COUNTERING SHRINKAGE CRACKING IN RENDERS

S. MOEED

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3rd Year Undergraduate Project, 2001-2002,
School of Engineering, University of Warwick

Summary

An investigation was performed into ways of reducing shrinkage cracking in cementitious renders used to line rainwater harvesting tanks. Crack reduction was measured via both leakage rate through the renders and direct measurement of the cracks propagated. Emphasis was placed on crack distribution and how this affected leakage rate. Methods of reinforcing mortar were used, the most successful being wire mesh reinforcement which reduced the leakage rate by a factor of ten. Mesh reinforcement was also the most successful in reducing shrinkage. Other renders tested included fibre reinforcement and an expansive additive to compensate for shrinkage. This investigation was a refinement of previous work carried out by Tom Constantine in 2001 but looking into different methods of waterproofing renders.

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Appendices:

1. Introduction

1.1. Rainwater Harvesting

River flows together with the annual turnover of groundwater account for less than 40% of the rain and snow, which falls on the world's land surfaces[1]. For people in many developing countries rainwater harvesting is a viable and relatively inexpensive option to overcome water shortages. In many countries there is the problem of irregular rainfall throughout the year with heavy precipitation over certain periods but drought at other times. Therefore a system of collection and storage needs to be implemented, such as collection of roofwater, which is channelled through drainage pipes into a tank (see figure 1 below).

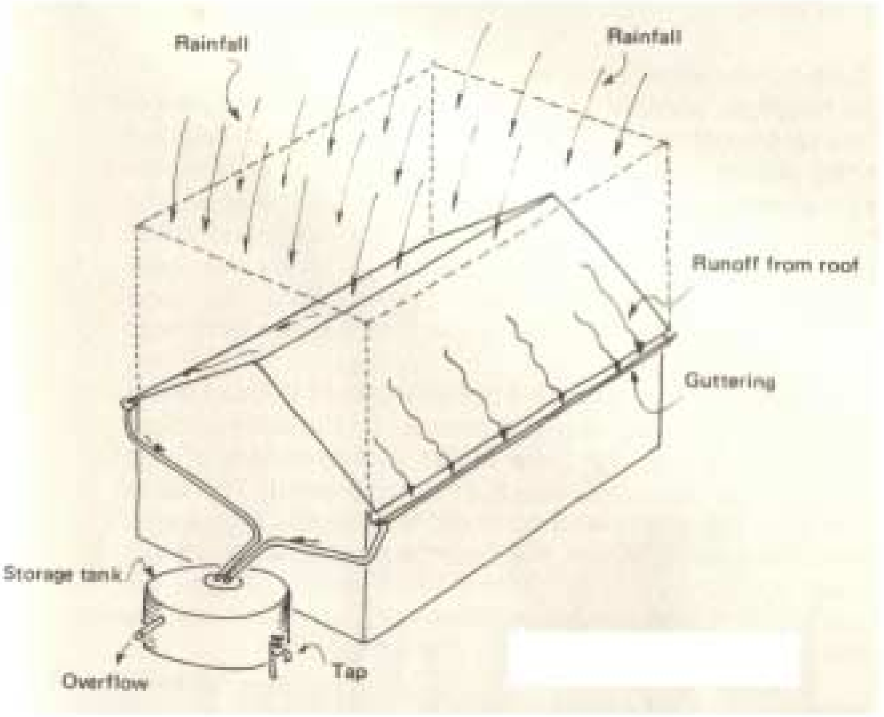

Figure 1: Arrangement of roof catchment tank (from Watt 1978)

This project deals with the render used to line the tanks to ensure they are waterproof. Tanks of up to 15m³ can be made from either bricks, rammed earth, or be dug in sitú. Earth and bricks are permeable and therefore a mortar is applied to the inside of the tank as a render. As this mortar dries it tends to shrink and the lining will therefore crack as the mortar is constrained on the tank walls. This cracking leads to leakage in

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[1] Pacey pg.1

the tank, which is obviously undesirable. The leakage of rainwater harvesting tanks can be reduced if measures are taken to reduce the cracking in renders. It is important that the tanks are cheap to produce and that any materials used are available locally.

1.2. Methods to reduce cracking and leakage

A number of different methods can be used to counteract shrinkage cracking in mortar or just reduce the leakage rate through the mortar:

1. Crack distribution (by the use of a reinforcement such as chicken mesh or fibres). So that a few large cracks are replaced by many small ones.
2. The use of a non-shrinking mortar or a substance, which swells to counter the shrinkage, for example ettringite cement.
3. Filling the cracks once formed or using a waterproofing paint on the surface once the cracks have formed.
4. Applying the mortar in two layers possibly with a cement-water wash in between.
5. The use of super-plasticisers, which reduce the amount of water required for workability and hence the shrinkage during curing.
6. The use of other chemical admixtures such as strength increasing admixtures or waterproofing admixtures.

For the purposes of this study not all of these methods could be tested, as there were a limited number of test rigs and a limited amount of time. Previous projects had looked into the use of admixtures but there had been less research into reinforcing the mortar with mesh or fibres. It was decided to investigate the effects of crack distribution on the leakage rate, this was therefore the main focus of the study. It was also decided to look at applying two layers of mortar and the effectiveness of a swelling agent to counteract shrinkage.

1.3. Previous studies

Tom Constantine conducted research into this topic in the academic year 2000 – 2001. He found there was a problem with obtaining accurate results, particularly with the leakage tests in the second study. This was therefore the initial focus in the project as it is necessary to have a method of testing which is reliable and therefore gives credible results on which a conclusion can be reached.

1.4. Project Objectives

- To measure leakage flow through renders in order to recommend methods of effective waterproofing for water tank construction.
- To improve on the experimental method used in the previous year to yield more credible results.

2. Background Theory

2.1. Tank Construction

Tanks can be made of brick, rammed earth or built in sitú. The Development Technology Unit (DTU) at Warwick University is involved in the research, design and building of roofwater harvesting tanks. Probably the strongest of tanks would be those dug in sitú as the surrounding earth provides a strong tank wall and good base for the render.

2.2. Ferro-cement tanks

Water tanks made from wire-reinforced cement-mortar can be used as an alternative to earth or brick tanks. They are built by hand trowelling mortar onto a mesh of wire reinforcement, which forms the walls and shapes the tank (see figure 3 below). This forms cylindrical tanks with thin walls, which vary in thickness from 3 to 10cm depending on the size of the tank[2].

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[2] Watt pg.11

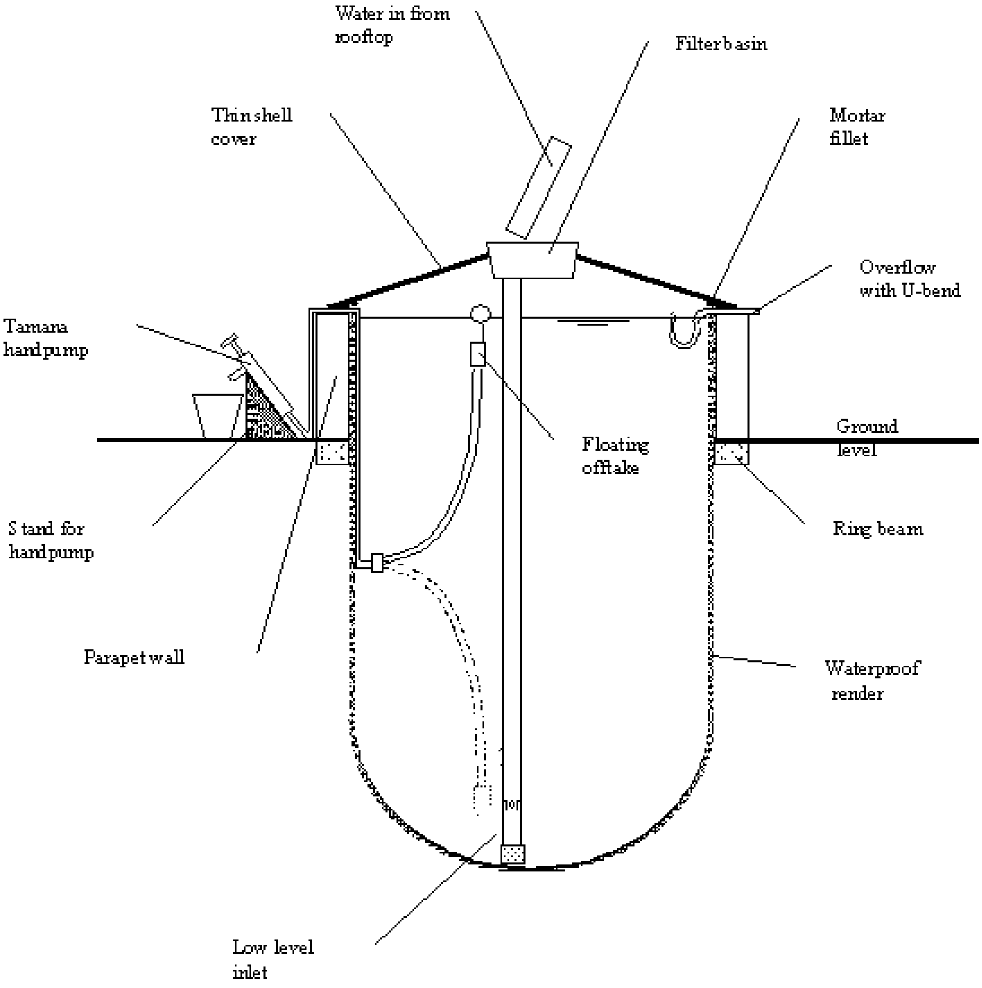


Figure 2: Diagram of partially below ground rainwater harvesting tank (DTU Website)

2.3. Mortar

Mortar is made from mixing building sand cement and water in certain proportions depending on the application. The material used for lining RWH tanks is a cement rich mortar, with a cement to sand ratio of 1:3, for this application it is beneficial to keep the water content down to a minimum as this improves the quality of the mortar once cured. The cement used is Ordinary Portland Cement.

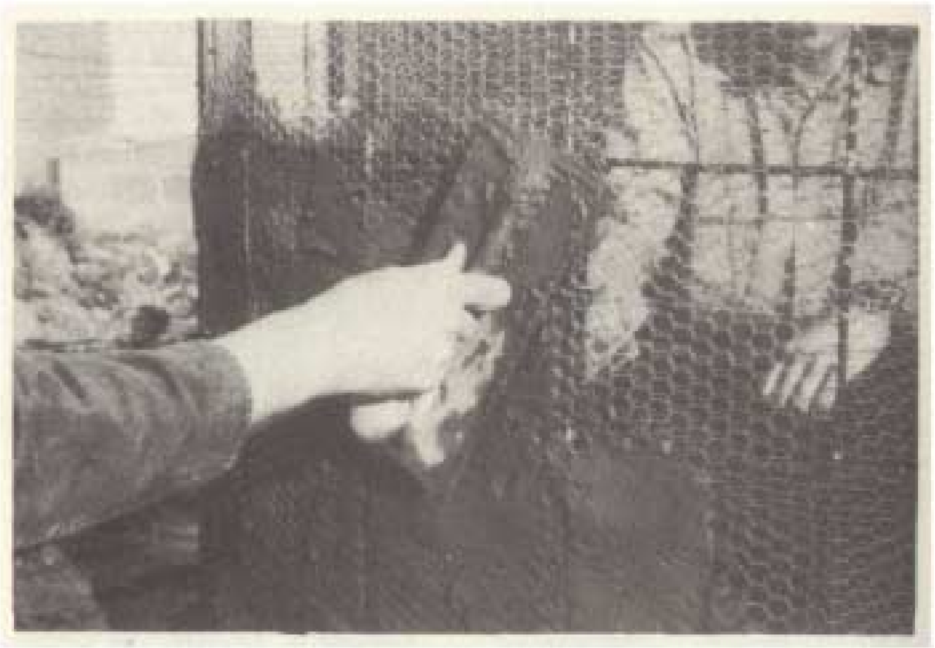


Figure 3: Construction of ferrocement tank wall (from Watt 1978)

2.4. Hydration of cement

The main compounds of Portland cement are Tricalcium silicate, Dicalcium silicate, Tricalcium aluminate and Tetracalcium aluminoferrite. In the presence of water, the silicate and aluminates listed above form products of hydration, which in time produce a firm and hard mass – the hydrated cement paste. Figure 4 below details hydration product development over time for ordinary Portland cement.

When cement is mixed with water, for an initial period the consistency of the cement-water paste remains relatively constant. Initial set occurs between two and four hours after mixing at normal temperatures, at this point the mix begins to harden at a much faster rate. Strength gain does not start until after the final set which occurs some hours later. The rate of strength gain is rapid for the next one or two days, and continues, but at a steadily decreasing rate, for at least a few a months. In order to increase the strength of cement or mortar, there needs to be ample water supplied during hardening in order to maintain the ongoing hydration reactions. For this reason mortar is cured in a humid environment. Curing is discussed in greater detail in section 3.3.1.

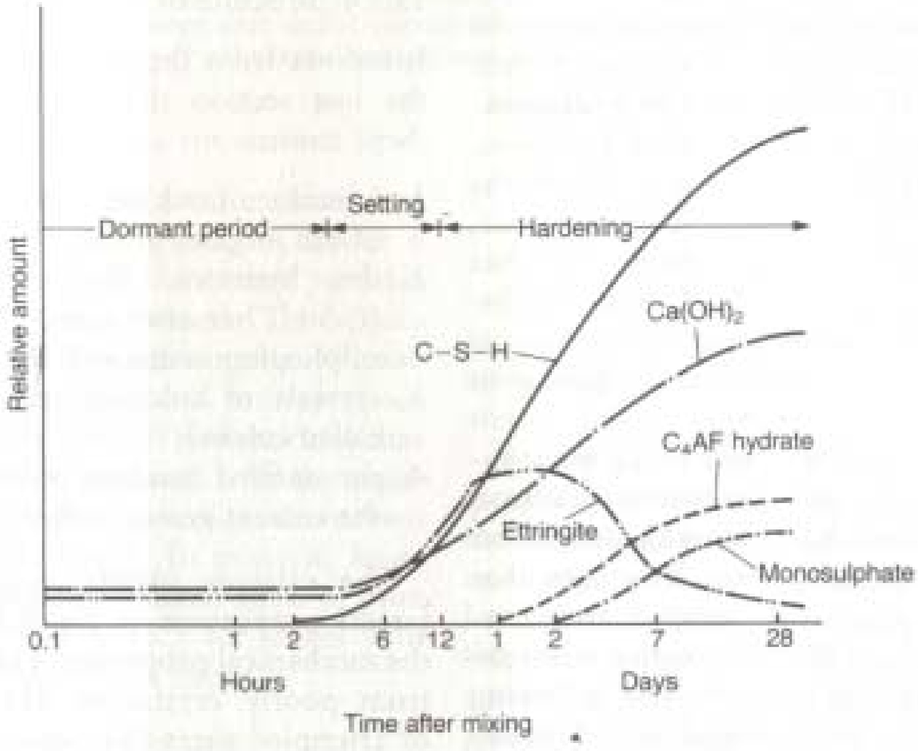


Figure 4: Typical Hydration product development in Portland cement paste (Illston 1994)

3. Literature Review

3.1. Previous studies

Constantine T, 2001

In 2001 Tom Constantine, a Warwick student, conducted an investigation into the shrinkage and cracking of mortar. Constantine experimented with various admixtures for concrete :–

- Silica fume, which reduces the porosity of concrete and therefore increases strength, which can lead to a reduction in cracking.
- Superplasticiser, which increases the workability of concrete therefore requiring less water, which also leads to less porosity as well as a reduction in shrinkage cracking.
- Harilal leak seal, an Indian admixture for waterproofing concrete.

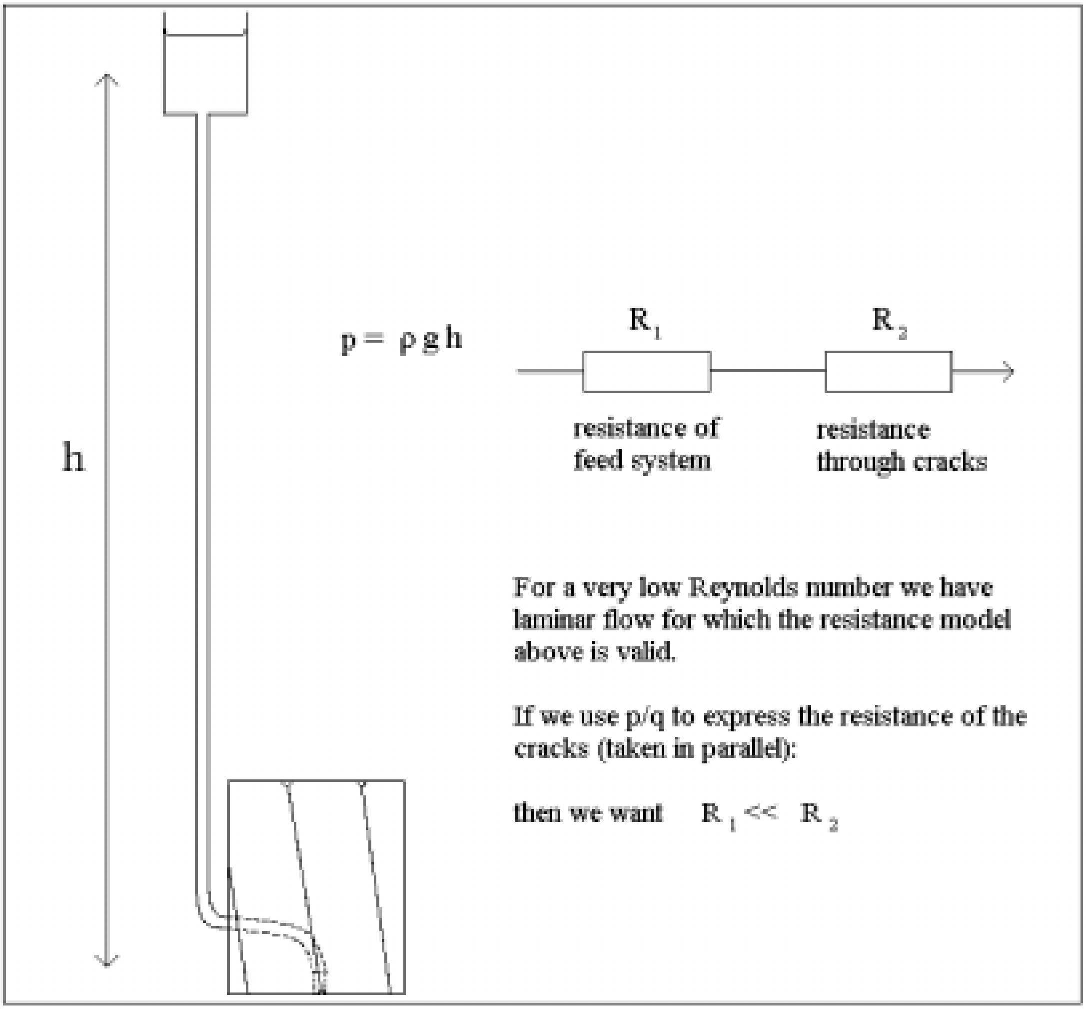
He also tested a sample of plain mortar. In the leakage tests, over a period of 55 minutes the total water lost was as follows:

Sample	Water lost in 55 minutes (ml)
Plain mortar	77.6
Mortar containing Silica Fume	39.5
Mortar containing Harilal Leak Seal	40.7
Mortar containing Superplasticiser	32.5

Table 1: Summary of Constantine's leakage test results with respect to total water loss

He found the mix with Superplasticiser to give the lowest leakage rates.

However, as can be seen from the results above, the rate of water loss is very small. Tom experienced problems with his test rigs and due to this low leakage rate it was believed that the resistance in the rig was too great (see figure 5 below), and therefore there was no guarantee that all the cracks were being fed.



For a very low Reynolds number we have laminar flow for which the resistance model above is valid.

If we use p/q to express the resistance of the cracks (taken in parallel):

then we want $R_1 << R_2$

3.2. Shrinkage and cracking of concrete

Neville 1995:

When water moves out of a porous body, which is not fully rigid – contraction takes place. During hydration, while the cement paste is plastic, it undergoes a volumetric contraction (of the order of 1% of the absolute volume of dry cement). However the extent of hydration prior to setting is small and as the hydrating cement becomes rigid, contraction induced by loss of water is restrained.

Water can also be lost by evaporation from the surface of the concrete while it is still plastic. Similar loss can occur by suction by the underlying dry concrete or soil. This is called Plastic Shrinkage as it occurs while the concrete is still in a plastic state.

Magnitude of plastic shrinkage is affected by amount of water lost from the surface, which is influenced by temperature, ambient relative humidity and wind velocity. The rate of water lost does not necessarily predict shrinkage, a lot depends on the rigidity of the mix.

Water can be bought to the surface of concrete by bleeding. Water in the mix tends to rise to the surface of freshly placed concrete, this is caused by the inability of the solid constituents of the mix to hold all of the mixing water (water having the lowest specific gravity). If the amount of water lost per unit area by evaporation exceeds the amount bought to surface by bleeding, surface cracking can occur, this is called plastic shrinkage cracking.

3.2.1. Plastic shrinkage

Plastic shrinkage is greater the greater the cement content of the mix. Retardation of setting allows more bleeding and leads to increased plastic shrinkage, on the other hand greater bleeding capacity prevents too rapid a drying out of the surface of the concrete reducing plastic shrinkage cracking. In practice it is cracking that matters, however, in this case, due to the mortar being constrained, cracking occurs due to shrinkage.

3.2.2. Thermal cracking

This occurs only in large volumes of unreinforced concrete. The heat of hydration (hydration is an exothermic reaction) causes expansion. Cooling from the temperature peak of this reaction results in cracking, due to a temperature gradient and internal stresses. This form of cracking is not applicable to the mortar lining situation as the layer of mortar is too thin for a substantial temperature gradient to form.

3.2.3. Carbonation shrinkage

This occurs due to the reaction of Carbon Dioxide present in the atmosphere with the hydrated cement. This is not a major concern in this application as drying shrinkage leads to the vast majority of shrinkage and cracking in the constrained mortar.

3.2.4. Concreting in hot weather

The deformation of mortar also depends on the surrounding environment. In practice the tanks will be built in hot conditions and therefore the effect of heat needs to be taken into consideration. Plastic shrinkage can be prevented by keeping down the rate of evaporation of water from the surface of the concrete, 1kg/m^2 per hour should not be exceeded. Evaporation is increased when the temperature of the concrete is much higher than ambient temperature, then plastic shrinkage can occur even if the relative humidity of the air is high. It is therefore best to protect concrete from the sun and wind, place and finish fast and start curing quickly. Avoid placing concrete on a dry subgrade. Another type of cracking is caused by differential settlement of fresh concrete due to obstruction to settlement e.g. large particles of aggregate or reinforcing bars, this is plastic settlement cracking.

3.2.5. Drying shrinkage

As the name implies, this shrinkage occurs as water is lost from the cement paste.

Illston 1994 :

Hydrated cement paste has a considerable affinity for water and therefore its overall dimensions are water sensitive i.e. loss of water results in shrinkage. The water content also has an effect on porosity, to illustrate this it is useful to look at the way in which water behaves in the paste (see fig.6 below).

- *Water vapour* – largest voids may only be partially filled with water, and remaining space will contain water vapour.
- *Capillary water* – located at the capillary and larger gel pores, it is the bulk of water not influenced by the attractive forces of solid surfaces. Water in voids larger than 50nm is considered free in that it’s removal does not lead to any overall volume change. However, water in pores smaller than about 50nm is subject to capillary tension forces, and its removal may lead to some shrinkage.

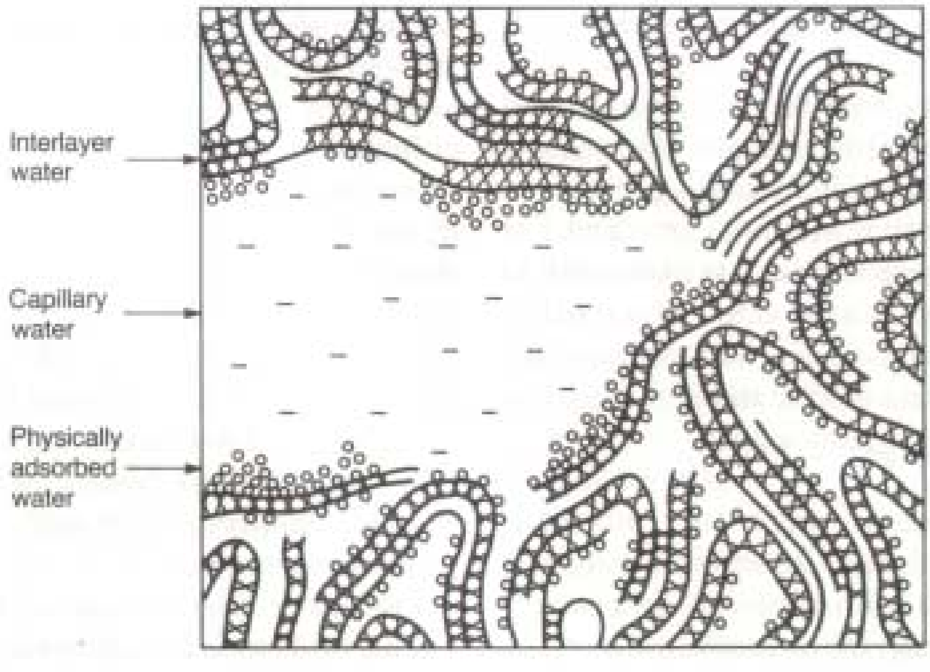


Figure 6: schematic of types of water within hydrated cement paste (from Illston 1994)

- *Adsorbed water* – Close to solid surfaces and under the influence of surface attractive forces. A large proportion of this water can be lost on drying to 30% relative humidity and this loss is the main contributing factor to drying shrinkage.
- *Interlayer water* – This is the water in gel pores narrower than about 2.6nm, this is under the influence of two surfaces and therefore more strongly held. It can only be removed by strong drying – i.e. elevated temperatures and/or relative humidities less than 10%. Its loss results in considerable shrinkage as strong forces pull the solid surfaces closer together.
- *Chemically combined water* – Water that is combined with the fresh cement in hydration reactions. This is not lost on drying.

Figure 7 below illustrates the relationship between water/cement ratio and shrinkage.

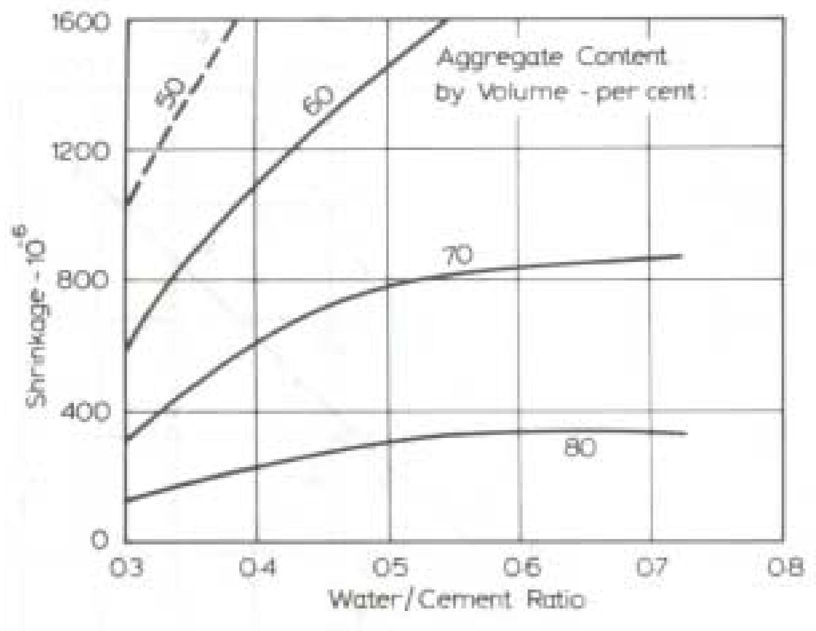


Figure 7: Influence of water/cement ratio and aggregate content on shrinkage (from Neville 1995)

The shrinkage of cement or mortar is larger the higher the water/cement ratio as this determines the amount of evaporable water in the cement paste and the rate at which it can move to the surface. The amount of shrinkage is not equal to the volume of water removed as it is also influenced by other factors such as gel particle size. The affect of aggregate leads to less shrinkage in concrete in comparison with mortar, which does not contain aggregate. Also the type of water removed has an affect as discussed earlier, emptying of the capillaries results in water loss with no shrinkage, but once capillary water is lost, the removal of adsorbed water takes place and causes shrinkage. When no moisture movement to or from the cement paste is permitted, shrinkage occurs due to withdrawal of water from the capillary pores by the hydration of the hitherto unhydrated cement called self desiccation. This shrinkage is restrained by the rigid skeleton of the already hydrated cement paste and also by the aggregate particles.

From a graph of early shrinkage (Figure 1.1., Appendix 1), it can be seen that after 24 hours mortar has shrunk by 0.0045 of its original volume i.e. 0.45%. At this point the graph becomes level, it can therefore be concluded that the majority of shrinkage occurs within the first 24 hours and so the figure of 0.0045 has been taken as the value for shrinkage strain for the plain mortar used in testing.

3.3. Preventing shrinkage and cracking

For a sample of constrained mortar, i.e. in this application mortar is held by the tank walls, improving the mortar strength can reduce cracking. Increasing tensile strength will increase the shrinkage strain that can be tolerated before cracking occurs:

as $\varepsilon_{yield} = \sigma_{yield} / E$

3.3.1. Factors affecting mortar strength

3.3.1.1. Water Content

Illston 1994:

The strength of cement paste is governed by its porosity, which depends on the water cement ratio and degree of hydration. The higher the water content the greater the porosity and volume of voids, which leads to a weak mortar. Figure 8 below shows the effect of age and water content on the strength of the mortar.

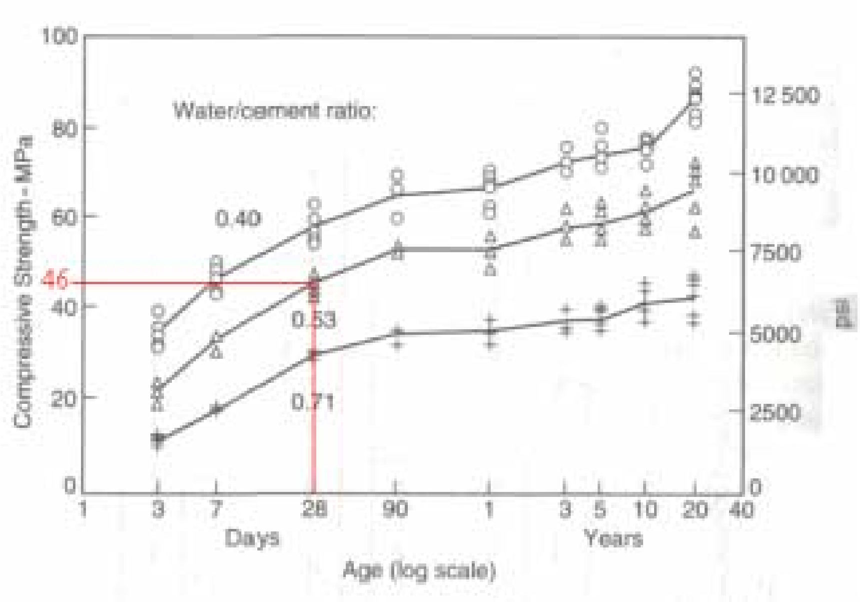


Figure 8: Effect of age and water/cement ratio on concrete strength (Neville 1995)

However, too low a water content will reduce the workability of the mortar and therefore a compromise between strength and workability is required.

3.3.1.2. Effect of age

The degree of hydration increases with age. This leads to an effect on the strength as can be seen in figure 8 above. Hydration reactions are never complete, and in the presence of moisture, concrete will continue to gain strength for many years. The rate of increase, however, will be very small in such situations.

The water/cement ratio used for the mix was 0.5, and each sample was tested once it was 28 days old. The graph in figure 8 indicates a figure of around 46Mpa for the compressive strength of the samples, (in SI units 46×10^{-6} N/m^2). According to British Code of Practice BS 8007:1987, the relationship between the compressive and tensile strength of concrete can be defined by the formula:

$f_t = 0.12\,(f_c)^{0.7}$ (eq. 1)

Where f_t is the tensile strength and f_c is the compressive strength[3].

However, this usually gives an underestimate of tensile strength, presumably to ensure a safety margin in concrete and mortar used for building. A graph showing the relationship between compressive and tensile strength can be seen in figure 1.2. appendix 1, from this graph the best fit overall is given by the expression:

$f_t = 0.3(f_c)^{2/3}$ (eq. 2)[4]

Using this formula with a value of 46 Mpa for compressive strength taken from the graph in figure 8 the tensile strength of the plain mortar samples can be calculated to be 3.85 Mpa (3.85×10^{-6} N/m^2). Values for tensile strength will be used in section 5 in order to calculate an expected relationship between crack width and number of cracks for the purposes of comparing the theoretical predictions with actual results.

3.3.1.3. Effect of curing

Neville 1995 and Illston 1994:

The object of curing is to keep concrete saturated until the originally filled water space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement. Hydration is greatly reduced when the relative humidity in the capillary pores drops below 80%[5]. It therefore follows that for hydration to continue, the relative humidity inside the concrete has to be maintained at a minimum of 80%. Once the concrete or mortar surface is no longer liable to damage, curing can take place. This can be done by covering the surface with wet material, submerging it in

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[3] Neville pg.310
[4] Neville pg.310

water completely or leaving it in a sealed environment to reduce evaporation and maintain high humidity in the air surrounding the specimen. Some form of curing i.e. preventing water loss from the concrete surface is not only important to maintain hydration and therefore strength gain, water loss also leads to plastic shrinkage and increased permeability (due to increased porosity) – which is a problem when the material is required for waterproofing. Figure 9 below illustrates the influence of curing on concrete strength.

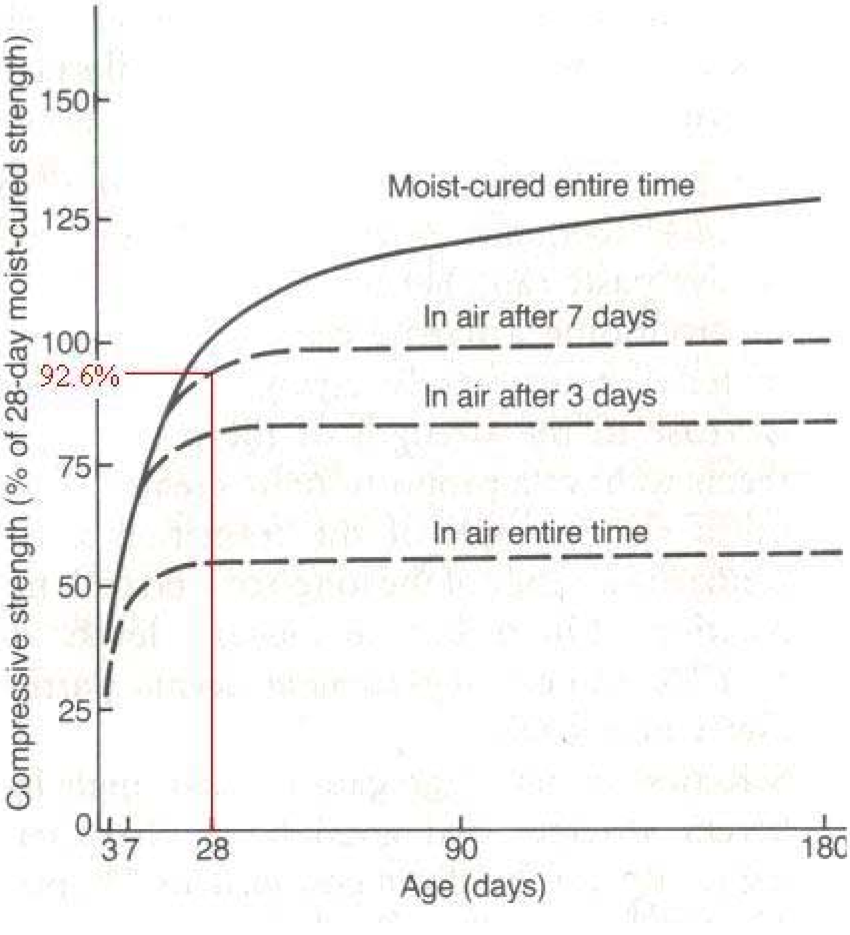

Figure 9: Influence of curing conditions on concrete strength (From Illston 1994)

The data from this graph can be used to make the figures for tensile and compressive strength attained in section 3.3.1.2. more accurate. The graph in figure 8 shows data for samples, which have been moist, cured the entire time. Due to time restrictions the samples used were only cured for seven days and then left to dry in air for another 21

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[5] Neville pg.318

days before testing was carried out. From the graph above it can be seen that the actual compressive strength is therefore 92.6% of the previous figure, giving a new value of $42.6\text{x}10^{-6}$ N/m^2. Using equation 2 defined in section 3.3.1.2. the tensile strength becomes $3.66\text{x}10^{-6}$ N/m^2.

3.3.2. Admixtures

Rixom 1978:

These are chemicals that are added to the concrete immediately before or during mixing. They significantly alter its fresh early age or hardened state, to advantage or gain in properties. There are different types of admixtures:

- Water reducing
- Accelerating
- Air entraining
- Retarding
- Superplasticising
- Water-proofing

For the purposes of this report only those that may help reduce shrinkage cracking or leakage are discussed.

- Waterproofing – concrete absorbs water by capillary action. These admixtures aim to prevent penetration of water into concrete, for example vegetable or animal fats.
- Water reducing – in order to reduce the water: cement ratio whilst retaining workability. This will enable the use of a low amount of water thus reducing drying shrinkage and increasing strength. The most effective of water reducing agents are superplasticisers:
- Superplasticisers – Long molecules wrap themselves around cement particles giving them a negative charge so they repel each other, resulting in a dispersion of cement particles improving workability. These can also be used to produce concrete of normal workability but high strength due to reduction in water/cement

ratio. Superplasticisers can reduce water content for a given workability by 25 to 35%.

If the initial water/cement ratio is 0.5, a reduction in water content by 30% would mean a new ratio of 0.35. This corresponds to a compressive strength of 61.3 MPa, (see graph fig.1.3 appendix 1), if 92.6% of this value is used (due to each sample being cured for 7 days) the compressive strength is 56.8 MPa. Using equation 2, as defined in section 3.3.1.2. the tensile strength can be calculated to be 4.43 MPa ($4.43\text{x}10^{-6}$ N/m^3).

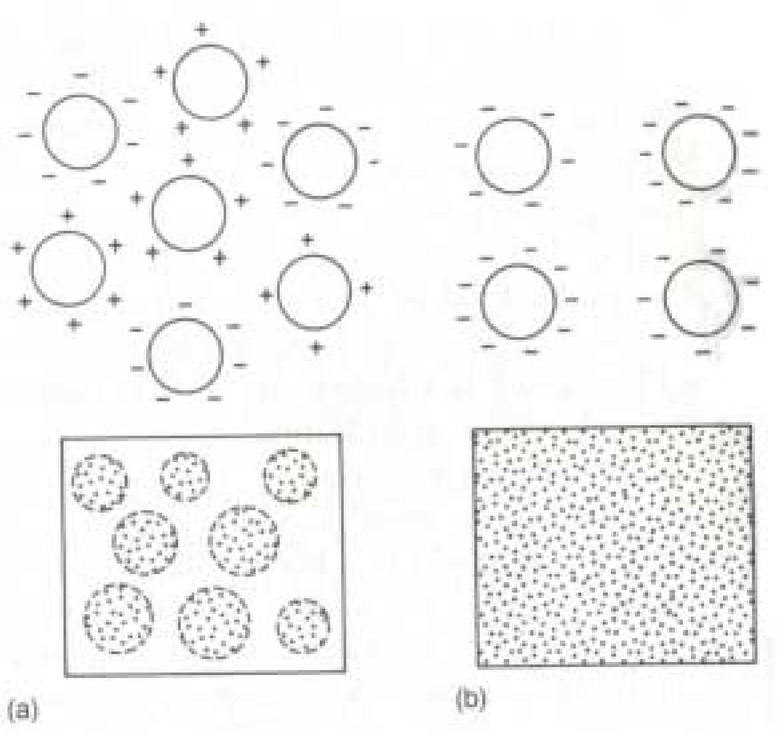


Figure 10: Dispersing action of plasticising admixtures (From Illston 1994)

(a) flocculated particles
(b) dispersed particles after admixture addition

There are also strength increasing admixtures which can have the effect of reducing cracks by producing a mortar with greater tensile strength so there is greater opposition to crack propagation.

3.3.3. Expansive cements

Odler 2000:

Expansive cements are inorganic binders that generate expansive (compressive) stresses in the hardened paste in the course of hydration, counteracting the tensile stresses generated by chemical shrinkage and drying shrinkage. Thus the generation of these expansive stresses may prevent the formation of cracks in concrete in the course of drying. Cements that meet these requirements are called *shrinkage-compensated cements*. The setting and hardening properties of concrete mixes made with shrinkage-compensated cements differ little from those made with ordinary cements, but the impermeability of the hardened concrete increases significantly

3.3.3.1. Expansive cements based on ettringite formation

Odler 2000 and Illston 1995

During hydration reactions, prior to setting, ettringite is regularly formed in ordinary Portland cement. It is the result of the reaction of gypsum with C_3A to form calcium sulphoaluminate (ettringite):

$C_3A + 3CSH_2 + 26H \rightarrow C_3A \,.\, 3CS \,.\, H_{32}$.

However, this formation of ettringite does not cause expansion as it will crystallise out, this can be seen in figure 4 section 2.4., which details the products of hydration over time. The formation of ettringite will lead to shrinkage compensation if the ettringite is formed after setting, at a stage when the paste has already attained certain rigidity. There are shrinkage-compensated cements available, which will reduce shrinkage in concrete through ettringite formation.

3.3.4. Reinforcing mortar

The reinforcement of mortar aids in increasing mortar strength, as the material used for reinforcement has a greater tensile strength than the mortar itself. Here two types of reinforcement are discussed:

- Fibre reinforcement
- Wire mesh reinforcement

3.3.4.1. Fibre reinforcement

Bentur 1990:

Fibre reinforcement is used in cementitious materials in:

a) Thin sheet materials, in which conventional reinforcing bars cannot be used. In these applications fibres act to increase strength and toughness.

b) Components, which must withstand locally high loads.

c) Components in which fibres are added to control cracking induced by humidity and temperature variations.

In application (b) and (c), the main role of the fibres is to control the cracking of the composite. The effect of fibres in fibre reinforced concrete is illustrated in the schematic (figure 11) below. The fibres improve the 'ductility' of the material, i.e. its energy absorption capacity.

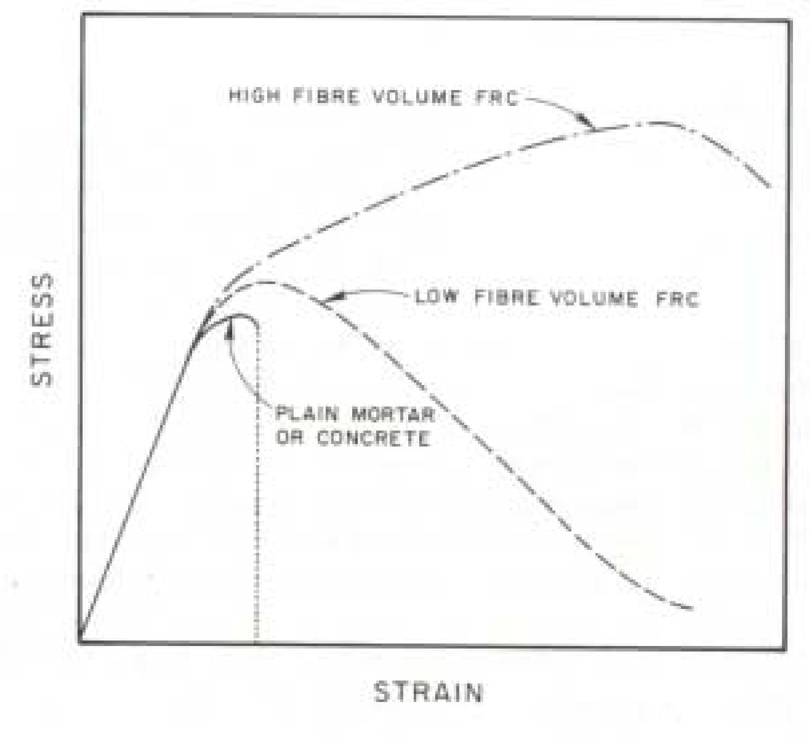


Figure 11: Typical stress-strain curves for low fibre volume and high fibre volume FRC
(From Bentur 1990)

3.3.4.2. Mesh reinforcement

Watt 1978:

The weakness of mortar in tension occurs due to planes of weakness between the edges of discrete lumps that make up the mortar. These are exaggerated by shrinkage during curing and the imperfect bond between each layer of mortar that is trowelled on. In compression these planes of weakness are held together by the load, but under tensile loading they will open up beyond their elastic limit, and cause the mortar to fail. In reinforced mortar, the mortar is assumed to contribute greatly to the tensile strength of the composite layer. This is due to the wire mesh, distributed relatively densely through the mortar, will allow the load to be taken throughout the complete layer and will prevent the early concentration of critical stresses in planes of weakness. Any cracks that do form under moderate loading will not be wide enough to allow water to reach the reinforcing wires and start corrosion.

According to Watt (1978), the maximum tensile stress in a thin walled cylindrical tank, constructed using wire mesh reinforced mortar, is 1.26 Mpa. This figure is given for a tank of wall thickness 0.03m, it can therefore only be used as an approximation as the tank lining of interest should have a thickness of 0.01m.

Reinforcement has the benefit of not only increasing the strength of the mortar but can also enable better crack distribution and the mathematical analysis in section 4 shows that this can lead to a reduced leakage rate.

4. Crack Distribution theory

Flow through a crack can be modelled as laminar flow driven by a pressure gradient between two infinitely wide plates (Plane Poiseuille Flow). This is assuming that the crack length is much greater than the crack width. Figure 12 below shows flow between plates a distance 2R apart, a fluid element of width 2y has been highlighted for analysis.

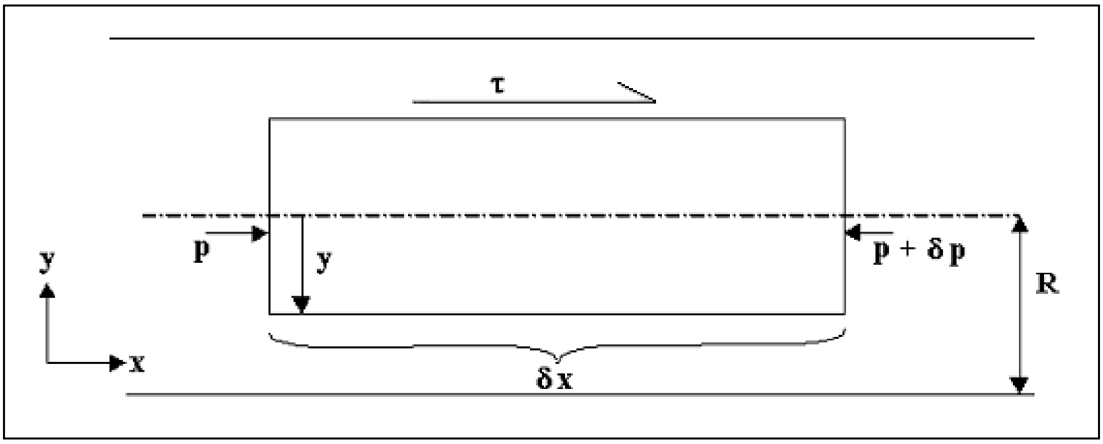


Figure 12: model for crack of width 2R, mortar thickness w (where w is parallel to x axis) and infinite length

y : distance from axis
p : pressure
R : ½ crack width

$$\tau = -\mu \frac{du}{dy}$$

τ : viscous shear stress for a Newtonian fluid

u : velocity parallel to axis shown

μ : viscosity of fluid

Force balance for a unit length into the paper:

$$p2y = -2\tau\delta x + (p + \delta p)2y$$
$$2\tau\delta x = (p + \delta p)2y - p2y$$
$$\tau = \left(\frac{\delta p}{\delta x}\right)y$$

where:

$$\frac{dp}{dx} = \frac{\Delta p}{w}$$

where Δp is pressure drop across a crack through mortar thickness of w

$$\tau = -\mu \frac{du}{dy} = -\frac{\Delta p}{w} \cdot y$$
$$\frac{du}{dy} = -\frac{\tau}{\mu} = -\frac{\Delta p}{w} \cdot y$$

Integrate to get velocity profile:

$$\int du = -\int \frac{1}{u} \cdot \frac{\Delta p}{w} \cdot ydy$$

$$u + c = -\frac{\Delta p}{2\mu w} y^2$$

$$at$$

$$u = 0, y = \pm R$$

$$\therefore c = -\frac{\Delta p}{2\mu w} y^2$$

$$u = \frac{\Delta p}{2\mu w}(R^2 - y^2)$$

Volumetric flow rate:

By symmetry:

$$Q = 2\int_0^R u(y)dy$$

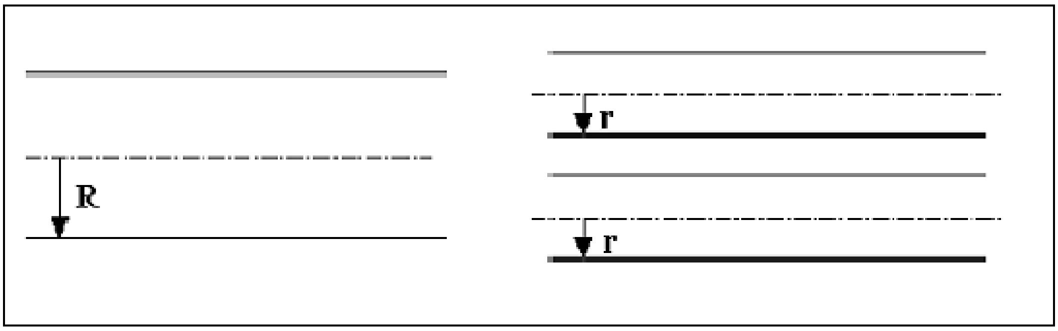
$$Q = \frac{\Delta p}{\mu w}\int_0^R (R^2 - y^2)dy$$

$$Q = \frac{\Delta p}{\mu w}\left[R^2 y - \frac{y^3}{3}\right]_0^R$$

$$Q = \frac{\Delta p}{\mu w}\left[R^3 - \frac{R^3}{3}\right]$$

$$Q = \frac{2\Delta p R^3}{3\mu w} \qquad \text{(eq. 3)}$$

Therefore Q α R^3



If the number of cracks is doubled but surface area remains the same (R=r/2), and if $Q_1 = KR^3$ is the flow through a single crack, then for the two half-sized cracks taken together the flow will be:

$$Q_2 = 2 \times K\left(\frac{R}{2}\right)^3 \qquad Q_2 = K\,\frac{R^3}{4}$$

It can therefore be concluded that distributing cracks in order to achieve twice as many cracks for the same surface are will quarter the flow through the cracks.

This analysis will only apply if the flow through the crack is laminar. The crack has the smallest surface area in comparison with the rest of the rig through which water will flow, therefore flow is least likely to be laminar in the crack.

For an estimated flow of 0.1m/s, and a crack width of 0.001m (a crack width of 1mm is likely to be the largest crack size possible), Reynolds number can be calculated:

$$\mathrm{Re} = \frac{U2R}{\mu}$$

where U: mean velocity = 0.1 2R: Crack width = 0.001 μ : viscosity = 10^{-3}

therefore Re = 0.01

A Reynolds number of less than 1 indicates that the flow is laminar. Therefore the Plane Poiseuille Flow analysis holds.

5. Reducing cracking in constrained mortar

In this section the methods that were tested are discussed in more detail.

5.1 Plain Mortar

Initially four samples of plain mortar were tested. All samples had a sand/mortar ratio of 3 and a water/cement ratio of 0.5, they were cured in a humid environment for seven days and left for cracks to form for a further twenty-one days. Therefore each sample tested was twenty-eight days old. The expected tensile stress for these samples was calculated to be $3.66\text{x}10^{-6}\text{N/m}^2$.

An expression for calculating crack width can be derived using stress, strain and Youngs Modulus for mortar in tension:

For mortar in tension:

$\sigma = \sigma_{UTS}$ where σ_{uts} is the ultimate tensile stress.

Youngs Modulus = stress/strain

$$\therefore \sigma = -E\varepsilon$$

$$\therefore \varepsilon = \frac{\sigma_{UTS}}{E}$$

Crack Width = circumference (-ε) / number of cracks, where –ε is the shrinkage strain less strain accommodated by tension. The shrinkage strain is 0.0045 (shrinkage of plain mortar – see appendix 1). Strain accommodated by tension is σ_{uts}/E.

Therefore:

$$2R = \frac{\pi d}{n} \times \left[0.0045 - \frac{\sigma_{UTS}}{E} \right] \qquad \text{(eq. 4)}$$

Substituting values for plain mortar:

Diameter of rig = 0.165m

$E = 28\text{x}10^{-3}\text{N/m}^2$ (Illston 1994)

$\sigma_{uts} = 3.66\text{x}10^{-6}\text{N/m}^2$

$R\ n = 1.13\text{x}10^{-3}$

Where *R* is half crack width and *n* is number of cracks. For example if we could expect ten cracks, then the average crack width would be: *0.00023m*, for plain mortar.

Referring to equation 3 in section 5:

$$Q = \frac{2\Delta p R^3}{3\mu w}$$

Substituting values:

In this case *2R = 0.00023*

R = 0.00012 m

Δp = ρgh

(in testing a head of 2m is required)

$\rho = 1000\ \text{kgm}^{-3+}$

$g = 9.81\ \text{ms}^{-2}$

h = 2m

therefore Δp = 19620 Pa

$\mu = 10^{-3}$

w (mortar thickness) = 0.01m

Therefore the flow rate through one crack of width 0.00023m is:

$Q = 0.0023\ \text{m}^3\text{s}^{-1}$

This is a leakage rate of 2.3 litres/s, in one day a crack of this size will leak 198720 litres, i.e. almost 200,000 litres leakage per day. This is a phenomenal amount, and it must be kept in mind that any measured leakage rate must eventually be projected onto a full size tank with a capacity of 10m^3 (1000 litres): diameter 2.5m, height 2m. *[Note: at such high flow rates the analytic neglect of the pressure drop (= velocity head) to get the flow into the crack becomes invalid.]*

5.2. Rockfast

Brown 2001:

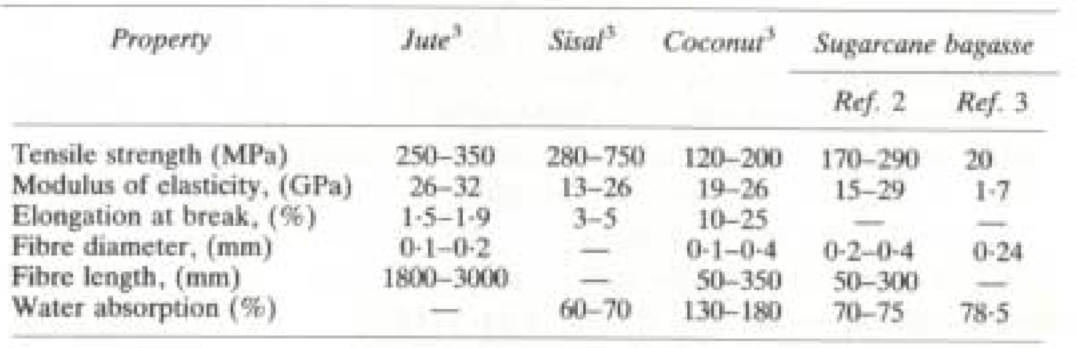
Rockfast cements are shrinkage-compensated cements based on the incorporation of calcium sulphoaluminate into a Portland cement system to give a composite cement which exhibits rapid setting, high early strength and dependent on proportions either shrinkage compensation or positive expansion. According to the literature by Blue Circle Cements, a 12% Rockfast replacement of Portland cement will lead to an expansion of 0.6% and a compressive strength of 45.2 N/mm^2 in 28 days. As the shrinkage of mortar is known to be 0.45%, an expansion of this much is required and therefore 9% replacement is required. According to this theory, therefore a 9% Rockfast replacement of Portland cement should lead to no cracking in the mortar.

5.3. Mesh reinforcement

The method of mesh reinforcement is currently being used in DTU rainwater harvesting tanks. For the purposes of testing a thin layer of mortar was plastered onto the rig. The mesh was placed over the first layer and a second thin layer was applied in order to incorporate the mesh into the mortar. In practice the mesh is held by wooden blocks a certain distance away from the tank wall and the mortar pushed through, but this was not seen as convenient or possible for the small scale on which it was being applied.

5.4. Fibre reinforcement

In tank construction fibres commonly used in fibre reinforced concrete (FRC) manufacture such as steel and glass would need to be purchased from a manufacturer, it was therefore decided to use vegetable fibres as these would be cheap, available and possible to process on site.



Property	*Jute*[3]	*Sisal*[3]	*Coconut*[3]	*Sugarcane bagasse*	
				Ref. 2	*Ref.* 3
Tensile strength (MPa)	250–350	280–750	120–200	170–290	20
Modulus of elasticity, (GPa)	26–32	13–26	19–26	15–29	1·7
Elongation at break, (%)	1·5–1·9	3–5	10–25	—	—
Fibre diameter, (mm)	0·1–0·2	—	0·1–0·4	0·2–0·4	0·24
Fibre length, (mm)	1800–3000	—	50–350	50–300	—
Water absorption (%)	—	60–70	130–180	70–75	78·5

Table 2: Properties of natural fibres (from Bentur 1990)

Sisal fibres were used as these were readily available, the fibre length was 5-10 mm and its diameter less than 0.2mm. The stress – strain curves of fibres show an ultimate strain in the range of 1 – 5%, which is much greater than that of the matrix (i.e. mortar). Therefore the mixing of 0.5% fibre (by weight to the mix) should have a positive effect on the strength of the mortar and reduce cracking, or distribute cracks.

In mixing technology, the increase in fibre content and length is associated with reduced workability. A fibre length of around 0.01m was used.

5.5. Double layer with nil coat in-between

Plain mortar mixed in the same proportions as before was used for this render. A thin layer of plain mortar was applied. This was cured for seven days and then left for a further week to dry and crack, then a cement-water wash (nil coat) was applied as the next layer. This layer was allowed to dry and crack for two days before the final layer of plain mortar was applied, this was cured for a further seven days and allowed to dry and for cracks to form for 21 days, as with the other renders. The expectation is that the first layer will crack, these cracks are filled by waterproof nil, then the second layer is applied and also shrinks and cracks, but hopefully in different places so the cracks do not overlap.

6. Leakage Testing

6.1. Experimental method

6.1.1. Previous problems

The experimental method used last year was not devised to simulate a water tank, but to create a condition in which the mortar would be constrained to induce cracking. The mortar was therefore set around a mild steel cylindrical pipe (length 140mm, diameter 165mm, wall thickness 5mm), this would ensure maximum constraint and cracking, and therefore give measurable flow rates. The test rig was required to be such that water could flow behind the mortar, i.e. between the outside of the pipe wall and the mortar. This was the area, which had given the most trouble in the previous year. A helical groove was machined into the outside of the pipe with a pitch of 50mm, and a depth of 3mm (this depth was not constant as the cross-section of the pipe was not a perfect circle). The groove was intended to be the channel through which the water would flow, therefore a way of keeping the channel clear was required so that when the mortar was applied it did not block the groove. Two different methods where tried - laying string in the groove and laying wire in the groove. Both were considered unsatisfactory, not allowing the water to flow freely through the channel, and therefore not ensuring all the cracks were fed.

6.1.2. Finding a solution

In order to find the best way of keeping the channel open it was decided to conduct a short test using three different methods.

- Method 1: using a thin length of string in the channel to act like a wick for the water through the channel:

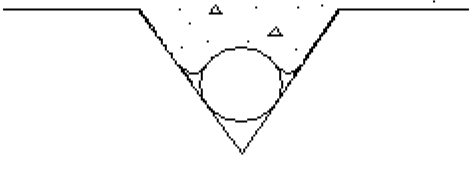


Figure 13: diagram showing string in v-shaped groove, with a layer of mortar on top.

- Method 2: Using a thick length of string to keep mortar from blocking the channel and allow water to flow through it:

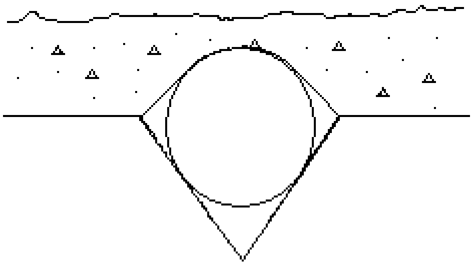


Figure 14: same as figure 13 but with bigger cross-sectional area of string so it acts as a barrier to the mortar entering the groove rather than a wick.

- Method 3: Using a crimped wire on order to keep the channel open and allow water to reach the mortar:

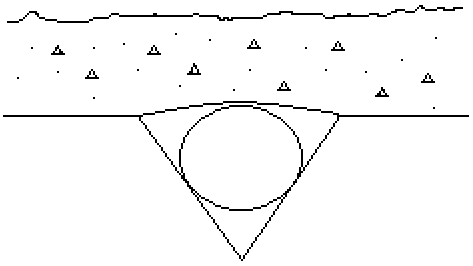


Figure 15: A wire is used instead of the string, the wire cross-sectional area is chosen so that it sits roughly flush with the pipe outside wall.

In order to test these methods each was applied to a rig with a piece of material wrapped tightly round the whole rig to keep the string and wire in place in the channel. It was hoped that the most effective method of keeping the channel open and allowing the water to flow through to the mortar would become apparent by measuring the leakage rate through the material. However, the leakage rate was faster than could be measured and flowed straight through the wrapping material bypassing the channel.

By doing this test it became apparent that a layer of material on the rig in between the mortar and the pipe wall would be very effective in keeping the channel open and would not have the drawbacks of stopping the water reaching the whole channel or slowing flow down significantly as the string did.

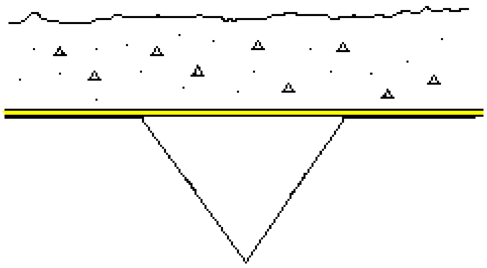


Figure 16: the channel is kept open by a piece of material between the mortar and the pipe.

As the material had to be wrapped tightly around the pipe, calico was chosen, being pure un-shrunk cotton it could therefore be shrunk onto the pipe. The calico was sewn to fit the circumference of the pipe, then shrunk onto the pipe in water.

6.2. Modifying the test rig

There were four existing rigs, which would need to be modified to ensure that the water flowed through the entire channel therefore feeding all the cracks. A manifold to better connect the channel was included, this had to be sawn by hand and filed to a v-shaped groove. A representation of the rig seen from front on (outside pipe wall) is shown in figure five below, originally the rig had only a helical groove (channel) and a hole for feeding water through from the inside at one end:

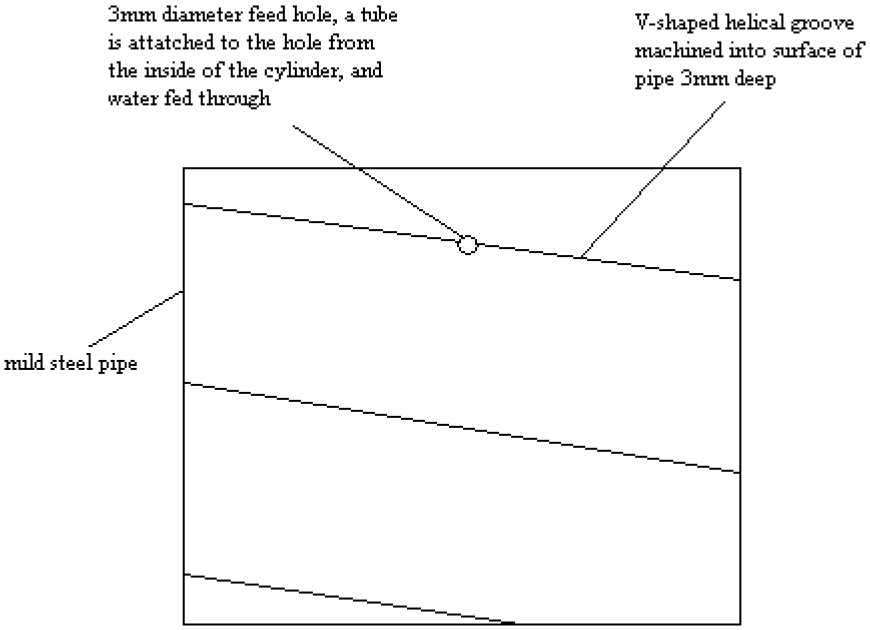


Figure 17: a representation of the front of the test rig (looking at the outside wall) – the original rig used in last year's tests (2001).

Two manifolds diametrically opposite eachother were included to run the whole length of the pipe, the original feed hole was blocked and a new hole drilled in the middle at a point where a manifold intersected the groove. The point at which this manifold intersected the last section of the channel was too near the end of the pipe. This was a problem as the ends were to be sealed due to the likelihood of water leaking from the ends, therefore a connecting channel was also included in the same manner the manifolds had been. Two bleed holes where then drilled into the pipe wall diametrically opposite the feed-hole intersecting the channel (therefore intersecting the second manifold). These were to ensure that air was pushed out of the channel as the water flowed around it, and would be immediately blocked as water came through.

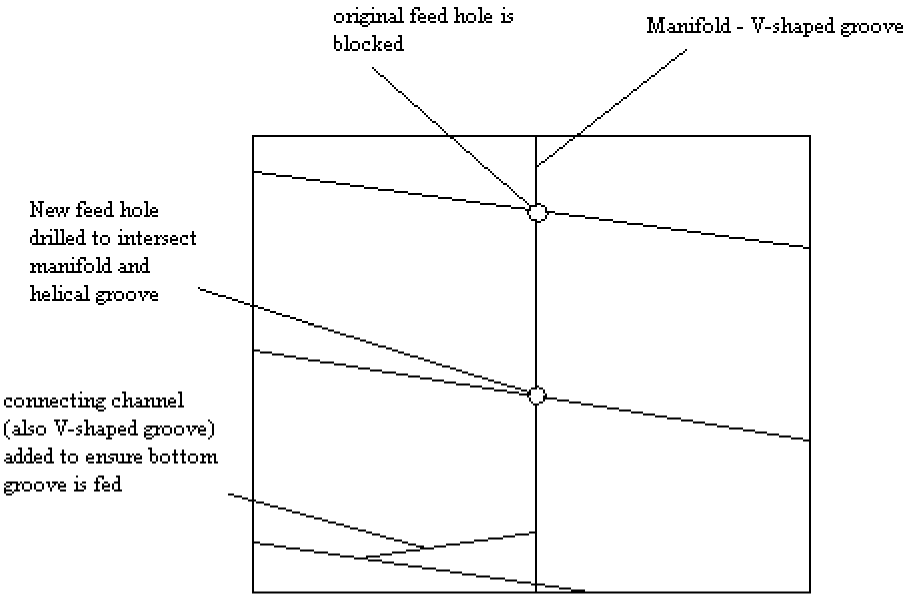


Figure 18: The test rig once modified to improve flow, the two bleed holes are not visible as they are on the other side, they also intersect with the channel.

The test rig was therefore set up as shown below, with a pipe to the feed hole, fed from the bottom to ensure that air was pushed up and out of the channel.

A two meter head was used in order to ensure the water was pushed up the groove and also to be able to compare results with a real tank, which has a height of 2m.

As well as modifying the existing rig, a new rig design was submitted using the same size and material for the pipe but with much closer grooves to ensure that the maximum crack area was fed (see appendix 2 section 2.3). The new design incorporated grooves at 1cm pitch, 2 manifolds diametrically opposite intersecting 2 feed holes at one end of the pipe (one on each manifold), and 2 bleed holes at the other end. This rig was designed so it could be tested upright rather than on its side.

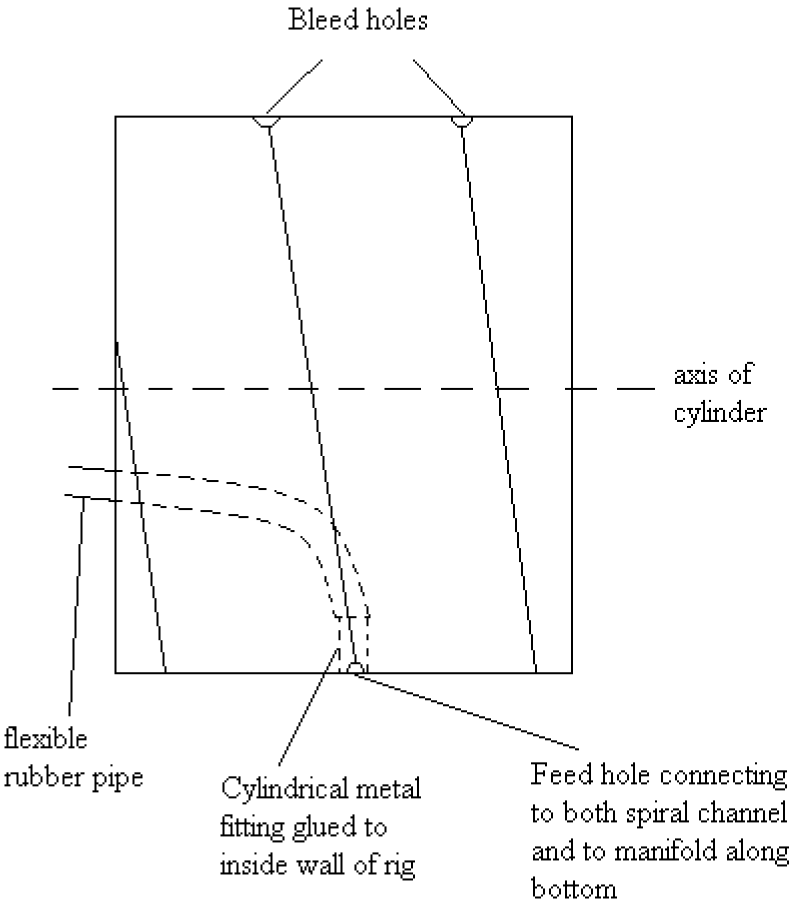


Figure 19: The test rig, as used for testing (looking at the pipe wall but with the rig on its side).

6.3. Constructing render samples

A 0.01m thick layer of mortar was initially applied to two rings, the cement : sand ratio used was 1:3. The water to cement ratio was 0.5. This formed a very thick paste, which was difficult to apply to the pipe wall (now covered in calico), as due to the dryness of the mix it had a tendency not to stick. However, it was decided to keep with a dry mix as more water in the mix the compromises on strength in the mortar. The rigs were left to cure in a bag for seven days before drying outside the bag for a further 21 days. This was done as in the last project it had been noted that it took 28 days for the cracks to form.

The mortar was then applied to the two remaining rings with the same ratios as used before of cement, sand and water. Due to concerns of leakage from the edges it was decided to modify the rings slightly by applying the calico so that roughly 2cm of the rings were left exposed at either end, these ends were roughened using a file. This was to ensure the mortar would stick to the pipe ends and reduce any leakage or seepage through the material if it protruded from the ends. Silicone sealant was also applied to the ends of all four rigs.

The last two of the four rigs were expected to yield better results as the plastering was of a better quality, with a constant thickness throughout. Also there had been more measures taken to prevent end leakage.

After these rigs had been tested the mortar was chipped off, at this point the newly designed rigs had also become available. With eight rigs, it was possible to test four variations of render with two rigs to each render. The renders were applied as described in section 5, the most difficult to apply being the wire mesh as it had to be held onto the outside of wet mortar ensuring no gaps between mesh and mortar:

Figure 20: making a wire mesh reinforced render, (on right – applying mesh into wet mortar, on left – mortar chipped away after testing to reveal mesh).

7. Testing

The rigs were set up so that a 2m head could be obtained. A pipette was attached to the top end of the pipe and water poured through a funnel into the pipette. Two people were required to conduct the testing, as a person was needed at the bottom end to block the bleed holes the moment water poured through them.

Initially testing went to plan as the water first emerged from the bleed holes before the cracks so it could be assumed that there was no air in the channel interfering with the flow. However, once the bleed holes were blocked it soon became apparent that water was flowing through the cracks faster than it could be poured through the pipette, therefore it was not possible to measure the leakage rate.

This proved that the testing method had been improved in the sense that flow was most definitely not inhibited in the channel. However, the leakage rate needed to be measured and so the set up of the experiment was altered. A wider pipette and pipe were used, initially the pipette had a diameter of 7mm, it was now 11mm. Also the pipette was moved down to the bottom so that the water level was not falling immediately at the point it needed to be measured, i.e. the person at the top could stop pouring when the person at the bottom had blocked off the bleed holes and ensured that the water was flowing through the cracks, and then after a few seconds the top of the water level would reach the pipette so the person at the bottom could time the drop. This worked well and a leakage rate was recorded.

Figure 21: set up of the rig showing pipe connecting to channel and pipette

Figure 22: Leakage through a crack

For later tests a reservoir was introduced so that testing only required one person. Water was held in a container 2m high, with a tap, which was attached to the rubber pipe. There was also a valve on the rubber pipe, positioned just above the pipette so one person could control the flow from the bottom (see figure 5 section 3.1 for a rough schematic of how the test was set up).

Crack measurement was done using a microscope with a graticule that measured to 1/20 of a millimetre.

7.1. Problems encountered during testing

As the leakage rate was high due to low resistance in the rig (see appendix 2 section 2.2.), ensuring accurate results was difficult as the water level in the pipette tended to drop very quickly. This was a problem, which could only be overcome by repeating tests and obtaining an average.

A major problem encountered was leakage from the ends, as can be seen below in figure 23. The mortar is wet along the edge below the silicone sealant, indicating water is leaking from the sealed edges:

This had to be overcome by observing leaks, marking them and applying greater quantities of sealant. In the case of the wire mesh samples this was done twice as the end leakage was excessive in these samples. Therefore, in the results there are three different flow rates for the mesh samples, the smallest being that with all end effects removed. This was also done once for the Rockfast sample, giving two flow rates for Rockfast.

Figure 23: A sample with end leakage

8. Results

8.1 Crack measurement results

Two different types of rig were used, the *original rig* used in last years experiments by Tom Constantine and the *new design* of rig detailed in section 6.2.

The plain mortar samples were both set on original rigs, as these were the first samples to be made and the rigs made to the new specification were not available at that time. There are no crack measurement results for the samples made with two layers of mortar with a cement-water wash, as no cracks were visible on these samples. The results are detailed in appendix 3 tables 3.1. to 3.8., and summarised in section 9.1 to enable analysis.

8.2. Leakage results

For the Rockfast tests there is only one leakage result, due to the failure of one rig (the original design), there was a blockage at some point in the groove and not all cracks were being fed also one of the bleed holes did not leak which implies air was trapped inside the channel.

As the results are different for the new rig and old rig, there are two tables – one showing the raw data as measured (appendix 3 table 3.9.) and table 3 below with the results for the new rig normalised so they can be compared with the old rig results.

Table 3: Normalised data for leakage rates

Rig	Type	Test number	Flow rate (m^3s^{-1} E-06)
Original	1) Plain	1	6.2
Original	2) Plain	1	7.6
Original	3) Plain	1	4.6
Original	4) Plain	1	3.7
Original	Mesh	1	0.51
New design	Mesh	1	0.43
		2	0.27
		3	0.23
Original	Rockfast	nil test	
New design	Rockfast	1	10.6
		2	5.6
Original	Fibre	1	4.8
New design	Fibre	1	4.7
Original	Double layer	1	2.2
New design	Double layer	1	2.7

9. Analysis

9.1. Analysis of cracking results

Table 4: Crack measurement results and projected expectations of flow

Sample	Number of cracks	Average crack width (E-03m)	Average crack surface area (E-03m^2)	Total crack surface area (E-03m^2)	Shrinkage	Expected flow rate (E-03m^{3}s^{-1}
Plain mortar 1	9	0.089	0.0075	0.067	0.00089	1.037
Plain mortar 2	8	0.093	0.0069	0.056	0.00075	1.04
Mesh 1	9	0.036	0.0012	0.01	0.00013	0.08
Mesh 2	9	0.034	0.001	0.0092	0.00012	0.06
Rockfast 1	7	0.100	0.0093	0.065	0.00087	1.31
Rockfast 2	9	0.088	0.0077	0.07	0.00093	1.01
Fibre 1	9	0.130	0.010	0.09	0.0012	3.16
Fibre 2	5	0.120	0.013	0.065	0.00087	1.56

9.1.1. Shrinkage

The shrinkage of the samples was calculated by dividing the total crack surface area by the actual surface area of the mortar on the rig. Analysis of these results reveals that the only effective method of reducing shrinkage was the wire mesh reinforced mortar. The addition of Rockfast made no difference to the shrinkage or crack distribution as the figures for shrinkage are similar to the figures for the shrinkage of plain mortar. Fibre reinforcement also made no difference, having one of the highest shrinkage values. The expected shrinkage for plain mortar, *0.0045*[6], is not reflected in the results, the highest shrinkage being 0.0012, almost a quarter of the expected value. The expected average crack width calculated in section 5.1., for an estimated 10 cracks around the set diameter of the test rig was 0.00023m, in reality the highest average crack width found in the fibre reinforced samples was 0.00013m, almost half the expected width.

9.1.2. Expected flow rate

The expected flow rate through each mortar lining was calculated using the value for average crack width substituted into equation 3 defined in section 5:

$$Q = \frac{2\Delta p R^3}{3\mu w} \qquad \text{eq. 3}$$

Where R is half the crack width. The figure obtained from this calculation was then multiplied by the number of cracks in each rig in order to give a total leakage value for the whole section of mortar. These flow rates will be used in the leakage results analysis below.

9.2. Analysis of leakage results

Table 5: Comparison of expected flow rate with actual

	Theoretical flow rate (E-03m^3s^{-1})	**Measured flow rate (E-03m^3s^{-1})**
Plain mortar 1	1.037	0.00463
Plain mortar 2	1.04	0.00371
Mesh 1	0.08	0.00051
Mesh 2	0.06	0.00043
		0.00027
		0.00023
Rockfast 1	1.31	
Rockfast 2	1.01	0.01056
		0.00560
Fibre 1	3.16	0.00480
Fibre 2	1.56	0.00474
Double layer 1		0.0022
Double layer 2		0.0027

The table above shows a comparison of the expected flow results according to the theory modelling a crack as laminar flow between parallel planes, and the actual flow rates obtained through measurement. The theory predicts a much higher flow through the cracks measured, in comparison with the actual flow, which in most cases is more

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[6] Neville 1995

than 100 times smaller. As well as comparison with the theory it is important to realise findings must be projected onto a much larger tank, which will hold 10m^3 of water (10,000 litres). The leakage rate for the area of mortar on the test rig was projected onto the larger area of a tank with a height of 2m and a diameter of 2.5m (see table 3.10. appendix 3). The calculation was done for the expected leakage rates and the actual leakage rates measured.

Table 6: results projected for leakage in one day in a tank of volume10m^3

	Expected leakage in full sized tank in one day (litres)	Projected leakage (from experimental results) in full sized tank in one day (litres)
Plain mortar 1	18755597	83758
Plain mortar 2	18809856	67010
Mesh 1	1446912	9188
Mesh 2	1085184	7808
		4909
		4091
Rockfast 1	23693184	
Rockfast 2	18267264	190979
		101202
Fibre 1	57153024	86869
Fibre 2	28214784	85806
Double layer 1		39718
Double layer 2		48869

In a 10,000 litre tank, ideally a leakage of more than 10litres a day is unacceptable. Therefore projecting the figures to a full size tank has produced leakage rates, which are far too high and seem unrealistic. Even using the values for mortar reinforced with chicken mesh, which give the lowest leakage, a full tank would be empty in two days.

10. Discussion

In section 1.4 two objectives were outlined:

- To improve on the experimental method used in the previous year to yield more credible results.
- To measure leakage flow through renders in order to recommend methods of effective waterproofing for water tank construction.

10.1. Experimental procedure

The problem encountered by Tom Constantine last year was too large a resistance in the channel, which therefore bought into question whether water was allowed to flow freely and feed all the cracks. The resistance in the rig was greatly reduced by removing all obstructions in the channel, however this then led to the problem of a leakage rate so fast it was difficult to measure. With such low resistance in the channel end leakage also became a problem and some results should have been repeated but could not be due to lack of time.

The rig produced a totally constrained state for the mortar and leakage was also made higher by the large pressure difference between inside the channel and the outside wall. In practice the mortar is backed by earth or bricks, which would serve to reduce the leakage rate. Therefore, with all these factors taken into account the rig is not an ideal approximation of real life. Projecting the leakage rates onto a tank with a 10,000 litre capacity does not yield accurate results for leakage in large tanks, as such tanks are in use and leakage rates are not as high as those calculated in this report. However, the test rigs give a good method of measuring leakage rate through mortar, if all unwanted leaks can be overcome. The rig can provide a controlled system, which allows water to flow freely behind mortar and a reliable method of testing flow rate through cracks. Therefore it is a good method for comparison between different measures to reduce cracking. From the results obtained in this report, wire mesh had the best performance in comparison with the other techniques tested.

10.2. Methods of waterproofing

Rockfast

Although expected to eliminate cracking in the mortar due to shrinkage compensation, the addition of Rockfast produced the same results as plain mortar, if not fairing slightly worse. The shrinkage of plain mortar was in fact less than that predicted by the theory, according to Neville plain mortar shrinks by 0.45%, in tests it was found to average at 0.082%. It is therefore possible that the amount of Rockfast used was too much and instead of shrinkage compensation, encouraged further expansion. Due to the constrained nature of the samples this may have led to internal stresses developing which would have caused cracking.

Fibre

The fibre-reinforced mortar also performed very badly, again giving no real difference from plain mortar. As fibres make mixing difficult, it is possible that this led to a poor quality mortar. During plastering, it was necessary to plaster from the bottom of the rig to the top (along the length of the cylinder) as any other way resulted in the mortar falling off. It is therefore also possible that this plastering action aligned many of the fibres in the wrong direction, as cracks propagated along the length of the cylinder and therefore the fibres would be required to be perpendicular to the cracks, rather than along the same line.

Double layer

The rigs coated with two layers of mortar and a cement-water wash between the layers, performed fairly well. It was harder to seal the ends of these rigs as the layer of render was much thicker than on the other rigs. This may explain why the leakage rate is higher than expected, seeing as no cracks could be identified on the mortar surface. Despite this, the leakage rate with this method of rendering was half that of the three previously discussed. In the building of a real tank using this method is inconvenient as the site will need to be visited at least three times for the application of each layer, and both mortar layers have to be allowed to cure and dry. This also increases expense.

Wire mesh reinforcement

This performed the best of all four methods, reducing the leakage rate from plain mortar by a factor of 10. However, there is a possibility that carbonation will occur with chicken mesh in mortar, particularly in hot countries. Carbon dioxide reacts with alkalis stripping the protective layer on steel, especially in hot countries with poorly made mortar. The mesh will rust in the mortar, leaving the mortar weak and prone to cracking. However, on the basis of the tests performed, wire mesh is most effective in preventing cracking.

10.3. Mortar Quality

Mortar quality is an important factor affecting mortar strength and cracking, that has not been addressed in this investigation. Implementing a rainwater harvesting project in a developing country involves teaching local workers the necessary skills required to build tanks.

The mortar needs to be as dry as possible, however, this makes the plastering job slightly harder and therefore, if emphasis in not placed on the correct water content plasterers may add more water to increase workability. Watt describes the problem of too much mortar being mixed in one go, which leads to a large amount becoming stiff as it is left out in the sun. In this situation it is not uncommon for the person plastering to add a little more water to make it workable again – this will also compromise mortar strength and quality. There also needs to be a great emphasis placed on proper curing, as this increases mortar strength. Without these measures being taken cracking will occur in mortar.

11. Conclusions

The use of test rigs with the channel kept open by a layer of material between the channel and the mortar worked well in reducing resistance in the water-feed path. The test rigs provide a method of comparing renders, however they do not provide a good approximation to a real size tank.

A better method of sealing the ends is required, as in some cases silicone sealant was not sufficient to stop end leakage. For this reason the tests in this report need, ideally, to be repeated.

The best render was the wire mesh reinforced mortar. Although it produced the same number of cracks, the crack sizes were greatly reduced. In plain mortar the average crack width was almost 0.1mm, for mesh the average crack width was 0.035mm, a reduction of almost two thirds. The leakage was reduced by more than a factor of 10.

11.1. Further work

The method of testing needs to be further improved so it can be used to better approximate real size tanks. The use of better seals at the ends of the rigs should reduce the leakage rate to reflect only the leakage from the cracks. One possibility is the combined use of silicone sealant and fix clips (used by Tom Constantine in 2001). If the flow can be reduced, it would make the leakage rate easier to measure and leave fewer margins for error in the timing of the drop in water level through the pipette.

There were many methods of waterproofing renders that were not tested in this report, for example the use of a waterproofing paint, the use of superplasticisers and other chemical admixtures. Also the methods tested need further development,

- testing with different amounts of Rockfast to obtain the right shrinkage compensation
- testing with different types of fibres
- longer term tests with wire mesh to study the effects of carbonation
- repeating tests with an improved end sealing technique

The tests also need to be repeated as two samples of each render are not enough to give conclusive results. The main recommendation that can be made is greater research into wire mesh reinforcement.

Appendix 1 – Concrete and Mortar Data

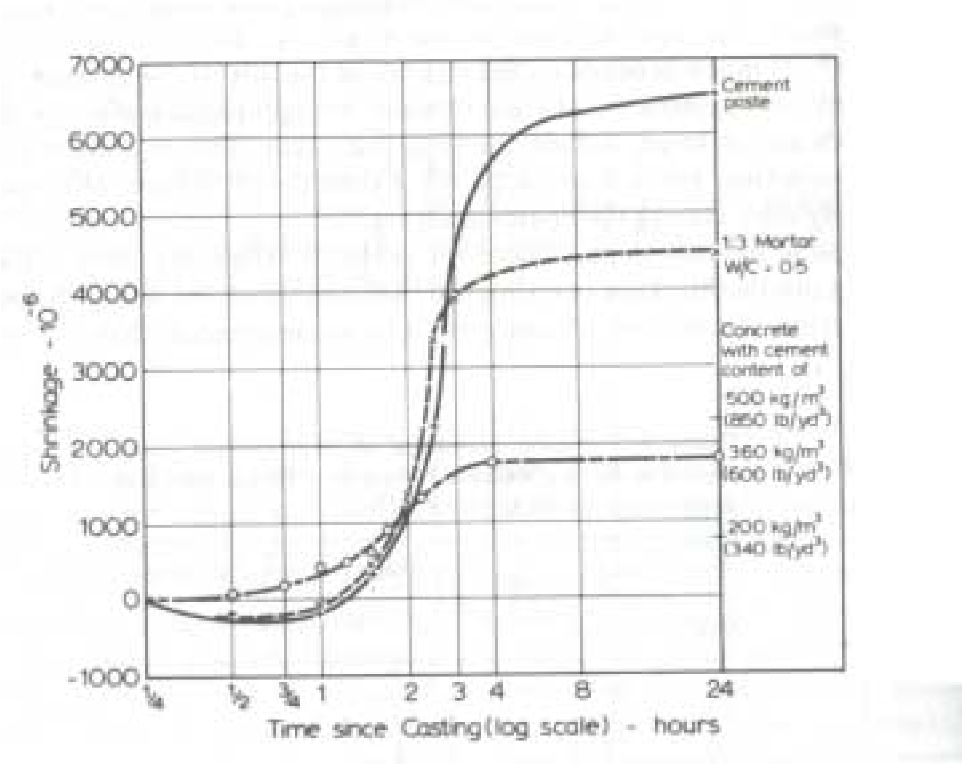

Figure A1.1.: Influence of cement content of the mix on early shrinkage (Neville 1995)

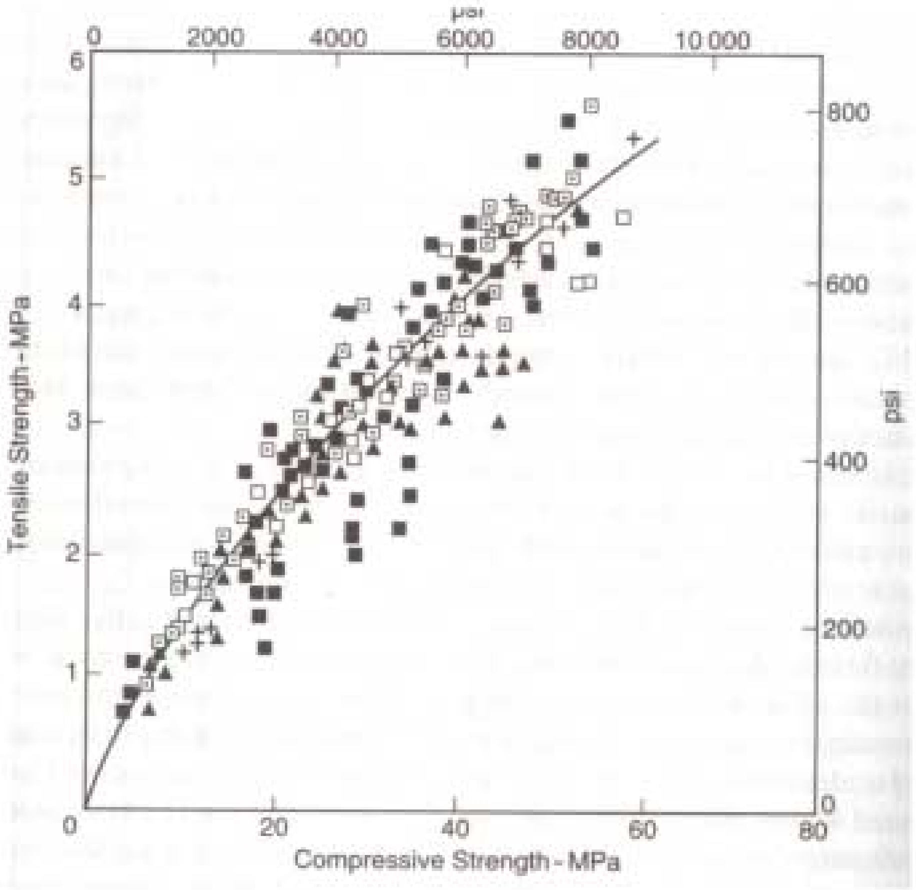

Figure A1.2.: The relationship between tensile and compressive strength (Neville 1995)

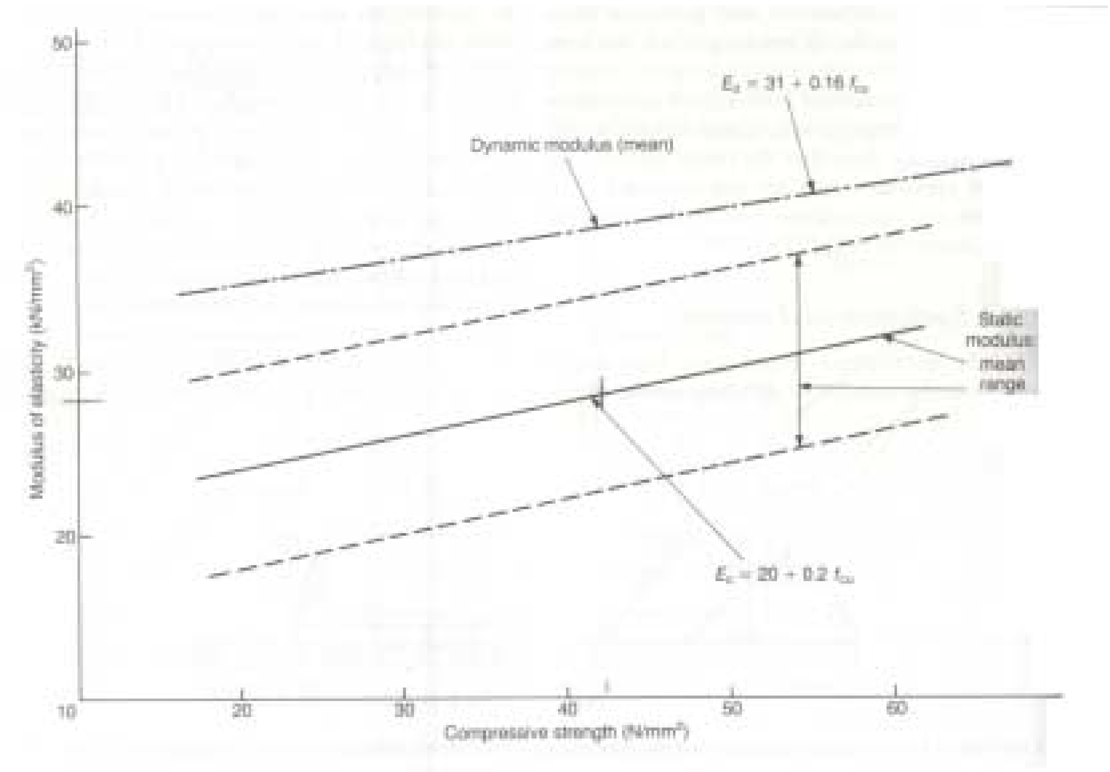

Figure A1.3.: The relationship between compressive strength and Modulus of elasticity (Illston 1994)

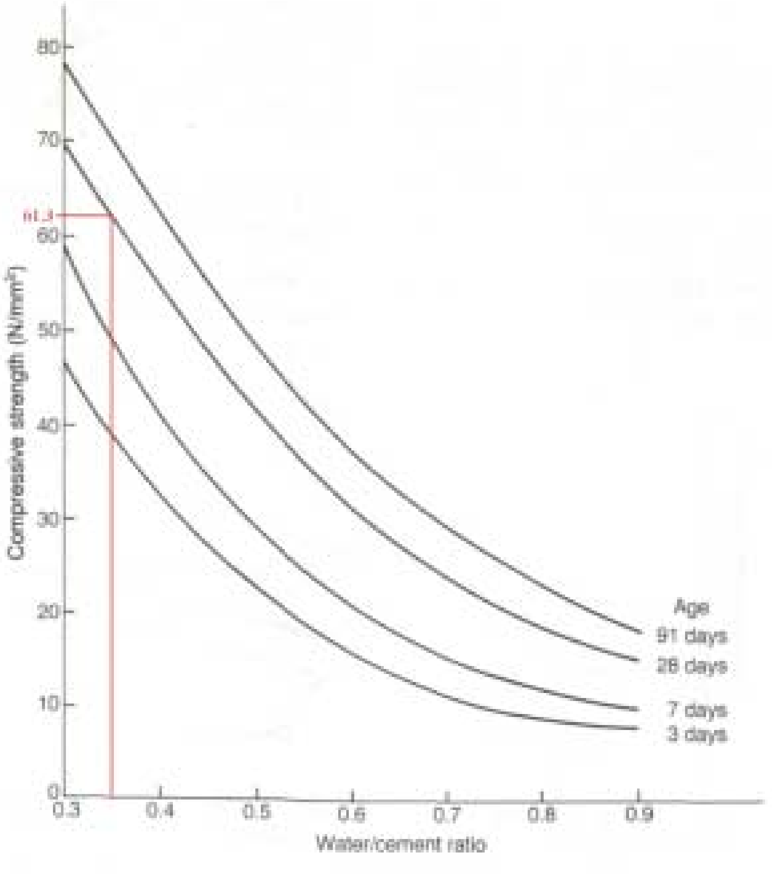

Figure A1.4 Relationship between water/cement ratio and strength (Illston 1994)

Appendix 2 – experimental procedure

A2.1. Calculations carried out before testing began

To ensure a measurable leakage rate through the rig:

Suppose threshold of interest is 1litre/day
Suppose tank is 1m diameter x 2m high
Mean pressure head 1m – (similar to experiment)

1litre/day loss = q Area secs/day
$q = 0.001/6.3*86000 = 1.84\text{x}10^{-9}\text{m}^3/\text{s}$ per m^2

Test rig:- Mortar area = $\pi \text{ x } 0.165 \text{ x } 0.14 = 0.0725\text{m}^2$
Therefore leakage rate per hour = $0.0725 \text{ x } 1.84\text{x}10^{-9} \text{ x } 3600$
$= 0.48\text{x}10^{-6} \text{ m}^3/\text{hr}$
= 0.48 ml/h ← just about observable

Check that surface tension of water does not prevent flow:

Surface tension of water at 20°C = $72\text{x}10^{-3}$ N/m
Force per metre on film acting downwards is: $72\text{x}10^{-3} \text{ x } 2 \text{ x } \cos\theta$
Assume $\cos\theta = 1$
$F = 1pw$, so $pw = 1.44\text{x}10^{-3}$, and $p = 1.44\text{x}10^{-3}/w$
If crack width w = 0.0001m (0.1mm), then p = 1440 Pa, i.e. 14 cm of water

A2.2. Resistance in rig

The flow rate through the bleed holes was measured i.e. water flowing straight through rig, bypassing cracks. This rate was 6 litres/second ($0.006\text{m}^3\text{s}^{-1}$ → 10^3 times faster than the flow rate through plain mortar), therefore resistance is negligible in the channel.

A2.3. Comparison of feeding cracks through channel and feeding cracks in an actual tank

In the test rig cracks are fed primarily at points where they are intersected by the channel, figure 2.1. below shows a schematic of the water distribution in a crack as fed by the channel:

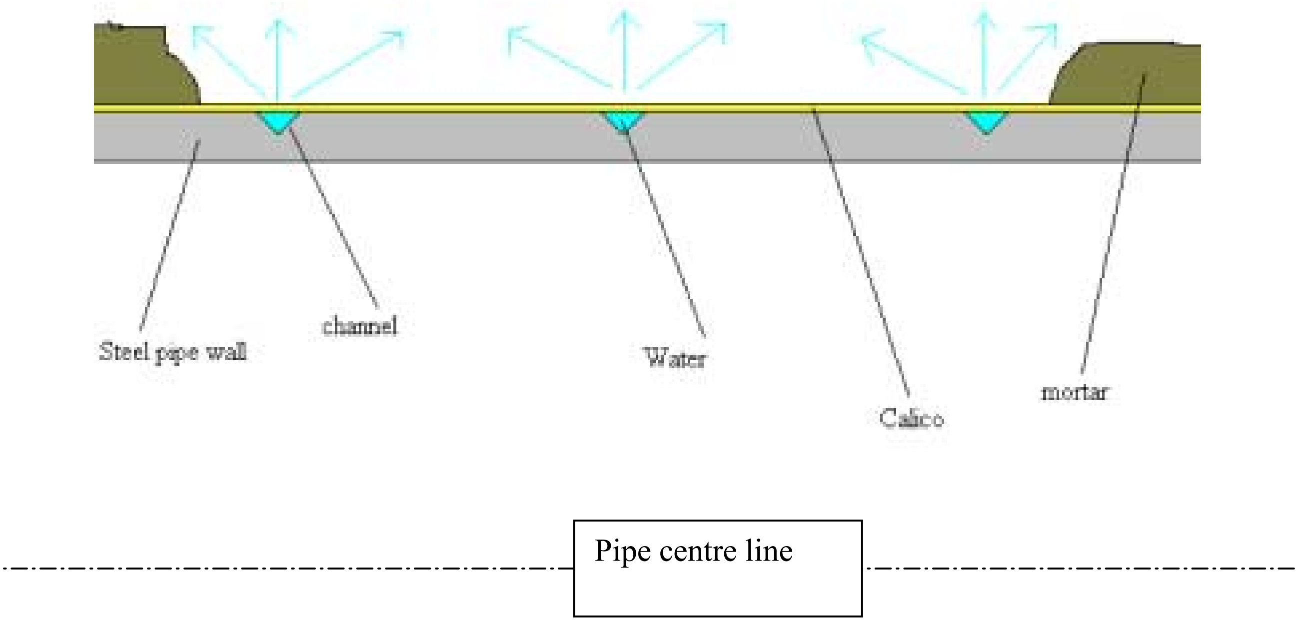

Figure 2.1.: Cross section of mortar and rig, at a point where there is a crack. Water is not evenly distributed through crack

If this is compared with the same situation in a real tank:

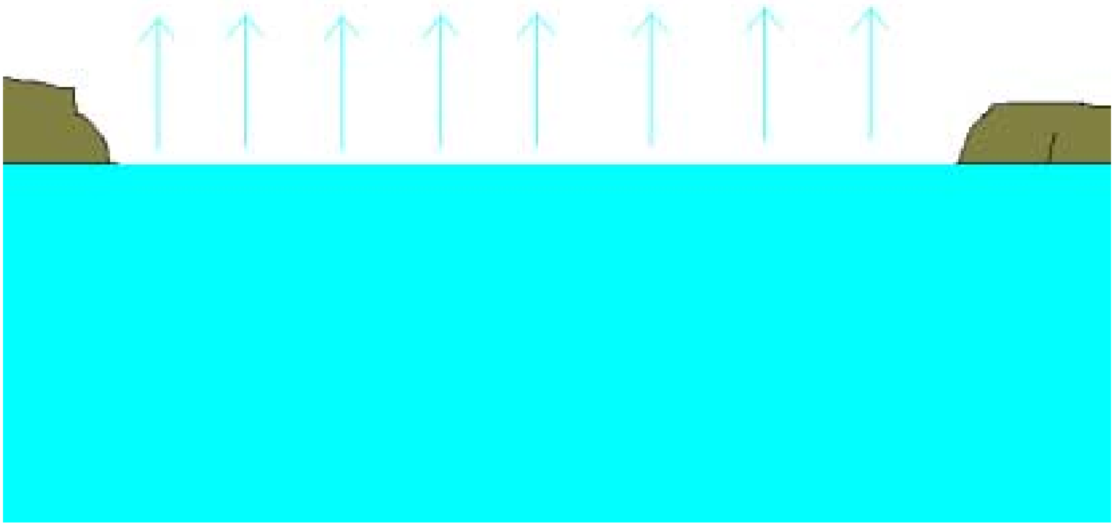

Figure 2.2: in a real tank water distribution is constant

This implies the measured leakage rate from the rig is an underestimate. However, it should also be taken into account that the rig provides the most severely constrained state to ensure maximum cracking. Also mortar lining in real tanks is backed by earth or bricks, whereas in the tests there is only air on the other side of the mortar, so the pressure difference is far greater which will lead to increased flow. Therefore it can be assumed that these factors will have a cancelling effect.

Appendix 3 - Results

***Table 3.1 Plain mortar 1* (original rig)**

Crack number	Length (m)	Average width (E-03 m)	Crack surface area (E-03 m²)
1	0.14	0.2	0.028
2	0.065	0.11	0.00715
3	0.038	0.07	0.00266
4	0.1	0.12	0.012
5	0.023	0.05	0.00115
6	0.081	0.15	0.01215
7	0.047	0.04	0.00188
8	0.056	0.03	0.00168
9	0.025	0.03	0.00075
Average crack width		0.089	
Total crack surface area			0.067
Average crack surface area			0.0075

***Table 3.2 Plain mortar 2* (original rig)**

Crack number	Length (m)	Average width (E-03 m)	Crack surface area (E-03 m²)
1	0.137	0.17	0.0233
2	0.02	0.05	0.001
3	0.04	0.06	0.0024
4	0.024	0.09	0.00216
5	0.095	0.11	0.0105
6	0.075	0.12	0.009
7	0.06	0.08	0.0048
8	0.043	0.06	0.00258
Average crack width		0.093	
Total crack surface area			0.056
Average crack surface area			0.00696

Table 3.3. Mesh 1 **(original rig)**

Crack number	**Length (m)**	**Average width (E-03 m)**	**Crack surface area (E-03 m²)**
1	0.03	0.04	0.0012
2	0.01	0.04	0.0004
3	0.025	0.02	0.0005
4	0.023	0.06	0.00138
5	0.038	0.04	0.00152
6	0.025	0.03	0.00075
7	0.035	0.04	0.0014
8	0.06	0.04	0.0024
9	0.03	0.03	0.0009
Average crack width		0.038	
Total crack surface area			0.01045
Average crack surface area			0.00116

Table 3.4. Mesh 2 **(new design)**

Crack number	**Length (m)**	**Average width (E-03 m)**	**Crack surface area (E-03 m²)**
1	0.01	0.03	0.0003
2	0.014	0.04	0.00056
3	0.026	0.02	0.00052
4	0.032	0.03	0.00096
5	0.034	0.03	0.00102
6	0.029	0.04	0.00116
7	0.056	0.06	0.00336
8	0.044	0.02	0.00088
9	0.01	0.04	0.0004
Average crack width		0.034	
Total crack surface area			0.00916
Average crack surface area			0.001017778

Table 3.5. Rockfast 1 **(original rig)**

Crack number	Length (m)	Average width (E-03 m)	Crack surface area (E-03 m²)
1	0.021	0.05	0.00105
2	0.034	0.07	0.00238
3	0.11	0.19	0.0209
4	0.018	0.03	0.00054
5	0.016	0.05	0.0008
6	0.07	0.06	0.0042
7	0.14	0.25	0.035
Average crack width		0.1	
Total crack surface area			0.06487
Average crack surface area			0.0093

Table 3.6. Rockfast 2 **(new design)**

Crack number	Length (m)	Average width (E-03 m)	Crack surface area (E-03 m²)
1	0.115	0.27	0.03105
2	0.068	0.04	0.00272
3	0.055	0.04	0.0022
4	0.025	0.05	0.00125
5	0.026	0.05	0.0013
6	0.13	0.14	0.0182
7	0.062	0.09	0.00558
8	0.055	0.06	0.0033
9	0.08	0.05	0.004
Average crack width		0.088	
Total crack surface area			0.0696
Average crack surface area			0.0077

***Table 3.7. Fibre 1* (original rig)**

Crack number	Length (m)	Average width (E-03 m)	Crack surface area (E-03 m^2)
1	0.125	0.37	0.04625
2	0.08	0.08	0.0064
3	0.038	0.18	0.00684
4	0.035	0.05	0.00175
5	0.117	0.15	0.01755
6	0.056	0.06	0.00336
7	0.035	0.17	0.00595
8	0.031	0.04	0.00124
9	0.024	0.06	0.00144
Average crack width		0.129	
Total crack surface area			0.091
Average crack surface area			0.0101

***Table 3.8 Fibre 2* (new design)**

Crack number	Length (m)	Average width (E-03 m)	Crack surface area (E-03 m^2)
1	0.054	0.09	0.00486
2	0.018	0.05	0.0009
3	0.131	0.22	0.0288
4	0.022	0.04	0.00088
5	0.131	0.22	0.0288
Average crack width		0.124	
Total crack surface area			0.064
Average crack surface area			0.0129

Table 3.9. Raw leakage data as measured

Rig	Type	Test number	Time taken (s)	Volume (m^3)	Flow rate (m^3s^{-1})	Flow rate (m^3s^{-1} E-06)
Original	1) Plain	1	9.6	0.000059	0.000006175	6.175
Original	2) Plain	1	7.8	0.000059	0.0000076	7.600
Original	3) Plain	1	2.4	0.0000111	4.63E-06	4.631
Original	4) Plain	1	16.0	0.000059	0.0000045	3.705
Original	Mesh	1	121.6	0.000062	5.078E-07	0.508
New design	Mesh	1	79.3	0.000054	6.8546E-07	0.685
		2	86.0	0.000037	4.3114E-07	0.431
		3	172.0	0.0000618	3.5912E-07	0.359
Original	Rockfast	nil test				
New design	Rockfast	1	2.8	0.000047	1.67E-05	16.761
		2	1.8	0.000016	8.88167E-06	8.882
Original	Fibre	1	3.6	0.0000173	4.80278E-06	4.803
New design	Fibre	1	8.2	0.00006175	7.53049E-06	7.530
Original	Double layer	1	4.5	0.00000988	2.19556E-06	2.196
New design	Double layer	1	2.0	0.00000858	4.2885E-06	4.289

Table 3.10. Comparison of expected leakage and actual leakage

	Expected flow rate (E-03m^{3}s^{-1})	Flow rate for 1m^2 of mortar (l/s)	Flow rate for full sized tank (s.a. 15.7m^2) (l/s)	Leakage in full sized tank in one day (litres)
Plain mortar 1	1.037	13.827	217.1	18755597
Plain mortar 2	1.04	13.867	217.7	18809856
Mesh 1	0.08	1.067	16.74	1446912
Mesh 2	0.06	0.800	12.56	1085184
Rockfast 1	1.31	17.46	274.2	23693184
Rockfast 2	1.01	13.47	211.4	18267264
Fibre 1	3.16	42.13	661.5	57153024
Fibre 2	1.56	20.80	326.6	28214784
	Measured flow rate (E-03m^{3}s^{-1})			
Plain mortar 1	0.00463	0.062	0.969	83758
Plain mortar 2	0.00371	0.049	0.776	67010
Mesh 1	0.00051	0.007	0.106	9188
Mesh 2	0.00043	0.006	0.090	7808
	0.00027	0.004	0.057	4909
	0.00023	0.003	0.047	4091
Rockfast 2	0.01056	0.141	2.210	190979
	0.00560	0.075	1.171	101202
Fibre 1	0.00480	0.064	1.005	86869
Fibre 2	0.00474	0.063	0.993	85806
Double layer 1	0.00220	0.029	0.460	39718
Double layer 2	0.00270	0.036	0.566	48869

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