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Properties of wet-mixed fiber reinforced shotcrete and fiber reinforced concrete with similar composition

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Abstract

Fiber reinforced shotcrete (FRS) is commonly used in slope protection, tunnel linings as well as structural repair and rehabilitation. For the design of shotcrete mixes, it is of interest to see if data on fiber reinforced concrete (FRC) can be employed as an initial guideline. In this study, various properties of FRS, including its compressive strength, flexural behavior, permeability and shrinkage behavior, are compared with FRC of similar composition. The results, based on five different mixes, indicate that the fabrication process (i.e., shotcreting vs. casting) can significantly affect compressive strength and permeability, but has relatively little effect on shrinkage behavior. The flexural strength of FRS is slightly higher than that for FRC in most cases, but the residual load carrying capacity in the postcracking regime can be significantly lower. Based on the differences in the properties of FRC and shotcrete, implications to material design are discussed.

Keywords: Shotcrete; Fiber reinforcement; Flexural behavior; Permeability; Shrinkage

1. Introduction

Shotcrete finds applications in many construction processes. Common examples include the repair and rehabilitation of concrete structures, the building of tunnel linings, as well as the stabilization of rock and soil slopes. To prevent cracking of the shotcrete layer, steel mesh is often placed before the shotcreting operation. The placing of mesh is a labor-intensive and time-consuming process. Moreover, the presence of mesh may result in a 'shadowing' effect, leading to the formation of large voids at regions where the shotcrete has difficulty penetrating the mesh. As an alternative to using steel mesh, the incorporation of fibers can also improve the crack resistance and strength of the shotcrete layer. Indeed, in many tunneling projects, over the world, with the use of fiber reinforced shotcrete (FRS), steel mesh in the lining can be removed [1]. In Ref. [2], the application of FRS (without steel mesh) in slope stabilisation, repair and the construction of shell structures is described. Based on available information in the literature, FRS appears to be a competitive alternative to mesh reinforced shotcrete for many applications. Indeed, various institutions have developed design guidelines for the use of shotcrete in practice [3,4].

Similar to concrete, the design of FRS is based on empirical information obtained from material tests [5,6]. When a new type of fiber is employed or when a certain application imposes new requirements on material properties, a large number of tests may have to be performed to come up with the appropriate mix design. Because concrete specimens are much easier to prepare than shotcrete specimens, it is of practical interest to see if tests can be conducted on fiber reinforced concrete (FRC) first to provide guidelines for the preliminary mix design of FRS. It should be emphasized that for the FRC results to be useful, the composition of the FRC must be suitable for shooting. Due to the difference in compaction processes, FRS and FRC with the same mix proportions are expected to have different properties. Banthia et al. [7] have conducted an investigation to compare the compressive and flexural properties of FRC and FRS with the same composition. In their work, deformed steel fibers with five different geometries were studied. In the present investigation, FRC and FRS specimens were prepared with different types of fibers including steel (ST), polypropylene (PP), polyvinylalchol (PVA), as well as a hybrid of PP and PVA. The compressive and flexural properties, shrinkage behavior and permeability of the FRC and FRS were measured. If a

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correlation between FRS and FRC properties exists, then, preliminary FRS compositions for various applications can be determined based on the results of tests on FRC.

FRS is commonly used in slope protection and surface repair of structures. In these applications, the surface area to volume ratio of the shotcrete layer is high. Shrinkage and restrained shrinkage cracking are therefore important concerns. The resistance to shrinkage cracking depends on the flexural behavior of the FRS, including both the flexural strength and the postpeak load-carrying capacity [2]. In some applications (e.g., protection of soil slopes), the shotcrete layer has to prevent water penetration, thus, the permeability of FRS is also important. Following the above discussions, the present study focuses on comparing the flexural properties, shrinkage and permeability of FRS and FRC. Because compressive strength is the most commonly reported parameter in concrete technology, it was also measured for comparison. Note that the conclusions drawn from the study are only applicable to the wet-mix FRS, prepared as described in the following section. Shotcrete prepared by the dry-mix process may perform differently.

2. Specimen preparation

In this paper, results from five different sets of specimens are reported. Each set consists of FRS and FRC members of the same composition. The mix proportion of the cementitious materials plus aggregate matrix is the same in all cases and is given in Table 1. (Note: the stone fines are crushed aggregates with size between 0.15 to 5 mm.) One set of specimens contained no fiber, i.e., plain matrix. The other four sets were prepared with 0.5% PP fiber, 0.5% PVA fiber, 0.5% ST fiber and a combination of 0.5% PP and 0.3% PVA (hybrid) fibers. Details of each fiber are shown in Table 2. For the shotcrete specimens, all the constituents were first mixed in a large portal mixer. The mix was then pumped through a pipeline and sprayed through a nozzle onto wooden forms to produce panels about 1.2 × 1.2 m in size. The shotcreting process was controlled by a robot arm that could rotate the nozzle and move it along different directions. During shotcreting, the panels were oriented at about 60° to horizontal. The nozzle tip was held at about 1 m from the panel, and the spraying direction was perpendicular to the panel surface. With controlled scanning motion of the nozzle, shotcrete was applied layer by layer onto the form. Spraying continued until the panel thickness was slightly higher than the thickness of the formwork. The extra shotcrete was carefully screeded off, and a float was employed to produce a smooth surface.

Table 1
Composition of mix (kg/m^3)

Cement	Stone fines	River sand	Water	Silica fume
430	1097	365	275	35

Table 2
Fiber details

	Length (mm)	Diameter (μm)	tensile strength (MPa)	E (GPa)	Specific gravity
ST (hooked)	35	500	1150	200	7.84
PP	15	37	80–110	3.5	0.9
PVA	12	50	1530	33	1.3

The panel thickness varied according to different testing requirements. For bending and shrinkage tests, panels of 100-mm thickness were made, and specimens of the required length were saw cut from the panel. For compressive strength and permeability tests, 200-mm-thick panels were prepared for the coring of the specimens. Because material close to the sides of the formwork might not be well compacted in the shotcreting process, materials within 50 mm from each side were cut off and discarded before specimens were obtained from the panels.

To reduce excessive rebound, wet-mix shotcrete with silica fume was employed. Silica fume improves the adhesive properties of shotcrete, enabling the cementitious matrix to stick onto inclined and vertical surfaces better. Accelerator was not used, as its addition will make a weaker shotcrete [8]. To quantify rebound, a separate panel (100 mm in depth) was prepared by shotcreting in the same way as described above. During shotcreting, a plastic sheet was placed on the ground around the panel so any rebound material could be collected and weighed. The panel was also weighed both before and after shotcreting. Knowing the weight of material inside the panel (W_s) and the weight of rebound material (W_r), the total rebound is calculated as the ratio $W_r/(W_r+W_s)$. Physically, this value represents the fraction of total material shot at the panel that goes into rebound.

A sample about 20 kg in weight was then taken from the shotcrete panel. Based on the measured weight and density, the volume was obtained. Water was then applied to wash out the particles in the sample, while fibers were carefully collected and weighed. Following Banthia et al. [9], the fiber rebound R_{fv} (in percent) was calculated using the following equations:

$$V_{fw} = ((M_{fw}/D_f)/V_w) \times 100 \tag{1}$$

$$R_{fv} = ((V_{fo} - V_{fw})/V_{fo}) \times 100 \tag{2}$$

where

D_f is the density of fibers
M_{fw} is the mass of fibers in the shotcrete sample taken from the panel
V_w is the volume of the shotcrete sample
V_{fo} is the original fiber volume fraction

V_{fw} is the fiber volume fraction in the shotcrete sample
R_{fv} is the fiber rebound by volume (%)

For the various mixes, the total rebound ranged from 6.1% to 7.3% while the fiber rebound (R_{fv}) was 9.0%, 8.0%, 7.8% and 7.2%, for steel, PP, PVA and hybrid fibers, respectively.

For each mix, FRC specimens of the required size were also prepared by casting into steel moulds. Compaction was performed with a hand-held vibrator. To avoid disturbance of the fiber distribution, the vibrator was not inserted inside the concrete but simply held in touch with the side of the mould and the surface of the concrete.

After the shotcrete panels and cast concrete specimens were made, they were kept wet for 1 day on the site before transporting (wet) back to our laboratory. Then, FRS specimens were cut or cored from the panels, and FRC specimens were removed from the moulds. All specimens for compressive, flexural and permeability tests were then kept in a 100% relative humidity curing room for 28 days. For the shrinkage tests, the specimens were instrumented with Demec gauges and placed in an environmental room at 50% relative humidity and 28 °C.

3. Experimental results

3.1. Compressive strength

Shotcrete is seldom required to carry compressive load. However, because the compressive strength of concrete is the most commonly reported material parameter, and concrete design is often based on this particular property, it is of interest to see how the compressive strength of FRS and FRC compares. To perform compressive strength testing, cylindrical specimens of $\phi 100 \times 200$ mm were employed. Shotcrete specimens were cored from the 200-mm-thick panels while concrete specimens were cast directly into steel molds. Testing was carried out after 28 days of curing. Three specimens were tested for each mix to obtain the average value. Test results for various compositions are shown in Table 3.

From Table 3, the compressive strength for FRC specimens is higher than that for FRS specimens in all cases.

Table 3
Compressive strength for various compositions of shotcrete and concrete

Composition	Shotcrete specimens σ_c (MPa)	Concrete specimens σ_c (MPa)	$(\sigma_c)_{FRS}/(\sigma_c)_{FRC}$
Plain	32.4	42.9	0.76
0.5% PP	32.2	38.6	0.84
0.5% PVA	25.7	36.8	0.70
0.5% Steel	33.4	58.0	0.58
0.5% PP + 0.3% PVA	26.6	44.5	0.60

σ_c is compressive strength.

Concrete specimens were compacted with conventional means, with the use of the vibrator. This appears to be more effective in removing trapped air than the shotcreting process was, where shotcreting compacts the concrete with pressure when it is shot onto the form. In most cases, the compressive strength of FRS specimens is below 75% of the value for FRC specimens. The results are in agreement with the findings of Banthia et al. [7] that FRS specimens generally exhibit significantly lower compressive strength than FRC specimens of the same composition do.

Although our major interest is to compare FRC and FRS specimens of the same composition, it is also informative to look at the difference in strength between plain and fiber reinforced specimens. For specimens with 0.5% PP and 0.5% PVA fibers, the compressive strength for both FRC and FRS specimens is lower than that for plain concrete. A possible explanation is that the incorporation of small diameter fibers into the mix makes compaction more difficult, and hence, more entrapped air stays in the final specimen. For the mix with steel fibers, the compressive strength for both FRC and FRS specimens is higher than that for plain concrete. Specifically, for FRC, the increase is over 30%, which is very high when compared with reported results [2]. In the specimen preparation process, the amount of material required for making all the specimens far exceeds the capacity of the portal mixer. As a result, many different batches (that should have had the same composition) had to be used. The exceptionally high strength of the steel fiber FRC specimen leads us to suspect that the particular batch for making these specimens had a different composition to the other batches. The compressive strength is hence different. For the case with hybrid fibers (0.5% PP + 0.3% PVA), the strength for FRC is slightly higher than in the plain concrete, while that for FRS is lower. The slight strength improvement for FRC may be due to the better control of cracks when more fibers are added. In the FRS specimens, however, this effect does not appear to be strong enough to compensate for the increased porosity due to insufficient compaction.

3.2. Flexural strength, toughness indices and residual load

The ASTM C1018 test method [10] was employed to study the flexural behavior of fiber reinforced matrices. Beam specimens of approximately $350 \times 100 \times 100$ mm in size were tested over a span of 300 mm to obtain the flexural strength and toughness indices. Note that the above member size is exact for cast FRC specimens, but ‘approximate’ for FRS specimens cut from the shotcrete panel, as the panel thickness varies slightly over its area. To ensure proper calculation of the various parameters, the actual size of each FRS specimen was measured. For each composition, three FRC and three FRS specimens were tested. To show the trend of the load versus deflection behavior, the averaged load versus deflection curves for various compositions of FRC and FRS are given in Fig. 1a to d. To analyse the results, the flexural strength, as well as the toughness indices I_5, I_{10} and I_{20}, are obtained according to the current version of ASTM C1018. Specifically, the toughness indices were calculated from the ratio between (i) the area under the load deflection curve up to 3, 5.5 and 10.5 times the first crack deflection and (ii) the area up to the first crack deflection. The results for flexural strength and toughness indices are summarized in Table 4.

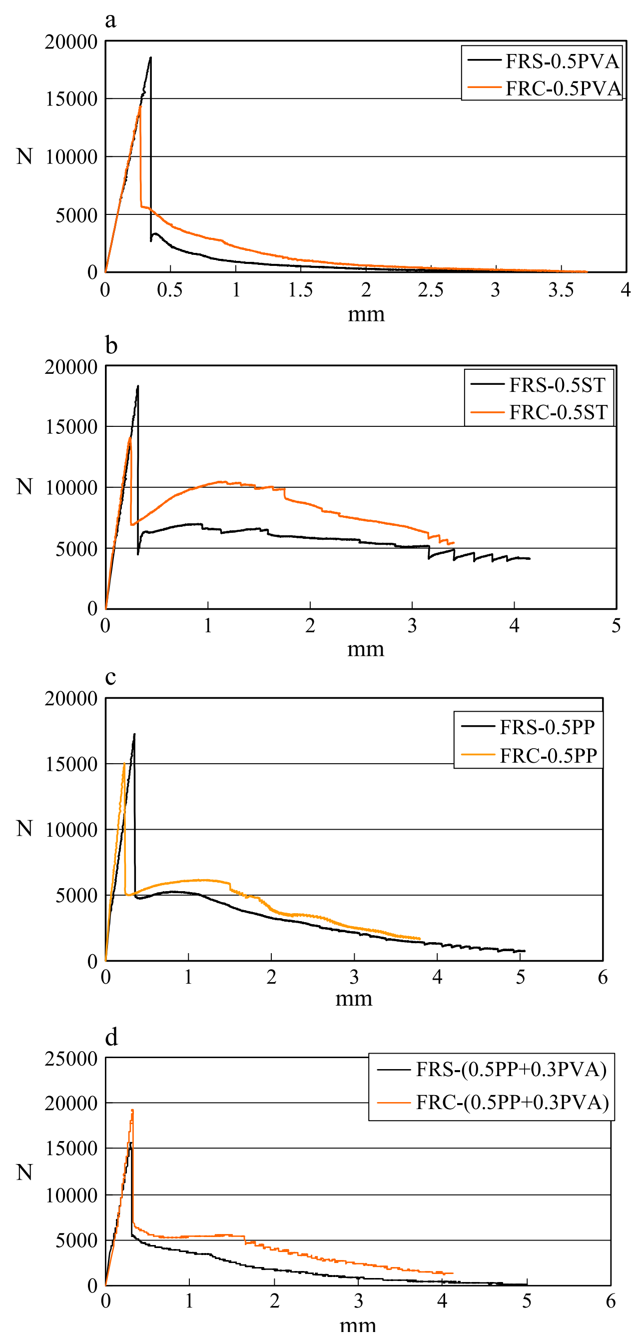

Fig. 1. (a) Averaged load/deflection curve of PVA fiber specimens. (b) Averaged load/deflection curve of steel fiber specimens. (c) Averaged load/deflection curve of PP fiber specimens. (d). Averaged load/deflection curve of hybrid fiber specimens.

Table 4
Flexural behavior of various compositions of shotcrete and concrete

Composition	Flexural strength (MPa)	Toughness indices (C1018)			$(\sigma_f)_{FRS}/(\sigma_f)_{FRC}$
		I_5	I_{10}	I_{20}	
Plain shotcrete	5.25	1.0	1.0	1.0	1.10
Plain concrete	4.79	1.0	1.0	1.0	
0.5% PP FRS	4.43	2.2	3.2	4.1	1.03
0.5% PP FRC	4.30	2.3	3.9	6.1	
0.5% PVA FRS	5.49	1.5	1.7	1.8	1.17
0.5% PVA FRC	4.68	2.0	2.3	2.4	
0.5% ST FRS	4.87	2.9	5.6	10.0	1.05
0.5% ST FRC	4.66	3.8	7.0	11.5	
PP + PVA FRS	4.57	2.0	3.0	3.9	0.80
PP + PVA FRC	5.72	2.2	3.6	5.1	

In calculating the toughness indices, the point corresponding to 'first crack' on the load deflection curve is subjectively determined. The accuracy of its determination has always been a concern. Moreover, as pointed out by Morgan et al. [11], I_5 and I_{10} are not very useful indicators of the postpeak load carrying capacity because they may fall within the zone of instability of the load versus deflection curve. Indeed, in the latest draft version of ASTM C1018, to eliminate these concerns, reporting of the residual loads at $L/600$ and $L/150$ (where L is the loading span) are recommended. Following this recommendation, the residual loads at $L/600$ (i.e., 0.5 mm) and $L/150$ (i.e., 2 mm) are shown in Table 5. As a reference, the peak load for each composition is also provided. In both Tables 4 and 5, each result represents the average from three specimens.

Results in Table 4 indicate that the flexural strengths for FRC and FRS specimens are within 20% of one another. In three out of five cases, they are within 10%. Moreover, for all cases, except the hybrid fiber composite, the FRS specimens exhibit a higher strength than the corresponding FRC. This trend, which is opposite to that for compressive strength, is again in agreement with the observations in Banthia et al. [7]. A possible explanation is as follows. The addition of fibers has two effects on the specimens. First, it makes compaction more difficult and hence increases the porosity of the specimen. Second, the presence of fibers provides bridging stresses to control the propagation of cracks. Under compression, failure occurs through the coalescence of propagating cracks. A higher porosity implies a larger number of weak zones for cracks to form.

Table 5
Peak and residual load from flexural test

Load (N)	FRS			FRC		
	Peak load	Residual load		Peak load	Residual load	
		$L/600$	$L/150$		$L/600$	$L/150$
0.5% PP	17 254	4897	3264	15 029	5486	3961
0.5% PVA	18 555	2333	283	14 332	4091	583
0.5% Steel	18 298	6388	5827	14 020	8230	8606
Hybrid	15 588	4524	1730	19 220	5690	3956

It appears that in the cases studied, the bridging stress provided by fibers is not sufficient to compensate for the increased crack density. As a result, the compressive strength is dominated by the porosity, and the FRC specimens that have lower porosity exhibit higher compressive strength.

In bending, failure is caused by tension and is governed by the largest crack in the specimen. With increased porosity, the maximum crack size is also likely to increase. However, for the propagation of a single crack, bridging stress provided by fibers is effective in delaying ultimate failure. While the overall compaction of FRS specimens is not as good as that for FRC specimens, ‘squeezing’ of the mix at the nozzle of the shotcreting gun may densify the fiber/matrix interface. Moreover, in the shotcreting process, preferential alignment of fibers may occur [6]. With a better interfacial bond and better alignment, the fibers in FRS are more effective in controlling crack propagation. As a result, a higher flexural strength is obtained for FRS specimens in most cases. The exception is the hybrid fiber composite, where the FRC specimens exhibit higher flexural strength. In this case, the high fiber volume may have led to the formation of large pores in the FRS, causing a significant strength reduction that cannot be compensated for by the increased bridging effect. This argument is supported by the lower compressive strength of the hybrid (PP + PVA) FRS relative to FRC (Table 3), indicating a higher porosity of the shotcrete specimens.

From Table 4, the toughness indices (I_5, I_{10} and I_{20}) for FRS is always lower than that for FRC of the same composition. This differs from the findings in Banthia et al. [7] that some FRS specimens give higher toughness indices than corresponding FRC specimens do. When the toughness indices (I_5, I_{10} and I_{20}) for FRS and FRC of similar compositions are compared, they are normally within 20% and 25%, although a larger difference of over 30% is obtained for the 0.5% PP composite. However, if one looks at the results in Table 5, the residual loads of FRS at $L/600$ and $L/150$ are 11–43% and 18–56%, respectively, lower than in FRC. In other words, a much larger difference in performance between FRC and FRS is reflected by the residual load than by the toughness indices. From a practical point of view, we are interested in the actual force or stress that prevents the crack from opening. In this sense, the residual load values are more meaningful indicators than the toughness indices are, which represent ratios of areas. The above results show that comparison of postpeak flexural performance in terms of toughness indices may be misleading, and the residual loads should be considered, as recommended by the new draft of ASTM C1018.

FRS specimens with 0.5% of PP, PVA or steel fibers have higher flexural strengths than do corresponding FRC specimens, but lower load-carrying capacity after the first crack is formed. As explained above, the higher flexural strength is probably due to the preferential fiber alignment and better bond between the fibers and matrix in the FRS specimens. An improved bond, however, also makes it easier for fiber rupture to occur. After the peak load is reached, there are then less fibers bridging the crack. In addition, for fibers that are inclined to the crack, higher stress carried by the fiber will introduce higher stresses on the matrix around the fiber exit point, which increases the likelihood of local matrix spalling (Fig. 2) [12,13]. Either of these mechanisms can lead to a reduction in postpeak load. For the hybrid composite, the high porosity in the FRS specimen may affect both the peak load and the postpeak behavior, thus, the toughness indices and residual loads of FRS are also lower than those for the FRC specimens.

3.3. Permeability

To perform the permeability test, a novel approach developed at HKUST was employed [14]. Both cast FRC cylinders and cored FRS specimens with 100-mm diameter were cut into specimens 80 mm in length. A waterproofing primer was applied to the sides of the specimen, and its top and bottom were ground flat and smooth. The specimen was then put into the permeability cell, as shown in Fig. 3. In the cell, deionized water was added into a water reservoir above the specimen. Then, the permeability cell was placed inside an autoclave, where a pressure ranging from 0.67 to 1 MPa was applied at room temperature for 24 h to accelerate the penetration of deionized water into the specimen. The range of pressure was determined from experience to ensure that the water should penetrate deep enough into the specimen for reliable measurement of its depth. However, it should not penetrate through the whole depth. Otherwise, only a lower bound value for the permeability can be obtained. After the specimens were taken out of the permeability cell, the increase in mass was first measured. Loading was then applied as in the Brazil Test to split the specimen into two halves. From each half, the depth of water penetration was identified from the boundary between wet and dry concrete (which shows different colors). The penetration depth was measured at 10 locations across each section to obtain an average

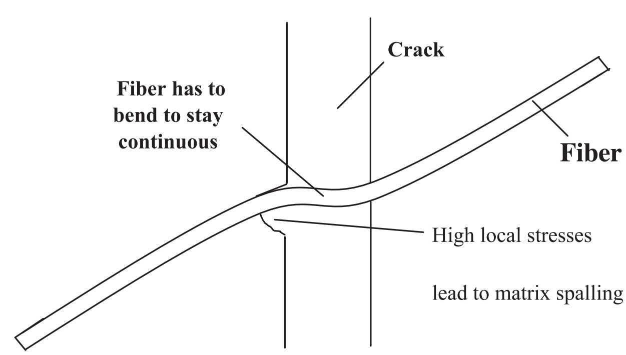

Fig. 2. Matrix spalling leading to reduction in fiber bridging force.

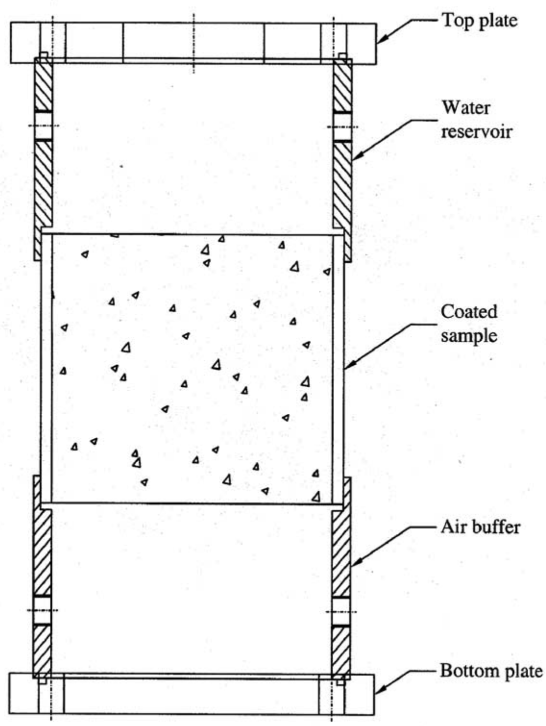

Fig. 3. Cell and specimen for the permeability test.

value. The permeability coefficient (k) was then calculated from Refs. [15,16]:

$$k = vd^2/2ht \tag{3}$$

$$v = M/Ad \tag{4}$$

where d = depth of penetration of concrete (m); v = the fraction of the volume of concrete occupied by pores; h = hydraulic head (m); t = time under pressure (s); M = the gain in mass (g); and A = cross-sectional area of the specimens (mm^2).

The permeability results for all tested specimens are shown in Table 6. The results indicate high variability of the permeability coefficient among the same types of specimens, which is quite common for permeability measurements. However, the difference between FRC and FRS specimens of the same composition is significantly greater than the variation among the FRC or FRS specimens themselves. For all mixes, shotcrete specimens exhibit higher permeability coefficients than do concrete specimens of the same composition, and are hence more permeable. This can again be explained by the higher porosity in shotcrete specimens resulting from less effective compaction. In the specimen preparation procedure, we observed that the PVA fibers had a tendency to ball up. The results indicate that this has a particularly large effect on increasing the permeability coefficient of FRS relative to FRC. Based on the results on compressive strength tests, we pointed out that the porosity in the fiber reinforced

Table 6
Permeability for various compositions of shotcrete and concrete

Composition	Specimen	Shotcrete k ($\times 10^{-12}$ m/s)	Concrete k ($\times 10^{-12}$ m/s)	Average $(k)_{FRS}/(k)_{FRC}$
Plain	1	8.110	0.442	16.7
	2	6.714	0.416	
	3	8.258	0.520	
0.5% PP	1	0.976	0.379	13.1
	2	5.933	0.380	
	3	8.026	0.376	
0.5% PVA	1	15.853	0.471	28.6
	2	4.131	0.530	
	3	15.133	0.227	
0.5% Steel	1	9.032	1.605	8.5
	2	11.515	1.041	
	3	6.484	0.520	
0.5% PP +	1	35.097	0.358	44.7
0.3% PVA	2	12.577	0.922	
	3	24.981	0.347	

specimens may be higher than that in the plain specimens. If so, the permeability for the plain FRC or FRS should also be the lowest. From Table 6, this is not the case, in general. The lower permeability for some fiber reinforced specimens may be due to the presence of fibers that reduce internal microcracking (e.g., due to shrinkage) in the cementitious matrix and hence improve the resistance to water penetration.

3.4. Shrinkage

To study the shrinkage of FRC, 500 × 100 × 100 mm concrete prisms were cast directly in steel moulds. FRS specimens of similar size were cut from shotcrete panels. After 1 day of curing, Demec gauges (with gauge length of 200 mm) were glued onto four surfaces of each specimen, as shown in Fig. 4. The specimens were then placed in an environmental room with a relative humidity of 50% and temperature of 28 °C. To measure shrinkage as a function of time, the strains recorded on four surfaces of each specimen were averaged. For each composition, and for each of the concrete and shotcrete mixes, three specimens were employed for shrinkage testing. Typical results are shown in Fig. 5a to c. Each line was obtained as the average reading for the four surfaces of a particular specimen. For all the compositions studied, the shrinkage behaviors of FRC and FRS were found to be very similar. In some cases, the

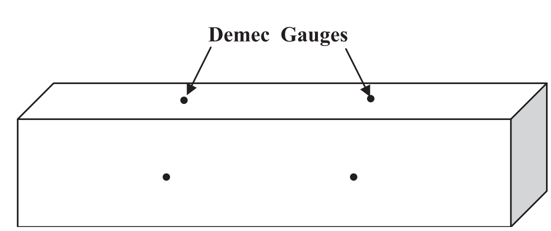

Fig. 4. Specimen for shrinkage measurement.

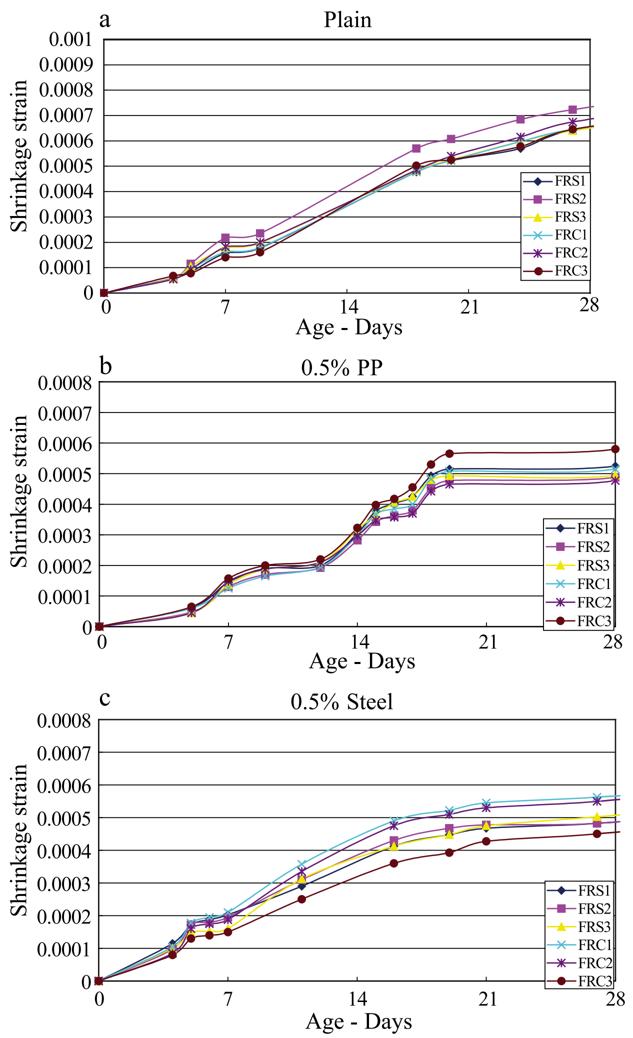

Fig. 5. (a) Shrinkage strain vs. time for plain concrete specimens. (b) Shrinkage strain vs. time for 0.5% polypropylene fiber specimens. (c) Shrinkage strain vs. time for 0.5% steel fiber specimens.

FRC specimens were found to shrink more. For other cases, FRS specimens showed higher shrinkage. From a practical point of view, the difference in the shrinkage behavior of FRC and FRS specimens is considered not significant [8].

4. Discussions and implications to design

In the discussion above, various properties have been measured for FRS and FRC with the same composition. From the results, we would like to see if it is possible to carry out preliminary mix design of FRS based on data on FRC. In the following discussions, we focus on two common applications of FRS, namely, repair of structures and waterproofing of soil slopes. In these applications, FRS is placed over a large area as a relatively thin layer. Shrinkage is therefore a major concern. In addition, differential and constrained shrinkage may result in high tensile stresses and cracking. The flexural strength is hence of interest, but the residual loads (at deflections of $L/600$ and $L/150$) are also important because they control the crack opening after cracking occurs. As FRS is not intended to carry compression, the compressive strength is not needed for design. However, because it is the most commonly measured parameter for cementitious materials, it is of interest to see if it correlates with the other FRS properties.

As shown in Fig. 5, the shrinkage behavior of FRS and FRC is very similar. Under similar conditions, the FRS and FRC specimens will shrink to similar extents. The flexural strength for FRS and FRC are similar, with FRS showing a higher value in most cases (four out of the five mixes studied). On the other hand, the residual loads of FRS at $L/600$ and $L/150$ are, respectively, 11–43% and 18–56% lower than the corresponding values for FRC. With higher flexural strength, it is more difficult for the FRS specimens to crack, but once cracking has started, the lower postcracking force will allow cracks to open wider. The implications to shotcrete layer design are as follows. In most applications, the strain due to restrained shrinkage is well beyond the strain when the flexural strength is reached. When there is significant restraint on the shotcrete layer, cracking will occur, and the crack opening is governed by the postcracking load-carrying capacity of the FRS. Because the residual loads for FRS are significantly lower than that for FRC, if one wants to come up with a trial mix for FRS with given residual load requirements, a FRC mix with much higher residual load values should be employed. In certain special applications, such as the repair of internal surfaces of a water or sewage pipe, the high humidity of the environment may limit the shrinkage to small values. For such cases, as long as the stress produced by restrained shrinkage does not exceed the flexural strength, no cracking will occur. Because the flexural strength of FRS is comparable to that of FRC, and higher in most cases, one can select preliminary FRS mixes directly from results on FRC, obtained either from the literature or from new tests conducted in the laboratory. (Note: when FRS mixes are designed based on FRC results, the FRC should have a composition suitable for shooting.) In summary, because most laboratories do not have proper shotcreting facilities, and shotcrete specimens are far more time consuming to prepare than concrete members is, it is advisable to perform preliminary tests on FRC specimens first. Based on the understanding that the flexural strength for FRS and FRC are similar, while the residual loads can be up to 50% lower for FRS, appropriate FRC mixes can be identified to prepare corresponding FRS specimens for further experiments.

When waterproofing is a concern, permeability is an important parameter to be considered. From Table 6, it is clear that the permeability of FRS can be one to two orders of magnitude higher than that for FRC of similar composition. To come up with a trial mix of FRS to fulfil permeability requirements, the composition for an FRC with much lower permeability should be employed.

It should also be pointed out that the compressive strength differences between FRS and FRC do not correlate well with the flexural strength and shrinkage behavior. From Table 3, the compressive strength of FRS is consistently below that of FRC, by up to 30–40% in three out of the four compositions of FRS. However, the shrinkage behavior of FRS and FRC is essentially the same, and the flexural strength of FRS (Table 4) is higher than that of FRC for most cases (except the case with hybrid fiber reinforcement, where there may be high porosity). In addition, despite the fact that both the compressive strength and residual loads for FRS are lower than for FRC, a correlation between corresponding mixes does not seem to exist. For example, the steel mix shows a higher difference in compressive strength between FRS and FRC than the PVA mix (Table 3), but the reduction of residual loads (at both $L/600$ and $L/150$) for the PVA mix is much higher (see results on Table 5). Therefore, it is not possible to predict the postcracking behavior from the compressive strength. If shrinkage cracking is an important concern, trial mixes for FRS should not be selected based on the compressive strength of FRC.

For permeability, except for the steel fiber composite, a larger relative difference in compressive strength does indicate a higher increase in the permeability of the FRS specimen. However, we do not have sufficient data to obtain a quantitative correlation between the compressive strength and the permeability of FRS. If waterproofing is important, the permeability test should be carried out.

5. Conclusions

In this paper, various properties for FRS were measured to provide new data for the interested reader. Moreover, the properties of FRS and FRC with similar compositions are compared. Based on our experimental results, FRS and FRC are found to exhibit similar shrinkage behavior. The flexural strength of FRS is similar with that of FRC (and is a bit higher in most cases), but the residual loads in the postpeak regime can be significantly lower. In addition, the permeability of FRS can be over one order of magnitude higher than the corresponding FRC. In practical applications of shotcrete, resistance to shrinkage cracking (with strain due to restrained shrinkage well beyond the strain at flexural cracking) and waterproofing is often a major concern. When test results on FRC are employed for the preliminary mix design of FRS, a FRC composition with higher residual loads and much lower permeability than the required values should be employed.

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