INFLUENCE OF POLYVINYL ALCOHOL FIBRE ADDITION ON FRESH AND HARDENED PROPERTIES OF CONCRETE

A. NOUSHINI[1*†], B. SAMALI[2], and K. VESSALAS[3]

[1, 2, 3] *Centre for Built Infrastructure Research, School of Civil and Environmental Engineering, University of Technology Sydney, Australia*

ABSTRACT

This investigation assesses the performance of using uncoated poly-vinyl alcohol (PVA) fibres of two geometric lengths (6 and 12 mm) in concrete. Based on total concrete volume, 3 fibre fractions of 0.25%, 0.5% and 1% were evaluated for their effect on fresh and hardened properties of PVA fibre reinforced concretes (FRCs). By carrying out a comprehensive set of experiments, an effective method of mixing fibre was adopted (based on modification of the Australian Standard AS 1012.2 test method). In comparison to control concrete (devoid of PVA fibre), slump and mass per unit volume were found to decrease while air content remained similar with increasing fibre addition. Optimum fibre addition was established for 0.25% PVA-FRC with 16% improvement noted in compressive strength compared to control concrete at 28 days. Relative strength gain from 7 to 28 days was also observed to be higher for all PVA-FRCs.

Keywords: Fibre reinforced concrete (FRC), polyvinyl alcohol (PVA) fibre, fresh properties, compressive strength

1. INTRODUCTION

Fibre reinforced concrete (FRC) is made by integrally adding and mixing discontinuous small randomly distributed fibres within concrete. Incorporation of polymeric fibres in concrete are recognised to be most effective in controlling and mitigating susceptibility to plastic shrinkage cracking. In the role of intrinsic reinforcement, these fibres contribute to improving the ductile and damping behaviour of the concrete. Indeed, limited research carried out to date on the novel inclusion of polyvinyl alcohol (PVA) fibres in engineered cementitious composites has proven that ductility and post peak behaviour may be enhanced (Gencturk 2011) . Fibres are known to increase energy absorption capacity and toughness when added to concrete. Concrete is considered to be a brittle material that is weak in tension and, thus, shows no post peak behaviour. The ductility of concrete may be improved by using fibres to enhance the tensile and flexural strength properties. Previous research has demonstrated that reinforcing concrete with micro fibres does not contribute

[*] Corresponding author: Email: amin.noushini@uts.edu.au

[†] Presenter: Email: amin.noushini@uts.edu.au

to the first crack stress as well as the maximum stress and its corresponding strain (Bayasi & Zeng 1993; Soroushian & Bayasi 1991) . Authors of past research studies have indicated that fibres assist with increasing the concrete's volumetric strain capacity after cracking by bridging cracks and, thereby, changing the post peak behaviour of FRC. In plain concrete, failure usually results suddenly after the maximum stress level has been reached, whereas in FRC this bridging effect allows the load to transfer across the crack preventing sudden failure. Depending on the type of fibre used and content of fibre added to the mix, the behaviour of FRC will vary.

2. RESEARCH SIGNIFICANCE

From amongst the many types of synthetic fibres used in concrete, PVA fibres are a relatively new inclusion. PVA fibres are known to be stable and durable in the alkali environment present in the concrete matrix (Garcia et al. 1997). These fibres are characterised by their high tensile strength (0.8-1.6 GPa), their elastic modulus (23-40 GPa) and hydrophilic surface, which creates a strong chemical bond with the cementitious material (Redon et al. 2004). The high tensile strength of PVA fibres contributes by sustaining the first crack stress and resisting pull out force due to the strong bond present between the fibre and the cementitious matrix. In contrast, the low lateral resistance of the fibres may also lead to fibre rupture before being pulled out of the matrix (Atsuhisa et.al, 2006). PVA fibres elongate and transfer the load to different parts of the matrix and as a result the load applied is distributed more evenly between the loading surfaces.

Monofilament PVA fibre is available in two commercial forms: uncoated and coated. The hydrophilic nature of the former virgin type poses a challenge when used in concrete. From a positive viewpoint, the fibre caters for a stronger bond formed with the cementitious matrix; however, due to higher water demand, the fibre also influences the rheological properties during the mixing stage.

To date, fibres are not widely used in structural elements although FRC has been accepted by the industry since the 1980s (Atsuhisa et.al, 2006). In recent times, fibres have become increasingly popular for many applications and the need for improvement in structural ductility has raised attention to utilising fibres in structures. Before fibres can be added to concrete, the properties of the FRC should be assessed. This study investigates the mechanical properties of structural concrete including PVA fibres focusing on the fresh properties and compressive strength.

3. BACKGROUND

There is little comprehensive literature available on PVA-FRC comparing to other types of synthetic fibre reinforced concrete. On the characterisation of the fresh properties of PVA-FRC, researchers have investigated that by using fibres in concrete, the workability of the mix decreases (Bangi & Horiguchi 2012). Comparing 6mm length PVA fibre in two different diameters, 16 and 40 µm, it is observed that air content has remained constant at the rate of 1.7% for both mixes but slump has decreased dramatically from 209 to 49mm with an increase in fibre diameter (Bangi & Horiguchi 2012). Fibres with smaller diameter showed 115% higher compressive strength than the other fibre size and both PVA concrete mixes demonstrated lower air content (AC) and compressive strength compared to reference concrete. These results are also supported by Li and Yang (Li 2008; Yang 2008). Furthermore, According to the results of an experimental study carried out on PVA fibre reinforced mortar (Debs et al. 2006), it has been reported that for the mixes with fibre volume fraction of 2%, 3% and 4%, the compressive strength and tensile strength increased from 35MPa to 45MPa and 4 to 4.6MPa, respectively, with an increase in fibre volume fraction.

4. EXPERIMENTAL PROGRAM

4.1. Materials

Seven series of concrete mixes were prepared using materials with specific properties explained below. Shrinkage limited Portland cement (PC) and fly ash (FA) were used as the binder for all fibre reinforced concrete mixes. Shrinkage limited Portland cement was used in this study to minimise concrete drying shrinkage. The fineness of FA by 45 μm sieve was determined to be 94% passing (tested in accordance with AS 3581. 1-1998).

A maximum nominal size of 20 mm aggregate was used in all mixes. All aggregates were sourced from Dunmore, Australia, which includes 50/50 blended fine/coarse manufactured sand and 10 mm and 20 mm crushed latite gravel. The grading of all aggregates complies with the Australian Standard; AS 2758.1 specifications and limits. All aggregate was prepared to saturated surface dry condition prior to batching.

Drinking grade tap water was used for all mixes after conditioning to room temperature (23 ± 2 °C). Furthermore, in order to improve the workability, a polycarboxylic-ether based high range water reducing admixture (HWR) was used. Non-coated polyvinyl alcohol fibre of 2 different geometries, 6 and 12 mm, were used in all FRC mixes (Table 1).

Table 1: Properties of PVA fibres

Type	Specific gravity [g/cm3]	Diameter [mm]	Thickness [dtex]	Cut length [mm]	Tensile strength [MPa]	Young's modulus [GPa]	Elongation [%]
W2-6	1.29	0.014	1.8-2.3	6	1500	41.7	7
W2-12	1.29	0.014	1.8-2.3	12	1500	41.7	7

4.2. Mixing proportions

Mixes were prepared to obtain characteristic compressive strength at 28 days (f'_c) of 60 MPa to conform to AS 3600 requirements as structural concrete (ranging from 20 MPa to 100 MPa) even after adding fibres which may cause strength reduction, along with a slump of 80±20 mm. In order to obtain the desired slump, HWR dosage was varied. Details of the mix proportions for all mixes are presented in Table 2.

Mix proportioning of the ingredients was carried out by weight. The fibre volume fractions employed were up to 0.5%; only one mix with 1% fibre (FRC.5) was performed and results are demonstrated in Table 3 and Table 4 to prove that incorporation of higher than 0.5% fibre volume fraction produced non-cohesive concrete. Each set of mixes were prepared to a volumetric size of 0.06 m^3 and used to mould 6 cylindrical specimens (100 mm × 200 mm).

Table 2: Mix proportions

Materials	NFRC.1	NFRC.2	FRC.1	FRC.2	FRC.3	FRC.4	FRC.5	Unit
Cement	430	301	301	301	301	301	301	kg/m3
Fly Ash	0	129	129	129	129	129	129	kg/m3
Sand	635	635	635	635	635	635	635	kg/m3
10mm Aggregates	390	390	390	390	390	390	390	kg/m3
20mm Aggregates	700	700	700	700	700	700	700	kg/m3
HWR	0.923	1.215	1.308	1.385	1.692	2.469	6.923	Lit/m3
6mm PVA fibres	0	0	3.225	0	6.450	0	12.900	kg/m3
12mm PVA fibres	0	0	0	3.225	0	6.450	0	kg/m3
Water	151	151	151	151	151	151	151	kg/m3
Water/C*	0.35	0.35	0.35	0.35	0.35	0.35	0.35	N/A
V_f** [%]	0	0	0.25	0.25	0.50	0.50	1.00	-

*Cementitious materials (binders)
**Fibre volume fraction

4.3. Mixing regime and placing

For Non-Fibre Reinforced Concrete (NFRC) mixes, mixing was performed in accordance with AS 1012.2. However, for FRC mixes, due to the presence of the fibres, standard mixing regime suggested in Australian Standard for traditional concrete, is slightly modified. Accordingly, after a comprehensive pre study, a mixing sequence was achieved based on Australian Standards with modifications as explained below.

Fine aggregates were firstly dry mixed with PVA fibres in a vertical pan mixer. Coarse aggregates were then added and the mixture was further mixed for approximately 3 minutes. Thereafter, cement, fly ash and water were introduced and mixed for 3 minutes. In order to adjust the slump, HWR was added within the first minute of adding cementitious material. Following the 3 minute mixing, a rest for 2 minutes was applied followed by an additional 3 minutes of mixing to achieve a completely homogeneous concrete. Then slump was tested to check the workability. After mixing and finishing all the fresh properties tests, the fresh mix was placed into the moulds (6 cylinders for each batch) using a scoop. In addition, a table vibrator was used to achieve proper compaction and also to minimise the amount of entrapped air within the mix. Once all moulds were filled and surface levelling completed, moulds were covered with plastic sheets and wet towels to keep the specimens from drying out. Approximately 24 h after demoulding, the specimens were placed in a water tank to be cured in lime-saturated water at a temperature of 20±2 °C until the testing date.

4.4. Testing procedure

Slump, air content and mass per unit volume were measured to study the rheological properties of concrete at plastic state following Australian Standard; AS 1012.3.1, AS 1012.4.2 and AS 1012.5, respectively. Behaviour of the concrete under compression has also been determined by conducting uniaxial compressive tests. Cylindrical specimens were tested under load rate control condition in an 1800 kN universal testing machine following AS 1012.9 (load rate equivalent to 20±2 MPa compressive stress per minute).

5. RESULTS AND DISCISSION

5.1. Fresh properties results

Slump, mass per unit volume and air content tests results are presented in Table 3. As shown in Figure 1, slump decreases with increasing fibre addition. Plot of HWR to cementitious materials (PC and FA) is also presented in the same figure to demonstrate a better understanding of the effect of fibre on workability together with additions of HWR. FRC.5 incorporating 1% fibre showed zero slump even with very high percentage of HWR/C (cementitious materials) ratio due to high fibre content in concrete paste that affects the mix cohesiveness and bond. Higher percentages of fibre have also been investigated in a small mix. Results show that by adding higher amounts of HWR, namely 2.3% HWR/C, it is not likely to obtain good workability and segregation happens which is not desirable.

Table 3: Fresh properties of NFRCs and FRCs

Mix reference	Vf [%]	Fibre length [mm]	HWR / C* [%]	Slump** [mm]	Air Content** [%]	Mass per unit volume** [kg/m3]
NFRC.1	0	0	0.25	110	0.7	2510
NFRC.2	0	0	0.33	100	1.1	2450
FRC.1	0.25	6	0.36	90	1.4	2410
FRC.2	0.25	12	0.38	60	1.3	2390
FRC.3	0.50	6	0.46	45	1.5	2390
FRC.4	0.50	12	0.67	20	1.4	2320
FRC.5	1.00	6	1.90	0	1.2	2270

*Cementitious materials (binders)
**Slump, Air content and Mass per unit volume calculated to the nearest 5 mm, 0.2% and 10 kg/m^3 respectively, in accordance with AS1012.3.1, AS1012.4.2 and AS1012.5

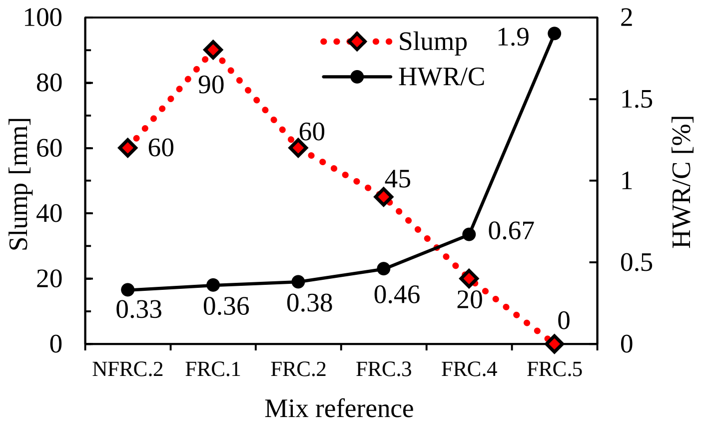

Figure 1: Slump versus HWR/C for FRCs compared to control

Mass per unit volume (MPV) of the concrete is an important factor in characterising concrete. Generally the MPV of concrete decreases by adding synthetic fibres. This is possibly due to the lower mass per unit volume of the fibres. Results presented in Table 3 show that by increasing the amount of fibre in the mix, the value trend of volume density decreases. The drop in the mass per unit volume is highly depended on the volume and amount of fibres in the matrix as well as the length and number of fibres. Later it is discussed how this value is related to the compressive strength (Figure 3).

5.2. Compressive strength results

This test was performed on 100×200 mm cylindrical specimens following AS 1012.9 procedures. The compressive strength of NFRCs and FRCs with different volume fractions at the age of 28 days are presented in Table 4 and Figure 2. Strength effectiveness (S.E) which can be defined as additional strength achieved for FRCs compared to the control mix (Eq. (1)) is also calculated.

$$S.E = \frac{FRC\ strength - NFRC.2\ strength}{NFRC.2\ strength} \times 100\% \qquad (1)$$

Table 4: Compressive strength of NFRCs and FRCs at the age of 7 and 28 days

Mix reference	7 day compressive strength			28 day compressive strength - f'_c		
	Average Strength* [MPa]	Standard deviation [MPa]	Strength effectiveness [%]	Average Strength [MPa]	Standard deviation [MPa]	Strength effectiveness [%]
NFRC.1	61.5	1.4	N/A	73.5	1.2	N/A
NFRC.2	46.0	1.7	N/A	57.5	3.2	N/A
FRC.1	48.0	4.1	+4.0	67.0	3.2	+16.3
FRC.2	43.5	3.6	-5.5	64.5	3.2	+11.7
FRC.3	40.5	3.5	-12.6	63.5	2.5	+9.9
FRC.4	39.5	2.4	-14.4	58.5	2.8	+1.5
FRC.5	25.5	1.8	-44.9	34.0	1.7	-41.0

* Average compressive strength of the test specimens calculated to the nearest 0.5 MPa in accordance with AS 1012.9

According to the 28 day results of FRC mixes, FRC.1 containing 0.25% of 6mm PVA fibres, shows the highest strength and 16.3% improvement in compressive strength gained compared to the control mix. Concurrently, compressive strength is decreased by fibre addition. Generally, in the same percentage, shorter fibres act better than longer fibres in terms of compressive strength. Furthermore, the mix with 1% fibre showed much lower strength in comparison to the control concrete which may be due to low workability and weak fibre distribution. Relative compressive strength gained from 7 to 28 days of FRCs versus control is illustrated in Figure 2.

Qualitative observations during the compression test demonstrated more ductile behaviour in failure for specimens with higher volume fractions and samples including longer fibres. Whereas the control concrete specimens mostly exploded after reaching the ultimate strength.

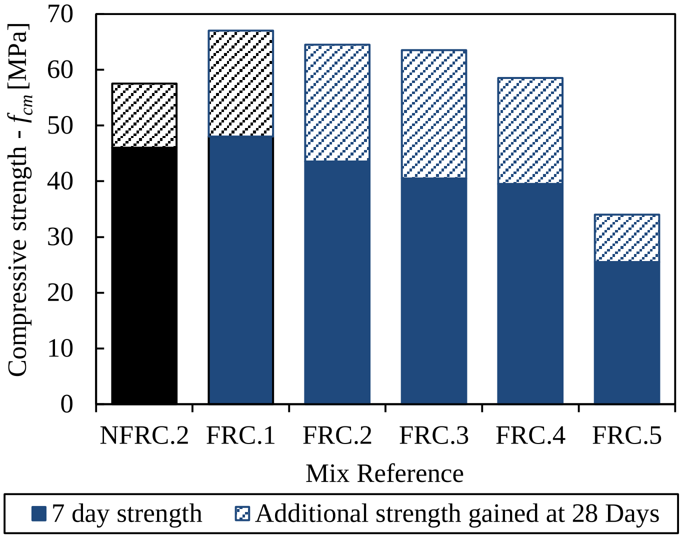

Figure 2: Compressive strength development from 7 to 28 days of FRCs compared to control

It is well known fact that compressive strength decreases with reduction in mass per unit volume which can also be inferred from the results of the two different categories of concrete mixes, NFRCs and FRCs, shown in Figure 3. However, comparing FRC.1-4 to NFRC.2, all of the four FRCs have higher compressive strength although their MPV is lower than NFRC.2 which is a deviant from the mentioned statement.

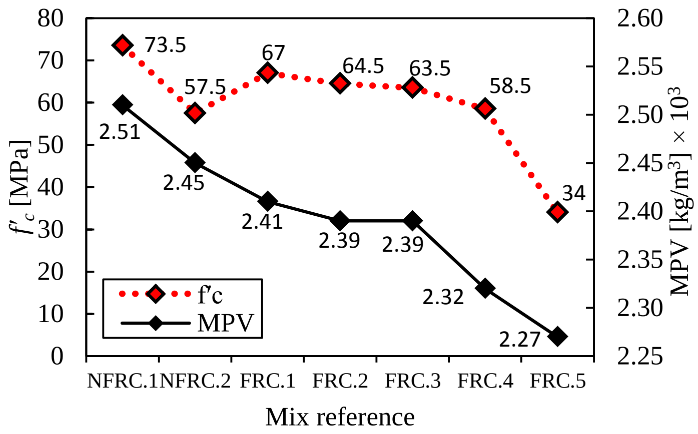

Figure 3: 28 day compressive strength versus Mass per unit volume (MPV) for NFRCs and FRCs

6. SUMMARY AND CONCLUSIONS

The effect of non-coated PVA fibres in different volume fractions ranging from 0.25% to 1% in two geometric lengths, 6 and 12mm, have been investigated. Fresh properties and compressive strength were tested and the results compared to the control concrete mix.

The following conclusions can be drawn from this study:

- Less workability is observed for mixes having more fibre even with a higher amount of HWR. Mixes with longer fibre show lower slump compared to shorter fibre for the same fibre volume addition. As a result, it can be concluded that adding PVA fibre decreases concrete slump.
- Air content is increased by introducing fibre into the concrete mix and it has an increasing trend by fibre volume addition.
- Mass per unit volume of concrete is decreased by adding fibres in the mix. This is possibly due to the lower density of the fibres contributing to a lower volume density.
- Characteristic compressive strength at 28 days (f'_c) increases by fibre addition and optimum fibre volume fraction is found to be 0.25% with approximately 16% improvement in f'_c. It can also be concluded that shorter fibres act better in terms of compressive strength compared to the longer fibre.
- Strength gain rate from 7 to 28 days is almost double for FRCs compared to the control concrete. It can be concluded that PVA fibres help with improving the compressive strength in later ages.

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