filter performance indicator, as detailed previously (Section 4.2.2.5).

The test filters were commissioned in the test apparatus (Section 4.2.2.4), and samples of the retentate and filtrate collected. All samples were measured for turbidity using a Hach 2100A nephelometric turbidity meter. An apparent colour assessment was made using a Lovibond daylight 2000 nessleriser, comparing samples against standardised colour disks. The test filters were operated for a period long enough to establish constant flow (260 h). An assessment for microbiological performance and flow rate was taken at three time intervals to ensure the filters were representative of those produced previously.

Results

The use of natural river water as the challenge water did not result in greatly diminished flow rates compared to previous experiments where distilled water was used as the challenge water (Table 7). Nor did the use of river water result in the build up and visible growth of algae. The river water sample used almost certainly contained *E. coli* initially (2000 CFU.100 ml^{-1}, P.J. Sallis personal communication), but this was probably at least an order of magnitude below that produced by the inoculation.

The filters performed at a similar level to those fabricated and tested in previous experiments, with bacterial removal rate being in the same order of magnitude, and flow rate within 10% of that achieved for similar time intervals in earlier experiments (Section 4.3.1 to 4.3.4).

The results for the colour and the turbidity removal from the challenge water show a marked decrease in both colour (62%) and turbidity (80%) of the retentate within the first 4 days of the experiment (Figure 24). This is likely to be attributable to the settlement of the raw water in the reservoir, leading to a reduction in suspended material, reducing the turbidity and apparent colour of the retentate.

Over the same period, the performance of the filter improved, consistently reducing the turbidity to below 5 NTU (WHO 2003b). The turbidity of the filtrate was consistently low, and the performance of the filter showed no tendency to reduce during the test period, with >86% and >95% turbidity removal throughout.

Colour removal from the challenge water was not as consistent as turbidity removal. Colour removal rates ranged from 37%-81%, though performance was improving towards the end of the test period. The removal rates for colour produced a sample that was close to, but not always below, the level of the WHO guideline of 15^{0}Hazen (2003b).

Table 7: Summary results for flow rate and bacterial removal for filters challenged with coloured water

Sampling time (h)	Flow rate, ($lm^{-2}h^{-1}$)	Bacterial removal (%)
80	3.975	99.99
100	3.988	>99.99
266	3.986	>99.99

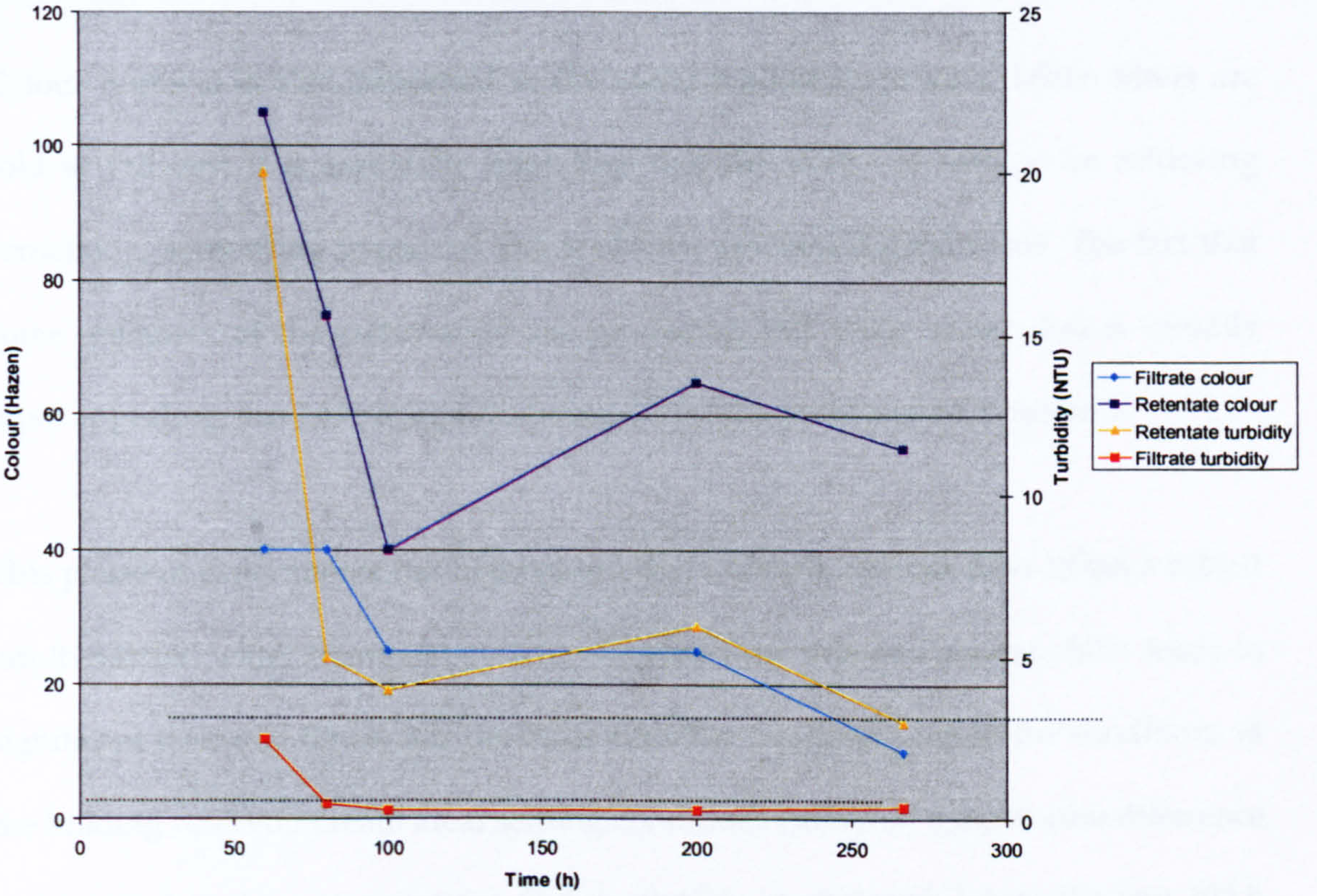


Figure 24: Results for colour and turbidity removal experiment; dashed lines show the WHO guideline levels.

Discussion

The World Health Organisation note that, whilst not directly responsible for ill-health, colour poses a potential visual deterrent from highly contaminated sources (2003b). Nevertheless, the removal of colour is of great importance. If a filter fails to remove colour from water, and the filtrate looks no different to the retentate, consumers perceive that the treatment systems are ineffective. It has been demonstrated in intervention studies that by changing the easily identifiable physical parameters of a water sample during the treatment process (i.e. colour, temperature and taste), that the role of filters is better understood and that the assimilation of point-of-use systems is more effective (Sobsey 2002).

Colour removal is also important in the social marketing process. When filters are sold at full cost it is especially important that the units are seen to be achieving something; even if the impact of this is of little epidemiological value. The fact that some members of the community are producing and using water that is visually more appealing, can have a significant impact on the uptake of such systems.

This phase of experiments has highlighted that a simple ceramic filter offers a robust 'multi-barrier' water treatment system. The low flow rate of a ceramic filter leads to significant retention times; this provides a further treatment step as the conditions in the holding reservoir create ideal settling conditions (minimal temperature difference and no surface shear or agitation). Sedimentation, as observed during the first 100 h of this experiment, is a highly effective method for removing suspended material, specifically larger aggregated clumps of organic material and sediments which have been shown to harbour significant pathogen loads, (Huq *et al* 1996).

The removal of colour and turbidity can have a significant bearing on the effectiveness of any further treatment to which the water is subjected. Both UV and chlorine disinfection systems are noticeably more effective in low turbidity, low-colour waters, where there is less shielding for pathogens and reduced levels of organic matter and therefore lower chlorine demand.

Colour is a subjective and often subtle parameter. Colour can result from suspended or dissolved material and the detection of colour requires good eyesight. The removal of turbidity can also serve as a good visual indicator for the failure of a filter during operation. Turbidity, whilst measured using a turbidimeter in these experiments, could alternatively be measured with a simple Jackson candle turbidimeter or calibrated tube:

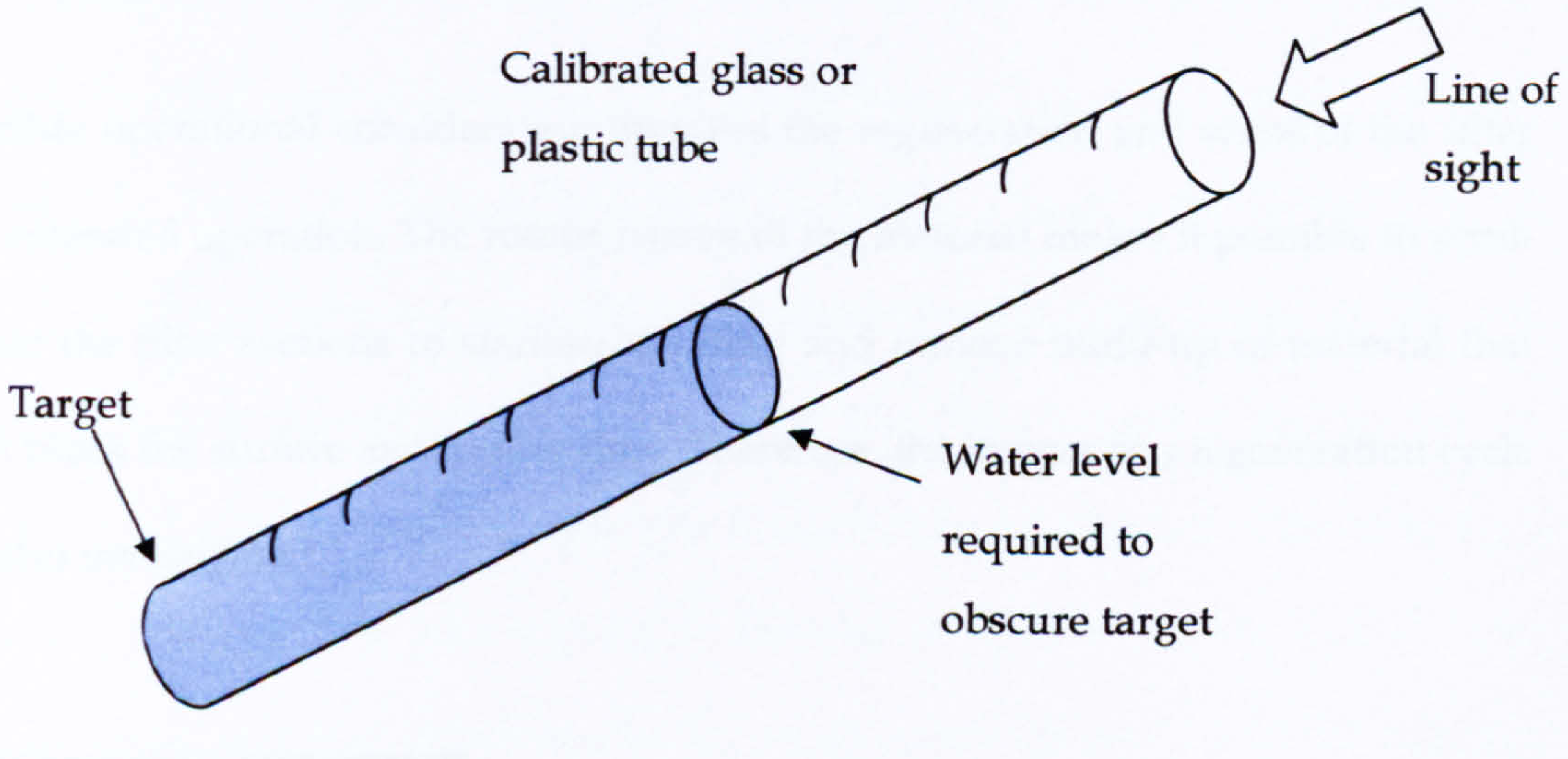


Figure 25: Diagram of a simple Jackson candle turbidimeter.

The ability to readily monitor the turbidity of the treated water offers potential for an online check to ensure that the ceramic filters have not failed, or developed leaks or short circuits.

4.3.6 Duration and regeneration

Objective

The duration for which simple ceramic filters can operate efficiently is an important factor in considering their application. Where the filter is to be used for treating water that contains little suspended material, but that still presents a risk to health, such as the treatment of tube-well waters[7] or water from unreliable sources such as community water vendors, the operation of the filter is likely to be unhindered by the obvious build-up of solid material. However, the treatment of poor quality surface waters with high solids and turbidity loads might cause long-term blockage and deterioration of the filters. To test this, filters were assessed over an extended period.

A further operational consideration involves the regeneration and reuse of the filter after extended operation. The robust nature of the material makes it possible to scrub or heat the filter sections to sterilise the filter and remove build-up of material that could block the surface and hinder flow. Therefore, the impact of a regeneration cycle was also investigated.

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[7] Tube-well waters, whilst perceived to be of a high quality, are frequently a source of potential contamination (Islam *et al* 2001, BGS 2001)

If the predominant removal process operating in the sample filters is a depth filtration method, allowing the permeation of the pathogens into the structure of the filter but not through the filter, a cleaning system that removes a thin surface layer throughout the filter's thickness, whilst not impairing future performance, is important. Whereas, if a size exclusion mechanism predominates, as in membrane filtration systems where the bacteria will be retained on the top surface of the filter, more intensive, but non-destructive, cleaning of only the top surface of the filter will be required. To gain a better understanding of the filtration mechanism in operation within the sample filters, and to inform the development of a suitable regeneration strategy, an assessment of the removal mechanism operating in the sample filters was a further objective of this experiment.

Method

As one of the objectives of this experiment was to investigate the long term performance of the filter, the filters that had been prepared for the investigation into temper volumes were re-commissioned for this experiment. At the end of their operation for the temper experiment, (Section 4.3.2), the filters were operated for an additional 1056 h. Flow rate was monitored periodically and the filtrate quality was measured once at the end of the 1056 h period. The filters were then regenerated by heating to 400 ^{0}C in a muffle furnace, (the filters remaining attached to the glass bells but requiring re-sealing with silicone as detailed in Section 4.2.2.4), flushed with distilled water, and then reattached to the distribution network. Further monitoring of the flow rate and filtrate quality was then resumed to determine the effects of regeneration.

To gain further insight into the bacterial removal mechanism during operation, filters were fixed and examined after operation using SEM (Section 4.3.4). This was achieved by commissioning and operating a set of filters (filters previously used in Section 4.3.3). By fracturing the filter tangentially, to expose the flow path, as well as using samples of the filters' upper surfaces, it was possible to expose the potential retention sites of the bacteria. In order to fix any bacteria supported within the depth of the filter structure, filter fragments were immersed in gluteralderhyde solution (2.5%) for 24 hours then critical point dried to preserve their structure (Bell and Safiejko-Mroczka 1997). These samples were then mounted and gold coated ready for examination. The Scanning Electron Microscope and operating conditions used are described in Section 4.3.4.

Results

Having operated the filters for 1056 hours, the flow rate for all samples remained consistent with no obvious reduction in flow after steady state flow had been achieved (100 h) (Figure 26).

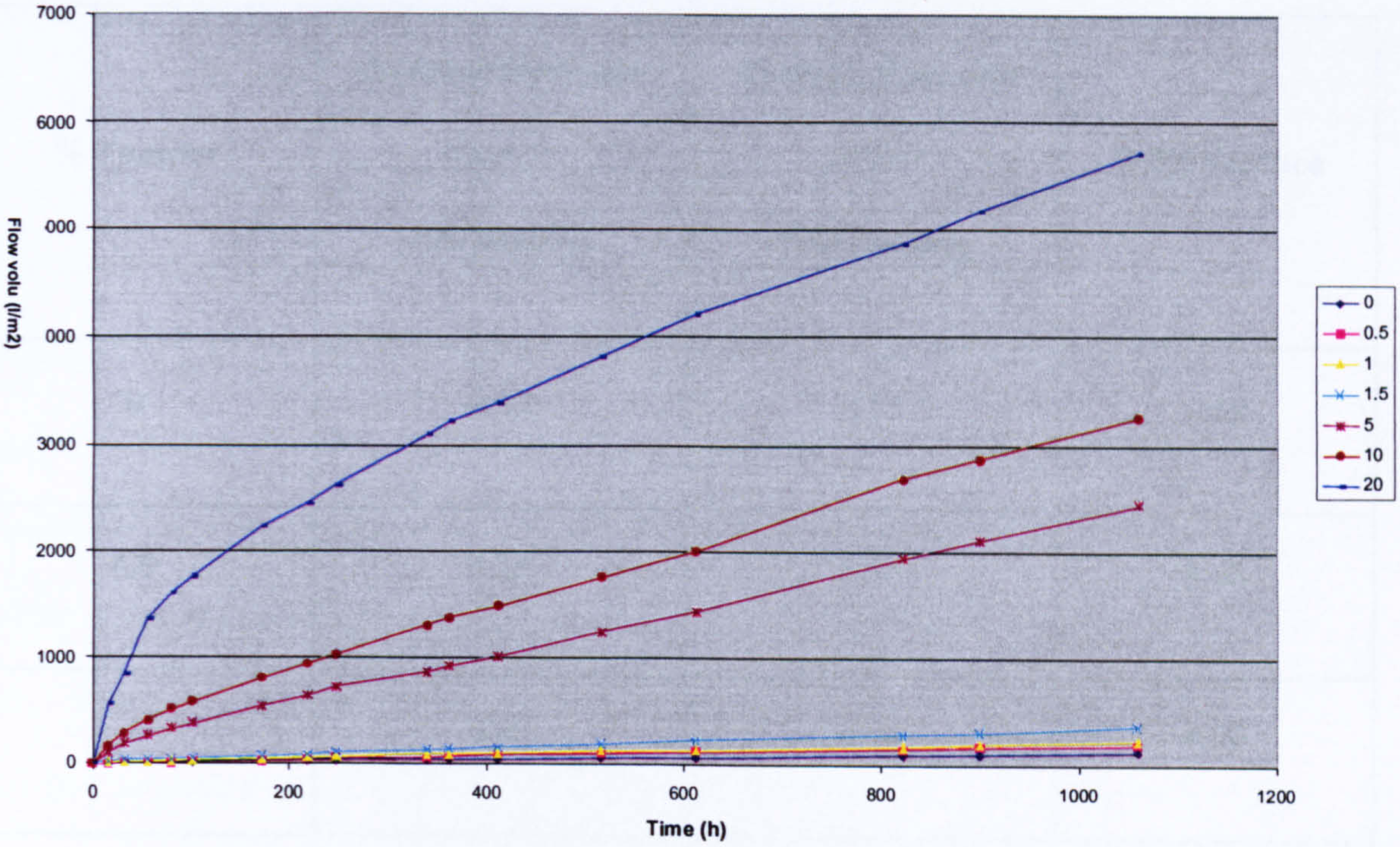


Figure 26: Results from extended duration flow experiment.

Table 8 shows the average flow rates pre and post regeneration. It was found that there was no appreciable difference between the performance of the filters with a consistent average removal rate greater than 99.98% both before and after regeneration.

Table 8: A comparison between performance pre and post regeneration.

% Temper	Average flow rate $lm^{-2}h^{-1}$ Pre heating	Average flow rate $lm^{-2}h^{-1}$ Post heating	% Difference
0	0.13	0.13	0.69
0.5	0.20	0.20	0.65
1	0.23	0.24	4.50
1.5	0.36	0.35	-1.24
5	2.32	2.40	3.13
10	3.31	3.30	0.01
20	5.40	5.40	0.40

The regeneration process appears to have had minimal effect on the flow performance of the filters, with no obvious difference noted. The largest differences occurred with the 1 and 5% temper samples. However, these differences are, in real terms, not great and may be yet further reduced were the experimental duration to be increased; as a comparison drawn between the mature filters, between 800 and 1000 h, and the regenerated samples produced even less of a difference.

Under the randomly selected fields of view that were examined, the SEMs of the filter surfaces and flow paths showed no evidence of bacteria. This may be due to the limited number of views used or to the failure of the fixation process. One explanation for the observed absence of bacteria is that the filters may have channelled flow through specific flow paths, with the majority of flow being exuded from the areas that were not sampled for SEM analysis. These flow paths would be very difficult to identify under normal operating conditions, making it difficult to identify an area in which the bacteria may be retained.

Discussion

The objective of these experiments was to run the filters to a point of breakthrough, where either the filtration performance deteriorated or the flow rate reduced substantially; however, Figure 26 confirms that this did not occur over the 1056 h of the study. This would suggest that when treating low turbidity waters, the filter has a workable duration of tens of weeks between regenerations. When using the filter against more turbid surface waters, the build up of solid material might reduce the flow rate more rapidly, necessitating regeneration well before potential breakthrough has occurred. By way of comparison, in operation the TERAFIL ceramic filter system operated in India has achieved a working life of five years allowing for regular regeneration, by scrubbing (Khuntia *et al* 2002).

Due to the intended application of these filters at the point-of-use with no infrastructure available for monitoring flow and performance, it is important to understand their long-term performance. The end users will not have access to water monitoring equipment. Therefore, the protocol for using and cleaning the filters must be sufficiently conservative to ensure that adequate filtration is consistently achieved in order to maintain the treatment system's reputation and guarantee that the users are motivated to persist with the system. For the integration of point-of-use systems to be successful, and for a 'social marketing' strategy to stand any chance of success, the filters must be perceived to be effective (personal communication Jenkins 2004).

In this experiment heat was used to re-commission the filters. This was perceived as a sustainable process as all communities use fires or ovens for cooking. Placing the filters in the fire will expose them to a moderate heat, i.e. 400 ^{0}C, which will be enough to clean the filters but not to change their fired structure.

Chemical cleaning and scrubbing with bleach (hypochlorite) is a simple cleaning method as bleach is relatively cheap and available to many potential user groups. However, the benefit of heating is that it removes the risk of exposure to the potentially high concentrations of bacteria that will have amassed on the inside surfaces of the filters during extended operation. Additionally, it can be achieved by even the most remote communities that lack access to any chemical cleaning products. The disposal of the concentrated sediments from the filter units, containing associated pathogens, is an important issue requiring consideration in the life cycle of the product, especially when used in dense urban areas in which space may be at a premium. It is recommended that the disposal of the concentrated sediments is to a sanitary facility or a latrine, a practice that is also suggested by Procter and Gamble when using their PuR ® coagulation sachets.

4.3.7 Manufacturing reproducibility

Objective

Experiments in Sections 4.3.1 to 4.3.6 have shown that simple ceramics can produce effective water filters, although the performance of these filters has been seen to vary according to fabrication and operating conditions. The objective of the manufacturing reproducibility experiments was to assess how reproducible the filtration characteristics were between production runs, and the effect of utilising alternative materials. This was achieved by examining the variability that was found within a given production batch and between batches produced in different fabrication runs.

Method

Having investigated the effect of temper on simple ceramics (Section 4.3.2), a second set of filters was produced using fabrication conditions identical to those in the initial temper investigation and operated for 200 h under the same conditions as the original experiment. The performance achieved by the original filters was then compared to the reproduced filters for the flow period from 0 – 200 h.

Further comparisons were also drawn between the performance of filters produced in the current investigation, and the performance of filters in previous investigations (Sections 4.3.1 to 4.3.6), where the materials and techniques used were similar.

Finally, a set of filters was produced to replicate one set of conditions, 10% paper fibre temper, 900 ^{0}C firing, 10 mm section thickness, but using three different clay materials, ball clay, china clay and buff school clay. The performance of these filters was then compared to that achieved previously using identical fabrication conditions with the exception of the clay material which, in the earlier experiments, had been hyplas.

Results

Table 9: A comparison of filter performance achieved in two production runs using identical fabrication conditions.

% Temper	Average flow rate $lm^{-2}h^{-1}$ Run one	Average flow rate $lm^{-2}h^{-1}$ Run two	% Difference
0	1.25	1.47	15
0.5	0.20	0.21	9
1	0.28	0.29	1.7
1.5	0.35	0.43	18
10	3.11	3.30	6

Although the 20% temper filter was reproduced in the second run, the silicone seal attaching it to the filter bell failed, leading to gross contamination; hence data is not included.

Figure 27 includes all the results from the comparable experiments conducted during all investigations. It shows that there are two regions in which there appears to be a relatively linear relationship between percentages temper and flow rate. In the first instance this occurs between 0 and 1.5%, with a second linear region having a relatively higher flow rate for a given temper composition occurring between 5 and 20%. Between 1.5 and 5%, however, the increase in flow rate with temper addition is greater and non-linear. This region of rapid transition would be interesting to characterise further, as it may have a link to chemical and physical changes within the filter structure that result from small changes in temper composition. However, for this investigation it occurs below the region of flow performance that is relevant to the target specification of the filters.

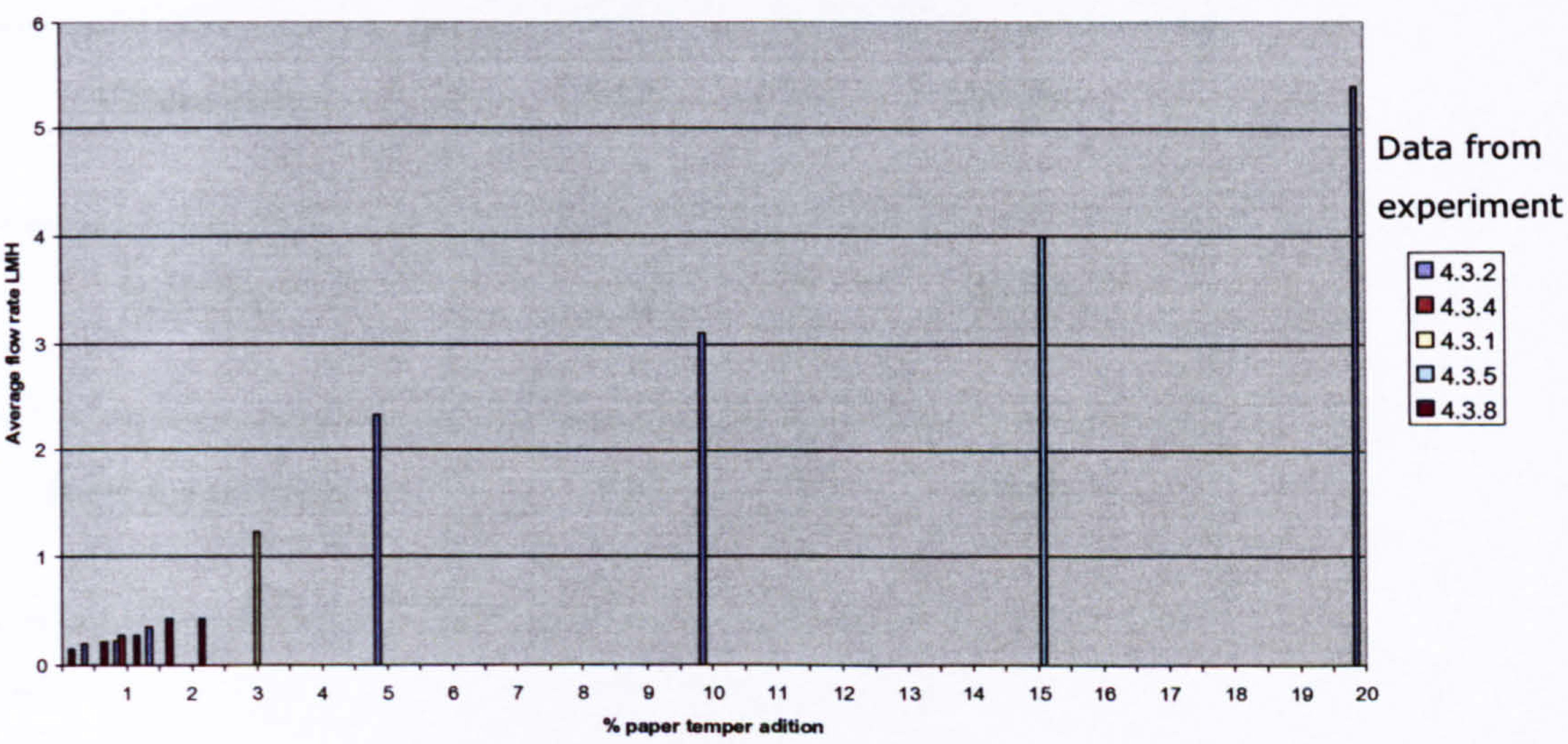


Figure 27: A comparison of average flow rate and temper addition across all experiments.

The clay comparisons (Table 10), show that there is no noticeable difference between the filtration performance according to the clay body used. This could be due to the relatively low firing temperatures 900 ^{0}C since lower temperature firings reveal less of the specific mineral characteristics of the individual clays than firing at maximum temperatures when higher fractions of low melting point minerals would begin to flux causing reduced porosity .

Table 10: Effects of clay material on the filter performance for flow rate and bacterial removal efficiency.

Clay material (including 10% paper fibre temper)	Average flow rate $lm^{-2}h^{-1}$	Average bacterial removal rate %
Hyplas	3.31	99.98
China clay	3.33	>99.98
Ball clay	3.28	>99.98
Buff school clay	3.20	99.97

Discussion

The ability to reproduce the filtration characteristics achieved in the earlier investigations is an essential requirement for filter production. Limitations in the availability of laboratory testing and flow monitoring facilities in the field dictates that only a very small fraction of the filters would ever be subjected to rigorous quality control assessments. Therefore, there is an absolute requirement that the fabrication method achieves a predictable and reproducible performance capacity that obviates the need for quality testing of each individual filter.

This series of experiments demonstrates that the filtration characteristics achieved in earlier investigations can be readily reproduced, and supports the contention that it is possible to produce filters using local material and the simple techniques of local potters. This not only ensures sustainability in the production and supply of the filter units, but also serves as a capacity building step in the development of a local industry. Capacity building is seen as a crucial step in achieving long term sustainability (Jenkins 2004)

4.3.8 Carbon adsorption of Arsenic

Objective

Adsorption on carbon is an effective method of metals removal and wood-derived charcoal is a cheap and abundant source of carbon. The primary objective of this assessment was to determine if charcoal had sufficient adsorptive capacity to remove significant levels of arsenic from contaminated drinking water.

The capacity of carbon to adsorb metals is a function of the physical and chemical conditions of the water and the affinity of the metal for the carbon in preference to the water (Manju *et al* 1998). Efficient treatment by the process of adsorption requires an adsorbent with a high surface area. It is possible to increase the surface area of carbon through activation to open up the internal structure, or by grinding the carbon into small particles so increasing the external surface area.

Adding a volume of wood-derived charcoal carbon to the raw water within a ceramic filter vessel would, due to the slow flow rates and long filtration duration, allow a long contact time to be achieved that may produce significant levels of arsenic adsorption.

Method

To gain an overview of the suitability of wood-derived charcoal carbon as a low-technology arsenic adsorbent, a range of investigations was conducted to assess the performance of this material and to take steps towards optimising it for use. The adsorptive capacity of the carbon was assessed in relation to its particle size and the effect of a simple heat activation process.

The challenge water: Adsorption capacity and efficiency can be affected by the chemical conditions of a sample water (Pattanayak *et al* 1998). For the purpose of these tests, a synthetic groundwater was prepared to reflect the conditions found in Bangladesh's tube-wells (Petrusevski *et al* 2002). Distilled water was supplemented with 275 mg/l bicarbonate and adjusted to pH 6.6 using HCl and temperature was standardised to 25 ^{0}C for all tests. The synthetic groundwater was spiked with arsenic in the trivalent form as sodium arsenate. The initial arsenic concentrations were set to match the higher limits found in Bangladesh by the BGS (BGS and DPHE 2001), approximately 200 µg/l.

The adsorbent: Commercial charcoal was purchased in the form of untreated mixed lump wood barbeque charcoal. 500 grams of charcoal were placed in a rotary rock crushing mill (Fritsch 01.151) and the crushed output was then placed in a set of sieves on a mechanical shaker, (End Rock 24761). Samples were sieved for 10 minutes and graded to fractions of 10>5>1>0.2mm.

To activate the charcoal, a simple heating process was applied. A sample of charcoal of a uniform size was heated in a muffle furnace at 500 ^{0}C (red heat), for 30 minutes before being quenched in cold water. This process reduced the apparent density of the charcoal; for all adsorption experiments using this heat-activated charcoal (HAC) the sample mass is specified post heating i.e. as activated weight.

The procedure: For each test, the required mass of charcoal, of the specified particle size, was added to an acid-washed glass conical flask. 250 ml of the arsenic spiked water was then added and the sample stirred for 2 minutes with a glass rod to ensure the dispersion of the charcoal in the water. The flasks were then placed in a static incubator at 25 ^{0}C.

After contact, samples were taken for analysis by filtering through a Whatman GF -A paper, and the filtrate collected and stored in acid washed 250 ml medical flat bottles. All samples were analysed within an hour of collection, and a control sample was prepared and filtered in the same manner without chemical addition and stored and tested alongside the treated samples.

Arsenic analysis was carried out by atomic adsorption spectrophotometer with hydride generator, using a Varian AA 400 and a VGA76 HG according to the manufacturers' specifications (Niezielski 2002).

Batch tests of conditions for charcoal adsorption: A range of HAC samples and charcoal samples of different particle size were prepared (Table 11). These were then combined with the challenge water as described above. Treated water samples were collected after 18 hours to represent the upper limits of the expected retention time in a household ceramic filter system.

Further samples of treated water were also collected from two of the unactivated charcoal adsorbents (samples A and B from Table 11) to assess performance with longer adsorption periods, of up to 48 hours.

Table 11: Charcoal specification for adsorption experiments.

Fraction name	Pre-treatment	Charcoal particle size (mm)
A	None	1mm<A<10mm
B	None	0.5mm<B<1mm
Dust	None	Dust, <0.2mm
HAC	Heat-activated	1mm<HAC<10mm
Unfractionated	None	Unfractionated sample <10 mm

Results

Figure 28 shows the arsenic removal efficiency for different charcoal fractions and HAC achieved in the batch test experiments. These results show an apparently exponential increase in adsorption capacity of the charcoal as the particle size decreases. The smallest particle (Dust) demonstrated a gram per gram removal rate nearly three times that of the largest fraction (A). The HAC also showed a marked increase in adsorption, with the removal rate being more than three times that of the unactivated charcoal with the same particle size (A). There is a decrease in the removal rate achieved by the two charcoal samples, A and B between hours 18 and 42, shown in

Figure 29 despite a constant arsenic level in the challenge water.

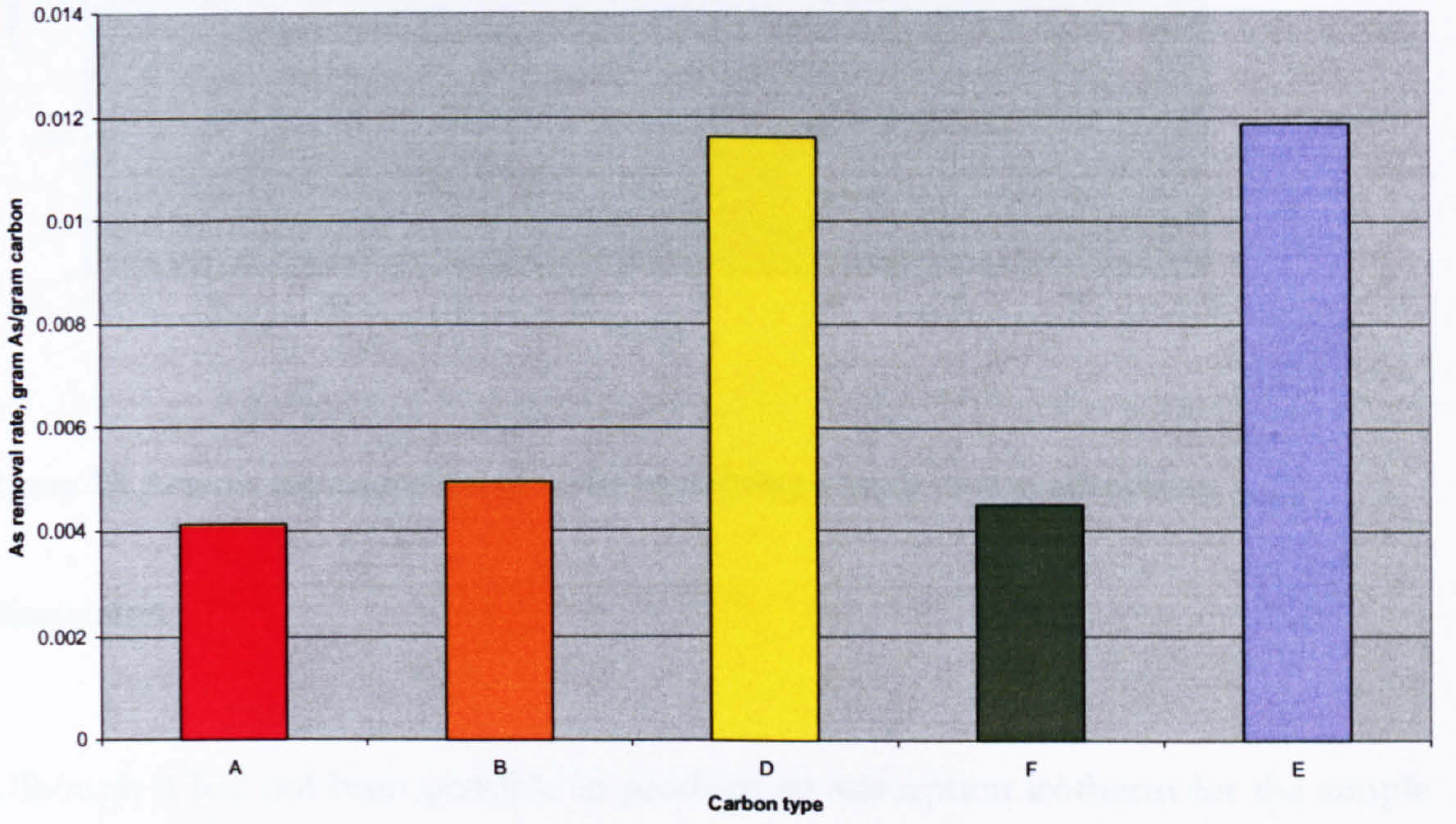


Figure 28: Chart to show the removal rate achieved by differing carbon specifications.

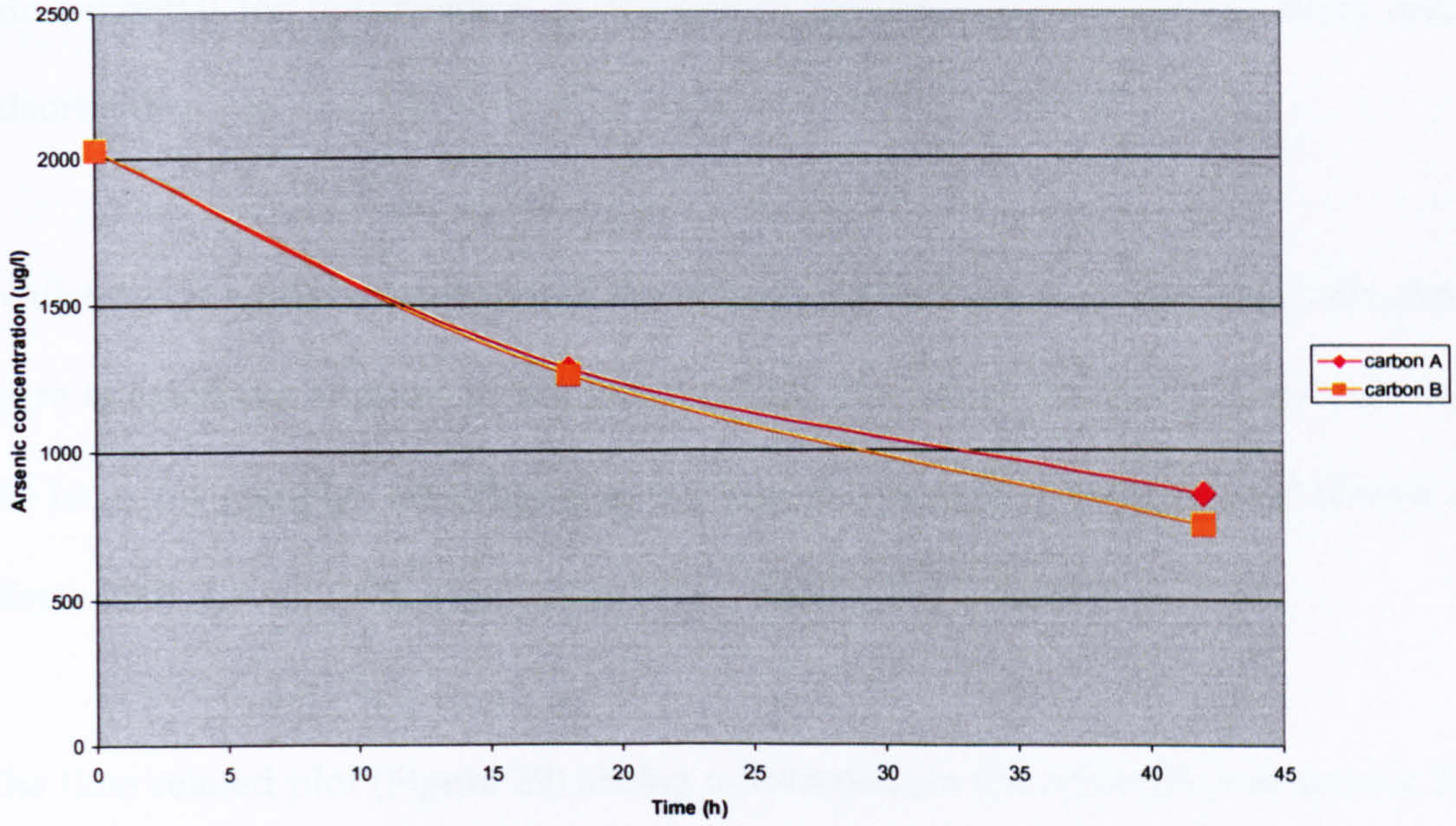


Figure 29: Arsenic concentration of water containing simple carbon adsorbent.

Discussion

Although it has not been possible to produce an adsorption isotherm for the simple wood-derived charcoal, these initial investigations confirm that arsenic was effectively adsorbed from the challenge water. The adsorption capacity, gram for gram, and the adsorption rate, suggest that there are potential benefits to be gained by incorporating carbon in a simple system to reduce arsenic loads. Although these experiments failed to meet the 0.01mg/l As target for treated water set out in the WHO guidelines (2003b), the removal capacity of the charcoal was established. Furthermore, the increase in adsorption capacity achieved through simple optimisation of the charcoal, either by reduction in particle size (the difference in performance between the sample A and the Dust sample) or heat activation (the difference in performance between the sample A and the HAC), supports the value and potential for optimisation in the use of charcoal derived carbon as an arsenic adsorbent.

Whilst this is a brief assessment of the efficacy of charcoal as an adsorbent for metals, there is extensive support in the literature for the use of low-cost carbon sources as the basis for complex adsorbents or for use in a simple unaltered state (Grens and Werth 2001; Lewis 1995; Manju *et al* 1998 , Sobsey 2002; Toles *et al* 1997).

The time related plot (Figure 29) shows a reduction in the adsorption of arsenic from the sample. The reduced uptake rate is likely to be due to the decrease in initial concentration, a driving factor in the adsorption of arsenic by carbon (Pattanayak *et al* 1998), rather than a result of depleted adsorption capacity.

4.3.9 Carbon recovery by simple ceramic filters

Objective

Having established the viability of simple charcoal-derived carbon as an arsenic adsorbent (Section 4.3.8) it was necessary to develop a technique for incorporating the adsorbent into a simple ceramic filter system. The micro-porous nature of the ceramic filters would be expected to retain the carbon and adsorbed arsenic, producing water that is free from both bacteria and arsenic.

Method

In order to investigate the capacity of ceramic filters to retain the charcoal adsorbent, a set of filters was prepared according to the specification in Section 04.2.2. Prior to bonding the filter to the glass bell, the upper apertures on the bell were filled with glass fibre wool and the bell then filled with 300 gm of fractionated charcoal, collected as a sample passing a 0.5 mm sieve. The filter was then bonded to the glass bell and attached to the distribution network and challenged with water as specified in Section 4.3.8. After a brief period of operation to equilibrate the flow (30 hours), the flow rate, bacteriological removal rate and turbidity of the filtrate were assessed over a period of 72 hours (Sections 4.2.2.5).

Results

The use of ceramic filters to recover the charcoal yielded results for flow rate within 3% of those achieved by a similar filter without the charcoal (Section 0). This agrees with the variation found in earlier experiments (Section 4.3.7), confirming that the charcoal did not hinder flow. The filtrate also showed no increase in turbidity, suggesting that the carbon was entirely retained by the ceramic filter (Table 12).

Table 12: Results for filer performance incorporating charcoal adsorbent

Performance characteristic	Bacteriological removal (%)	Flow rate ($lm^{-2}h^{-1}$)	Turbidity removal (%)
Performance level	99.99%	3.87	99.99%

Discussion

The charcoal recovery capacity of the filter, coupled with the lack of impact on the flow, suggests that the ceramic filter is compatible with simple charcoal sources as a multi-barrier filter. This would indicate that the carbon adsorbent could be usefully included as an adsorbent packing within the household filter units where arsenic or toxic metals are present in the raw water.

5 The design of a household filter unit

5.1 Chapter abstract

Having produced a filter medium of suitable strength, performance and reliability, a household filter unit utilising this medium was designed to optimise the benefits of reduced water contamination to the end user. This chapter looks at the physical requirements of a point-of-use filter and the capacity of a simple ceramic unit to fulfil domestic needs. The requirements of the end users, together with the performance capacity of the material, are considered in producing a design for a unit that is both user-friendly and effective. Since the inception of this project, work has been published on systems that draw on similar philosophies. A comparison is made here with this new work and with existing technologies and alternative approaches to filtration, and the placement of a locally-produced ceramic filter in the water treatment market is considered.

5.2 'Developing' a design

To produce a household filter unit from the ceramic material that has been developed in this investigation requires consideration of both social dynamics and good water handling and hygiene practice. Different communities in different countries will have their own preferred style for vessels and for the shape and style of the units, yet, to ensure optimum performance, the fundamental design must consider the same hygiene factors and operational principles.

Consideration of who is to use the household filter, and how it will be used, are essential. For example, questions need to be posed such as: how many people are to use a single unit? how often will it be filled? where will it be stored? how will the treated water be stored? and how will the water be removed for use? Such considerations are all important in making decisions regarding the final design of a filter unit; one potential solution is offered in this chapter.

5.2.1 Users

Population, demographic and habitation patterns are important considerations in specifying a filter unit. If the objective is 'to provide sufficient water for drinking from an acceptably-sized household unit', it is imperative to consider the average size and structure of a household and their predicted water consumption. For example, an extended family living in a small dwelling, a common family structure in developing countries, would result in a larger water demand per household filter unit than would a smaller family group. The occupation of the family is also significant; where the family are engaged in manual labour such as farming, drinking water demands are higher and the pattern of demand requires sufficient water to be available for those who must carry water with them to work in distant areas. Howard and Bartram (2003) suggest that the minimum per capita daily water requirement is 2 litres in temperate climates to 4.5 litres in hot climates.

5.2.2 Operation

The operation of the filter relies on periodic filling with raw water followed by the hygienic removal of the filtrate as required. In designing a filter unit, it is essential to consider its integration into the home, and to ensure that it is compatible with existing practices, and can be operated and maintained by those for whom it is intended. The salient issues and valuable experiences of previous water interventions that were relevant in the design of the proposed filter unit are summarised below:

Collection compatibility: A point-of-use filter will require periodic filling, hence the filter unit must be compatible with the users' preferred collection methods. Where collection is in large 20 litre containers or jerry cans, the preferred capacity containers across much of Africa, (Sobsey 2002), it is important that the filter units have a capacity to match. In communities in Bangladesh, water is typically collected in ceramic and metal kalishes, the standard collection vessels are typically smaller so the unit capacity must match. It is important to match the capacity of the collection vessel to the filter unit to ensure that there is no temptation to collect more water than can be treated and then to use the excess untreated and poorly stored water.

The daily pattern of water collection is also important. Where water is collected from a distant source, it is common practice to make fewer collections of larger volumes; where water is more readily available, typically a higher number of small volume collections are made. These are further factors that have a bearing on the potential capacity of the individual filter units.

Filling: A hygienic and safe method of transferring the water to the filter unit is an important design feature. When water is collected in basins and large shallow vessels, decanting the contaminated water from the collection vessel to the filter unit could be a source of spillage and hence potential contamination. It is important to ensure that any spillage will not contaminate the user, the clean water reservoir, or the outside face of the filter element that may come into contact with the treated water. It is also important that, if the filter unit is to be filled directly from the collection vessel, the unit is low enough to allow women and children, the principal family members responsible for water collection, to pour from large heavy collection vessels into the filter element without undue wastage or inconvenience.

Stability: A ceramic filter filled with a day's water requirement will be of a substantial weight. The gravity flow path, top down, will make the centre of gravity relatively high in newly filled filters, making the units unstable. An important consideration is to make sure the unit has a wide and stable base to prevent the unit from falling and potentially injuring the users or fracturing the filter element.

Consideration of the footprint of the filter units will also be important; the filter units will commonly be used in small densely populated dwellings, lacking space to store a bulky unit.

Water Storage: Storage is important in two phases of the treatment process. Raw water must be stored in such a way as to protect the users from its potential contaminants, and the treated water must be stored to protect it from potential contamination by the users.

The operation of a point-of-use filter requires that there is a reservoir of contaminated water within the home; an important facet of the filter design is that it does not make this contaminated water easily accessible, which may tempt people to use it.

As well as safely storing the untreated water, the quality of the filtered water must be preserved. The safe storage of good quality water in the home is a topic that has received considerable attention (CDC 2001; Sobsey 2002). With the design and distribution of their improved water storage containers, both Oxfam and the Centre for Disease Research (CDC), independently highlighted the impact that a well-designed home storage unit could have on health (CDC 2001). Whilst intended principally for disaster relief situations, both units have come to be widely used for domestic collection and storage in many communities.

Safely extracting the water from the storage container is another important element of the final unit configuration. Studies show that the use of containers with devices such as spouts or taps/spigots, protect the water during storage and household use (Sobsey 2001). Trevett (2002) has supported this assertion, and from his work (Table 13), it can be seen that ensuring minimal contact between the users and the clean water is an important element in preserving water quality.

Table 13: The relationship between serving method and water quality in the home (Trevett 2002).

Serving method	Geometric mean[8] ThC.100 ml^{-1} (number of samples)
Dip cup	86 (74)
Ladle	182 (77)
Pour	23 (78)

Further investigations by Trevett (2002) into the importance of covering water containers has concluded that water quality in covered and uncovered wide neck tinajas (the preferred household storage vessels in Guatamala) is the same; however, the use of a cover could act as a deterrent from using the raw water and limit the presence of water-borne disease vectors such as mosquitoes.

Finally, with regard to the material of the storage unit, the quality of water stored in well-designed ceramic water storage vessels has been shown to be comparable to that stored in well designed plastic containers, (Ogutu *et al* 2001).

[8] ThC refers to thermo tolerant coliforms, an indicator of faecal pollution.

Appearance: The unit has to be neat and appealing as the cost will represent a significant proportion of the users' capital and it will be a large article in a modest home. The appearance of the unit is also a potential tool in promotion. A unit that looks appealing will help to market the technology independently of knowledge concerning its potential health gains.

The use of ceramics to store water in the home is preferred in some communities. A study in Kenya of 43,000 households found that 93% of households preferred the use of traditional ceramic vessels to more modern plastic containers (Makutsa *et al* 2001). In addition to appealing to the traditions of user groups, a ceramic vessel has a further advantage in that due to surface evaporation the unit and its contents will stay cool. An important benefit cited by users of ceramic storage vessels is that the water is not only more pleasant to use but there is also a social status factor associated with being able to offer cool water to visitors (Feachem *et al* 1986).

Incorporating basic operational guidelines into the filter unit's design, either as text or graphics, could also facilitate the education of users to adopt the correct operational procedures following the guidance of the PHAST initiative (Simpson-Hebert *et al* 1997).

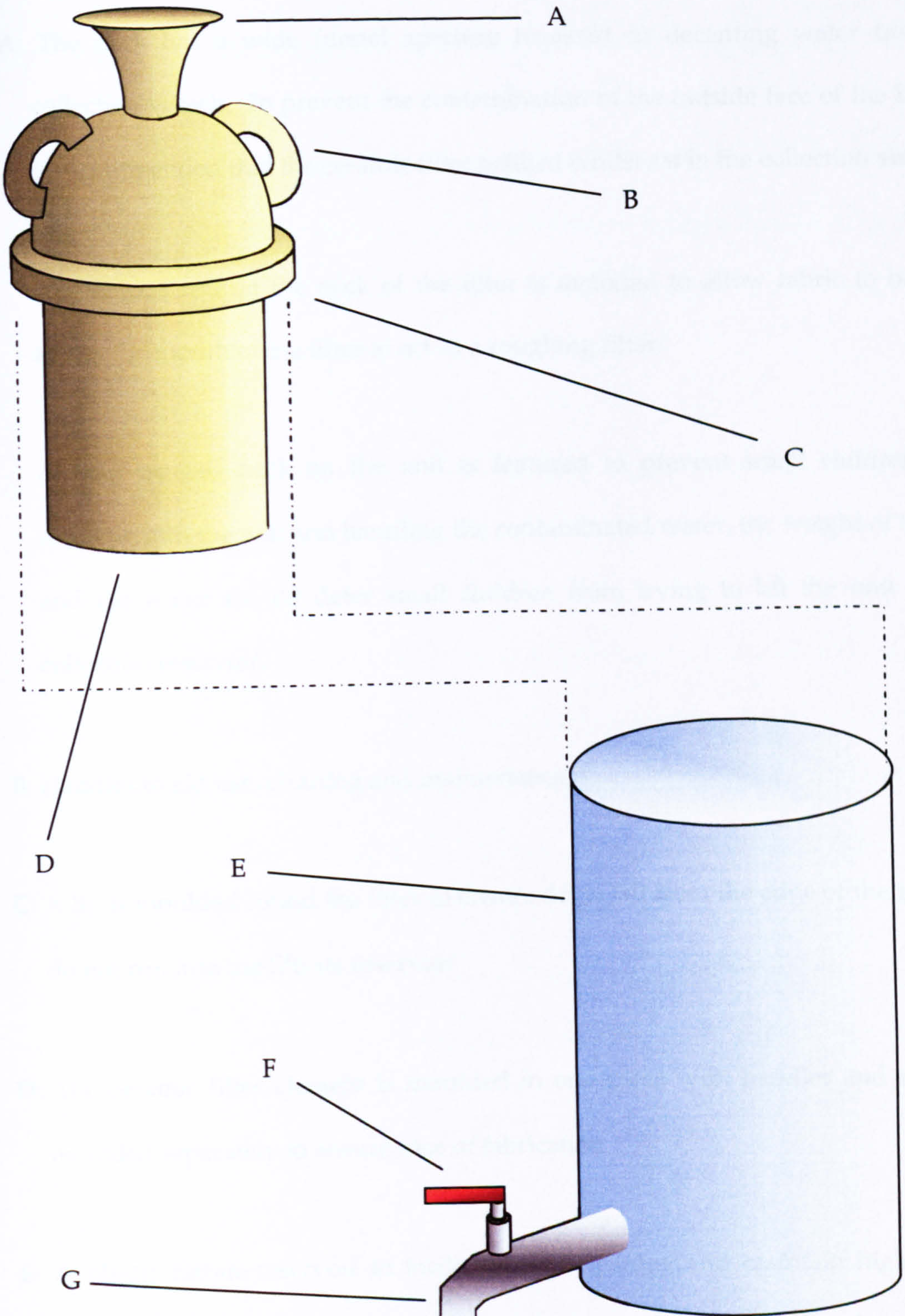
Maintenance: Cleaning the filter unit must include periodic rinsing of both the inner and outer faces of the ceramic element, together with the cleaning of the filtrate receptacle, neck and outside surfaces. To ensure that this is easy to do and there is no risk of damaging the units, it is important that the units are robust and are provided with lifting handles to assist the maintenance process.

All parts must be of simple configuration and it is important that any taps do not leak and that the filters seal properly to the filtrate reservoir.

5.3 The proposed unit

Taking into consideration all of the issues raised so far, the following proposal is advanced: (The following design is for a unit configured for application to urban and rural areas of Bangladesh.) In the presented configuration the filter provides a Multi-barrier treatment system incorporating sedimentation, filtration, safe storage and carbon adsorption. The proposed unit is shown in Figure 30.

Figure 30: Proposed unit design



Key to the design features shown in figure 30:

A: The neck has a wide funnel aperture to assist in decanting water from the collection vessels. To prevent the contamination of the outside face of the filter, it is recommended that the ceramic filter is filled whilst sat in the collection vessel.

A generous roll on the neck of the filter is included to allow fabric to be fixed across the mouth of the filter to act as a roughing filter.

A long tapered neck on the unit is featured to prevent small children from reaching into the unit and handling the contaminated water, the weight of the unit and the water should deter small children from trying to lift the unit off the collection reservoir.

B: Handles to aid use, cleaning and maintenance.

C: A lip is moulded round the filter to ensure drips fall from the edge of the unit and do not run into the filtrate reservoir.

D: The ceramic filter element is moulded in one piece with handles and the neck moulded separately to ensure ease of fabrication

E: A plastic filtrate-reservoir to facilitate easy cleaning and maintain high quality water during household storage. Standing the filter on stones or a low wooden block will ensure that the tap is clear of the floor and prevent a source of damp mud and dirt under the unit. The use of an inside out flow path allows for a sealed storage vessel; this in turn prevents the use of ladles and hands for water removal, so maintaining more hygienic conditions in the treated water reservoir.

F: The use of a tap will reduce the contact with the clean water reservoir. A metal tap will be robust and easy to clean, but the bonding of an inflexible metal tap flange to a thin flexible plastic collection vessel would be difficult, hence the unit has a flattened face against which to seat the tap.

G: A long spout on the tap will prevent contamination of the tap from spills and drips from filling the unit.

The unit can be filled with an appropriate amount of ground charcoal. Non-activated carbon may be less efficient than its activated equivalent, requiring larger volumes to achieve the same level of arsenic removal, yet this is not the limit state of the desgin. The volume of a ceramic filter, hence its carbon containing capacity, is dictated by the low flow rates typically achieved by ceramic filters. The use of an inefficient adsorption material is not critical when the design constraint for flow rate dictate the use of a sufficiently large vessel to allow the incorporation of large volumes of an inefficient adsorbent.

5.3.1 Viability

Capacity building is now considered an important part of successful development initiatives. The development of a locally-produced filter unit has the potential to support a new and profitable local industry. The production and supply of ceramic units and filtration ancillaries is possible either requiring no adaptation of existing ceramic facilities or as a new small scale industry.

For a filter unit to be viable as a marketable commodity there must be a market willing to pay a price that reflects the costs of production. Current research supports the contention that this exists (CDC 2001; WCW 2000; WSSCC 2000). Further to a viable market, there must be the skills and facilities to produce such units efficiently. As an element of the field visit to Bangladesh, visits were made to several small-scale potteries (range 1-10 employees) with different production capacity in Dhaka city; furthermore on returning to the UK, colleagues in Akra, Ghana, in Entebe, Uganda, and, in Lima, Peru were asked about the viability of local fabrication and the possibility of establishing small enterprises to produce filter units and the possible fabrication costs (Table 14). These discussions concluded that small-scale ceramic production was common practice in all these areas, that households use a range of ceramic and plastic water storage and collection vessels and that it was unanimously considered that there was a market for simple water treatment devices.

5.3.2 Costs

Currently, the purchase of water can account for up to 20% of the daily earnings of a family, (WCW 2000); despite the contention that water is a 'gift of the gods', the delivery of wholesome water is an economic good. However, it is essential to keep the production costs to an affordable minimum to ensure the availability of units to the poorest families (Table 14).

Table 14: Fabrication costs for filtration assembly elements in different countries (all priced in US dollars).

Location	Ghana	Uganda	Bangladesh	Peru
Filter element	4.50	2	2	3
Collection vessel	2	2	1	1
Tap fitting	1	0.5	0.75	0.6
Total (US$)	7.50	4.50	3.75	4.60
Percentage annual wage:	2	1.5	0.6	0.05

Work conducted by Clasen (2004) showed that 80% of the people surveyed within the Charenco district of Bolivia were willing to pay US$6.67, and prepared to pay up to a maximum of US$9.25, for a point-of-use treatment system. Whilst willingness to pay will fluctuate markedly according to the priorities of a community and their relative wealth, this is an indication that the unit prices are within an attainable range, i.e. the fabrication cost of the filter units is comparable to their perceived value (personal communication, S. Islam 2003).

One of the benefits of focussing on adapting existing local skills and materials, the approach taken in this project, is that there is no cost associated with the distribution of the units. There will be some cost in producing educational material and guidelines in an accessible format for the local potters to follow, but, having disseminated this information, local production would lead to considerable savings in the distribution cost.

5.4 Market Placement

"Point-of-use programmes in several countries have demonstrated that the market for safe water will readily absorb more effective treatment options if these are reasonably priced and properly promoted." (CDC 2001)

There is an increasing number of point-of-use treatment technologies available. During the course of this research, work has been published, though not peer reviewed (Langtene 2001; Khuntia *et al*, 2003; Clasen 2004), to support the efficacy of point-of-use systems, specifically the use of simple ceramics. Systems using Katadyn and Stafani candles (silver-treated, high-technology ceramics) have been shown to be effective filters with log reduction rates for *E. coli* of greater than 7.9 and 4 respectively. More significantly, these units have been seen to be effective in the field achieving up to a 77% reduction in diarrhoea incidents (Clasen 2004). It is notable that the *E. coli* removal rates achieved reach levels not dissimilar to those of industrial ceramic membrane filters (Komolikov and Blaginina 2002). It is therefore possible to suggest that in a similarly well-designed unit, and with the same support at the point of intervention, a simple ceramic filter produced using low-technology untreated media would be capable of achieving the same ultimate health gain, but in a significantly more sustainable fashion.

Systems that do not rely on high-technology ceramics have also been developed; some of these use local low-technology ceramics but combine them with an expensive bacteriostatic agent, silver, that cannot be resourced locally. The 'Potters for Peace' (PFP) filters that have been successfully operated in studies in Central America use this approach (Langtene *et al* 2002). Ceramic units are produced centrally by a relatively mechanised press-moulding technique, impregnated with colloidal silver. This has been demonstrated to yield good water quality but at a higher financial cost. The costs associated with centralised production methods must also be taken into account, as transporting bulky and fragile units is expensive.

The most simplistic system is the TERAFIL system (Khuntia *et al* 2002). Simple clay, sawdust and sand are mixed and fired to produce a sintered clay medium for use as a filtration element. This clay disk is then bonded into a metal or ceramic unit, using cement or epoxy resin, not universally available materials. Laboratory assessment has shown the TERAFIL system to be capable of removing 96% of *E. coli*, although there is little reference to the absolute concentrations and results are seen to vary slightly. The TERAFIL system was distributed to 1000 households following the cyclones in Orissa, and subsequently 30,000 further units have been distributed in the Orissa area, though as yet with no reported health intervention data.

The ceramic unit developed through the research reported in this thesis shares similar aims with many of the units that have recently been developed. Principally, it shares the objective of simple low-cost production and the use of local artisans in the manufacture of the units. However, where other systems resort to the use of expensive or imported materials, the proposed system remains true to the objective of simplicity and universally available materials. Another distinguishing feature of this filter system is that it represents a multi barrier approach combining filtration, sedimentation, improved storage and adsorption to treat a greater range of contaminants.

How the proposed treatment regime might fit into the current water supply market is an important consideration. Recently, some of the world's largest multinational companies have developed technologies to assist in water treatment. Procter and Gamble ®, with their PuR® water treatment sachets, and Unilever ® with an as yet unreleased technology, exhibit a clear interest in service provision in developing countries. Although earning generally less than one US$ per day, the people of developing countries are viewed as a potential billion dollar business. Despite the questionable altruism of these companies, their venture into water treatment technologies for the poor of developing countries may not be the exploitative travesty that it might at first appear. These multinationals already have a presence in many developing countries, and therefore have intimate knowledge of the best techniques for marketing to such populations. Marketing represents an essential element in disseminating technologies and health messages. Procter and Gamble ® and Unilever ® also represent large and stable organisations that are not likely to run short of funding or fall foul of cuts in public financing; a common problem for smaller charities and NGOs. Whilst the ceramic water filter system, proposed in this research, does not meet the product and marketing needs of a multinational organisation, the work of the private sector in the dissemination of the health and hygiene message may prove invaluable in generating water quality and health issue awareness in the same target communities.

6 Conclusions

6.1 Chapter abstract

Presented in this chapter are a synopsis of the objectives of this work and a summary of how and where these were met. Experiences gained from this research, have been brought together to present some possible lines of future study following on from this investigation

6.1.1 Conclusions

The objectives formulated at the outset of this thesis determined the direction of the work, and, to a varying degree, have been successfully achieved. What follows are the objectives as defined in Section 1.2.2, with the conclusions drawn from the study reported against each of these initial objectives:

- "To develop a robust, low-cost, treatment regime the production of which requires no imported materials or external supervision."
    - The use of a simple tempered ceramic material produced from readily available clays and food and fibrous waste products provided a robust filtration medium with no filter elements failing during operation.
    - It was demonstrated that bacteriostatic agents (i.e. silver) were not necessary to produce effective microbiological filters; through this study removal rates of 99.98% were achieved in the absence of bacteriostatics agents.

- Production of effective low-technology filters was demonstrated to be viable at a cost appropriate to perceived value, not relying on centralised high technology production methods or economies of scale.

- Using only simple ubiquitously available materials and universal techniques it has been shown that it is possible to produce a low-technology filter that can substantially improve the quality of contaminated drinking water removing physical (colour and turbidity) and biological contaminants.

* "To establish the skills, knowledge and needs of the end user and reflect these at each stage of the design to ensure feasibility of production and facilitate effective assimilation of the system into the daily routine."

  - Water related issues are context specific. An assessment of the skills and knowledge of a potential producer and user group in Bangladesh concluded that the production and integration of a simple ceramic household filter was viable in that context.

  - User focused design led to the conceptual development of a system comprising a 20 l ceramic filter vessel, a plastic receptacle using a metal delivery tap, and ground charcoal. The conceptual design incorporating features to minimise recontamination and optimise performance as a point-of-use filtration system

- The use of a range of grades of materials and production techniques did not identify any critical factors exist within the proposed production methods. Furthermore, there are wide margins of tolerance around each specified production parameter ensuring good filtration performance from units produced under variable production conditions with minimal quality control restrictions.

- "To assess the performance and possible adaptation of the filter in the removal of non-biological contaminants, specifically the removal of arsenic from groundwater."

  - The incorporation of low-technology, sustainably-sourced adsorbents, produced from charcoal, resulted in substantial capacity to remove arsenic from contaminated waters.

  - Simple ceramic filters in combination with charcoal adsorbents can remove bacteria, toxic metals and undesirable colour and turbidity from contaminated drinking water.

- To investigate operation and maintenance regimes, and establish best practice for the handling and regeneration of contaminated filter units.

    - The ceramic filter material could be effectively and easily cleaned by simply reheating to below the original firing temperature. This regenerated the filtration performance (flow and bacterial removal) to its original level

6.1.2 Further work

Although this work represents a significant and unique step towards achieving a sustainable water treatment regime in developing countries, a number of issues remain unresolved and need to be the focus of future work

- An assessment of the ability of the proposed ceramic filter system to remove viruses is needed.

    - A preliminary investigation into the use of a bacteriophage to model the efficacy of the filter suggested that this may be an effective tool in assessing the capability of the filter against smaller contaminants.

- An exacting analysis of the physical structure and characteristics of the filter material may led to further optimisation of the filter's potential performance.

- The development and optimisation of the unit design, matching what is possible in production and desired by the consumer.

    - An assessment of the critical flow characteristics of the filters to model the effect of static head and alternative filter geometry on pressure and flow rates.

    - Evolving the design of the units, such as aspect ratio corrugated walls and multiple chambers, may improve flow and utilise more of the filtration capacity.

- A pilot trial involving the field production of the filter units, with the aim of an intervention study into health impacts.

    - This would offer the opportunity to assess the bacteriological performance in the field and correlate this with the physiological impact on water-borne disease.

- A further investigation into increasing the capacity of simple adsorbents.

    - The use of alternative low-cost materials, may improve the ability of the filter unit and its efficacy against pesticides and other non-biological contaminants of concern.

- To establish the viability of the filter as a tool for 'capacity building'.

    - An economic review of cost and price structures for fabrication and sales would provide valuable information about market placement.

- To investigate the use of the PHAST initiative (Simpson-Hebert 1997) in the development of suitable educational support material.

    - Such material would assist the dissemination of this system, in both its production and operation.

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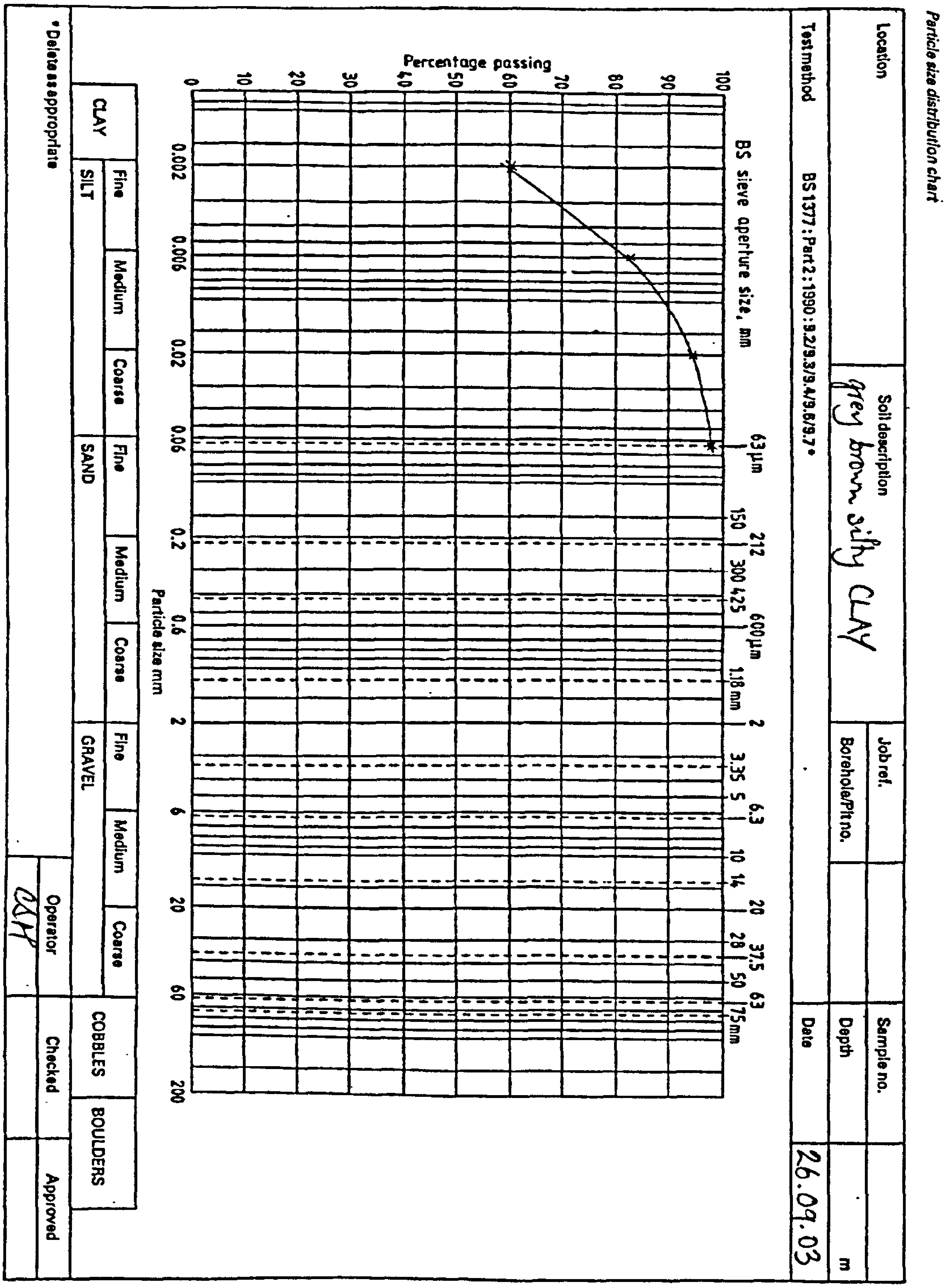
Appendix 1

Particle size distribution of the Bangladeshi clay sample



BS 1377 : Part 2 : 1990

Particle size distribution (Pipette sedimentation) Form 2.P

Location Bangladesh		Job ref.	Matt S
		Borehole/ Pit no.	
Soil description grey brown silty CLAY		Sample no.	
		Depth	m
Test method	BS 1377 : Part 2 : 1990 : 9.4	Date	26.09.03
Method of preparation			

CALIBRATION

Pipette no.		
Volume of pipette	V_p	11.06 mL

SAMPLE DATA

Dry mass of soil	m	12.408 g
Particle density ~~measured~~/assumed*	ρ_s	2.65 Mg/m³

~~PRETREATMENT*~~

~~Pretreated with~~		
~~Initial dry mass of sample~~	m_o	g
~~Dry mass after pretreatment~~	m	g
~~Pretreatment loss~~	$m_o - m$	g
		%

Viscosity of water at ......°C*	η	mPa·s
$D = 0.005531 \sqrt{\frac{\eta H_t}{(\rho_s - 1)t}}$		mm*

$K = \left(\frac{W_1 \text{ etc.} - W_r}{m}\right) 100\ \%$
At 25 °C, $D = \frac{0.05221}{\sqrt{(\rho_s - 1)t}}$ mm

TEST DATA

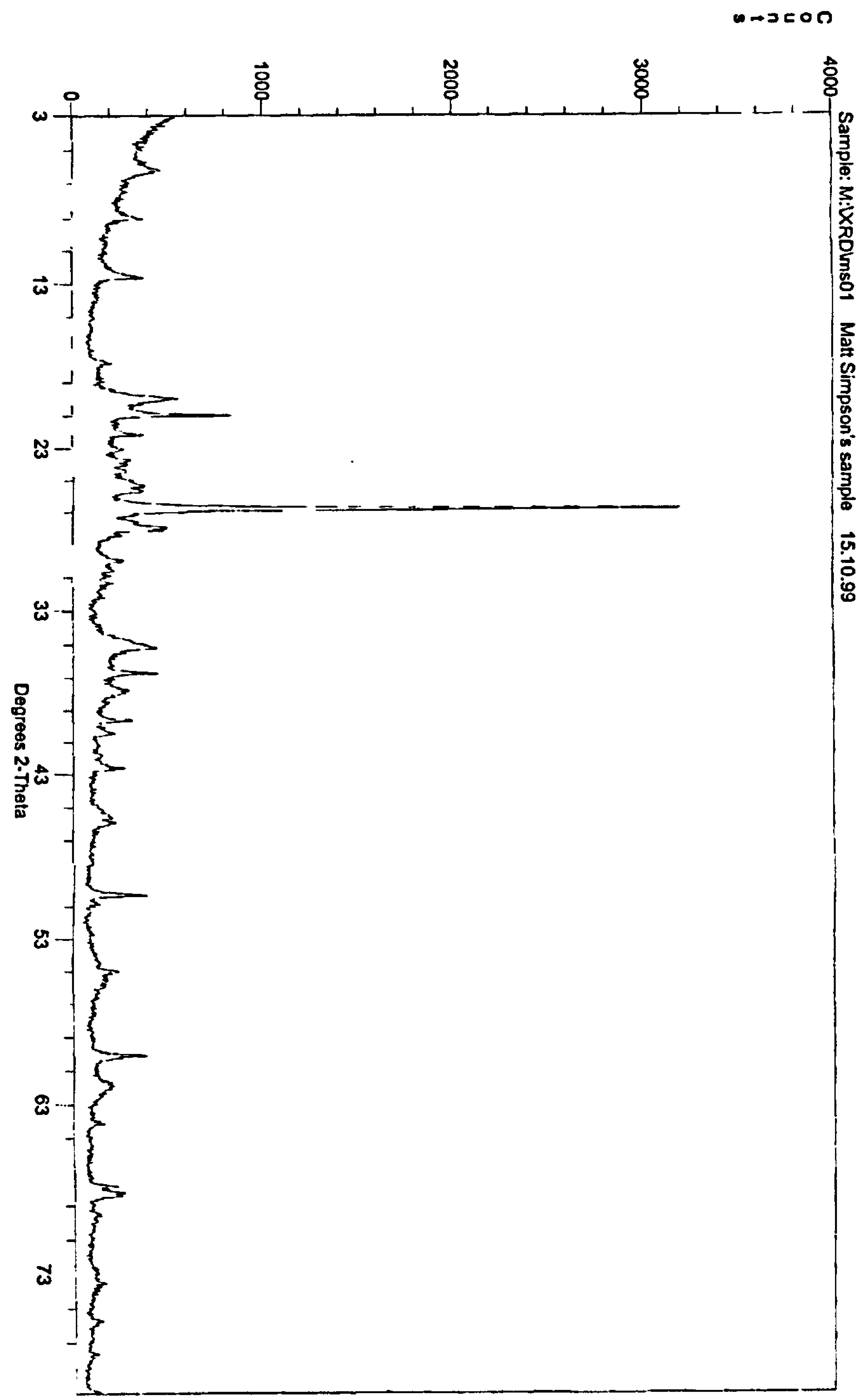
Pipette sample ref.									dispersant only	
Date			26.09	26.09	26.09					
Time										
Elapsed time	t	min	4m 5s	46m 0s	6h 54m					
Temperature	T	°C	25.0							
Bottle no.			1	22	33					
Mass of bottle + solids		g	11.795	11.953	12.127				10.294	
Mass of bottle		g	11.514	11.704	11.940				10.272	
Mass of solids in V_p	m_1 etc.	g	0.281	0.249	0.187				m_r	0.022
Mass of solids in 500 mL	W_1 etc.	g	12.703	11.257	8.454				W_r	0.995
Mass of soil in 500 mL	(W_1 etc. − W_r)	g	11.708	10.262	7.459					
Particle diameter		mm	0.02	0.006	0.002					
Percentage finer than D		%	94.4	82.7	60.1					

* Delete as appropriate

Operator	Checked	Approved
CBH		

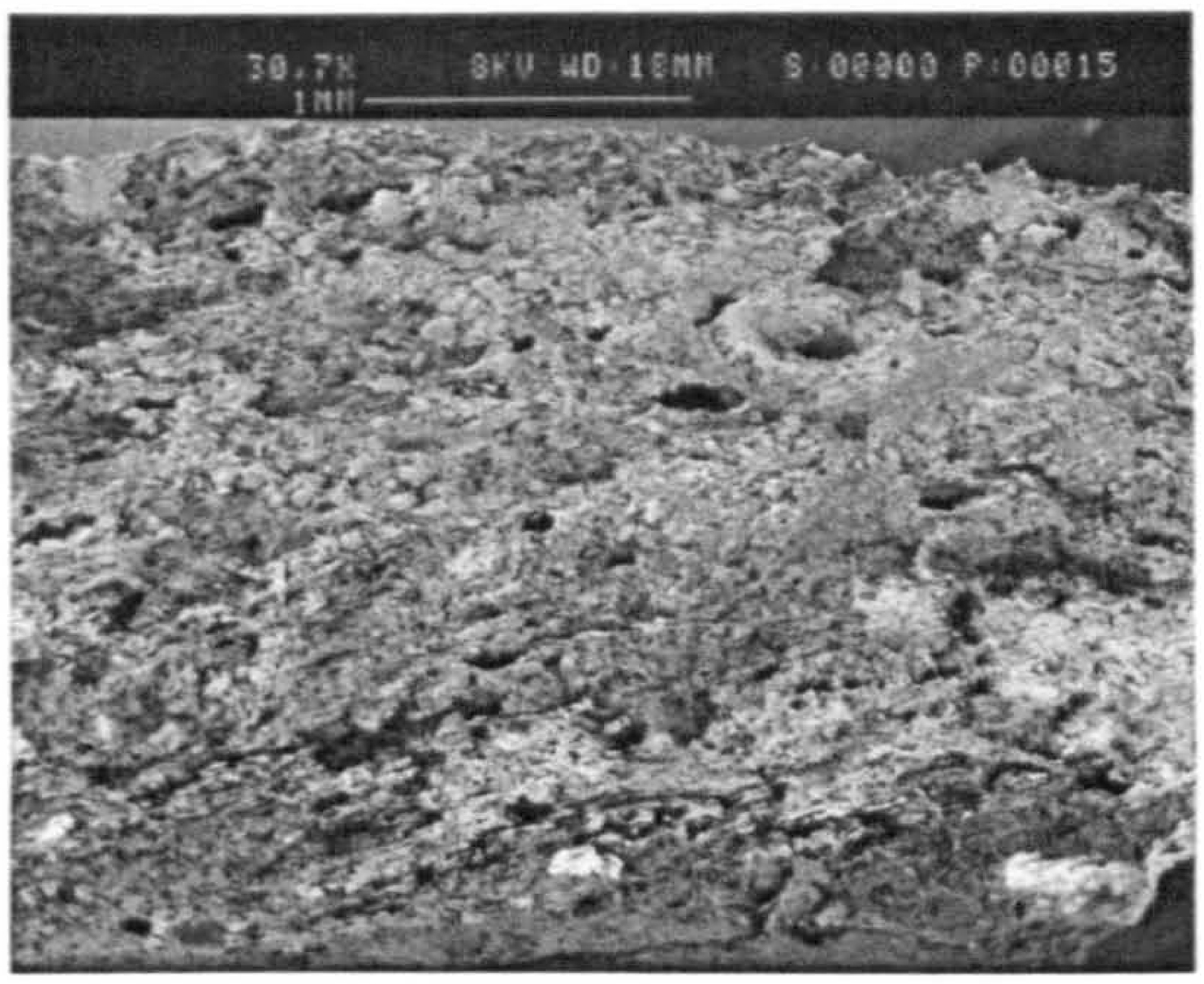
60

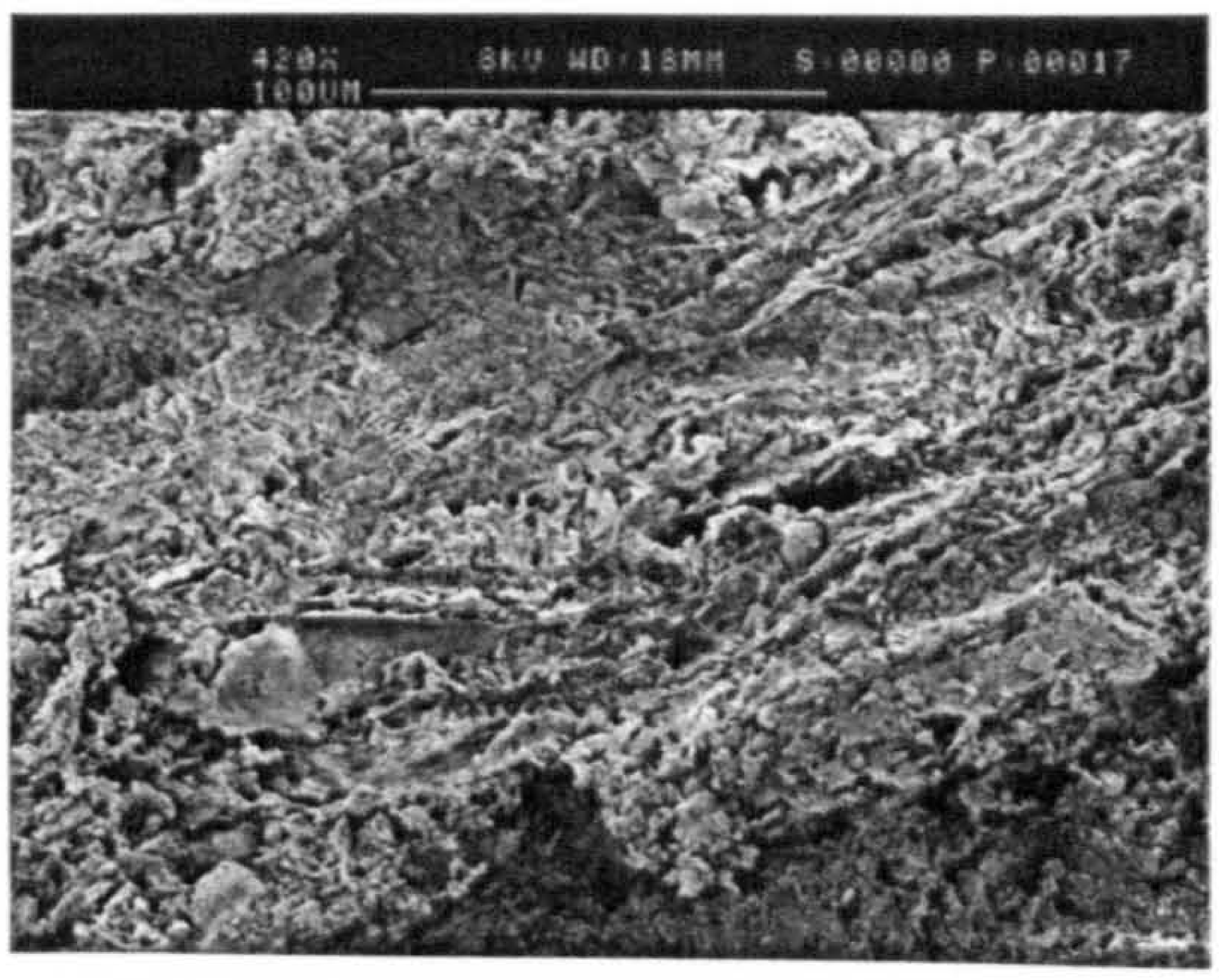
X-ray diffraction analysis of Bangladeshi clay sample.

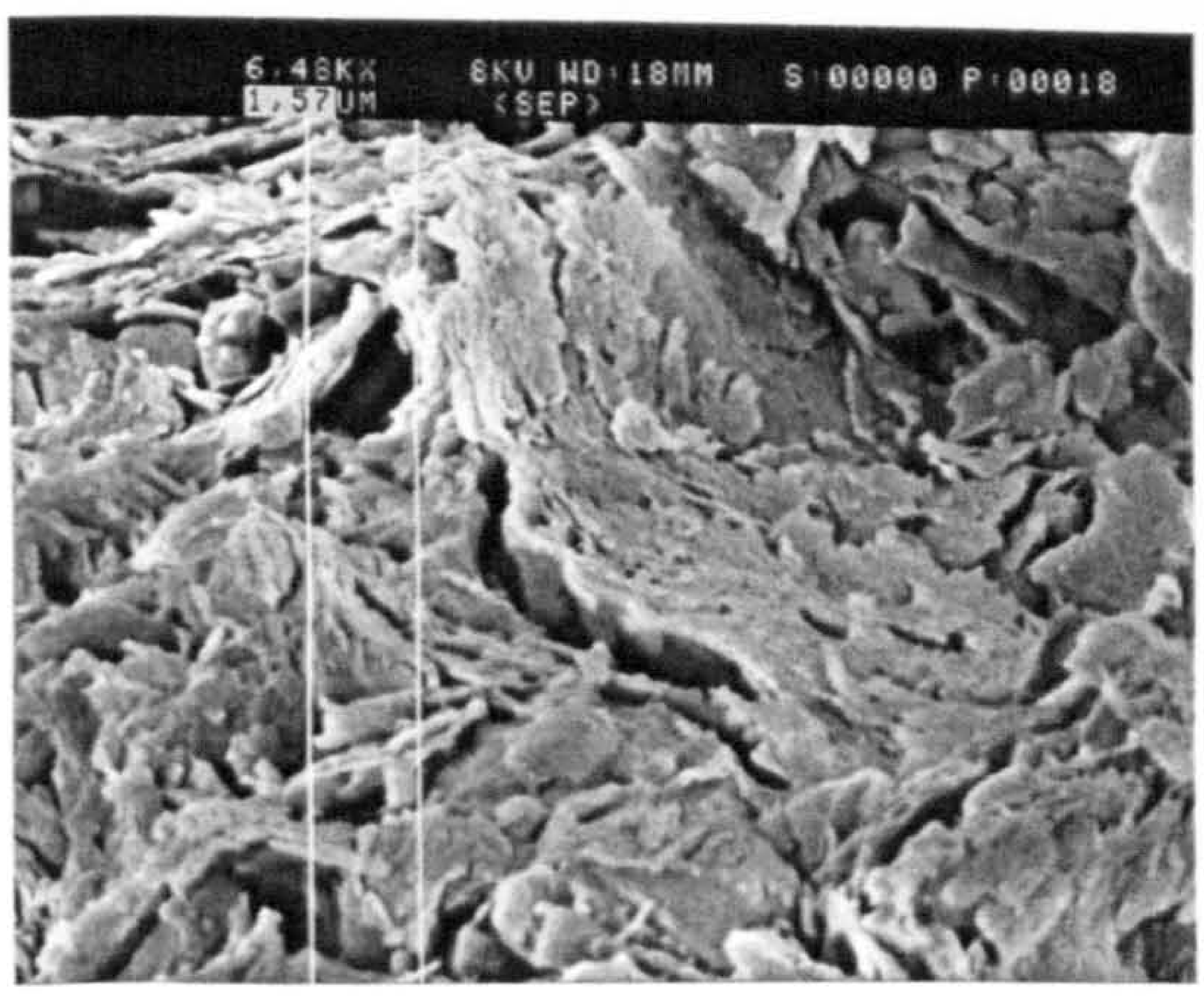


Appendix 2: SEM images of filter sections

Slip cast sections







Press moulded sections