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EFFECT OF FIBRE REINFORCEMENT ON THE PROPERTIES OF GROUND GRANULATED BLAST FURNACE SLAG-CEMENT-BENTONITE SLURRY

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Abstract: Slurry walls are used as cut-off walls and are designed to meet strength and permeability criteria, with the latter often being a governing factor. An investigation was undertaken to explore the use of polypropylene fibres in cement bentonite ground granulated blastfurnace slag slurry walls in order to assess the effect of fibres on permeability in the main. Flow, bleed and both undrained and drained strength were also measured. Fibres reduced both the flow and bleed. They also marginally increased the permeability. Undrained strength together with strain to failure increased. However, under drained conditions strain to failure increased compared to mixes with any fibre.

1. INTRODUCTION

The problems created by the migration of liquid pollutants from landfill and contaminated sites are widely recognised and to control this environmental regulations regarding pollution of adjacent land and groundwater have become more stringent. It is generally accepted that the most practical solution to counteract the negative effects of contamination of groundwater at depth and facilitate compliance with regulations is containment. Although there are many types of containment system, including active walls, one that is well recognised as offering good performance, safety and economy is the slurry cut-off wall.

There are two principal methods for the construction of slurry walls, both requiring the excavation of a deep vertical trench. The double phase technique involves supporting the trench with bentonite slurry until it is excavated to the required depth. The construction slurry is then displaced by a more dense soil bentonite (SB) mixture, which is left in place to cure and form the containment barrier. In the single phase technique, a self-hardening cement bentonite (CB) slurry is used to both facilitate construction and form the fabric of the cut-off wall. Since this process involves only one major operation, CB slurry walls are easier, quicker and in some cases, cheaper to construct than SB slurry walls. Construction of slurry walls has been described by many, including FPS (2006) and RYAN and DAY (2002).

Research has shown that the ability of a particular CB slurry mix to achieve design requirements almost exclusively depends on the nature and relative proportions of its constituent materials. Designers are often forced to specify mixes that are only capable of achieving a specified permeability to the detriment of overall performance. Typically, bentonite contents are increased and cement contents correspondingly reduced. This inevitably leads to losses in strength and setting ability, in addition to the desired reduction in permeability. Developments in the use of cement replacement materials have to some extent overcome this problem. Indeed, the partial replacement of cement with ground granulated blastfurnace slag (GGBS) is known to have a beneficial effect on strength, setting ability and permeability. Unfortunately, the addition of GGBS to CB slurry reduces strain to failure and thus compromises the ability of the material to withstand deformations without cracking.

This paper describes the results of an investigation to evaluate the use of polypropylene fibre reinforcement in enhancing the overall performance of CB slurry mixes. A mix design used by Arup and Partners for the construction of CB walls at the Pride Park site in Derby, UK (BARKER et al., 1998) was used as the basis of this work.

2. PERFORMANCE REQUIREMENTS FOR SLURRY WALLS

The long term ability of CB walls to perform as effective hydraulic containment barriers and the ease with which they can be constructed is strongly influenced by the properties of the slurry that forms them.

2.1. DENSITY

Density should be sufficient to provide the necessary hydrostatic force required for the structural stability of the trench (JEFFERIS, 1981). The slurry density required to achieve this will depend on the nature of the surrounding ground. XANTHAKOS (1979) states that although the initial density of CB slurry ranges from 1040 kg/m^3 to 1150 kg/m^3, it usually rises to around 1250 kg/m^3 by the end of excavation. For self-hardening slurries in-trench density of 1300 kg/m^3 is generally thought to be the threshold level above which workability is impaired.

2.2. BLEED

Low bleed characteristics are desirable since excessive loss of water constitutes a loss of useful slurry volume and indicates that the slurry mix is unstable. Although maximum bleed levels of 2% are often specified, JEFFERIS (1981) states that bleed of less than 1% can be achieved by a well designed CB slurry mix.

2.3. RHEOLOGICAL PROPERTIES

The rheological properties of CB slurry are extremely important in determining bleed characteristics, filter loss, setting times and ease of construction. The slurry needs to be thick enough to support the solid material within it and be fluid enough to facilitate excavation of the trench. Parameters that are used to indicate the capacity of a slurry mix to fulfil these criteria include viscosity, gel strength and thixotropy (BOYES, 1975).

Thixotropy is the property of hydrated bentonite to set to a gel-like consistency but to return to a fluid state upon agitation. This is extremely useful for maintaining solid material in suspension during periods when agitation from construction activities has ceased. The thixotropic behaviour of bentonite is the main reason for its inclusion in CB slurries.

2.4. SETTING TIME

The setting time required depends on the method of excavation and the depth of the cut-off wall (Jefferis, unpublished). Setting time should always be adequate to facilitate continuity of day joints. Setting times in excess of 36 hours may be required to ensure that slurry remains workable after weekend or bank holiday periods (PRIVETT et al., 1996). In addition to affecting construction, setting time will determine the amount of excavation spoil that gets trapped permanently within the wall (JEFFERIS, 1981). Longer setting times allow more spoil to settle out of the slurry and consequently promote the development of better barriers. Setting time is extended by GGBS replacement since GGBS has lower hydraulic activity than OPC. Barriers containing GGBS are generally excavated slightly deeper into impermeable strata to allow for the accumulation of spoil near their bases.

2.5. FILTER LOSS

During barrier construction slurry is lost to the surrounding ground. Initially, hydrated bentonite particles begin to occupy pore spaces between soil grains. The degree of penetration and hence the volume of slurry lost depends on the porosity of the ground. Eventually enough bentonite particles accumulate to form a tightly packed low permeability seal called a filter cake (XANTHAKOS, 1979). The filter cake has the dual purpose of reducing further slurry loss from the trench and providing a skin of semi-solid material on which the hydrostatic pressure of the slurry can act. The latter is important for trench stability.

Slurry loss can be reduced by ensuring that colloidal material (within slurry) is well dispersed. JEFFERIS (1981) reported that a CB slurry mix exhibited 40% less filter loss when 80% of the cement was replaced with GGBS. This was attributed to the reduced tendency of bentonite particles to aggregate in the presence of GGBS.

2.6. PERMEABILITY

Permeability is the most important parameter for cut-off walls. Regulations concerning the containment of waste and contaminated ground are becoming increasingly stringent and permeabilities below 10^{-9} m/s are often required. The specification of permeability is complicated by the fact that for CB slurry, permeability is dependent on a number of external factors. All research indicates that permeability reduces with increasing curing time, time of permeation and confining pressure.

An increase in the solids content and in particular the bentonite content of CB slurry will also lead to a reduction in permeability (MANASSERO et al., 1995). Sodium bentonite produces lower permeability slurry than calcium bentonite and the partial replacement of cement with GGBS reduces permeability by 1 to 2 orders of magnitude (KHERA, 1995).

2.7. STRESS-STRAIN CHARACTERISTICS

Slurry walls require sufficient strength to withstand the forces exerted on them. Such forces include self-weight, lateral earth pressures from soil and nearby structures and hydrostatic pressures from differential groundwater levels (MEGGYES and PYE, 1995). Since the magnitude and distribution of forces is difficult to assess, the material strength required is not usually known. In an attempt to overcome this problem, a minimum strain at failure of 5% was once commonly specified. However, since strain at failure is influenced by external factors, an unqualified value such as this is of little real significance (PRIVETT et al., 1996).

Strain at failure is influenced by drainage conditions, cement content and effective confining stress. CB slurry samples in undrained compression usually fail before 1% strain has been achieved (KHERA and SO, 1997). In contrast, samples in drained triaxial compression can be taken to strains of 15% without exhibiting any detrimental effects (JEFFERIS, 1981). Very large effective confining stresses lead to high strains at failure and post peak strength development. This type of material behaviour has major implications for designers of CB slurry cut-off walls. Toward the top of walls, where confining stresses are low and undrained conditions are likely to exist, the risk of low strain structural failure is a real possibility. If such conditions are foreseen, additional strain at which failure occurs can be achieved by reducing the cement content of the mix. This, however, will almost certainly lead to a reduction in strength.

In addition to being influenced by cement content, the compressive strength of CB slurry is dependent on time elapsed since mixing. At 28 days, a conventional mix is likely to have an unconfined compressive strength of between 500 kPa and 1000 kPa. However, the maximum strength will not be developed until the cured material is around 100 days old (MEGGYES and PYE, 1995).

3. LABORATORY TESTING

The laboratory testing for this research was, in the main, undertaken in accordance with BS1377 (BSI, 1990). Where this Standard was not appropriate alternatives have been adopted.

3.1. MIX DESIGN

The materials used to make up the basic slurry comprised sodium bentonite, Ordinary Portland cement conforming to B.S. 12 (BSI, 1978) and ground granulated blast-furnace slag produced by the Frodingham Cement Company, Scunthorpe, UK. In accordance with PRIVETT et al. (1996), potable tap water was used in the preparation of the mix. The proportions of the constituent materials that make up the basic mix are presented in Table 1.

Table 1

Proportions of constituent materials by weight in CB slurry

Component	Mass per unit slurry volume (kg/m^3)
Bentonite	35
Cement	30
GGBS	120
Water	934

For the assessment of the effect of fibres on the properties of slurry, the mix design used for the construction of what was once the largest CB slurry cut-off wall in the UK located at Pride Park, Derby was selected for evaluation. The mix specification is given in Table 2.

The fibre mix comprised the basic mix with the addition of 0.2% (by weight) Fibrin, type F23©, polypropylene fibres. These Fibrin F23 fibres were developed for use in concrete to reduce surface cracking. They are 12 mm long, 18 μm in diameter and are coated with a chemical agent to ensure good dispersion when mixed with water.

Table 2

Specification for the basic slurry mix, as used at Pride Park, Derby (BARKER et al. 1998)

Property	Requirement	Test method
Bleed	<4% (after 24 hours)	Measuring cylinder
Density	1119 kg/m^3 (±10 kg/m^3)	Mud balance
Viscosity	–	Marsh funnel
Permeability	$<1 \times 10^{-8}$ m/s at 28 days	Triaxial cell
Strain at failure	>3% at 90 days (at an effective confining pressure of >120 kPa)	Drained triaxial compression
Undrained shear strength	>25 kPa at 14 days	Undrained triaxial compression
Unconfined compressive strength	>150 kPa at 90 days	Unconfined compression

3.2. SAMPLE PREPARATION

Bentonite and water (90% by weight of bentonite) were mixed in a mechanical mixer for 30 minutes. Fixed mixing period was employed in order to standardise the mixing time as the properties of CB slurry are highly dependent on it (JEFFERIS, 1981). After mixing, the bentonite/water slurry was left to stand overnight to hydrate. Jefferis (unpublished) states that this is important for proper hydration of montmorillonite particles, and thus for the reduction of bleed.

In making a fibre mix, 10% of the water was used to disperse the fibres. Cement and slag were added to this mixture. In preparing the basic mix (i.e., with no fibres present) the water was added directly to the cement and slag. The resulting fibre-reinforced or basic cementitious paste was added to the bentonite solution and the combination blended in the mixer to form either fibre or basic CB slurry, as appropriate. Again the mixing time, which was set at 30 minutes, was carefully controlled.

Samples required for triaxial testing were produced in individual 38 mm diameter cylindrical tubes. After mixing, the slurry was poured into the tubes, which were pre-coated with release oil to facilitate subsequent extrusion of samples. The tubes were vibrated to release trapped air from the slurry and were then sealed to prevent drying during curing. Samples were cured in an upright position at a temperature of about 20 °C.

3.3. TESTING OF FLUID SLURRY PROPERTIES

All tests to determine properties of the fluid were carried out on fresh slurry that had been mixed for a standard period of 30 minutes. After test, slurry was discarded. It was not recycled for further testing.

3.3.1. BLEED TESTING

In order to determine bleed, 1 litre of slurry was poured into 1000 ml measuring cylinders. The cylinders were sealed with double layers of cling film and left undisturbed for a period of 24 hours. Volume of any bleed water on top of the slurry was then measured.

3.3.2. DENSITY MEASUREMENT

The measurement of slurry density is usually carried out using a mud balance. However, Jefferis (unpublished) states that measurements from the instrument are only generally accurate to 10 g/l. Since the influence of fibres on slurry density was likely to be an order of magnitude less than this, the method was considered unsuitable.

Instead, slurry density was determined by weighing a known volume of slurry. The tests were carried out in conjunction with the bleed determinations. Volumes and weights were measured immediately after mixing and after samples had been left undisturbed for a period of 24 hours. This was done to determine any increase in density due to settlement of the slurry or by loss of slurry water through evaporation.

3.4.3. RHEOLOGICAL PROPERTY DETERMINATIONS

Rheological slurry properties such as apparent viscosity, plastic viscosity and gel strength are usually determined by the use of a Fann viscometer or flow cones such as the Marsh Funnel. However, it was felt that these instruments were likely to be prone to clogging when used to measure the viscosity of CB slurry containing fibres. A device which works on similar principles to the Marsh funnel is the Keller Colcrete P.120 flowmeter. The instrument is used mainly for fluidity control of cement based grouts. It comprises a sheet metal channel marked with centimetre graduations, a 2 litre tundish and a plug. The opening at the bottom of the tundish has a diameter of 36 mm and consequently cannot be clogged by fibre reinforced slurry. A diagram of the device is shown in Fig. 1.

In determining flow characteristics and gel strength development, the flowmeter was wetted and set in a horizontal position. 1.14 litre of fresh slurry was poured in the tundish. Slurries were left to stand in the tundish for 10 seconds, 10 minutes and one hour, after which the plug in the tundish was withdrawn. The point to which the slurry flowed was measured to the nearest 5 mm. Tests were also conducted on slurry samples which were allowed to stand in the tundish for two hours, but after this length of time slurries were too viscous to flow far enough along the channel to allow full evacuation of the tundish.

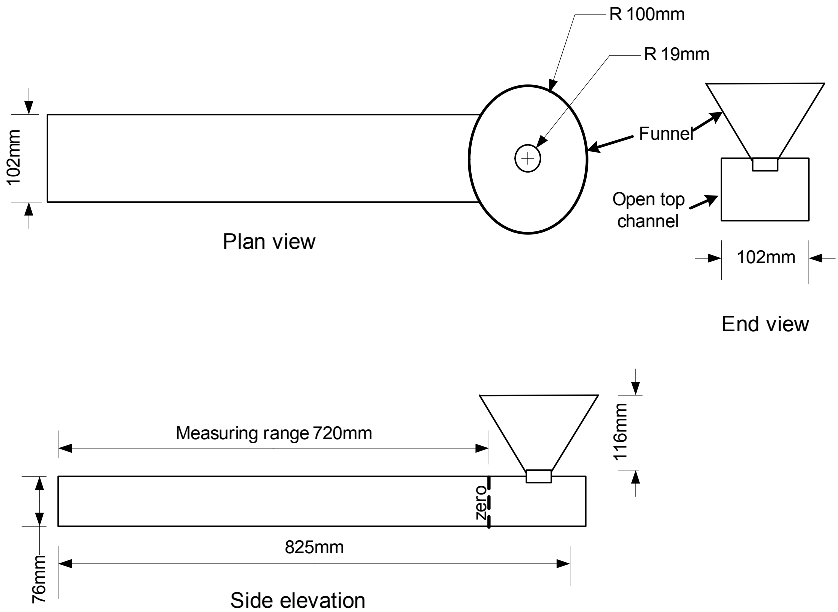

Fig. 1. Colcrete P120 flowmeter

3.5. TESTING OF HARDENED SLURRY PROPERTIES

Samples of both basic and fibre reinforced CB slurry were tested after curing periods of 28, 60, and 90 days. The 28 day and 90 day periods were chosen as being those most widely used by researchers and in industry. The 60 day period was included so that the influence of curing period on slurry properties could be monitored more closely.

3.5.1. PERMEABILITY TESTING

Testing was generally carried out in a triaxial cell in accordance with B.S. 1377:1990: Part 6, Section 4 (British Standard Institute, 1990). After full saturation, the cell pressure was set to produce an average effective confining stress of 60 kPa. According to PRIVETT et al. (1996), this is the minimum value required to ensure that a satisfactory seal is made between a rubber membrane and a sample. A differential back pressure of 20 kPa, corresponding to a hydraulic gradient of approximately 27, was then applied across the sample. These values were set to provide a measurable flow of water through samples and were calculated using Darcy's law. To allow pore pressures and hence flow patterns within samples enough time to settle to a steady state, each permeability test was continued for a period of at least 9 days.

3.5.2. UNCONFINED COMPRESSION TESTING

Unconfined compression tests are of little use in determining the behaviour of CB slurry under the conditions that exist in a trench. The test is only really useful in determining the repeatability of material (PRIVETT et al., 1996). To this end, three samples per mix per curing period were subjected to unconfined compression tests. The tests were carried out in accordance with B.S.1377: 1990: Part 7, Section 7 (BSI, 1990). Axial strain was applied at a rate of 0.5 mm/min.

3.5.3. UNDRAINED COMPRESSION TESTING

In the short term, CB slurry responds to applied load in an undrained state. This is due to the low permeability of the material. As such, undrained shear strength (c_u) and undrained strain at failure are important slurry properties.

As part of this research, undrained tests were carried out in accordance with B.S.1377: 1990: Part 8, Section 8 (BSI, 1990). Samples from each mix and curing period were tested under confining stresses of 60 kPa and 120 kPa. Tests were carried out at different confining stresses so that the results could be combined with those from unconfined compression testing in an attempt to determine c_u. Axial strain was applied at a rate of 0.4 mm/min.

3.5.4. DRAINED COMPRESSION TESTING

Tests were generally carried out in accordance with B.S. 1377: 1990: Part 8, Section 8 (BSI, 1990). Samples that were already set up in triaxial machines, subsequent to permeability determinations, were used for the tests. Specimens were drained from both ends and subjected to axial compression at a rate of 0.002 mm/min. Preliminary tests indicated this to be the maximum rate at which deviator stress could be applied without significantly increasing pore water pressure.

4. ANALYSIS AND DISCUSSION OF RESULTS

The principal purpose of this research was to determine the effects of the addition of polypropylene fibres to a CB slurry mix. To facilitate this, test results for fibre samples have, where possible, been directly compared to those from basic samples of the same age. To assess the performance of both mixes against industry requirements, the test results, again where possible, have been checked for compliance with the specification of wall constructed at Pride Park (BARKER et al., 1998) given in Table 2.

4.1. BLEED DETERMINATIONS

The average bleed from basic samples was 3.76% and that from samples with fibres 0.76% (both expressed in terms of total sample volume). These values suggest a reduction in bleed, due to the inclusion of fibres in the basic mix, of approximately 80%. Indeed, both fibre samples showed significantly less than 1% bleed. Since no sample (basic or fibre) exhibited bleed greater than 4%, complete compliance with the specification (BARKER et al., 1998) was achieved.

The results compare well with those from research into the effects of fibre reinforcement on the bleed characteristics of concrete (RAMAKRISHNAN et al., 1987). It is believed that fibres act as inhibitors to the settlement of solid particles, particularly cement particles, suspended within fluid slurry. Essentially, fibres are thought to increase slurry viscosity by physically restraining the movement of solid particles.

Since low bleed is important for maintaining useful slurry volume and mix stability, the reduction in bleed brought about by the inclusion of fibres has practical benefits. In addition, it may be possible to reduce bentonite content and increase water content, and still achieve compliance with bleed specification. Since bentonite is an expensive CB slurry component, this could lead to savings in costs. The extent of these savings would, of course, be limited by the effect on permeability and other slurry properties.

The relatively small deviations between bleed values from samples of the same mix suggest that the volume and weight determinations, carried out as part of the bleed testing procedure, were acceptably accurate.

4.2. DENSITY MEASUREMENTS

The mean initial density of basic slurry samples was 1110 kg/m^3, which was 99.2% of its theoretical value. The corresponding value for fibre samples was 1102 kg/m^3, 98.5% of its theoretical value. The theoretical density of the fibre mix is slightly less than that of the basic mix due to the relatively low density of the fibres (910 kg/m^3). A possible reason for the discrepancy between the theoretical and measured densities is that air bubbles may have been entrained into slurry samples during mixing. Thus, the larger discrepancy for fibre samples indicates that the presence of fibres promotes air entrainment.

Both fibre and basic samples displayed an increase in density over the 24 hour test period, although the increase was more pronounced in samples containing fibres. On average fibre samples lost 0.4% of their initial volume whereas basic samples only lost 0.1%. Weight determinations made at the start and end of the test periods indicate that the changes were in volume only. The fact that the density of all samples increased over a period of 24 hours without any observed loss in weight supports the air entrainment theory. The larger losses in volume exhibited by the fibre samples indicate that the fibre samples were better at expelling air bubbles or simply that they contained more bubbles to expel.

The presence of air in cut-off wall materials is not desirable. Bubbles locked into the wall after the slurry has cured constitute voids, which will inevitably reduce strength and increase permeability. However, it is unlikely that reduction in density, brought about in the fibre mix by air entrainment, is of sufficient magnitude to have a significant effect on trench stability.

4.3. RHEOLOGICAL PROPERTY DETERMINATIONS

Flow properties were determined by use of a Keller Colcrete P120 flowmeter (Fig. 1). The results, presented in Fig. 2 as plots of flow distance against the logarithm of setting time, show that both the basic and fibre mix exhibited most reduction in flow distance during the first ten minutes of setting. The difference in the flow distances exhibited by the basic mix between setting periods of 10 minutes and 1 hour is only 24% of that exhibited between 10 seconds and 1 hour. The corresponding figure for the fibre mix is 30%. For both mixes, the relationship between flow distance and the logarithm of setting time is linear. This suggests that the relationship can be represented by an equation of the form

$$f = -a . \log (t) + b$$

where f is the flow distance, t is the setting time and a and b are constants. The constant a, which relates to the gradient of the lines, is approximately equal to 48 for both mixes. This indicates that the difference in the flow distances achieved by basic and fibre samples is independent of setting time. The values of the constant b are approximately 455 and 430 for the basic and fibre mixes, respectively. Indeed, the flows measured for the fibre samples were on average 25 mm shorter than those for the basic samples.

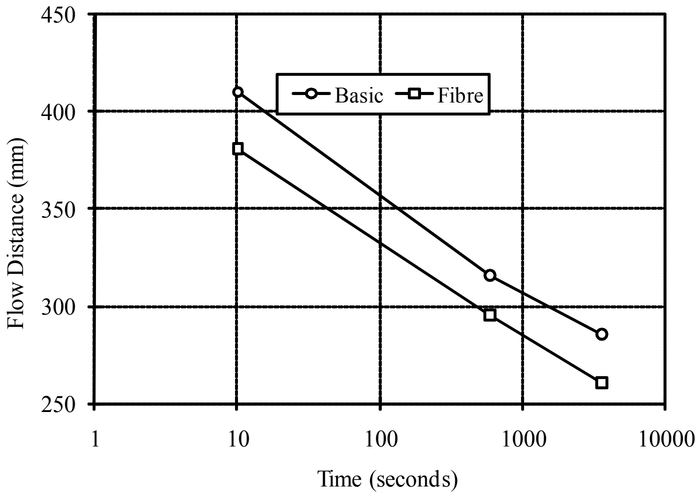

Fig. 2. Relationship of flow against setting time for basic and fibre reinforced CB slurry

The results indicate that the addition of fibres to the basic mix has a small but real effect on rheological properties. As expected, the magnitude of the effect, at least in terms of flow distance, seems to be independent of setting time. This suggests that fibres have a purely physical effect on the properties of fluid slurry, and do not affect the interactions which take place between the cement and bentonite particles. These interactions, as illustrated by the reducing rates of decrease of flow distance with setting time in Fig. 2, are time dependent.

The practical implications of the reduced flow characteristics of the fibre mix are not believed to be significant. The 10 second flowmeter reading achieved by the fibre mix is greater than the minimum distance of 350 mm that is usually acceptable for grouts. Since grouts generally need better flow characteristics than CB slurry this is encouraging. As mentioned above, the effect of the fibres does not appear to be time dependent, and therefore should become no worse with setting time.

4.3.1. PERMEABILITY DETERMINATIONS

The results of final 9 day permeabilities of all the samples are shown in Fig. 3. Where measurements were not taken at exactly 9 days from the start of testing, values

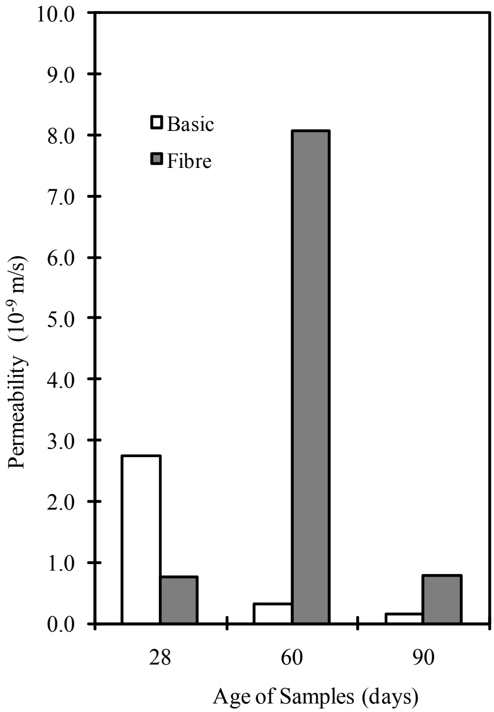

Fig. 3. Permeability of basic and fibre reinforced specimens at a range of curing periods

were interpolated from those obtained directly before and after the designated test period had elapsed. The 9 day results indicate that the permeability of all samples was below 10^{-8} m/s, as required for compliance with the BARKER et al. (1998) specification. Indeed, with the exception of two samples (28 day old basic and 60 day old fibre), all permeabilities were less than 10^{-9} m/s.

The 9 day permeability of both 60 and 90 day basic cured samples was lower than that for corresponding fibre samples. Conversely, the 28 day fibre sample exhibited lower permeability than the basic sample of similar age. It is possible that some of the variation in measured permeability was due to the use of different triaxial test machines.

The 9 day permeability of the basic mix reduced with sample age. The permeability of the 90 day basic sample was only 6% of that of the 28 day sample. The results suggest no similar pattern for the fibre samples. Indeed, the permeability determined for the 28 day fibre sample is very similar to that determined for the 90 day sample.

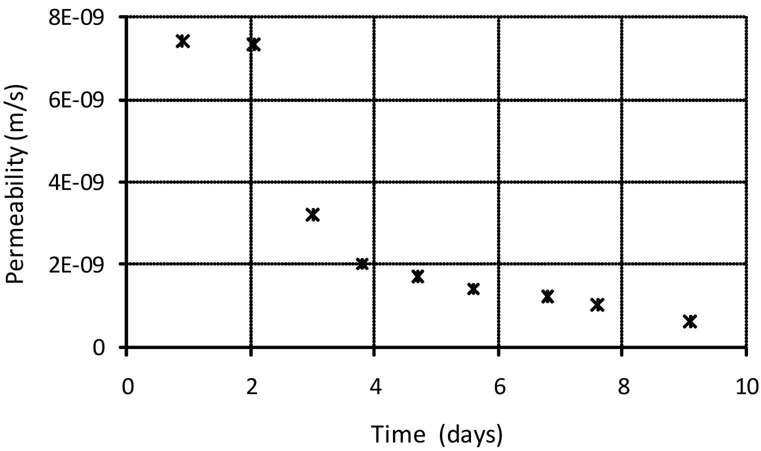

Fig. 4. Change in permeability with permeation time for specimens with permeability less than 0.5×10^{-9} m/s

All the specimens with 9 day permeability of greater than 0.5×10^{-9} m/s exhibited a reduction in permeability up to about 7 days. Thereafter, there was no significant reduction (see Fig. 4). For specimens with 9 day permeability less than 0.5×10^{-9} m/s there was little change in permeability with time of testing (see Fig. 5). The reason for this is not clear. However, the results indicate that permeability tests should be conducted for at least seven days or until constant values are obtained.

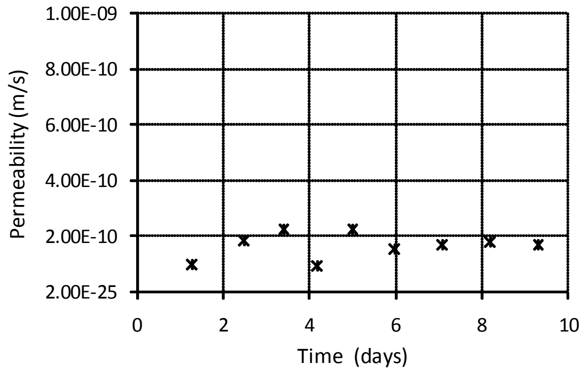

Fig. 5. Change in permeability with permeation time for specimens with permeability greater than 0.5×10^{-9} m/s

The slightly higher permeabilities exhibited by the fibre samples are believed to be a consequence of particle packing and poor bonding between the fibres and the cement-bentonite matrix. At such interfaces, discontinuities in the structure of the cured slurry material are likely to constitute lines of weakness along which flow can take place with slightly greater ease compared to the matrix. The influence of fibres on permeability was, however, relatively small.

4.3.2. UNCONFINED COMPRESSION STRENGTH AND REPEATABILITY

Unconfined compression strength (UCS) tests were carried out on three samples per mix per curing period to give some indication of the repeatability of the properties of the basic and fibre mixes. The results indicate that there was no real difference in results for both the basic and fibre mixes.

Table 3

Average UCS and strain at failure of sets of three samples

Averages of 3 samples	28 B	28 F	60 B	60 F	90 B	90 F
UCS (kPa)	169	189	273	564	336	558
Strain at failure (%)	0.59	1.05	1.01	1.67	0.90	1.58

B – Basic CB
F – CB containing fibre
28, 60 and 90 refer to age of samples in days

Although unconfined tests are not relevant to conditions within cut-off walls, for interest, the average peak strength and average strain at failure achieved by each set of samples are shown in Table 3. Values of both parameters are greater for fibre samples than for basic samples of the same age. As with the undrained testing the effect of curing period is obvious. Since all 90 day samples exhibited unconfined compressive strengths well in excess of 150 kPa, complete compliance with the Arup specification was achieved.

4.3.3. UNDRAINED COMPRESSION TESTS

Specimen results of stress strain relationships for undrained tests conducted at confining pressure of 60 kPa and 120 kPa cured at 28, 60 and 90 days are shown in Fig. 6.

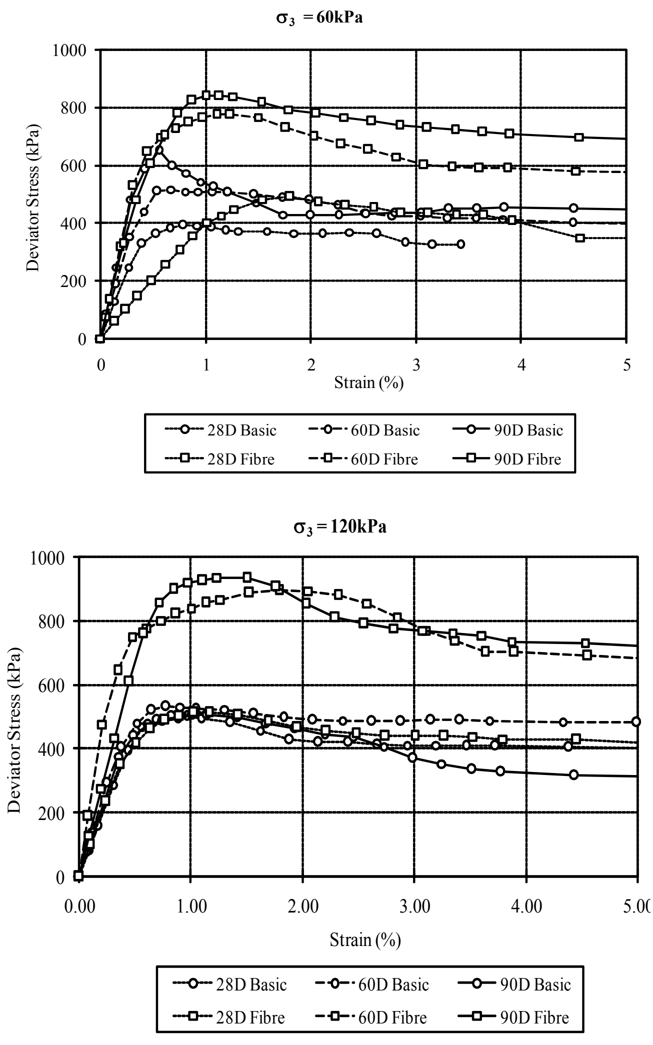

Fig. 6. Deviator stress versus axial strain relationship
for undrained triaxial compression tests at 28, 60 and 90 days

The slope of the stress strain curve steepens between 28 day and 60 day with no change thereafter. Results thus indicate that there is an increase in stiffness of specimen. In almost all cases specimens with fibres showed increased strain to failure. Typical results for specimen tested at confining pressure of 60 kPa and 120 kPa are shown in Figs. 7 and 8, respectively. Maximum deviator stress versus axial strain curves for samples cured for 28, 60 and 90 days and tested at cell pressures of 60 kPa and 120 kPa are shown in Figs. 9 and 10, respectively. There is significant improvement in strength when fibres are included and significant improvements were observed for 60 day and 90 day specimens. This suggests that formation of bonds between fibres and the matrix which helps to give overall strength increase.

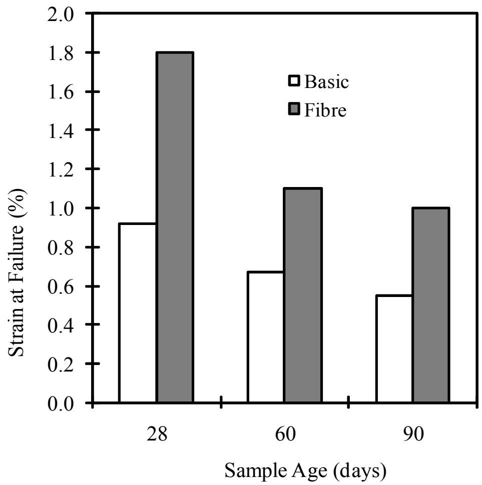

Fig. 7. Strains at failure achieved for samples tested at cell pressure of 60 kPa (undrained triaxial test condition)

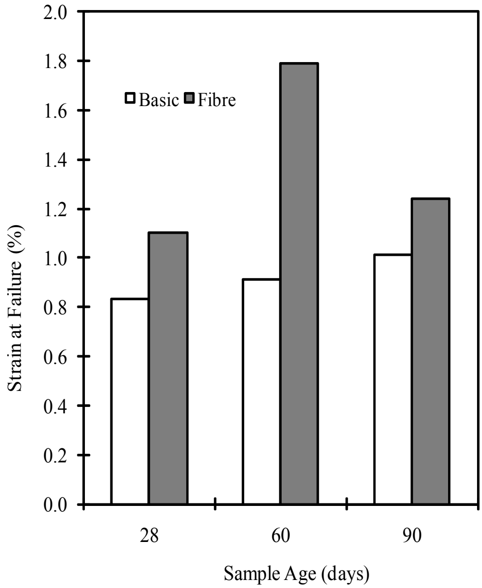

Fig. 8. Strains at failure achieved for samples tested at cell pressure of 120 kPa (undrained triaxial test condition)

Results of all the triaxial tests, including unconfined compression tests, in terms of cohesion and angle of friction are summarised in Table 4. No trend was observed in changes in cohesion except that values range between 50 kPa at 28 days and 72 kPa or more beyond 60 days. However, there was an increase in angle of friction (*Ø*) with time from 34° at 28 days to 45° at 90 days.

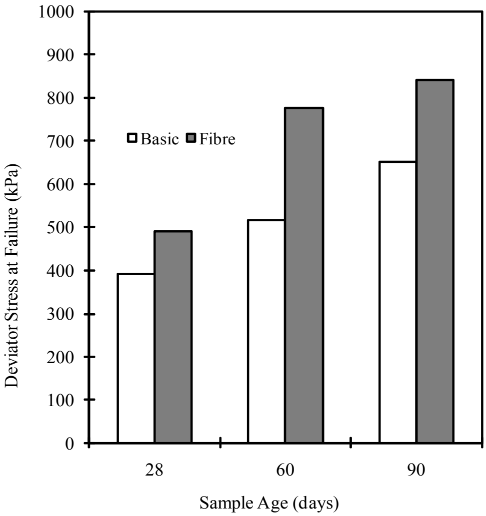

Fig. 9. Maximum deviator stress achieved for specimens tested at cell pressure of 60 kPa (undrained triaxial test)

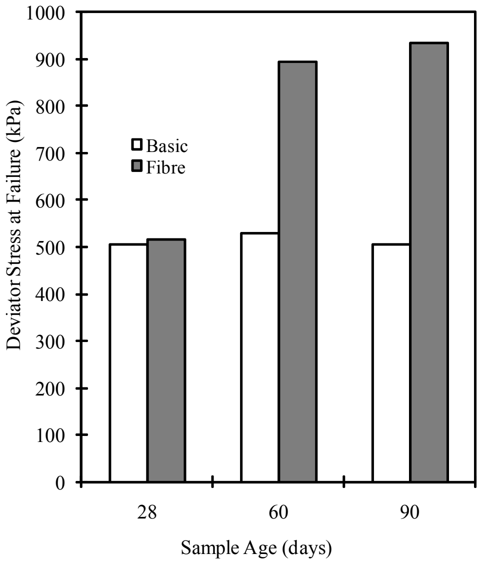

Fig. 10. Maximum deviator stress achieved for specimens tested at cell pressure of 120 kPa (undrained triaxial test)

Table 4

Summary of strength parameters from undrained triaxial tests

Time (days)	Cohesion (kPa)	Angle of friction, Ø (degrees)
28	50	34
60	116	38
90	73	45

The lowest value of undrained shear strength (c_u) achieved by any fibre sample was 95 kPa, which is well in excess of the 25 kPa required for compliance with the specification used at Pride Park (BARKER et al., 1998).

Inclusion of fibres also makes the specimens more ductile compared to unreinforced mixes as can be seen from results shown in Fig. 6. The increase in strains at failure due to the addition of fibres ranges from 23% to 97%. This type of behaviour was observed by DALL'AQUA et al. (2000), who investigated properties of fibre reinforced cement stabilised kaolin and laterite soils. Inclusion of fibres thus reduces brittleness. This would be of benefit in situations where there is need to avoid catastrophic failure, such as may be the case for structures in earthquake zones. Cut-off walls built from fibre reinforced slurry are likely to have a greater capacity for withstanding dynamic loads and in the short term, maintained loads, than those built from a basic mix.

4.3.4. DRAINED COMPRESSION TESTS

These tests were carried out at an effective confining stress of 120 kPa for 28 day and 90 day samples and of 60 kPa for 60 day samples. Results showed that there was about 15% increase in strength of reinforced specimens compared to unreinforced specimens (Fig. 11) at both 60 and 9 days. At 28 days fire reinforced specimen show a small strength reduction. This again suggests that cementitious bonds are formed after 28 days. In terms of strain inclusion of fibres suggests that fibre reinforced material is a little brittle compared to unreinforced material as shown in Fig. 12. Reasons for this are not clear.

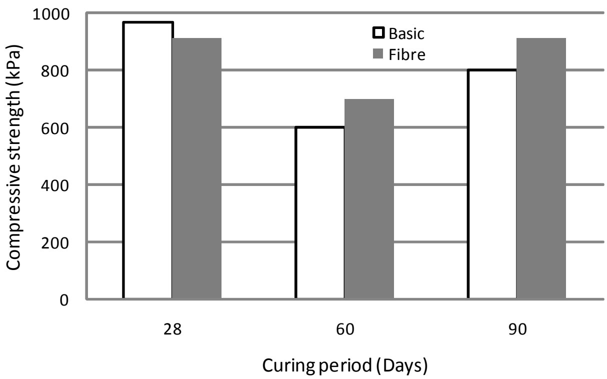

Fig. 11. Effect of fibres on compressive strength – drained tests

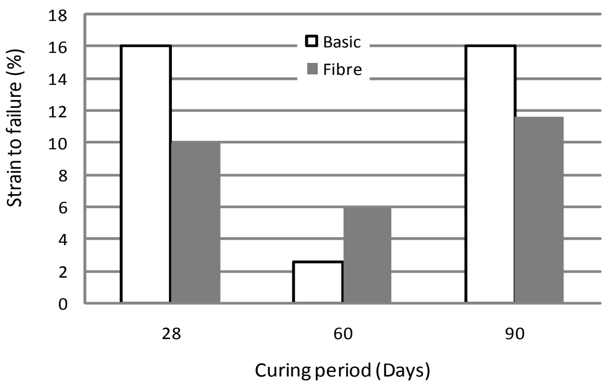

Fig. 12. Effect of fibres on strain to failure for drained tests

The relationship of volumetric strain and axial strain, shown in Fig. 13, illustrate that volume changes within fibre samples and basic samples follow similar trends. However, all fibre reinforced samples exhibit lower volumetric strain for any given axial strain than basic samples of the same age. The volume of all samples decreases as deviator stress is increased. As peak stress is approached, the rate of change in volume is reduced but still remains positive. Only after failure has occurred, do samples show any signs of maintaining constant volume with increasing axial strain.

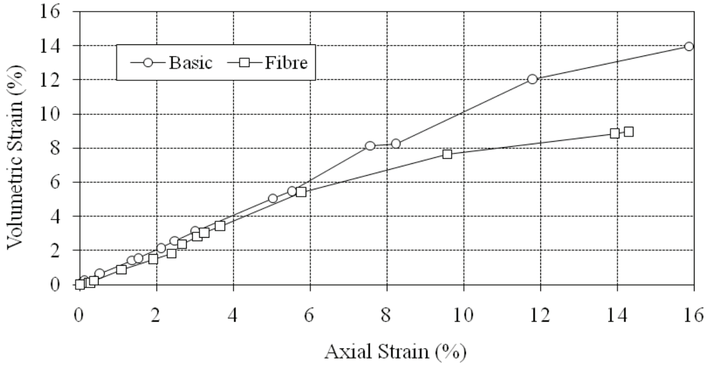

Fig. 13. Volumetric strain/axial strain relationship

5. CONCLUSIONS

The following conclusions are drawn from this investigation.

- Short polypropylene fibres can be mixed homogeneously in a cement bentonite slurry.
- An indication of the flow properties of fibre reinforced CB slurry can be gained by use of a Keller Colcrete P.120 flowmeter.
- The results of the bleed determinations indicate that the inclusion of polypropylene fibres significantly reduces bleed in CB slurry. This has significant benefits for slurry loss and in-trench mix stability.
- Density determinations suggest that fibres may entrain additional air bubbles into fluid CB slurry during mixing. However, much of the additional air seems to be expelled within a period of 24 hours from the cessation of agitation.
- The results of tests carried out using the Keller Colcrete P120 flowmeter suggest that fibres have a small detrimental influence on the flow properties of CB slurry. This is not believed to be of sufficient magnitude to compromise the efficiency of slurry trench construction.
- Permeability was slightly increased by the addition of fibres to the basic mix. However, all samples containing fibres exhibited 9 day permeabilities of less than 1×10^{-8} m/s and two thirds exhibited permeabilities of less than 1×10^{-9} m/s.
- In general, permeability was observed to decrease with time of permeation. This is attributed to the beneficial effect on curing brought about by the permeation of water through samples.

- Undrained shear strength and strain at failure were increased significantly by the addition of fibres to the basic mix. Tests carried out in unconfined conditions indicated similar trends.
- In drained compression tests, samples containing fibres exhibited reduced strains at failure compared to basic samples of the same age.

Overall, the results of the laboratory testing indicate that significant improvements to the properties of CB slurry can be made by the addition of polypropylene fibres. Not only has the fibre mix outperformed the basic mix in most tests, it has also achieved 100% compliance with the Arup specification.

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