Summary

This working paper carries out an investigation into cracking in cementitous renders used to waterproof cheap hand-built water tanks in the developing world. A study of the theory behind cracking in mortar is followed by a review of readily available admixtures that affect the properties of mortar. Extensive experimentation has been carried out on these different mixes of mortar, with the result that the investigation suggests the use of a superplasticiser will reduce the cracking and hence the leakage in a mortar rendered tank. A further recommendation is to add silica fume to the mortar to increase its strength and help reduce cracking. Further investigation into the subject is also recommended.

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Chapter 1: Introduction

1.1 Overview

In the developing world, many communities don't have access to a reliable water source, and as such have to travel long distances to find water. The Developing Technology Unit (DTU) in the University of Warwick is working on providing a source of water to such communities. This project is involved with the production of low cost water tanks to provide people with water.

Uganda is an example of where the tanks will be used, because it has high rainfall during some parts of the year and periods of drought at other times. This sort of climate is ideal to implement rainwater harvesting (RWH). Runoff water from rooftops can be collected and stored in a large tank next to the house. The tank itself can be either above-ground or below-ground and is constructed from local materials such as rammed earth. The defining factor in the production of these tanks is that they have to be cheap and therefore made from readily available materials from local sources. However, such materials are permeable and hence not suitable for storing water.

Waterproof renders consisting of a thin layer (10mm) of mortar, are applied to the walls of the tanks to allow them to store water. These cementitous renders are prone to shrinkage induced cracking, which causes leakage reducing the effectiveness of the tanks. This project is concerned with investigating and developing methods of reducing any cracking, and hence allowing more reliable water tanks to be constructed.

1.2 Project Aims

As stated above, the purpose of this project is to conduct a study of cementitious renders used to waterproof tanks used for RWH. This study will centre on investigating the amount of, and seriousness of cracks in various types of mortar based renders. The experimental side of the study will report on various measures of crack reduction available, and combined with an investigation into the theory behind crack development in cementitious materials, lead to conclusions on which mix of mortar is most suitable for the use described above.

Steve Turner, a graduate of engineering from the University of Warwick in 2000, had begun a similar study into leakage from waterproof renders in the summer before the commencement of this project. He had cast some mortar samples to experiment on, but was unable to carry on, and these samples were inherited and experimented on as an extension to this investigation. These samples provided an introductory look into cracking in cementitous renders, and Steve's notes are provided in the appendix, followed by results taken from the samples he prepared. These results are later used in the analysis and to draw conclusions. Chapter 9 illustrates problems with the procedure and highlights any alterations made to the design of test equipment.

Chapter 2: RWH Tanks

2.1 Description of tanks

Much research has been carried out by the DTU on the forms of water tanks to be used for RWH, so only a brief summary of the types of tanks is given in this report to familiarise the reader. There are 3 types of water tank that can be used for RWH:

- Above ground
- Below ground
- Overhead (roof of building)

The cheapest being below ground tanks as the surrounding ground provides support for the walls and therefore less emphasis must go into designing the tanks for strength. This project was undertaken with below ground tanks in mind although the principles developed can be applied to all types of tank.

The soil walls of the below ground tank are normally reinforced with rammed earth which can then be rendered. In readiness for the waterproofing mortar the tanks walls are scored to provide a good gripping surface on which to plaster. The mortar must be of a suitable consistency to allow plastering, not too thick, and not too runny. A capacity of 10,000 litres is average size for one of these tanks. Figures 2A below, taken from the DTU web site, show the excavation and completion of a partially below ground tank, PBG, combining the benefits of both designs.

Fig 2A

2.2 Pros and Cons

The pros and cons of the 3 types of tank.

	Pros	Cons
Above Ground	Helps prevent contamination from water run off. Easy to identify and repair cracks and leaks. Water can be extracted using a simple tap. Can be used in any environment regardless of soil types.	Expensive. Needs lots of free space. Weaker than below ground tanks. Must be designed to be strong enough to hold enough water. Easily damaged.
Below Ground	Cheap. Economical on space. Earth provides sidewalls so are very strong. Not easily damaged.	Hard to spot any cracks or leakage. Pump needed to extract water. Contaminated water could drain into tank. Dangerous to children and animals (should they fall in). Need stable soil conditions to prevent failure of sidewalls
Overhead	Increased water pressure due to head created from elevation. Economical on space. Easy to identify and repair cracks and leaks. Can be used in any environment.	Weaker than below ground tanks. Expensive. Must be designed to be strong enough to hold enough water. Failure of tank can potentially cause serious injury.

Chapter 3: Cement Theory

3.1 How Does Cement Harden?

Water is the key ingredient that causes cement to harden. The process by which cement powder combines with water to harden is called hydration. This process is when the major compounds in the cement react with the water to form hydrates. The water used is vital in determining the strength and end properties of the mortar. Cement is vulnerable to imperfections in additives and impure water can cause weak mortar. The water cement ratio is also important when mixing mortar. Too much water will result in weak mortar whereas too little will make it unworkable and not appropriate to use for many of the tasks in which it is employed. This will be discussed further in sections that follow.

3.2 Hydration

Hydration only occurs when the cement has access to moisture. Moist cement will hydrate and cure, but this process stops once the sample has dried out. This means that the strongest mortars are left to cure for a long period of time. This process can last months and even years. Amounts of water added to mortar, and the length of time it is wet for before drying out, are vital factors when considering the strength and usefulness of mortar. Portland cement has five major constituents. These are listed in the table below.

Cement Compound	% weight	Chemical formula	Alternative chemical formula
Tricalcium silicate	50	Ca_3SiO_5	$3CaO{\cdot}SiO_2$
Dicalcium silicate	25	Ca_2SiO_4	$2CaO{\cdot}SiO_2$
Tricalcium aluminate	10	$Ca_3Al_2O_6$	$3CaO{\cdot}Al_2O_3$
Tetracalcium aluminoferrite	10	$Ca_4Al_2Fe_2O_{10}$	$4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$
Gypsum	5	$CaSO_4{\cdot}2H_2O$	N/A

All of these compounds undergo hydration when exposed to water, but only the calcium silicates contribute to the overall strength of the mortar. Tricalcium silicate reacts more quickly than dicalcium silicate, and so is responsible for most of the strength of the mortar after the first 7days of hydration. The manner in which each of the calcium silicates affects strength of mortar will be discussed individually.

3.2.1 Tricalcium silicate

Tricalcium silicate reacts rapidly with water to release calcium ions and hydroxide ions. The reaction is exothermic and therefore a lot of heat is produced. The chemical equation is given below.

Tricalcium silicate + water ⟶ Calcium silicate hydrate + Calcium hydroxide + Heat

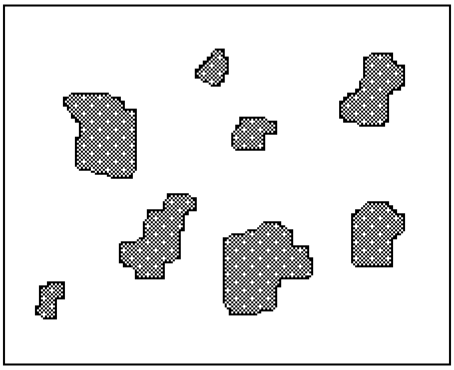
$$2\,Ca_3SiO_5 + 7\,H_2O \longrightarrow 3\,CaO{\cdot}2SiO_2{\cdot}4H_2O + 3\,Ca(OH)_2 + 173.6kJ$$

The Ph rises to over 12 due to the presence of alkaline hydroxide ions. The reaction continues over time, gradually producing more calcium and hydroxide ions until the effect is a saturation of these ions. Crystallisation of the calcium hydroxide now begins to occur, while at the same time calcium silicate hydrate crystals forms. The evolution of heat from the reaction increases due to *Le Chatlier's principle.* This is where ions precipitate out of solution, accelerating the reaction of tricalcium silicate to calcium and hydroxide ions.

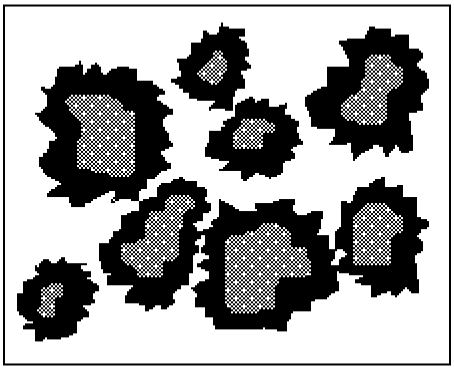
The formation of calcium hydroxide and calcium silicate hydrate crystals increases. The crystals act as a starting point for more calcium silicate hydrate to grow upon, and so they get bigger as further hydration takes place. This makes it harder for water to reach the unhydrated tricalcium silicate, and hence the reaction slows down. As further crystal growth continues the speed of the hydration reaction is constrained by the rate at which water can penetrate through to the unhydrated tricalcium silicate, so over time the production of calcium silicate hydrate becomes slower and slower. The diagram below (figure 3A) illustrates the process.

Figure 3A

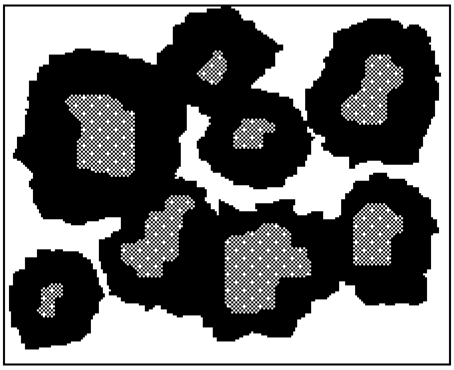
Hydration not yet occurred. Pores filled with water.



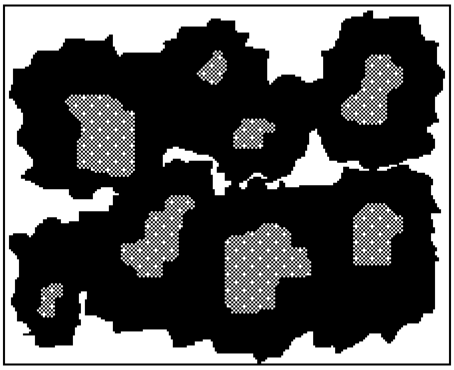
Beginning of hydration. Calcium silicate hydrate builds up.



Hydration continues. Spaces filled with water and calcium hydroxide



Nearly hardened concrete. Most space filled with calcium silicate hydrate. Remaining gaps mainly calcium hydroxide solution



3.2.2 Dicalcium silicate

Dicalcium silicate affects the strength of mortar much more slower than tricalcium silicate. It reacts with water in a similar way but is much less reactive and so less heat is evolved. The products of the hydration of dicalcium silicate are the same as those for tricalcium silicate, and are shown below.

Dicalcium silicate + water ⟶ Calcium silicate hydrate + Calcium hydroxide + Heat

$$\mathbf{2\ Ca_2SiO_4 + 5\ H_2O \longrightarrow 3\ CaO{\cdot}2SiO_2{\cdot}4H_2O + Ca(OH)_2 + 58.6\ kJ}$$

The production of calcium silicate hydrate and calcium hydrate occurs in a similar way as shown in the above diagram, but over a longer period of time.

3.2.3 Tricalcium Aluminate

The amount of tricalcium aluminate is relatively small but can have a significant affect on the properties of the hardening cement paste. The hydration of tricalcium aluminate can occur extremely fast which can lead to a phenomenon known as flash setting. This can occur because the reaction between tricalcium aluminate is very violent and can result in advanced hydration over a very small period of time (a few seconds). This is undesirable as it would cause premature setting of the cement mixture and makes it very difficult to work with. When the clinker first forms in the kiln there is nothing to stop flash setting of the material should it come into mortar with a small amount of water. Because of this gypsum is added as it suppresses flash setting. Gypsum is added to the clinker before the whole mixture is ground down to make cement paste.

3.2.4 Gypsum

When gypsum is added to the clinker, it reacts with the tricalcium aluminate to form calcium sulphoaluminate.

Tricalcium aluminate + gypsum $\longrightarrow$ Calcium sulphoaluminate

$$3CaO \cdot Al_2O_3 + CaSO_4 \cdot 2H_2O \longrightarrow 3CaO \cdot Al_2O_3 . 3CaSO_4 \cdot 31H_2O$$

A lot of heat is produced in the hydration of tricalcium aluminate and a rapid rise in the temperature of cement paste within five minutes of water being added hints that not all of the tricalcium aluminate becomes calcium sulphoaluminate, resulting in limited rapid hydration which explains the rapid rise in heat.

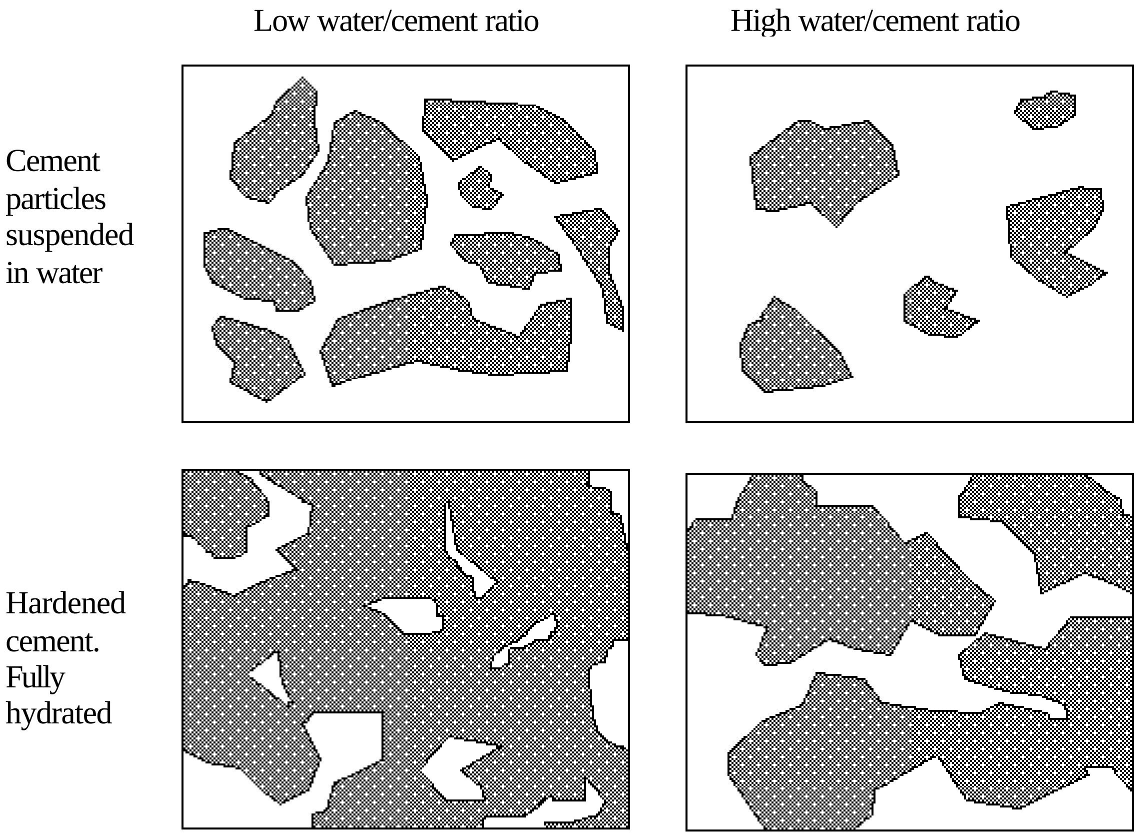
Chapter 4: Strength of Mortar

The strength of mortar is determined by 2 main factors.

1. The amount of water used (water / cement ratio).
2. The length of time for which the mortar is left to cure.

Total hydration requires an exact amount of water, much less than what is used in practice to add to cement. An excess of water is provided to increase the workability of the mixture and allow it to be worked into the desired position. Any excess of water not used up by hydration will simply remain in the mixture and reside in pores in the microstructure. Once the mortar dries, the water will evaporate out of the mixture leaving the pores empty. The more excess water used, the more will be left over after hydration has occurred and therefore the larger the pore volume will be. It can therefore be seen that the strength of mortar reduces as more water is used. If the amount of water used is much greater than that needed by hydration, the space taken up by pores in the microstructure will be relatively large and the porosity of the mortar will increase. This can be illustrated in the diagrams below (figure 4A).

Figure 4A

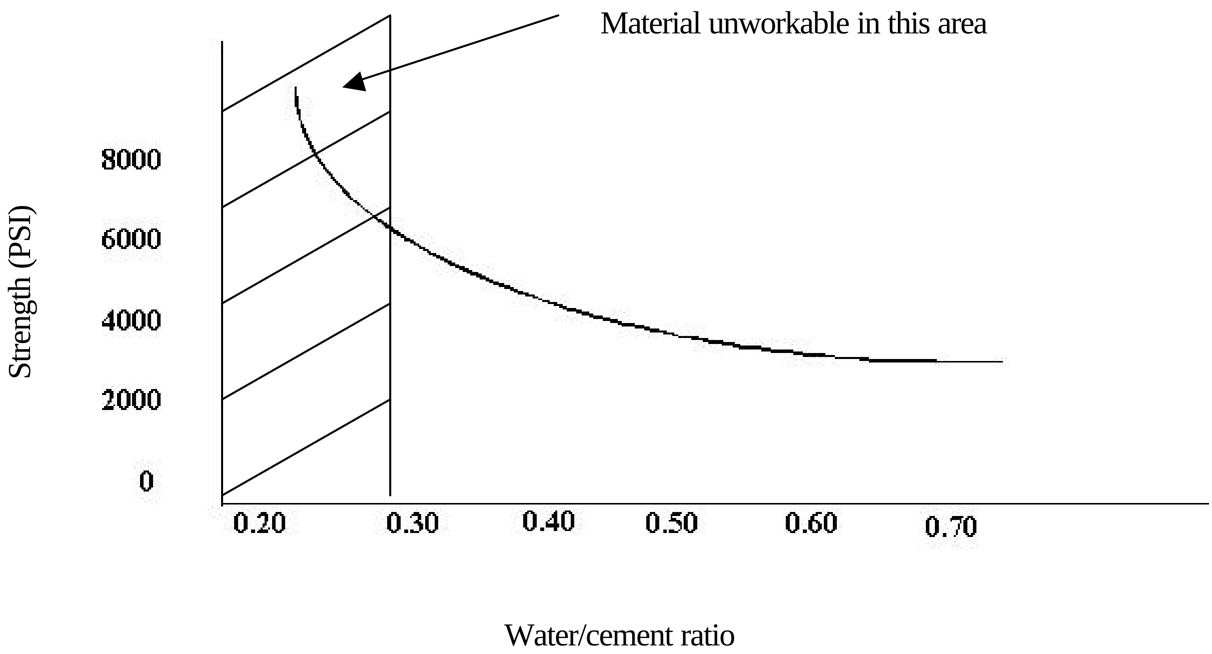


It can be seen from the diagrams above that the mixture with the lower water cement ratio has fewer pores than the high ratio mixture. Porosity of the cement/mortar is directly linked to its strength and the lower the porosity the higher the strength.

Achieving the theoretical maximum strength by using the exact amount of water for complete hydration is not achievable in reality as there will always be some pores present, even if the cement has been highly compacted. The trade off between strength of mortar and the workability desired to use the material depends on what task the mortar needs to perform. For casting in moulds it must be very liquid to allow pouring, but while this does increase workability it will result in weak mortar. For applications such as plastering, less water is used and the paste is much more viscous and will be stronger and less porous once set.

The graph below (figure 4B) shows how the water cement ratio affects the strength of the mortar produced. The graph highlights the limit of workability of concretes and mortars, below which it would be impossible to use the mix for any practical purpose.

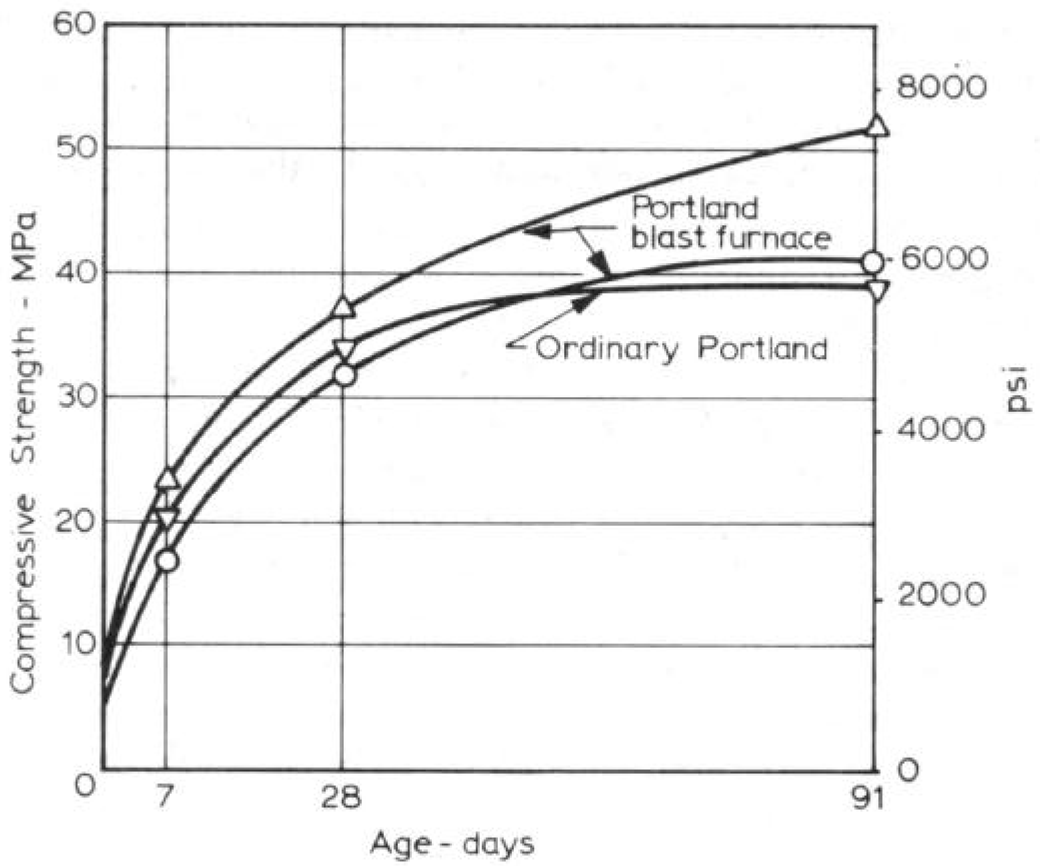
Figure 4B



The other factor that decides the strength of mortar is the length of time it is allowed to cure. Curing is the continuing process of hydration. It can take years for all of the calcium silicates to become hydrates and so the longer the mortar is left to cure the stronger it will be once dry. The graph on the following page (figure 4C) taken from "Properties of Concrete" by A.M.Neville, illustrates the manner in which different types of cement harden over time. The 7 and 28 day points have been plotted because they are commonly used indications of the strength of concretes and mortars. It can seen from the graph that even after 90 days the different types of cement are still increasing in strength, and many will do so for months afterwards, although at a very slow rate.

Figure 4C

0.6 water/cement ratio concrete



Chapter 5: Cracking in Mortar

5.1 Why does Mortar crack?

It has already been shown that mortar is a very complex material and many reactions take place within the cement to allow it to harden. A very common problem with the material is that over time cracks appear on the surface. Internal cracks are also common and in structures it is possible that cracks propagate unseen through the material for a long distance before finally breaching the surface. As the mortar is being used as a waterproofing agent in this investigation it is important to keep cracking to a minimum.

When cement powder is mixed with sand and water to form mortar it can be of various viscosities, but there is always a volume of water present which will be lost at some stage during the curing and drying processes. This loss of water changes the volume of the mortar and therefore the material shrinks. If the mortar is unconstrained then this change in volume is not a problem because the material will simply shrink with no damage to its properties. If the mortar is constrained during curing and drying, then it cannot change its volume as easily. Tension builds internally, and if this force exceeds the materials yield stress then it will crack. Mortar has a very low strength in tension compared to its strength in compression and so cracking occurs very easily in a constrained sample.

Theoretically, the strength of cement paste is much higher than those values actually achieved. The theoretical strength has been estimated to be up to 10.5Gpa, but this theory is based on perfect surface texture and internal structure. In reality, the material is not homogenous and there are many stress concentrations that are set up in the material. These concentrations allow very high local stresses to accumulate resulting in micro-cracking. Thousands of micro cracks are present in every meter squared of mortar but these do not cause any significant structural problems. Larger cracks of the order of 1mm or more, while not as common, represent a more significant reduction in the yield strength. These cracks can initiate from places such as the suspended aggregate, and any small imperfections in the material.

Cracking is caused by restraints acting against the shrinkage of the mortar, the tank wall in this case. Another form of restraint is non-uniform shrinkage within the mortar itself. When the paste dries, moisture is lost first from the surface and only later do the internal sections dry. This sets up a moisture gradient, which is part of what is called differential shrinkage. If a specimen dries in a symmetrical way this is not much of a problem, but in extreme cases warping can occur if the specimen dries in a non-symmetrical way. Because of the fact that the surface dries much quicker than the interior, size and shape of a specimen are extremely important factors in how much the mortar shrinks and to what extent it cracks.

Differential shrinkage should not be a factor considering the thickness of mortar used in this project. In theory the layer of mortar should be as thin as possible to counteract differential shrinkage, but considering the project is looking at renders with a thickness of the order of 10mm, the amount of shrinkage caused in this way will be negligible. The main consideration for this will be when the tank walls are left to dry. They should be left covered, with even heat distribution throughout so as not to allow one area of the tank to dry before the rest, which could cause cracking at the boundary between the two differently dried areas. Also, the walls should not be exposed to sunlight while drying, as this is likely to cause uneven heat distribution resulting in uneven rates of drying, and in turn a moisture gradient which could lead to cracking.

Chapter 6: Mathematical Model

Cracking in cementitious materials is progressive and as such can occur over long periods of time, although the majority of cracks initiate and propagate to nearly full length in the first month after drying begins. The effect a crack has on the material properties depends on its length, depth and width. When considering a cement based material for strength, it is found that the wider the crack the greater the resultant reduction in strength. This section will attempt to model how crack width affects the permeability of mortar. When considering a crack in concrete it is useful to make assumptions to make analysis easier. Two methods of analysis are shown in this section for different assumptions about how a crack can be modelled. They are shown below.

6.1 First Method

From fluid theory, flow through a crack can be approximated to flow through a tube (see figure 6A). Assume the pressure gradient, G, is parallel to the axis of the tube. For such an arrangement the forces can be derived as follows.

$$\text{Axial force} = \text{Gäë . 2ðr är} \qquad \textbf{1.}$$

$$\text{Viscous Shear force} = \text{2ðr äë . í .}\left(\frac{\text{dõ}}{\text{dr}}\right) \qquad \textbf{2.}$$

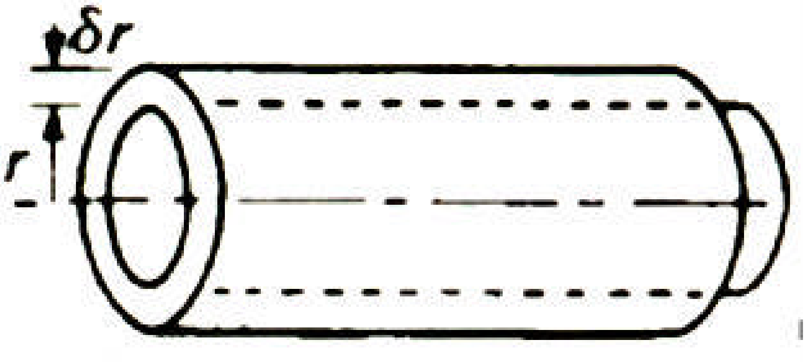
Equating 1 and 2 above produces the following expression for Gär:

$$\text{Gär} = \text{í}\left(\frac{\text{dõ}}{\text{dr}}\cdot \text{är}\right) \qquad \textbf{3.}$$

Substituting 3 for Gär into the equation for the viscous shear force yields the following:

$$\text{Viscous Shear Force} = \text{2ðr äë . í}\ \frac{\text{dõ}}{\text{dr}}\left(\text{är} + \frac{\text{d}^2\text{õ}}{\text{dr}^2}\text{är}\right) \qquad \textbf{4.}$$

Fig 6A



The laminar flow stresses ô$_{inner}$ and ô$_{outer}$ can be derived as follows and substituted into the force expressions in 1 and 2 on the previous page:

$$\text{ô}_{inner} = \text{í}\ \frac{d\text{õ}}{dr} \qquad \textbf{5A.}$$

$$\therefore\ F = \text{äë} \cdot 2\text{ð}r \cdot \text{ô}_{inner} \qquad \textbf{5B}$$

$$\text{ô}_{outer} = \text{í}\left(\frac{d\text{õ}}{dr} + \frac{d^2\text{õ}}{dr^2}dr\right) \qquad \textbf{6A}$$

$$\therefore\ F = \text{äë} \cdot 2\text{ð}(r + \text{ä}r)\text{ô}_{outer} \qquad \textbf{6B}$$

From 5B and 6B above the net force can be derived:

$$\text{Net Force} = 2\text{ð}d\text{ë} \cdot \text{í} + \frac{d\text{õ}}{dr} \cdot \text{ä}r + r\frac{d^2\text{õ}}{dr^2} \cdot \text{ä}r \qquad \textbf{7.}$$

To solve this differential equation set F to zero and reduce as shown below:

$$r\frac{G}{\text{í}} - \frac{d\text{õ}}{dr} - r\frac{d^2\text{õ}}{dr_2} = 0 \qquad \textbf{8.}$$

Solving this second order differential equation for the velocity distribution across the top of the tube of radius R yields the following:

Knowing that: $\frac{d\text{õ}}{dr} = 0$ at $r = 0$

$\text{õ} = 0$ at $r = R$

$$\text{õ} = \frac{K}{8}\left(R^2 - Rr^2\right) \qquad \textbf{9.} \qquad \text{Where } K = \frac{G}{\text{í}}$$

The mean velocity, $\bar{\text{õ}}$, can be found from 9 above by substituting the expression for õ in the equation shown below:

$$\bar{\text{õ}} = \frac{\int_0^R 2\text{ð}\, r\, \text{õ}\, dr}{\text{ð}r^2} \qquad \textbf{10.}$$

The result is shown below:

$$\boxed{\bar{\text{õ}} = \frac{K}{16}R^2} \qquad \textbf{11.}$$

The variable R, which represents the size of the crack, is of interest and equation 11 above shows that if the crack size R, has a square relationship with flow rate. An example is if a crack were twice the size, the flow would increase by 4.

6.2 Second Method

An alternative assumption of the form of a crack can be used to verify the above result. A laminar crack between two plates of width t, length b and thickness L. In this example the pressure gradient G = pressure drop/L.

$$\therefore \text{pressure force on layer } (F) = Gbdy \cdot \text{äë} \qquad \textbf{1.}$$

Shear force on bottom of layer = $\text{bäë} \cdot \text{í}\ \frac{\text{dõ}}{\text{dy}}$ **2.**

Shear force on top of layer = $\text{bäë} \cdot \text{í} \left(\frac{\text{dõ}}{\text{dy}} + \frac{\text{d}^2\text{õ}}{\text{dy}^2} \right) \cdot \text{dy}$ **3.**

Equating 2 and 3 above yields the following differential equation.

$$\frac{\text{d}^2\text{õ}}{\text{d}^2\text{y}} = -\text{G} \qquad \textbf{4.}$$

This can be solved in the same way as equation 8 in section 5.1 above. Using õ=0 at y=t/2 gives:

$$\text{õ} = \frac{\text{G}}{2}\left(\frac{\text{t}^2}{4} - \text{y}^2 \right) \qquad \textbf{5.}$$

The mean velocity, $\bar{\text{õ}}$, can be found from 5 above by the following integral.

$$\bar{\text{õ}} = \frac{\text{G}}{2} \int_0^{\frac{t}{2}} \left(\frac{\text{t}^2}{4} - \text{y}^2 \right) \text{dy} \qquad \textbf{6.}$$

Therefore:

$$\boxed{\bar{\text{õ}} = \frac{\text{G}}{2} \frac{\text{t}^2}{4} \left(\frac{2}{3} \right)} \qquad \textbf{7.}$$

6.3 Summary

Both the model for a tubular crack and the model for a laminar crack come to the same conclusion.

Mean velocity (flow per unit area of crack) $\propto t^2$

In the context of this investigation the result of the analysis is that: -

$$\textbf{Flow} \propto \quad \textbf{(crack length x crack width}^2\textbf{)}$$

IF the length of the crack is much bigger than the width (as should be the case)

The consequence of this result is that mortars should be designed to spread any shrinkage between many small cracks rather than few wide ones. The width is of great importance due to the fact it affects flow rate by a power law. Any small increase in crack width would increase flow rates dramatically.

Chapter 7: Admixtures

7.1 Overview

There are many different admixtures available on the market able to change many different properties of mortar, yet the most popular two types improve the material properties in the following areas:

1. Strength
2. Watertightness

These two factors are of interest to this project as they both can affect the mortars suitability as a render under the conditions set out in section 2. As highlighted, cracking is the major cause of leakage and cracking only occurs if the internal stresses in the mortar exceed its yield strength. Increasing this strength will reduce the amount of cracking for a given internal stress, thereby reducing the leakage. The usefulness of the second point is rather more apparent, although the manner in which admixtures that claim to improve watertightness do so is likely to be closely related to the strength of the material.

7.2 Tested Admixtures

The admixtures used in this investigation were inherited from previous research carried out by the DTU, and all satisfy the above criteria of being cheap and readily available in the developing world. The four admixtures are listed below.

1. Silica Fume
2. Superplasticiser (complast 211)
3. Harilal Leak seal
4. Festegral

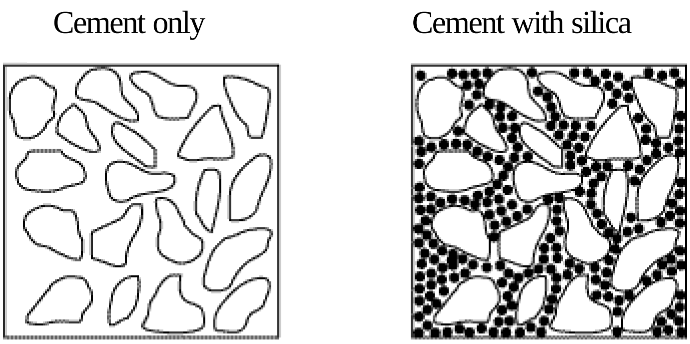
Another product was available for testing, which was a slurry-based layer that was to be sandwiched between two layers of plain mortar. This product, ferrofest, claimed to reduce shrinkage when used in this way, and hence reduces cracking and improves the water tightness of the mortar. Where available, an analysis of the theory behind each of the admixture's claims is given below.

7.2.1 Silica Fume

Silica Fume is created by heating quartz, coal, iron and wood at 1800^{o}c and collecting tiny particles from the emissions. These spherical particles have a diameter of approximately 0.1 microns (of the order of 100 times smaller than cement particles). Silica Fume increases the strength of concrete mixes and is used worldwide in all types of application, and hence is very readily available.

The silica particles, being so small, are able to fill spaces between cement grains and so displace excess water and act as nucleation sites for hydration to begin. This is known as the microfiller effect, and results in reduced porosity of concrete (or mortar as in this case) and hence it is stronger. Figure 7A below illustrates this effect.

Fig 7A



Another effect of silica fume that adds to the mortar strength is the pozzolanic effect. The amorphous silica particles have a very large surface area due to their small diameter and react with the calcium hydroxide in the cement to form calcium silica hydrates, which are the hydrate products found in hardened cement. This increase in the amount of hydrates adds to the strength of the material.

7.2.2 Superplasticiser

Plasticisers are used in concrete to reduce the amount of water needed to reach a required workability. In a normal concrete mix, cement particles tend to agglomerate, trapping mix water that would otherwise be used for lubrication. When superplasticiser is added to the mix, it is absorbed onto the cement particles causing electrostatic repulsion and dispersing the cement particles evenly throughout the concrete mix. The result of this is that water is not wasted because it is being more effectively used for hydration, and hence lower water:cement ratios can be used to achieve the same workability of mix as when the superplasticiser is not used. The reduction in water in turn increases the strength of the cement.

7.2.3 Harilal Leak seal

There is no indication on the packaging of this Indian admixture as too how it affects the permeability of cement.

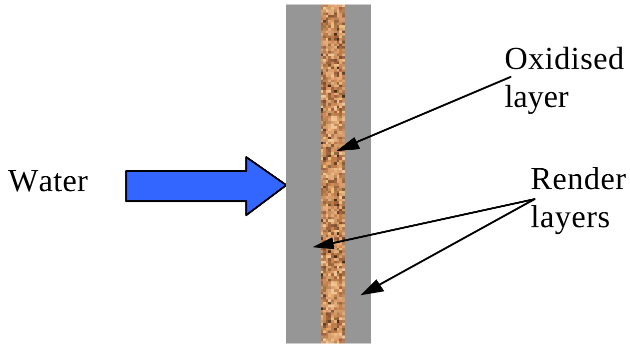
7.2.4 Festegral

There is no indication on the packaging of this Mexican admixture as too how it affects the permeability of cement.

7.2.5 Ferrofest

Ferrofest is not an admixture, and instead of being mixed in with the rest of the mortar ingredients, is sandwiched between two layers of plain mortar. It is iron based and claims to reduce the effects of shrinkage in concrete by expanding to counteract the shrinkage. During wet curing of the mortar, the iron within Ferrofest oxidises causing the layer to expand. These oxidised particles will clog up the pores in the plain layers and the associated expansion will help close any cracks formed in either layer of plain mortar, and therefore should reduce permeability. Figure 6B below illustrates the application of Ferrofest.

Fig 7B



The proportions of each admixture were provided by the manufacturers and are shown in figure 6C below.

Figure 7C

Sample	**Admixture % (cement weight)**
Harilal Leak Seal	2
Festegral	4
Silica fume	10
Superplasticiser (Complast211)	0.8
Ferrofest	100

Chapter 8: Variables

Three variables have been identified as appropriate for investigation in respect to waterproofing an underground water storage tank with mortar. Section 5 showed how upon curing and drying, mortar is prone to cracking. Because this is the root cause of any leakage from the tank, the variables chosen for investigation are all related to how much the mortar will crack and the resultant effects. They are as follows.

1. Shrinkage
2. Cracking
3. Leakage

Shrinkage – As the mortar dries, the associated water loss causes a change in volume that will be measured experimentally to determine the amount of shrinkage in each specimen of mortar.

Cracking – Cracking occurs in samples that undergo constrained shrinkage, and hence internal stresses build up causing crack initiation and propagation if the mortar's yield strength is surpassed.

Leakage – The purpose of the leakage experiment will be to determine what effects crack size has on water loss. Ultimately this will lead to conclusions stating whether it is better to have shrinkage accounted for by few large cracks or many small cracks.

Chapter 9: Experimental Procedure

The mortar must be of a suitable plastering viscosity, so a water cement ratio of 0.6 was used as a standard. All tests mentioned below use this ratio with the exception of the superplasticiser, which uses a ratio of 0.5 for reasons explained earlier.

9.1. Shrinkage

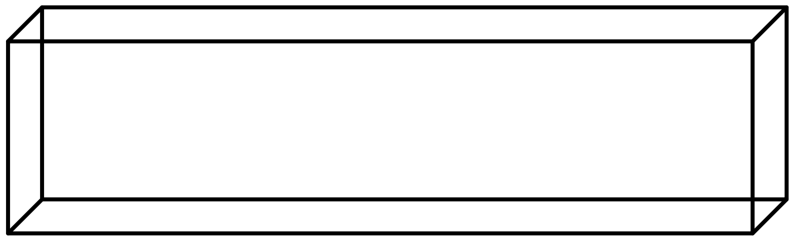
This variable proved very difficult to measure accurately as there are two possible means of shrinkage that occur at different stages. The manner in which the experiments were undertaken will be shown and then the associated problems discussed.

9.1.1. Procedure

Many methods of experimentation on concrete have been done in the past resulting in standard tests that the industry recognises and that are established as the way in which experiments with concrete are undertaken. British Standards (BS) 1881: part 5 (1970) and BS 2028 (1968), are two such standards relating to shrinkage measurement in concrete. However due to equipment and time factors, these standards could not be applied to this set of experiments, although they are of a very similar nature.

Firstly mortar was cast into blocks of dimensions 50 x 50 x 225mm and left to cure for a measured period of time. Once hardened (24 hours) small areas of the surface were dried using acetone and two metal tabs bonded to the surface of two opposing faces. These tabs were at a distance apart, which decreased as the blocks underwent shrinkage. The strain is then measured between the tabs using a dial gauge with an accuracy of 0.2 micro strain. The blocks were left to dry end-up so as to expose the greatest surface area to the air, to get even drying, thus helping to prevent warping. Two opposing sides were measured to monitor any possible warping that may occur during drying (see fig 9A).

Figure 9A



The amount of time the blocks were left to wet cure (no drying) was a variable investigated in the first round of experiments. In the first round three identical plain mortar samples were cast and left to cure in wet conditions for different lengths of time (2 days, 4 days and 14 days) to see what effect, if any, this would have on the shrinkage observed upon drying. Subsequent tests involving the admixtures would use a period of 2 days wet curing and results taken during 28 days of drying.

Each admixture used would be tested for shrinkage, and these results compared to the results for the other variables under investigation, cracking and leakage, to see if there was any correlation. See section 10.1 for breakdown of exact experiments that will take place.

9.1.2. Limitations

The main problem with doing experiments on the shrinkage of mortar is that at the time of casting the material is viscous and will flow, and only hardens to a point where it can removed from the mould after 24 hours. Any reduction in volume during this period is extremely difficult to measure and was not attempted in this investigation due to the said problem. Because of this, the results obtained for the shrinkage of the mortar are only for the period subsequent to the metal tabs being bonded to the samples, about 24 hours. Any shrinkage during the setting and early curing processes is unknown.

It would clearly be preferable to have values for the exact shrinkage or associated volume change from casting through to dryness, but this is not possible in this investigation. However, observation of the samples prepared by Steve Turner back up the opinion noted from literature on the subject, that shrinkage during wet curing accounts for only a tiny fraction of overall shrinkage when compared to the drying process. The samples were cured for three months underwater before the onset of this investigation, and upon initial inspection had no signs of any cracking on the surface. Once the samples were left to dry, extensive cracking was noted after 1-2 weeks.

Due to the observations made on the samples it is assumed that the shrinkage during the period of curing is negligible.

9.2. Cracking

9.2.1. Procedure

The purpose of investigating cracking in samples of mortar is fundamental to the overall aims of the project. It ties in with the other two variables because it is the shrinkage that causes cracking, and the cracking that causes leakage. Cracking will occur in a sample of shrinking concrete/mortar if the sample is constrained and not allowed to shrink unhindered (see section 5).

Steel rings are to be used as the constraint in this experiment. Mortar is to be applied to the rings in a layer 10mm thick between two retaining clips at the top and bottom of the cylinder (see fig9B). The rings have the following dimensions:

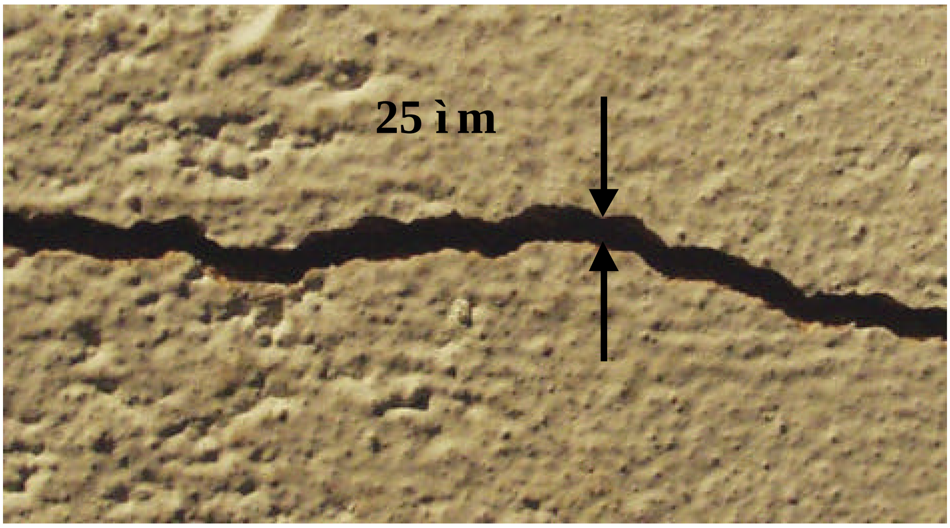
- Diameter = 170mm
- Height = 140mm
- Wall thickness = 5mm

Fig 9B

On application the mortar will adhere to the surface of the ring and harden around it. As the mortar layer dries, it will shrink and this movement will be constrained by the ring, resulting in internal stresses in the layer of mortar and eventual cracking. Cracks should begin to initiate towards the end of the first week and will have propagated significantly by weeks 1-2. The specimens will be left to dry and crack for 28 days, the same testing length as the shrinkage experiments.

Regular checks are made on the mortar covered rings to watch for signs of cracking or propagation of existing cracks. The width of any crack is vital as to determining the effect it has on the overall structure and flow rate of leakage water, so this is measured using a microscope with a lens calibrated with divisions every 50ìm allowing measurements to made in 25ìm increments. Fig 9C below illustrates a crack seen on the surface of a specimen prepared by Steve Turner prior to the commencement of this project.

Fig 9C



9.2.2. Limitations

This experiment only registers cracks that have broken the surface of the mortar and would not account for any cracking beneath the surface. However, any leakage that may take place would require a surface breaking crack to allow the water to escape. For this reason sub-surface cracking is not an important factor in this investigation as it is to do with leakage, but such cracks must be considered because over time they will eventually propagate to the surface and allow leakage.

When considering the use of mortar as a render for water underground water storage tanks, it is desirable to have the tank permanently filled or at least have some moisture present to keep up the relative humidity in the tanks, as the more time it is left empty to dry, the greater the likelihood of cracks emerging. It has been noted the specimens investigated, cracks generally appeared after 1-2 weeks so if the tank was left dry longer than this period, then extensive cracking is likely.

Another factor to consider is the rate at which the mortar dries, and therefore the rate at which it shrinks and what relationship this has to cracking. The quicker mortar dries, the greater the likelihood of cracks initiating. The reason for this is that creep plays a part in relieving the internal stresses that build up inside the material due to constrained shrinkage. If the samples dry slowly then the material will creep and result in reduced cracking compared to a sample that was dried very quickly. It is for this reason that the relative humidity of a near empty water tank must be kept high by covering it with polythene (for example), because if humidity were low, the moisture would be able to leave the surface of the render with greater ease.

9.3 Leakage

9.3.1 Procedure

The leakage experiments have been designed to run in conjunction with the cracking experiments. The steel rings as shown in fig 9B in section 9.2.1 were modified with a spiral groove run from top to bottom. This groove was `V` section and, due to warping in the rings, had a varying depth of between 2-3mm. The depth was set at a minimum of 2mm to ensure it could not be blocked with mortar, as it had to act as a channel for water to flow through. The pitch of the spiral was set to 48mm. The reason for this is that the channel is designed to be in contact with every crack in the mortar to feed each with water and allow leakage through them. The minimum crack length noted from samples prepared by Steve Turner was 50mm after one month and as these samples were to be left for the same amount of time and would generally be weaker because of the reduced curing, it was thought that no crack in any of the samples would be beneath the 48mm in length that the lathe was capable of machining.

Once any mortar was applied to the rings, there was no way of telling whether the channel was blocked and so it was decided to test various measures to stop it getting blocked.

Two methods were devised and tested prior to any of the experiments taking place. The first involved placing a length of string in the channel. This would act to stop the channel getting blocked and also acted as a wick to help draw the water down along. The second was to place thick wire in the channel which after consideration was to be crimped so as to stop it from sealing the channel and stopping the water feeding any cracks. Fig 9D below illustrates how the metal may seal the channel and prevent the water feeding the cracks.

Fig 9D

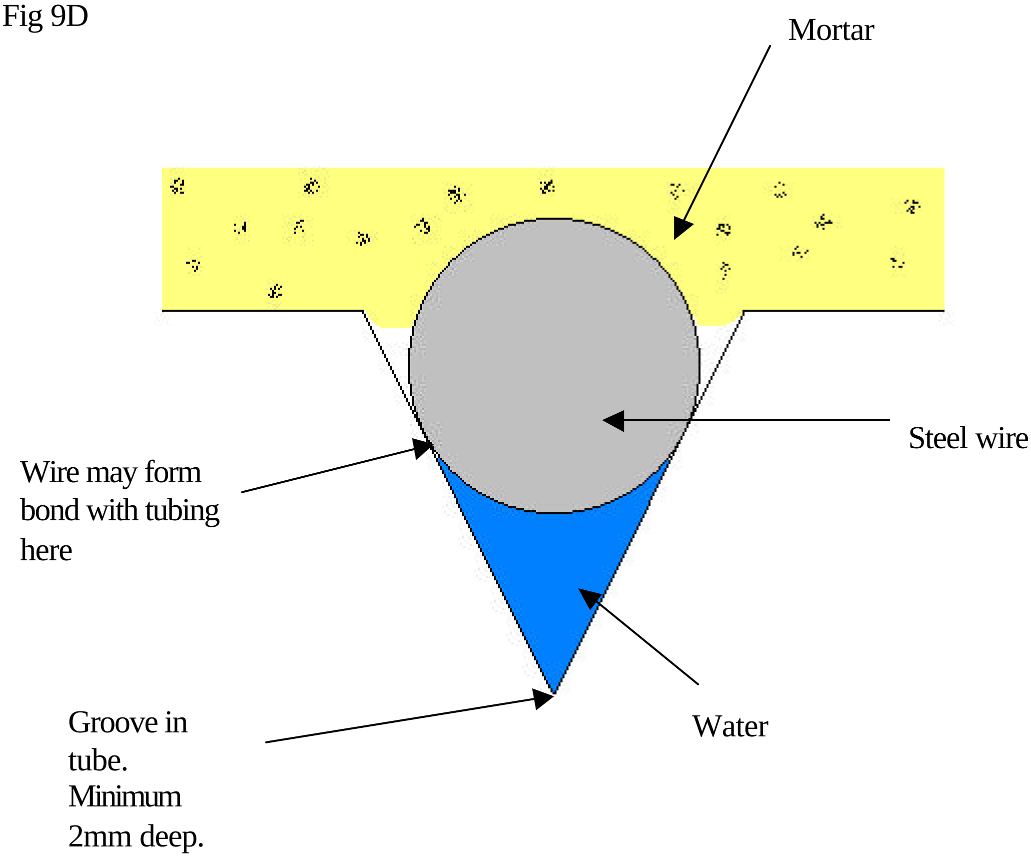
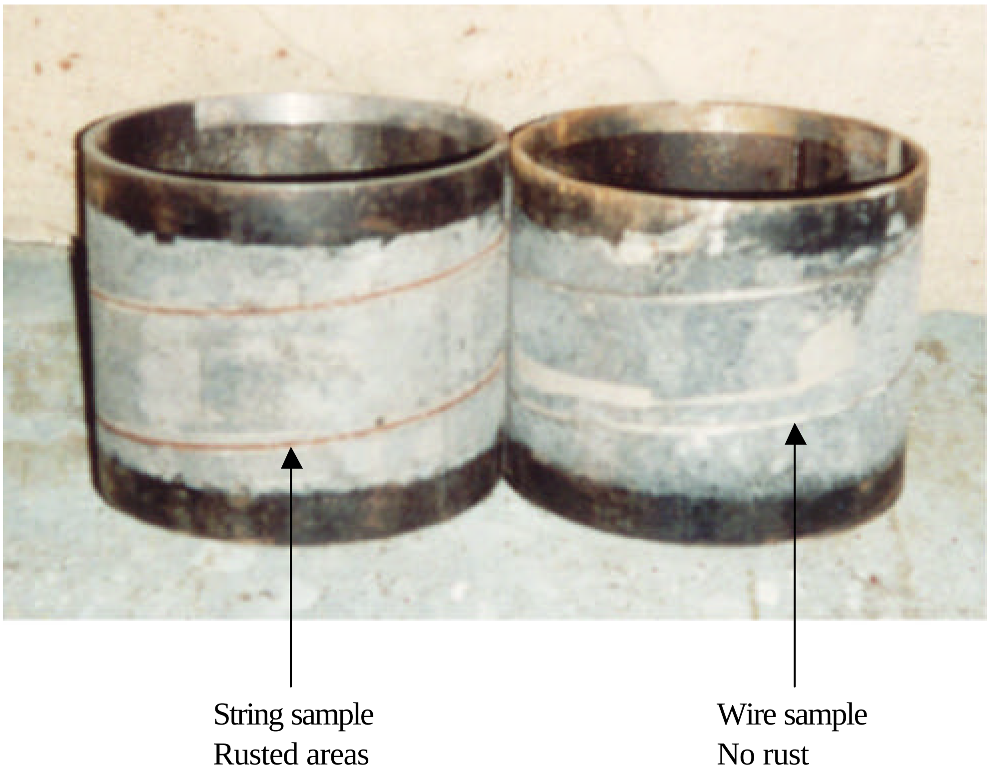


Figure 9D illustrates the way in which the two materials would prevent the channel getting blocked. Crimping the metal would prevent it sealing the channel and the string is porous and doesn't have a smooth surface finish so wouldn't seal the channel as the metal could.

Both of these methods were tested and any problems with their implementation noted. The string was exceptionally easy to lay in the crack and was simply taped at either end and posed no problem when plastering the steel in mortar. Because the steel wire was quite thick, it was very difficult to bend into shape and keep in the channel. It was carefully taped in place until the two ends could be fixed, but on removal of these tapes small sections of the channel were open. The results of two tests on each method were that the string kept the channel open and in both cases water flowed through the length of it. The wire method allowed the channel to get blocked on one occasion and so it was decided to use the string.

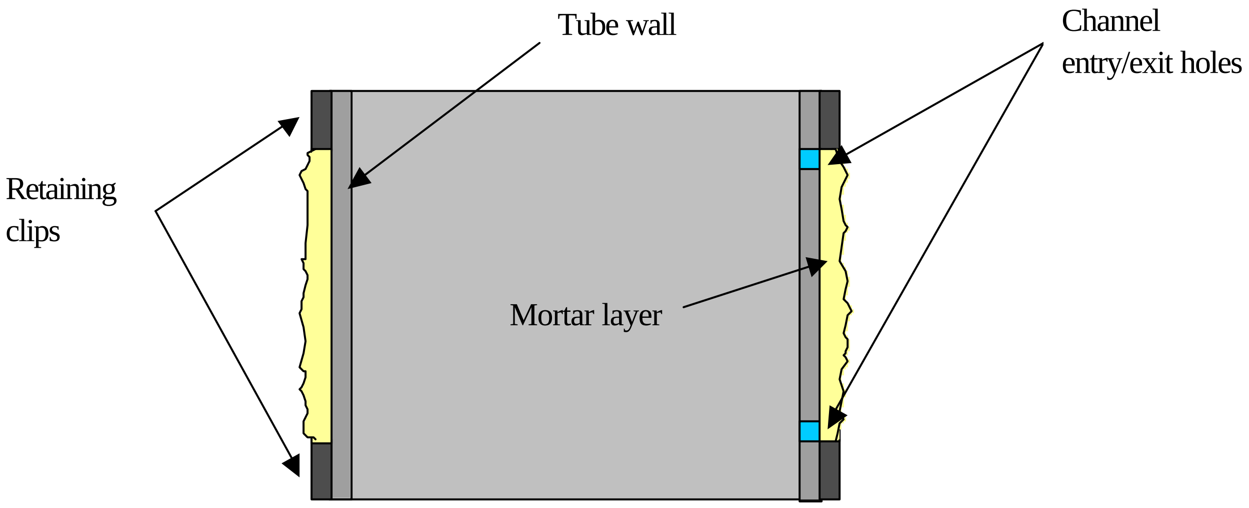
Once the mortar was removed and the lengths of string and wire removed, the channel was checked to see what state it was in. Both channels in which the string was used had a layer of rust along their lengths, showing that water did reach all areas of the channel, see fig 9E. The blockage in one of the wire samples was found to be caused by the wire coming out of the channel and it being blocked with mortar.

fig 9E



2.5mm diameter holes were drilled 25mm from the edges of the rings in the groove to provide a means of feeding the channel water. The channel was then sealed upstream of these holes to stop water leaking out through the top of the rings. Hollow tubing was bonded over the holes on the inside of the rings to allow rubber tubing to be fixed on and connected to a supply of water which comprised of a glass tube calibrated at 1ml intervals. Once this was full and attached to the groove, the samples were observed to see how much leakage, if any, occurred. Fig 9F below shows a cross section of plastered the steel tube, with retaining clips top and bottom, and feed points to the channel.

Fig 9F



The glass tube used to supply the groove was positioned with the water level 1.5m above the sample to provide a "head" of water to help drive water through the cracks. As each sample leaked the level of water in the tube dropped and so too did the head, which would result in less water pressure on the cracks, so after every measuring interval, the water was topped up to the zero point 1.5m above the base of each sample. The amount of water lost in each time interval was approximately equivalent to only 4cm or 2.7% of the total head.

In all of the experiments on this variable, the aim was to find the steady flow rate of water through any cracks. Expected results would show that there would be an initial period of instability where the flow rate changes from an initially very high level. This can be accounted for by the time needed for the groove to be filled with water, the string to become fully saturated and for the cracks to fill with water.

The full flow rates for each sample are included in the results to illustrate this point, but it is the steady flow rates that are of most interest. From the first leakage sample it can be seen that the flow takes approximately 7 minutes to settle to a steady level. To take into account any differences in the samples, readings were initially taken every minute for the first 10 minutes while flow rates are high, and then every 5 minutes for a further 45 minutes. Flow rates are calculated by recording how much water has leaked out of the samples over the test period (1 or 5 minutes) and using this value to find the total volume of water that would leak out over an hour period.

9.3.2. Limitations

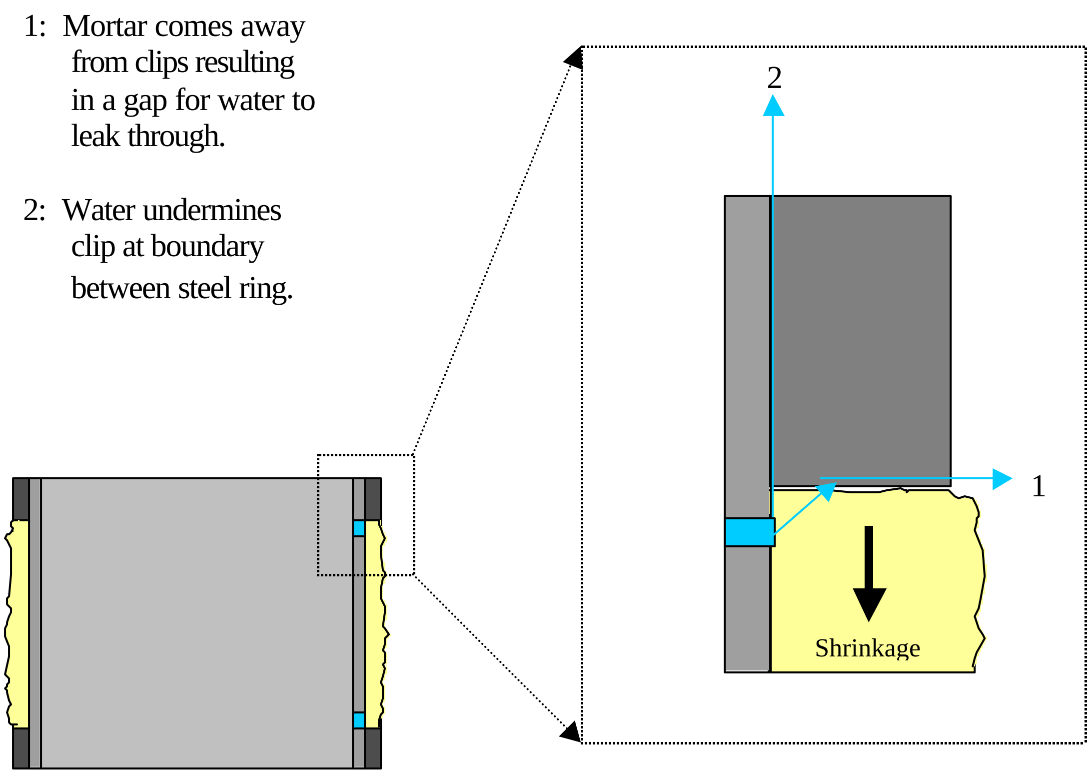
The experiments using the steel rings worked well for studying crack propagation, but problems were encountered when the leakage experiment was set up. There was inadequate sealing between the layer of mortar and the retaining clips, and due to the close proximity of the channel entrances to the boundary between the clips and the layer of mortar, water quickly leaked out. The manner in which this happened can be seen in figure 9F below, which is a photograph of the equipment and clearly shows water leaking from the top of the retaining clips.

Fig 9F

Upon manufacture of the samples, care was taken to ensure the boundary between the clips and the mortar was filled, but due to shrinkage along the axis of the cylinder, the mortar came away from the clips making it easy for water to drain out of the channel. Figure 9G on the following page shows diagrammatically how the experiment failed.

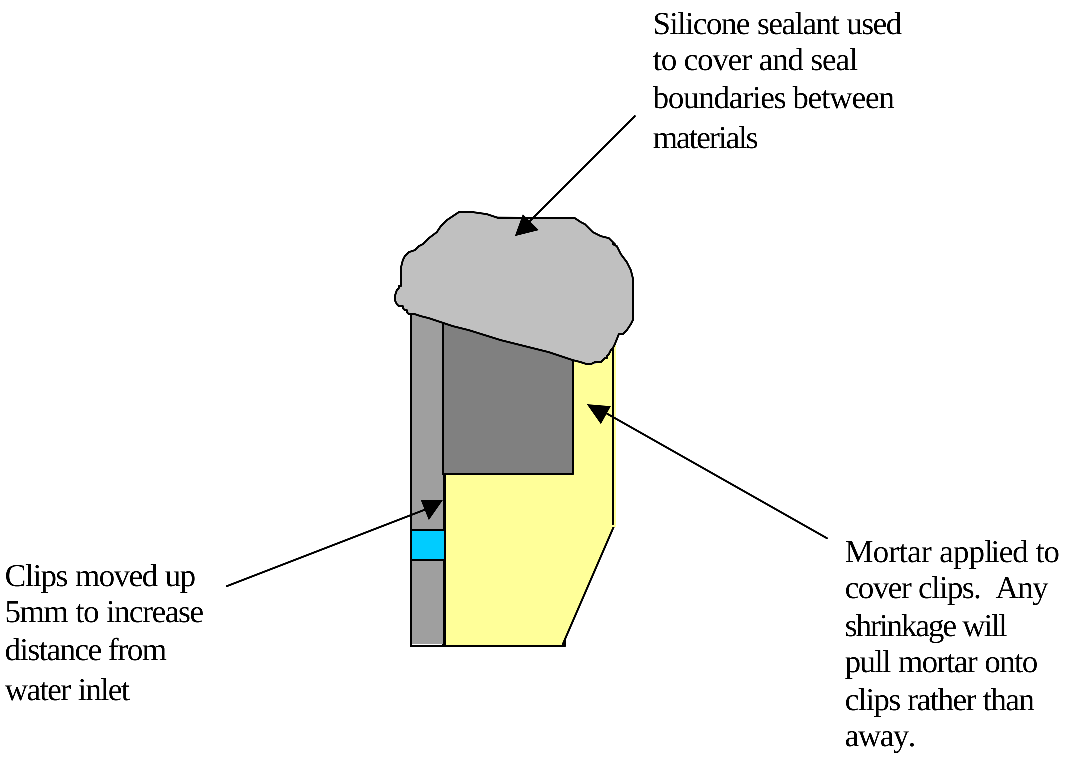
The net result of this leaking was that the samples had to be recast taking into account the means of failure of their predecessors. It was decided that to prevent the clips coming away from the mortar at the boundary between the two, that the clips would be enclosed in mortar themselves. The clips were also raised 5mm to increase the distance from the water feed holes. Once the samples dried and it was time to test for leakage, the added measure of sealing all exposed boundaries with silicone sealant was implemented. The boundary between the clips and the tubing was sealed to prevent any water undermining the clips and, the boundary between the mortar and clips was also sealed. Now any shrinkage of the mortar will result in it pulling into the clips rather than away from them, making the experiment less vulnerable to leaking.

Fig 9G



The diagram at the top of the following page, figure 9H, illustrates the changes in the design of the experiment.

Fig 9H



Due to the fact that the first round of samples had to be recast, a month of experimental time was lost, and the time constraints on this investigation made it not possible to conduct a second round of experiments. This means that the only 4 samples investigated for cracking and shrinkage were plain mortar, silica fume, Harilal Leak Seal and Superplasticiser Complast 211. Had there been time for a second round of experiments, another 4 samples could have been cast consisting of a ferrofest sample, a sample with a layer of pure cement paste sandwiched between 2 layers of plain mortar, and a further 2, possibly investigating the uses of multiple admixtures in each sample.

Chapter 10: Summary of experiments

10.1 Shrinkage

1st round – 4 blocks cast. 3 plain mortar (no admixtures), 1 pure cement paste (no sand). 3 plain blocks left for various lengths of time to wet cure, 2 days, 4 days, and 14 days respectively. Pure cement left for 2 days wet curing.

2nd round – 3 blocks cast, 1 using silica fume admixture, 1 using superplasticiser admixture, 1 using Harilal leak seal admixture. All left for 2 days wet curing.

Each block had its shrinkage monitored regularly for 28 days after drying began.

10.2 Cracking

1st round – 4 rings cast. 1 plain mortar, 1 with superplasticiser admixture, 1 with silica fume admixture, 1 with Harilal leak seal admixture.

Each sample was left to cure for 2 days before drying began. Samples left to dry for 28 dries and cracks monitored.

10.3 Leakage

1st round – 4 rings cast. 1 plain mortar, 1 with superplasticiser admixture, 1 with silica fume admixture, 1 with Harilal leak seal admixture.

Each sample began testing after having been dried for 28 days

Chapter 11: Previous Investigations

As mentioned in the introduction, Steve Turner began experimentation into cracking in waterproof renders before this project began - his notes can be found in the appendix as can results taken from the samples he prepared. The samples talked about in the included documents were of similar design to the rings cast in the main investigation experiments into cracking and leakage. The main difference was that the plain, ferrofest, and nil coat samples, were cast on larger sized steel tubing, a practice dropped for the reports own experiments to keep the procedure constant.

The leakage experiment was never carried out on these samples because it was decided that the chance of all of the cracks lining up with the holes in the tube were small. It was thought necessary to be sure that all cracks were fed with water to ensure correct leakage rates were measured, which is why it was decided that the rings be modified with a spiral groove, of a pitch that was no less than the length of the smallest crack in the specimens studied prior to commencing the investigation.

Results on the cracking of these samples are included for comparative purposes, although changes in the experimental design restrict their use somewhat for this purpose. The manner in which the render shrinks makes it vital that, for experimental purposes, there is no room for an element of unconstrained shrinkage. The gauze was thought to reduce the steel ring’s suitability as a constraint and may allow for some unconstrained shrinkage to be present.

To summarise, results from the samples prepared by Steve Turner, are included in the appendix and are referred to and considered in the analysis, although changes in the design of these experiments restrict exact comparisons being made.

Chapter 12: Shrinkage Results and Analysis

12.1 Shrinkage Results

The results for the set of shrinkage experiments are displayed over the coming pages, including graphical analysis. All numerical references to strain are as read from the equipment (x10^{-2} ì strain) from this point forward.

Table 12A and Graph 12A – Results for plain mortar with 2 days wet curing
Table 12B and Graph 12B – Results for plain mortar with 4 days wet curing
Table 12C and Graph 12C – Results for plain mortar with 14 days wet curing
Table 12D and Graph 12D – Results for pure cement paste with 2 days wet curing
Table 12E and Graph 12E – Results for Harilal Leak Seal with 2 days wet curing
Table 12F and Graph 12F – Results for Silica Fume 2 days wet curing
Table 12G and Graph 12G – Results for Superplasticiser Complast 211 with 2 days wet curing

Table 12A

PLAIN MORTAR 2 DAYS WET CURING		
Number of Days	**Side A**	**Side B**
-2	0	0
-1	2	2
0	1	2
1	-24	-25
2	-33	-33
3	-47	-43
4	-57	-53
5	-66	-61
8	-92	-83
9	-94	-86
10	-97	-89
11	-102	-94
12	-104	-95
19	-117	-112
25	-123	-117
26	-128	-121
28	-131	-125

Graph 12A

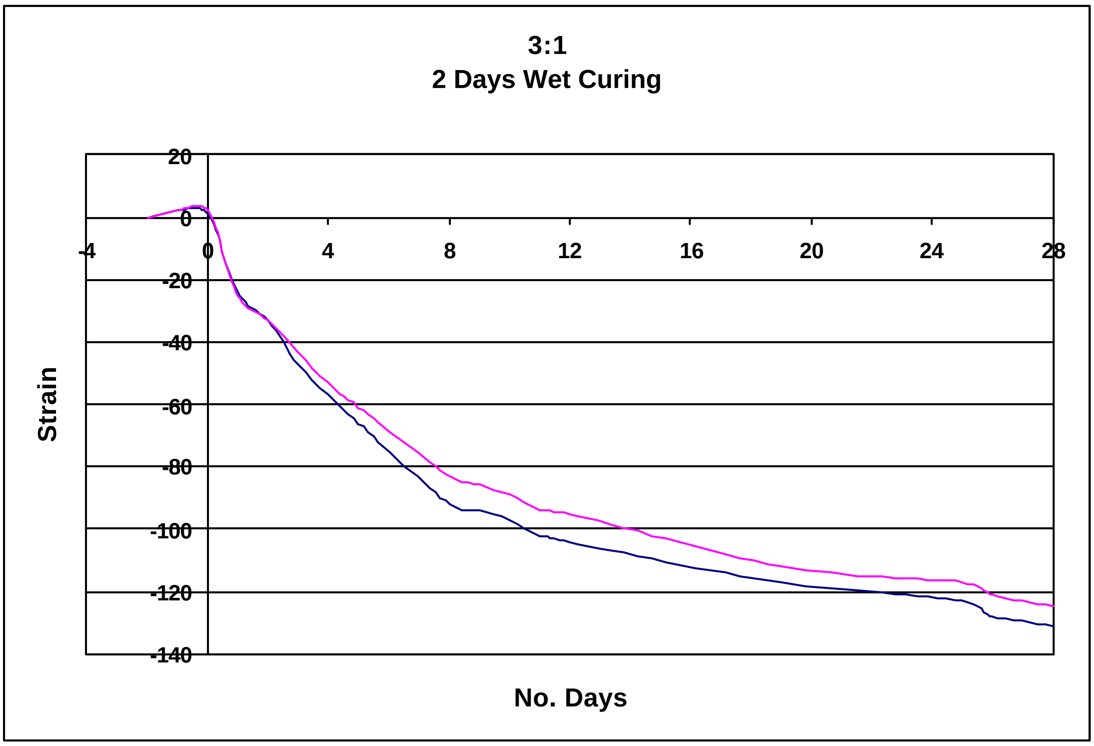


Table 12B

PLAIN MORTAR 4 DAYS WET CURING		
Number of Days	**Side A**	**Side B**
-4	0	0
-1	2	10
0	-7	-1
1	-16	-13
2	-25	-22
3	-33	-31
6	-53	-52
7	-58	-55
8	-62	-60
9	-69	-67
10	-72	-68
16	-95	-93
23	-108	-107
24	-111	-110
28	-115	-116

Graph 12B

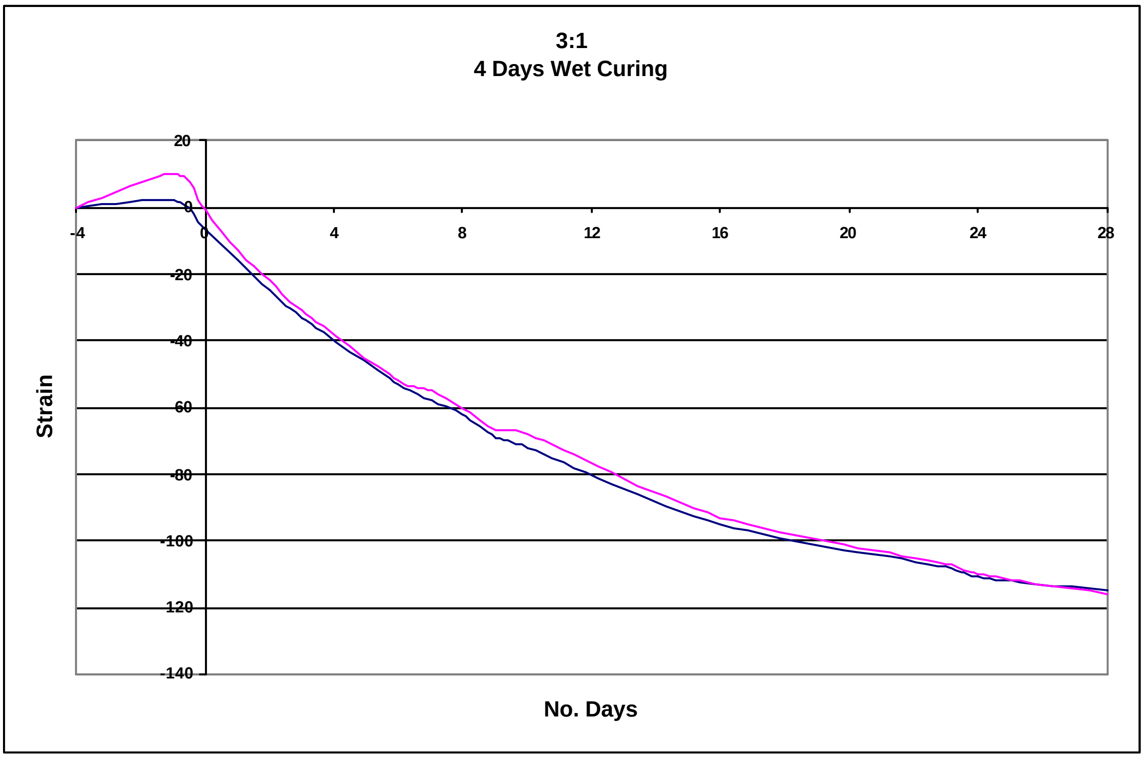


Table 12C

PLAIN MORTAR 14 DAYS WET CURING		
Number of Days	**Side A**	**Side B**
-14	0	0
-11	10	9
-10	12	10
-9	11	10
-8	12	9
-7	12	10
-4	11	9
-3	12	10
-2	12	10
-1	11	10
0	11	10
2	0	-2
5	-35	-34
6	-42	-39
8	-52	-50
13	-73	-68
14	-77	-72
17	-84	-79
20	-90	-84
22	-92	-87
26	-96	-91
28	-98	-94

Graph 12C

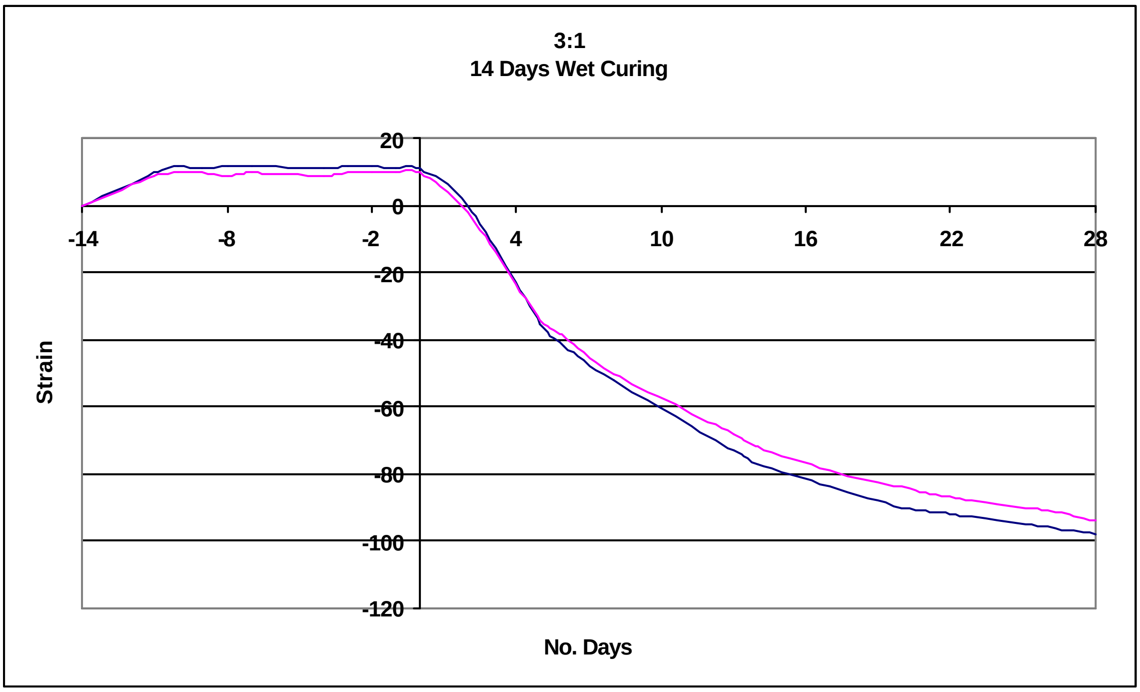


Table 12D

PURE CEMENT PASTE		
Number of Days	**Side A**	**Side B**
-2	0	0
0	20	15
1	-2	-9
2	-33	-38
3	-59	-64
4	-83	-86
7	-143	-151
8	-156	-163
9	-168	-176
10	-184	-192
11	-191	-199
24	-271	-277
25	-280	-286
28	-295	-304

Graph 12D

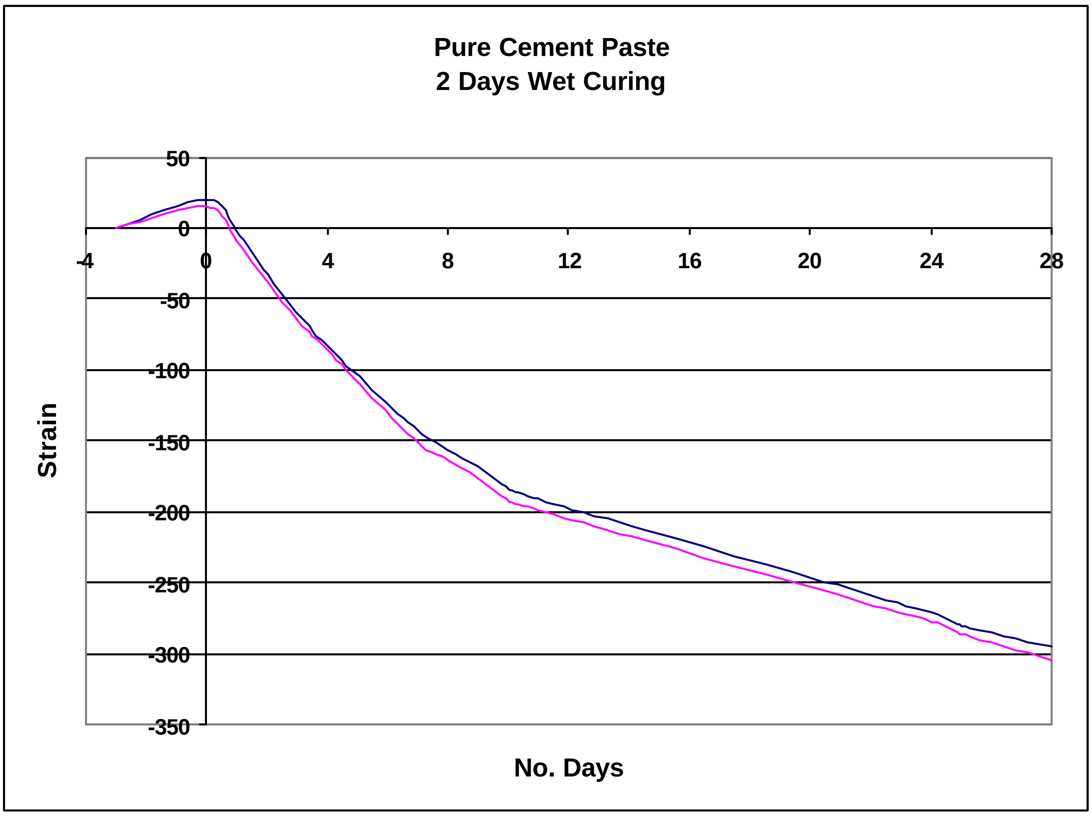


Table 12E

HARILAL LEAK SEAL		
Number of Days	**Side A**	**Side B**
0	0	0
1	-11	-9
2	-18	-16
3	-26	-21
6	-46	-44
8	-55	-54
9	-63	-66
12	-72	-71
15	-83	-81
16	-85	-83
19	-87	-86
22	-90	-88
23	-91	-90
26	-94	-91
27	-98	-94
28	-99	-96

Graph 12E

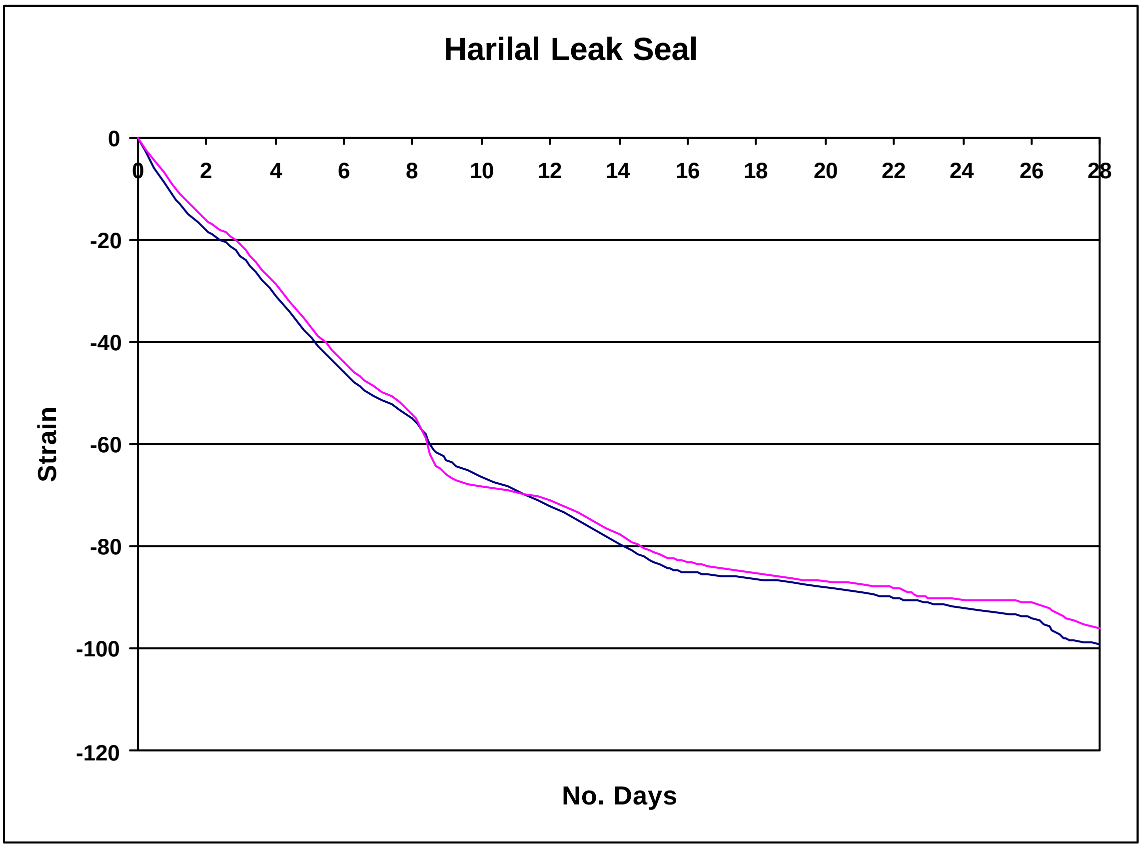


Table 12F

SILICA FUME		
Number of Days	**Side A**	**Side B**
0	0	0
1	-10	-8
2	-21	-22
3	-28	-26
6	-58	-60
8	-70	-71
9	-80	-81
12	-87	-89
15	-99	-101
16	-102	-104
19	-109	-109
22	-112	-111
23	-115	-114
26	-117	-116
27	-123	-122
28	-125	-125

Graph 12F

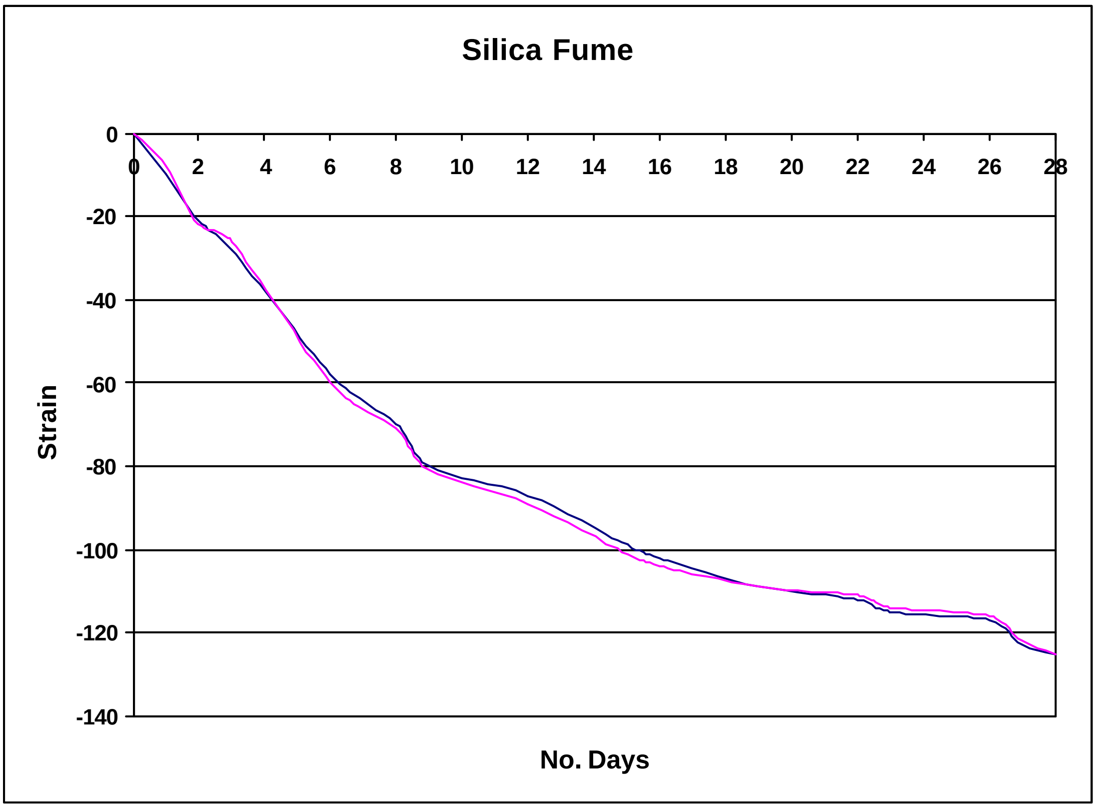
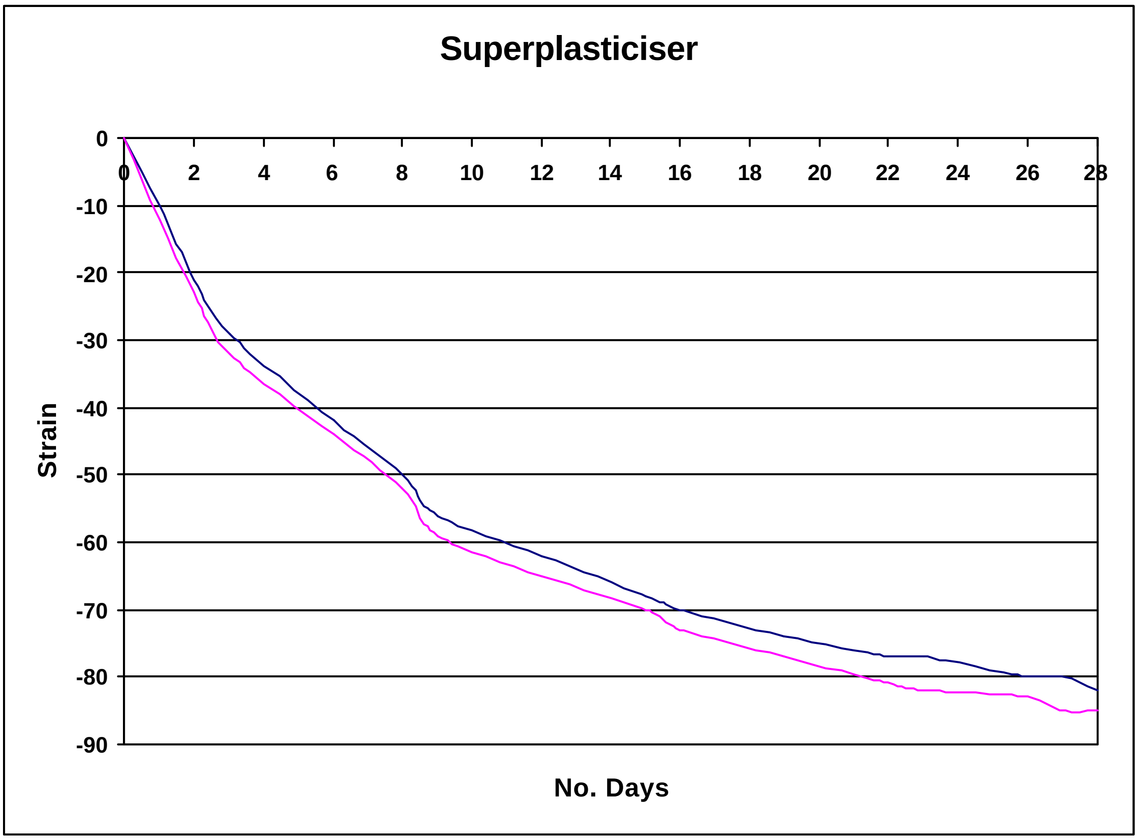


Table 12G

SUPERPLASTICISER		
Number of Days	**Side A**	**Side B**
0	0	0
1	-10	-12
2	-21	-23
3	-29	-32
6	-42	-44
8	-50	-52
9	-56	-59
12	-62	-65
15	-68	-70
16	-70	-73
19	-74	-77
22	-77	-71
23	-77	-82
26	-80	-83
27	-80	-85
28	-82	-85

Graph 12G



12.2 Shrinkage Analysis

The first round of shrinkage experiments consisted of 4 samples, 3 plain mortar and 1 pure cement paste. Graphs 12A-12G plot shrinkage against time and show well how each sample shrinks quickly at first before slowing, resulting in a relatively smooth curve of decreasing gradient. The two lines on each graph represent the two sides of each sample and it can be seen that generally warping has not been significant with any samples, including the second round of admixtures, because the lines remain close together throughout the plots. Any difference in the position of the lines would indicate a difference in the shrinkage of one side relative to the other. The sample with the most amount of warping was the plain mortar block wet cured for 2 days, with a 4.5% difference in strain between each of the two sides, but this figure remains small enough to not affect the validity of the result.

The next observation to be made is what affects the period of wet curing had on the shrinkage characteristics of each sample. Firstly, research shown earlier in this report predicted that the majority of shrinkage would take place after drying has begun. This indeed was the case and due to the fact that during wet curing the samples were at 100% humidity, no shrinkage was recorded. Instead the opposite occurred and all of the first round samples underwent an increase in volume. This increase in volume was seen in the sample wet cured for 14 days, to level off at approximately +10 micro strain. This result wasn't entirely unexpected as research showed that this it is not uncommon for cementitous materials to increase in size in 100% humidity conditions. Even after drying this affect can be seen, although was not investigated in this project.

The period of wet curing had a marked affect on the amount of shrinkage seen in each of the 3 identical plain mortar samples. The sample cured for 14 days shrank 25% less than the one cured for only 2 days. The sample that experienced 4 days wet curing had a 10% reduction in shrinkage compared to the 2 day sample. It was expected that the increased curing would increase the material's strength, but it was unexpected that it would affect the shrinkage in such a significant manner. 25% is a major reduction in shrinkage and even though the period of curing was of secondary interest in this report, the result shows that it is a field worthy of further investigation.

In the context of using the mortar as a render in a water tank it is undesirable to have a long period of wet curing, but it should be considered if it could reduce the overall shrinkage seen in the render. Even an extra two days has been seen to reduce the shrinkage by up to 10%.

A possible explanation for the reduction in the levels of shrinkage recorded can be linked to the material strength, as follows: It has been shown that cementitous materials shrink when water is lost through evaporation. As the material dries pores are left, basically cavities where excess water has been stored, which makes the material porous after drying and reduces the strength of the material. The longer the mortar cures, the stronger it will become and it would be able to resist the shrinkage forces associated with drying and water loss. It may therefore shrink less and instead have greater internal forces built up within the material when compared to a less cured and hence weaker mortar.

When looking at the results from the samples containing admixtures, it can be seen that they too have had a big effect on the shrinkage of the mortars. As mentioned in section 6, an admixture will generally make a mortar less permeable by one of the two following methods:

1. Reduce shrinkage
2. Increase strength

Silica fume is an admixture that is used to make cementitous materials stronger. This will in theory reduce permeability because the material would crack less for any given reduction in volume. This theory is backed up by this result because the addition of silica into the mortar has had a negligible effect on the shrinkage. It underwent a reduction in length of 125 micro strain compared to 128 for the average of both sides of the similarly cured plain mortar with no admixtures, less than a 3% change.

The superplasticiser had the biggest effect on the shrinkage characteristics of mortar. At 83 micro strain reduction, it experienced a 35% reduction in shrinkage compared to the plain sample. This was expected because the plasticiser allowed a reduction in the amount of water used, although the magnitude of the reduction is surprising seeing as only 17% less water was used to create the 35% reduction in volume.

It was not known at the beginning of the investigation how the Harilal Leak Seal would affect the permeability of mortar, but it can be seen that it is less like the silica fume than the plasticiser because it has resulted in a reduction in the recorded shrinkage of 24% compared to the plain sample. The next experiment on cracking will determine whether it also has an effect on the strength of the mortar.

All of the admixture samples were prepared and tested over the same period, and a small anomaly can be noted on the day 8-9 period on all of the graphs for these samples. The anomaly in question is a small kink in the graph indicating an increase in shrinkage over the one day period. It is interesting that it is present on all of the samples and is a good indication of the validity of the results because it shows all samples were tested under the same conditions. The increase in shrinkage can be explained by there being a temporary increase in the temperature of the samples over that period which would result in more moisture being evaporated and hence a greater reduction in volume.

Chapter 13: Crack Results and Analysis

13.1 Crack Results

The results for both rounds of the crack experiment are provided over the next 2 pages.

Table 13.1A

Plain			
Crack Number	**Width (divisions)**	**(Width ìm)**	**Length mm**
1	4	200	130
2	3	150	81
3	2.5	125	76

Table 13.1B

Silica Fume			
Crack Number	**Width (divisions)**	**(Width ìm)**	**Length mm**
1	1.75	87.5	95
2	1.5	75	130
3	1.5	75	130
4	1.25	62.5	20
5	1.25	62.5	66

Table 13.1B

Harilal Leak Seal			
Crack Number	**Width (divisions)**	**(Width ìm)**	**Length mm**
1	2.5	125	130
2	2	100	130
3	1.5	75	81

Table 13.1C

Superplasticiser			
Crack Number	**Width (divisions)**	**(Width (ìm)**	**Length mm**
1	2.5	125	98
2	2.5	125	62

Table 13.2A

Plain			
Crack Number	**Width (divisions)**	**(Width ìm)**	**Length mm**
1	3.5	175	130
2	2.5	125	130
3	2	100	28
4	1.5	75	43

Table 13.2B

Silica Fume			
Crack Number	**Width (divisions)**	**(Width ìm)**	**Length mm**
1	1.75	87.5	130
2	1.5	75	130
3	1.25	62.5	91
4	1	50	97
5	0.5	25	130
6	0.5	25	130

Table 13.2C

Harilal Leak Seal			
Crack Number	**Width (divisions)**	**(Width ìm)**	**Length mm**
1	2.5	125	130
2	2.5	125	130

Table 13.2D

Superplasticiser			
Crack Number	**Width (divisions)**	**(Width (ìm)**	**Length mm**
1	2.5	125	98
2	2.5	125	62
3	1.75	87.5	41

13.2 Crack Analysis

The first fact that can be noted from looking at the tables on the crack sizes is that there is a great range of lengths and widths of cracks across the samples, as well as the number of cracks per sample. The first round of results show that the silica fume sample was most extensively cracked in terms of quantity, but the plain sample had the widest cracks of all samples.

Multiplying the length and width of each crack and adding all values for each of the cracks in any one sample can be a simple piece of analysis. It will provide a rough idea of the total crack surface area for each sample. See table 13.3A below.

Table 13.3A

SAMPLE	TOTAL CRACK SURFACE AREA: ROUND 1 (ìm^2)	TOTAL CRACK SURFACE AREA: ROUND 2 (ìm^2)
Plain	47.65	45.03
Silica Fume	33.19	38.16
Harilal Leak Seal	35.33	32.5
Superplasticiser	20.00	23.59

It is accepted that cracks vary in width along their length and that each crack may be of different depths so these figures may not correlate exactly with the leakage rates shown later, but the figures correlate well with those seen for shrinkage. The plain sample, which was seen to undergo the greatest amount of shrinkage, also has the highest crack surface area up to 30% more than the next highest of Harilal Leak Seal.

Comparing silica fume with Harilal, the total area of cracking is very similar, although with silica fume the area is spread out over a greater number of thinner cracks compared to the few wide cracks of Harilal. The mathematical analysis of flow through cracks in section 6 would suggest a greater leakage rate for the Harilal sample because of the extra width of the cracks. Whether this is the case or not can be seen in the next piece of analysis.

From the shrinkage results it was shown that mortar with silica fume present experienced a similar level of shrinkage compared to plain mortar, while the Harilal sample shrank considerably less, yet the resultant cracking is very similar. This is an important development because it confirms that the silica fume sample is likely to be much stronger than the Harilal mortar. The strength seems to have affected the distribution of the cracks also, because the silica fume sample has many more cracks than any of the other samples, a fact which is true for both rounds of experimentation.

Overall these results correlate well with those from the shrinkage experiments and the superplasticiser has performed the best in this area of investigation as well. The superplasticiser experienced up to a 43% reduction in cracking compared to the plain sample, from a 35% difference in shrinkage levels measured. Even though the superplasticiser has enjoyed a significant reduction in shrinkage induced cracking, the cracks are relatively wide when compared to examples from the silica fume sample. This is predicted to be undesirable due to the much bigger flow rates that wide cracks may be subject to. The final piece of analysis of the leakage results will show whether the superplasticiser's reduction in crack area will be of benefit if it results in wider cracks.

Chapter 14: Leakage Results and Analysis

14.1 Leakage Results

The results of the Leakage experiments carried out on the 2nd round of crack samples is provided over the coming four pages.

Table 14A – Volume of water lost per time period, plain mortar sample.
Table 14B – Volume of water lost per time period, silica fume sample.
Table 14C – Volume of water lost per time period, Harilal Leak Seal sample.
Table 14D – Volume of water lost per time period, Superplasticiser sample.

Table 14E and graph 14E – Steady flow rates, plain mortar sample.
Table 14F and graph 14F – Steady flow rates, silica fume sample.
Table 14G and graph 14G – Steady flow rates, Harilal Leak Seal sample.
Table 14H and graph 14H – Steady flow rates, Superplasticiser sample.

Table 14A

PLAIN	
Time Interval (minutes)	Water lost (ml)
1	7
1	4.9
1	4.1
1	3.8
1	3.2
1	2.9
1	2.5
1	2
1	1.6
1	1.2
5	5.1
5	5
5	5.2
5	4.9
5	4.7
5	4.6
5	4.9
5	5.1
5	4.9

Table 14B

SILICA FUME	
Time Interval (minutes)	Water lost (ml)
1	6.2
1	4.4
1	3.5
1	2.6
1	1.7
1	0.9
1	0.6
1	0.4
1	0.5
1	0.4
5	2.1
5	2
5	2.1
5	1.9
5	2
5	2.2
5	1.9
5	2
5	2.1

Table 14C

HARILAL LEAK SEAL	
Time Interval (minutes)	Water lost (ml)
1	7.1
1	5.4
1	4.1
1	3.6
1	2.8
1	1.1
1	0.8
1	0.5
1	0.4
1	0.4
5	1.7
5	1.6
5	1.7
5	1.5
5	1.7
5	1.6
5	1.6
5	1.5
5	1.6

Table 14D

SUPERPLASTICISER	
Time Interval (minutes)	Water lost (ml)
1	6.6
1	5
1	4.1
1	3
1	1.4
1	1
1	0.7
1	0.4
1	0.3
1	0.2
5	1.1
5	1
5	1.1
5	1.1
5	1.1
5	1.2
5	1.1
5	1
5	1.1

Table 14E

PLAIN	
Total time (minutes)	Flow rate (ml/hour)
1	420
2	294
3	246
4	228
5	192
6	174
7	150
8	120
9	96
10	72
15	61.2
20	60
25	62.4
30	58.8
35	56.4
40	55.2
45	58.8
50	61.2
55	58.8

Table 14F

HARILAL LEAK SEAL	
Total time (minutes)	Flow rate (ml/hour)
1	426
2	324
3	246
4	216
5	168
6	66
7	48
8	30
9	24
10	24
15	20.4
20	19.2
25	20.4
30	18
35	20.4
40	19.2
45	19.2
50	18
55	19.2

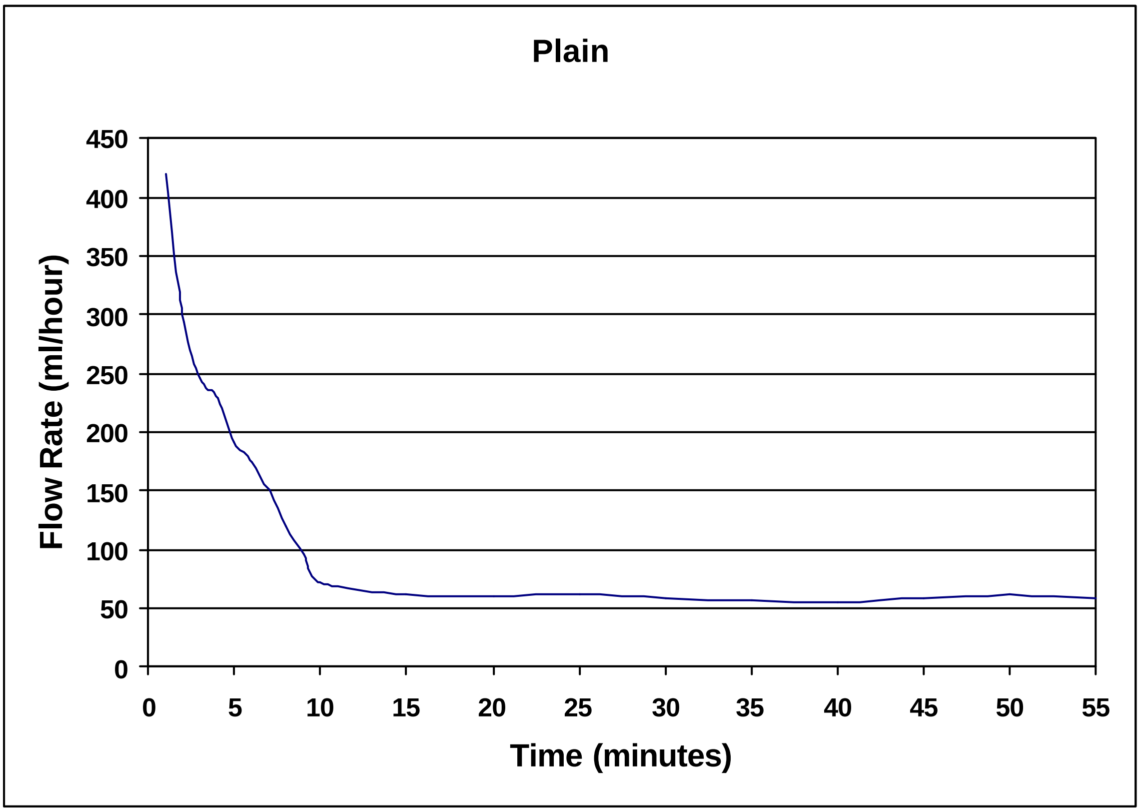
Table 14G

SILICA FUME	
Total time (minutes)	Flow rate (ml/hour)
1	372
2	264
3	210
4	156
5	102
6	54
7	36
8	24
9	30
10	24
15	25.2
20	24
25	25.2
30	22.8
35	24
40	26.4
45	22.8
50	24
55	25.2

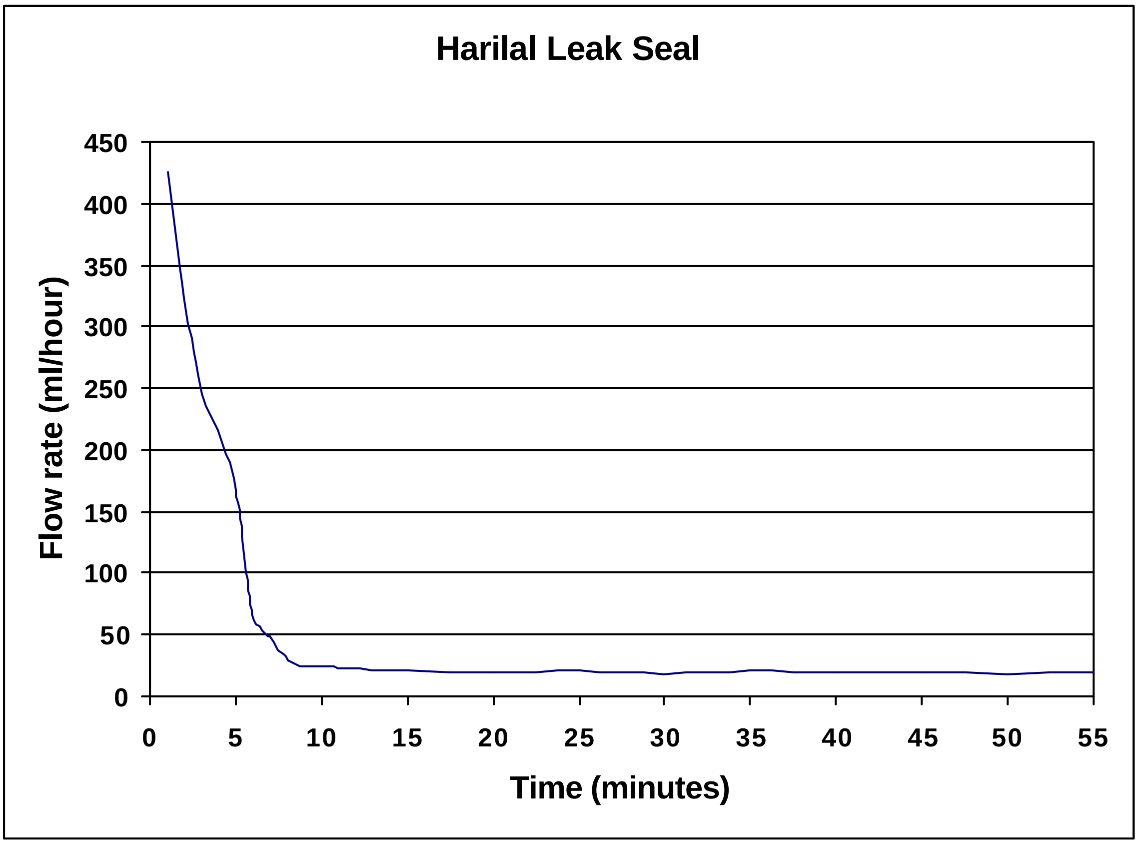
Table 14H

SUPERPLASTICISER	
Total time (minutes)	Flow rate (ml/hour)
1	396
2	300
3	246
4	180
5	84
6	60
7	42
8	24
9	18
10	12
15	13.2
20	12
25	13.2
30	13.2
35	13.2
40	14.4
45	13.2
50	12
55	13.2

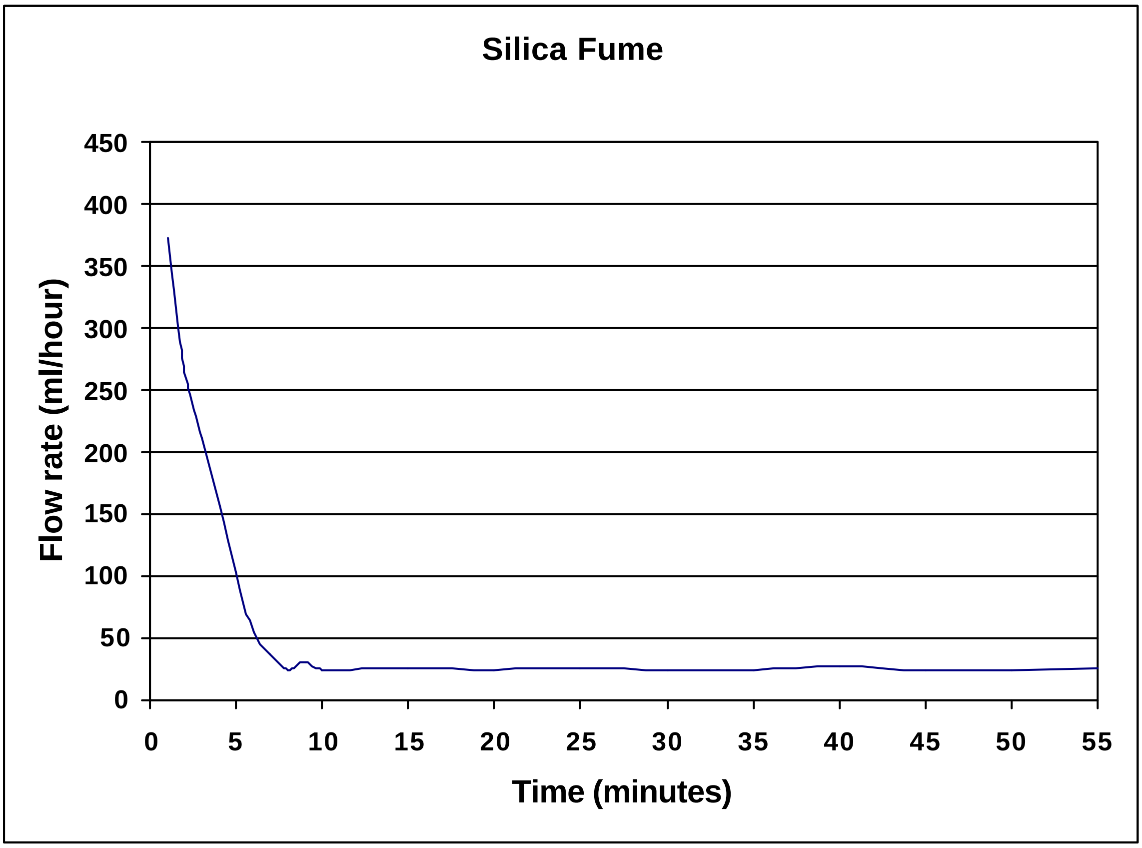
Graph 14E



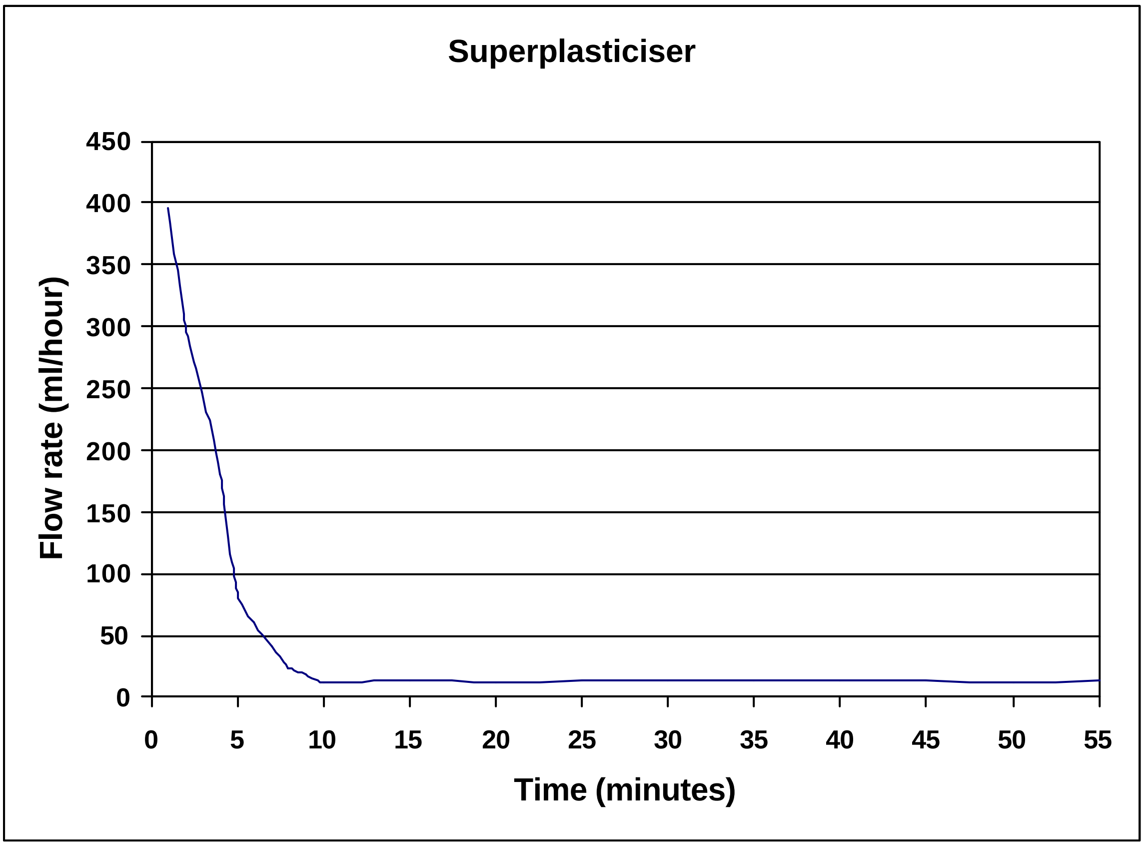
Graph 14F



Graph 14H



Graph 14H



14.2 Leakage Analysis

The first thing to check when looking at the results for the leakage experiments is whether initial flow rates for each sample are of a similar magnitude. This is an important factor because if one sample has a much lower initial flow rate when compared to the others, this may restrict the amount of leakage seen due to the water not flowing through the groove quickly enough. This doesn't seem to be the case because all initial flow rates are of the same order of magnitude and the final flow rates seen are much lower than initial rates so shouldn't be restricted in any way. It should be reiterated that leakage results are only available for the samples from the second round of crack investigation.

As expected water levels in the test equipment drop significantly in the first few minutes of experimentation which can be apportioned to the groove filling with water and saturating the string. On all of the samples it has taken approximately 7-10 minutes for the flow rates to level off to a constant rate. The first few seconds of very high flow is, as mentioned above, due to the groove in the testing rigs filling with water. The flow drops off very quickly but remains higher than final values until around the 7 minute mark. Prior to this the medium flow rates can be attributed to the cracks filling with water. Over the first 7 minutes of the of the experiment it can be assumed there is little or no actual leakage from the mortar, rather than the flow can be explained on the water gradually filling every crack before being able to seep out onto the surface. Evidence of this is that no water was visible on the surface of the mortar for the first 5 minutes or so of each experiment. Subsequent to this moisture was visible originating from some of the cracks.

It has been stated that steady flow rates are of the most interest in this round of experiments, and it was predicted that it might take a few minutes for the flow to settle to this steady level. Comparing the steady flow rates shows some interesting correlations with previous results. The plain sample, which was the most cracked prior to the leakage test, experienced a significantly higher flow rate than any of the others with the equivalent of approximately 59ml per hour lost. The silica Fume sample which had a crack surface area 15% lower than the plain sample, had a steady flow rate of only 24ml per hour, 40% lower than the plain sample. This result could be of extreme importance because it would confirm the theory that for any given area of cracking, it is desirable to have it spread over a larger number of thin cracks rather than over a smaller number or wider cracks.

Subsequent results correlate with the total area of cracking. Harilal Leak Seal leaks at a rate of approximately 20ml per hour leakage, while 13ml per hour is the rate for the superplasticiser.

Comparing the silica fume sample to the Harilal is of interest because they both underwent similar levels of cracking, but had different numbers and widths of cracks. The Harilal sample came out on top as it leaked approximately 17% less. When this is compared to the 16% less cracking it experienced, the result becomes more important, because in this case it seems to go against the theory that crack width is the most important factor when considering leakage through cracks in mortar. All of the crack surface area of the Harilal sample was taken up by 2 long wide cracks with an average width of 125ìm, while the silica sample had 6 much thinner cracks with an average width of only 54ìm.

The superplasticiser leaked the least of all of the four samples, 76% less than the plain sample. It did also crack the least out of the 4 samples so this was not entirely unexpected, but again the cracks were of greater width than many cracks seen on other samples so initially this results seems to go against the theory that width is the key to how much water leaks from any one sample. The study on whether crack width affects leakage has proved inconclusive, a matter which is discussed in a following chapter.

Chapter 15: Summary of Analysis

The results from the experiments of the three variables have provided extremely relevant information on the suitability of each type of mortar for use as a waterproofing render on water tanks. The correlation between the shrinkage recorded from examples of each type of mortar and the amount of cracking has been high. The only exception to the pattern of high shrinkage causing high cracking was the relationship between the plain mortar, and the sample with silica fume added to it. The addition of silica had negligible effect on the shrinkage of the mortar, but this sample cracked significantly less than the plain mortar, a fact that has been attributed to the extra strength of mortar with silica fume added to it.

The remaining two admixtures, Harilal Leak Seal and the superplasticiser, both led to reduced shrinkage recorded in the mortar when compared to a plain sample. This reduction in shrinkage was confirmed by the experiments on cracking, where the two admixtures had far less cracking than the plain sample.

The silica fume sample experienced greater cracking than the other two admixtures but the extra strength of the mortar caused a spread of the shrinkage over a greater number of cracks, which according to section 6 would have a large effect on how much water leaked from it. Unfortunately the experiments proved inconclusive on this subject, because there is evidence that both supports and contradicts this theory. Comparing the leakage rates and the crack characteristics of the silica fume sample with the plain sample supports the theory, while comparing the silica fume with the Harilal Leak Seal seems to contradict it.

If the reader refers to the appendix and the results of cracking in previously carried out work (Steve Turner's), it can be seen the similarity between the types of cracking on the mortar enhanced with silica fume. These samples underwent different curing times (3 months wet curing in this case) and the cracking resulting from drying is seen to consist of many thin cracks rather than wider ones as seen on other samples. Again the plain sample experienced fewer, but wider cracking. The superplasticiser performed well as it did in this set of experiments with all of its cracks relatively short and thin. The main result of interest out of these results is the performance of the nil coat layer. This method of applying mortar involves casting an initial layer of thin mortar, allowing it to dry, and applying an even thinner layer of cement slurry (no sand), and protecting this with a final coat of mortar. The thinking behind this is that when the first layer dries and cracks the pure cement layer will help fill any cracks, and because it is denser than mortar, will be more impermeable as well. There was no opportunity to explore this possibility in this investigation due to the failure of a round of experiments and the time involved in retesting them.

The Ferrofest sample also did well, but again there was no scope to test it in this investigation. Further experimentation into the performance of these type of "sandwich" layers is recommended.

A further admixture, Festegral, was used in Steve's samples, but was unavailable for testing in this experiment as there was insufficient quantities left to experiment on but a glance at the results of the cracking experiment using this admixture suggest a lack of performance.

Chapter 16: Discussion

The leakage experiment has been the source of most of the problems in this investigation. It needed careful planning when designing the experiment to make sure all of the possible unknowns were removed to ensure reliable results were produced. In hindsight there is still a problem with the experimental method used. Observation of the surface of the samples throughout the course of the experiment showed that not all of the cracks in the mortar were leaking. From here it can be concluded that even though the mortar layer is thin at 10mm, it is not definite that all of the cracks propagated the whole depth of the layer of mortar. If this was the case then any relationship between the level of cracking and the flow rate of water through any cracks is invalid.

For a crack to affect the rate of leakage of a sample, it must be deep enough to reach the water supply at the surface of the steel ring. If a crack does not propagate this deep, then it will in no way play a part in the observed leakage. Below is a picture of a crack in one of the samples (fig 15A). If an imaginary section is taken along the dashed lines, there is no way of telling how deep the crack goes. Figure 15B on the following page shows a diagram of how this crack may have propagated in depth.

Fig 15A

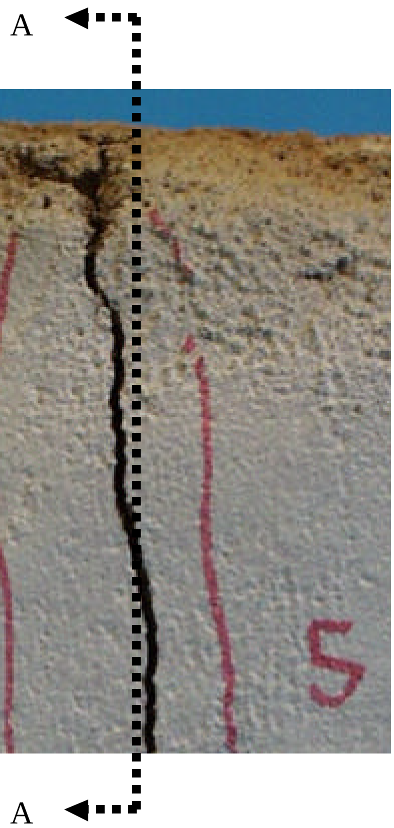
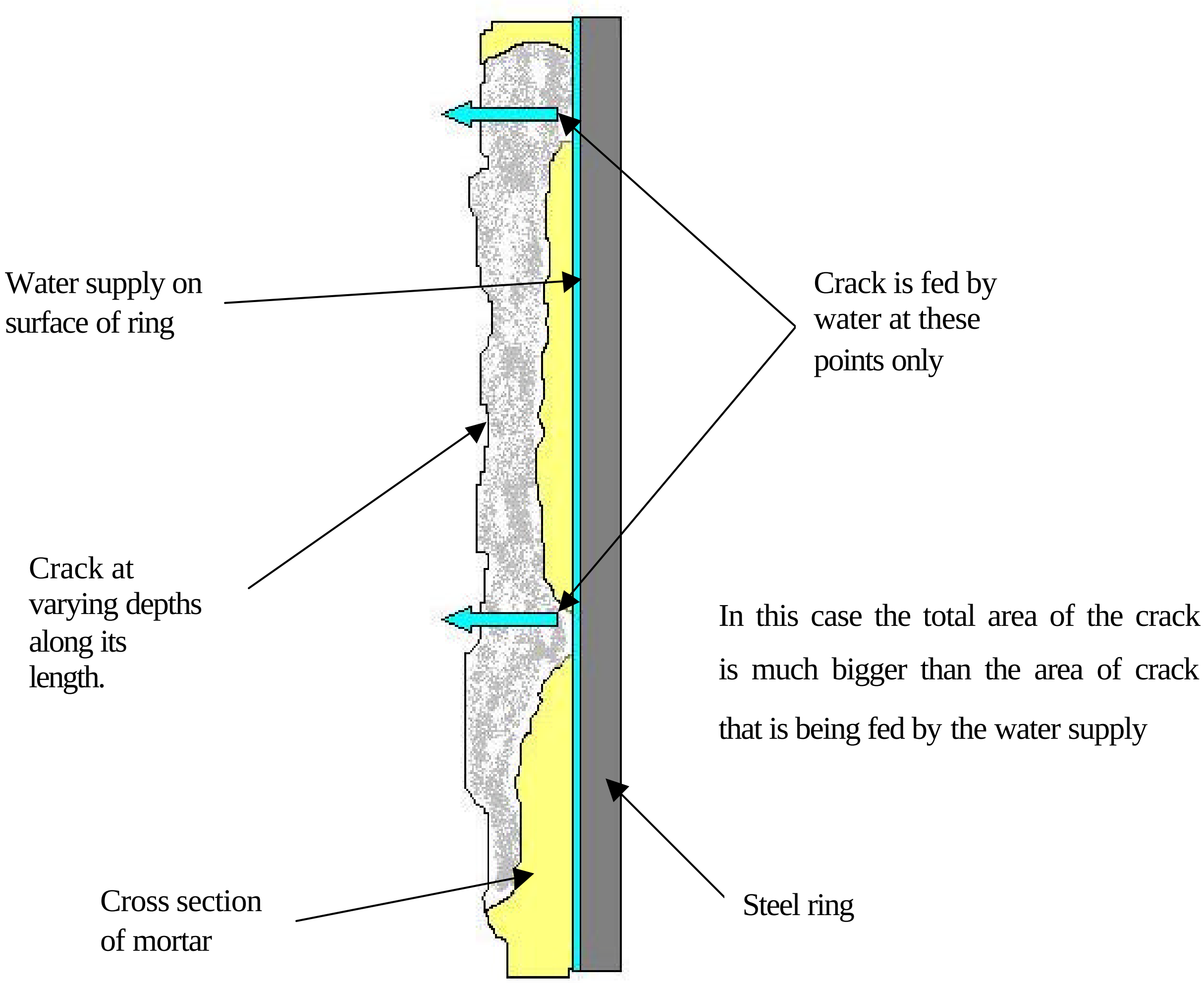


Figure 15B



To allow valid comparisons between crack area and leakage flow rates, the area of crack in contact with the water supply must be known. It was impossible to find this area in the bounds of this investigation. A possible way of doing it would be to cut down the length of each crack after the leakage results have been taken, but this was not possible using conventional methods because the disruption of the mortar would cause further crack propagation and be generally too intrusive to give accurate results.

Even though the comparisons between crack area and leakage may not be valid, the leakage results are still important. If a crack does not propagate the whole depth of the mortar layer, then it will not cause leakage and hence some tension has been released at no cost. It would be extremely desirable to have a mortar that relived the shrinkage-induced tension with purely superficial surface cracks, as it would then not leak at all. This hasn't been the case with any samples tested but anomalies that occur when comparing the leakage and the cracking of some samples can be explained by the possibility that not all of the cracks penetrate the full depth of the mortar. This helps to explain why the Harilal Leak Seal sample leaked slower than expected when compared to the silica fume sample.

There are many other factors to consider when looking at the experimental procedure for the leakage variable. Both shrinkage and crack measurements are relatively easy to perform reliably and accurately, but the leakage of water from a sealed vessel is notoriously unreliable, especially when the vessel is sealed with a material as coarse as mortar. The groove in the steel ring is basically a small water tank with the top and sides sealed with mortar. It must be well sealed to make any results for leakage useable. There are many places other than a crack in the mortar that water could leak from, as seen in the first round of leakage experiments where the water was lost at the boundary between the mortar and the retaining clip. The subsequent change in design of the experiment appeared to have cured this problem but the equipment can still not be guaranteed watertight. Had the first round of experiments not leaked, then two sets of results for leakage would be available for analysis, and this would show whether the results were repeatable, and hence increase their validity.

In chapter 6, it was suggested that the flow rate of water through a crack was related to the crack width by the relationship ÓLb^2 where L is the crack length and b is the width. This cannot be proved or disproved, as there is evidence both for and against it.

The only way to be entirely sure that any results from the leakage experiments are useful when considering water tanks, is to construct a tank as would be used in places like Uganda, render it with mortar and carry out a study of how much it leaks. In reality it would be impractical to do this for every type of mix, so the experiments used in this investigation are useful to determine which mixes of mortar are likely to be best suited to carrying out the desired task. However, the results provided should not be regarded as a guarantee of the suitability of a mix of mortar for the task it has been set to do.

Chapter 17: Conclusions

Analysis of the results from the three experimental methods has provided information from which conclusions can be made. The first conclusion is that admixtures have a definite impact on the properties of a mortar mix to which they are added, in some cases a dramatic impact. Of the three admixtures studied in this report, the superplasticiser has the largest favourable effect on the shrinkage properties of drying mortar, causing a 35% reduction in shrinkage. The silica fume had the least effect on shrinkage at only a 3.5% reduction when compared to plain mortar, although this is unsurprising because it is used as a strengthening admixture rather than one that reduces shrinkage. Prior to the results from the shrinkage experiment, it was unknown how the Harilal Leak Seal admixture would reduce leakage from a mortar rendered water tank. It can be concluded that it reduces the shrinkage experienced by a sample of mortar, rather than increasing the strength, although whether it affects the strength is unknown as no experiment was done on this variable.

The analysis of the cracking experiment shows correlation between shrinkage and cracking. The superplasticiser experienced the least cracking, which was expected after it was discovered how much it reduced shrinkage. It can also be concluded that increasing the strength of mortar will help distribute shrinkage over a greater number of thinner cracks. The superplasticiser underwent the least shrinkage but its cracks were wide when compared with those on the silica fume sample. Referring back to section 6, it was shown that increasing the width of a crack by a factor of 2 will increase the leakage by a factor of 4, so the type of cracking on the superplasticiser is undesirable when compared to the silica fume.

From the leakage experiment it can be seen that all of the three admixtures tested are favourable when compared to plain mortar. The plain mortar sample experienced most cracking by area, had the widest cracks, and had significantly greater flow rates through the cracks. Consistently throughout the investigation, the plain samples have preformed poorly when compared to the samples where admixtures have been used. Again the superplasticiser and the Harilal leak seal performed best in the leakage experiments. It was proposed in the discussion that any comparison between cracking and leakage would not be well founded due to the unknown surface area of crack being fed by the water supply. For this reason the result of the mathematical model in section 6 cannot be verified, although there is evidence both for and against it. The plain sample had by far the most significant cracking and had the highest flow rates by over a factor of 2 which supports the analysis in section 6, although the comparison between crack widths and leakage rates in the Harilal and silica fume samples go against the theory. This report recommends that an investigation into flow through channels of controlled widths be carried out to decide whether crack width has such a significant effect on flow rate.

The possibilities of mixing different admixtures in a sample of mortar was not looked into in this investigation due to the amount of time each round of experiments took, and the need to re-cast a round as explained previously in the report. From the results it is suggested that a mortar sample that has both silica fume and a superplasticiser added to the mix be investigated. The two factors highlighted in section 7 that affect the leakage through a mortar (strength and shrinkage), can be improved individually with these admixtures. It appears that no one admixture can improve both of these properties but combining the two that most significantly improve each one may combine the benefits of each.

Another possibility for further investigation would be to experiment on the ferrofest layer as described in section 7, and a similar layering technique using a sandwich of two plain coats and a thin layer of pure cement paste in the middle to act as a "filler" to block any cracks that form in the first layer. Many combinations of admixtures are available and many products are on the market that haven't been tested in this investigation due to time constraints. An exhaustive study of these would show which combinations of admixtures would be most suitable.

However, the conclusion of this report using the results recorded is that if using a single admixture, the superplasticiser is most suitable for use in a mortar to render a water tank. The report also recommends that a combination of the superplasticiser and silica fume in a sample of mortar is likely to combine the benefits of each, and further study into this possibility is recommended.

Chapter 18: Literature Review

AUTHOR	YEAR	TITLE	PUBLISHER
A.M.Neville	1981	Properties of Concrete	Pitman
S.B.Watt	1978	Ferrocement water tanks and their construction	Intermediate Technology Publications
T.N.W.Akroyd	1962	Concrete: Properties and Manufacture	Pergamon Press
P.L.Critchell	1968	Joints and cracks in concrete	C R Books
Edited by M.R. Rixom	1977	Concrete admixtures	Construction Press
F. D.Lydon	1982	Concrete mix design	Applied Science Publishers
D.F.Orchard	1979	Concrete technology	Applied Science Publishers
T.H.Thomas, B. McGeever	1997	WP49 Underground Storage of Rainwater for Domestic Use	DTU, University of Warwick
T.H.Thomas	2000	WP55 Very low cost Roofwater Harvesting in East Africa	DTU, University of Warwick
D.Rees	2000	TR-RWH 01 - Partially below ground (PBG) tank for rainwater storage - Instructions for manufacture	DTU, University of Warwick
D.Rees	2000	TR-RWH 03 - Experimental Rammed Earth tank of 6 cubic metres - Instructions for manufacture	DTU, University of Warwick

Chapter 19: Appendix

File 1: Steve Turner's experiment notes.

File 2: Results taken from the cracking experiment.