FLEXURAL AND TENSILE CHARACTERISTICS OF POLYVINYL ALCOHOL FIBRE REINFORCED CONCRETE (PVA-FRC)

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ABSTRACT

This paper presents the results of an experimental study investigating the effect of un-coated polyvinyl alcohol (PVA) fibres on the properties of hardened concrete. PVA fibre of varying length, 6 and 12 mm, with same diameter and aspect ratio (l/d) of 430 and 860, respectively, was utilised in different volume fractions of 0.125%, 0.25%, and 0.5%. In addition, 30% fly ash was also used as partial replacement of Portland cement in all fibre reinforced concrete (FRC) mixes. Uniaxial compression, splitting tensile, modulus of rupture (MOR) and modulus of elasticity (MOE) tests were performed following the Australian Standards to evaluate the mechanical properties of PVA-FRCs. Mid-span deflection of the flexural specimens was measured by means of a linear variable differential transducer (LVDT) at the centre of each specimen and load-deflection curves were prepared. Results show that adding PVA fibres to the mix generally improve the mechanical properties of concrete. Regarding the strength, the optimum fibre content goes to 0.25% for both fibre length and in the case of toughness and ultimate deflection 0.5% shows the highest values.

Keywords: Polyvinyl alcohol (PVA) fibre, fibre reinforced concrete, mechanical properties, flexural strength, modulus of rupture.

1. INTRODUCTION

Fibres are added in to a brittle-matrix composite to help improve three major aspects; toughness, ductility and strength (tensile) (Arisoy 2002). Fibres tend to increase toughness of the composite material by bridging the cracks and provide energy absorption mechanism related to de-bonding and fibre pull-out. Furthermore, they can increase the ductility of the composite by allowing multiple cracking. They may also help increase the strength by transferring load and stresses across the cracks.

It has been investigated (Li & Wu 1992) that in a brittle composite which is subjected to uniaxial tensile loading, the first macroscopic crack forms when applied load reaches the first cracking load capacity (cracking strength) of the material. Thereafter, the load across the crack will be shared by

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the bridging fibres and transferred back to the matrix via the fibres interface. If sufficient load is transferred, the next crack may form and the process repeats until the matrix is broken with a series of sub-parallel cracks. This process results in a significant increase in tensile deformation (ductility) due to opening of each individual crack from the large numbers of such parallel cracks. During the multiple cracking process, the composite load may even increase and exceed the cracking strength of the composite (Wu & Li 1995). The optimum performance of the composite highly depends on the compatibility of the fibre and matrix in terms of strength, elasticity and surface adhesion leading to an adequate load transfer mechanism (Felekoğlu et al. 2009).

From among mentioned properties, elastic modulus of the fibre is investigated to be more important in the reinforcing effect of fibre in the matrix (Beaudoin 1990). Fibres can only increase the strength of their composites when they have greater modulus of elasticity than that of the matrix (Zheng & Feldman 1995). Nevertheless, according to both theoretical and applied researches, fibres with lower modulus can still improve concrete properties, in relation to strain capacity, toughness, impact resistance and crack control (Zheng & Feldman 1995). The improvement of the above mentioned properties is in many applications of much greater importance than a slight increase in strength (Zheng & Feldman 1995).

Synthetic fibres have become more attractive in recent years as reinforcements for cementitious materials. This is due to the fact that they can provide inexpensive reinforcement for concrete and if the fibres are further optimized, greater improvements can be gained without increasing the reinforcement costs (Li et al. 1991; Wang et al. 1989).

The properties of synthetic fibres vary widely, in particular with respect to the modulus of elasticity. However, most of the synthetic fibres have lower modulus of elasticity compared to the cementitious materials which ranges from about 15 to 30 GPa (Zheng & Feldman 1995). Consequently, developing fibres with a very high modulus of elasticity for cement reinforcement have been studied. The surface structure of synthetic fibres is of great importance in addition to their mechanical and elastic properties as it affects the performance of the composite, i.e. their highly hydrophobic and smooth surfaces usually tend to reduce the composite performance (Li & Stang 1997).

During the past 20 years, polyvinyl alcohol (PVA) fibre has been introduced in the production of FRCs (Li 1998; Redon et al. 2001; Shen et al. 2008). PVA fibres act differently in a cement based matrix due to their surface formation and high strength (Li et al. 2001). The resulting composite, which exhibits a pseudo ductile behaviour, is called engineered cementitious composites (ECC). Li et al. (Li et al. 2002) improved the performance of ECC by using PVA fibres with proper adjusted surface properties in a suitable matrix. This high performance ECC presented a multiple cracking and strain hardening behaviour. Hence, these composites are recognized as extraordinary high performance materials against durability related problems because of their ability in crack resisting and crack width minimising performance (Kendall et al. 2008).

Advantages of PVA fibres are; high aspect ratio; high ultimate tensile strength; good chemical compatibility with Portland cement; good affinity with water; faster drainage rate; and no health risk if used. PVA fibres have a good effect on the flexural strength of the matrix because of their adequate interfacial bond with the cement matrix. This good interfacial bond is accredited to the non-circular cross-section of the fibres, and hydrogen bonds between the fibres and the cement matrix. (Zheng & Feldman 1995)

Beaudoin (Beaudoin 1990) investigated the flexural strength, toughness and splitting tensile strength versus fibre content for different type of FRCs with various percentages ranging from 0 to 1% volume fraction. Concrete proportions were water : cement : sand : gravel = 0.53 : 1.00 : 1.84 : 1.91. It has been reported that splitting tensile strength of PVA-FRCs, including 25 mm length PVA fibres, increases with increase in fibre content. Flexural strength was also having an ascending trend with fibre additions although a drop in strength was observed from 0.25% to 0.5% and optimum fibre content was given to 0.25%. Furthermore, a dramatic slump loss with fibre additions was observed and zero slump was recorded for 1% fibre content. It is also presented that slump loss was significantly higher in terms of PVA fibres compared to steel, carbon and glass fibres.

In the present work the performance of using uncoated PVA fibre of two geometric lengths (6 and 12 mm) in concrete has been assessed to investigate to what extent fibres can improve the mechanical properties and flexural capacity of plain concrete.

Table 1: Properties of PVA fibres

Specific gravity [g/cm^3]	Diameter [mm]	Thickness [dtex]	Cut length [mm]	Tensile strength [MPa]	Young's modulus [GPa]	Elongation [%]
1.29	0.014	1.8-2.3	6 and 12	1500	41.7	7

Table 2: Mix proportions of reference concrete

kg/m^3						Lit/m^3	Water/C*
Cement	Fly ash	Sand	10 mm aggregate	20 mm aggregate	Water	HWR	
301	129	635	390	700	151	1.215	0.35

* Cementitous materials

2. EXPERIMENTAL PROGRAM

2.1. Materials

Shrinkage limited Portland cement (PC) and fly ash (FA) were used as the binder for all 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 used in mix design 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, with specifications mentioned in Table 1, were used in all FRC mixes.

2.2. Mixing and samples preparations

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 control concrete (no fibres) are presented in Table 2. Mix ingredients were all measured and added to the mix by weight. All FRCs also followed the same proportioning and only fibres were added to the mixture by 0.125%, 0.25% and 0.5% of volume fraction of the mix.

For NFRC mixes, mixing was performed in accordance with AS 1012.2. However, for FRC mixes, due to the presence of the fibres, the standard mixing regime suggested in Australian Standard for conventional concrete was modified. Accordingly, the mixing time was increased to 3 minutes to achieve a completely homogeneous concrete. Slump was taken to check the workability and, thereafter, freshly mixed concrete was placed into moulds and compacted using an external vibrating table.

Curing of test specimens was carried out in accordance with AS 1012.8. Specimens were placed in a water tank after demoulding to be cured in lime-saturated water at a temperature of 20±2 °C until the testing date.

2.3. Testing methods

Uniaxial compression tests and splitting tensile tests were performed on cylindrical specimens of 100×200 mm at the age of 28 days in accordance with AS 1012.9 and AS 1012.10 specifications and method, respectively. Cylindrical specimens were tested under load rate control condition in an 1800 kN universal testing machine with a load rate equivalent to 20±2 MPa per minute for compressive test and 1.5±0.15 MPa per minute for indirect tensile test.

Flexural tensile strength or modulus of rupture (MOR) is obtained from four-point bending tests on 100×100×400 mm prisms at a loading rate of 1±0.1 MPa/min until fracture following AS 1012.11. Four-point loading was applied and mid-span deflection of the flexural specimens was measured by means of a linear variable differential transducer (LVDT) at the centre of each specimen. The flexural stress was calculated as;

$$f_{ct.f} = \frac{PL(1000)}{BD^2} \quad (1)$$

where $f_{ct.f}$ is the modulus of rupture or flexural stress (MPa), P is the maximum applied force (kN), L is the span length (mm), and B and D are the width and depth of the specimen (mm), respectively. Figure 1 shows typical arrangement of 4-point bending test.

Static chord modulus of elasticity (MOE) test was also carried out on 150×300 mm cylinders following AS 1012.17. All tests were conducted at 28 days of ageing and each of the below mentioned results is the average of 3 test specimens.

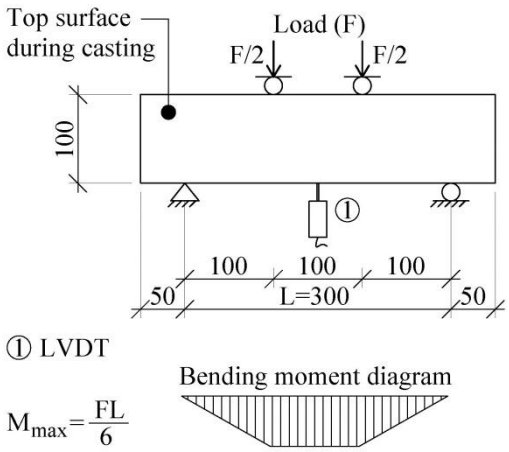


Figure 1: Typical arrangement for four-point bending test

3. RESULTS AND DISCUSSION

Table 3 presents the mechanical properties of FRCs and control concrete. Compressive strength, indirect tensile strength, MOR and MOE values were improved to different extends with following mentioned details in response to the fibre volume fractions.

Table 3: Mechanical properties of different mixes at 28 days of ageing

Mix Reference	Fibre length [mm]	V_f [%]	Compressive strength[1]- $f_{c,28}$ [MPa ± SD]	Splitting tensile Strength[2]- $f_{ct.sp,28}$ [MPa ± SD]	Modulus of Rupture[2]- $f_{ct.f,28}$ [MPa ± SD]	Modulus of Elasticity[3]- $E_{c,28}$ [GPa]
NFRC	-	-	60.0 ± 3.2	3.7 ± 0.5	5.6 ± 0.2	39
FRC.1	6	0.125	65.0 ± 4.6	4.6 ± 0.2	6.8 ± 0.3	39
FRC.2	6	0.250	67.0 ± 3.2	4.9 ± 0.2	6.8 ± 0.2	40
FRC.3	6	0.500	61.5 ± 2.5	4.2 ± 0.3	6.3 ± 0.1	38
FRC.4	12	0.125	63.0 ± 1.8	4.3 ± 0.1	6.6 ± 0.4	38
FRC.5	12	0.250	64.5 ± 3.2	4.7 ± 0.2	6.7 ± 0.2	39
FRC.6	12	0.500	58.5 ± 2.8	4.1 ± 0.4	6.2 ± 0.5	36

[1] Compressive strength calculated to the nearest 0.5 MPa in accordance with AS 1012.9.
[2] Splitting tensile strength and modulus of rupture calculated to the nearest 0.1 MPa in accordance with AS 1012.10 and AS 1012.11, respectively.
[3]Static chord modulus of elasticity determined to the nearest 1 GPa in accordance with AS 1012.17.

3.1. Compressive strength

By looking at the results, it can be noted that most of PVA-FRCs have higher compressive strength at 28 days ($f_{c,28}$) compared to the control except for FRC.6 which includes 0.5% volume fraction of 12 mm fibres. It can also be observed from Figure 2 that with a same fibre content shorter fibres act better than longer one in terms of compressive strength and the optimum fibre volume fraction goes to 0.25% for both fibre lengths with approximately 11.5% improvement in compressive strength.

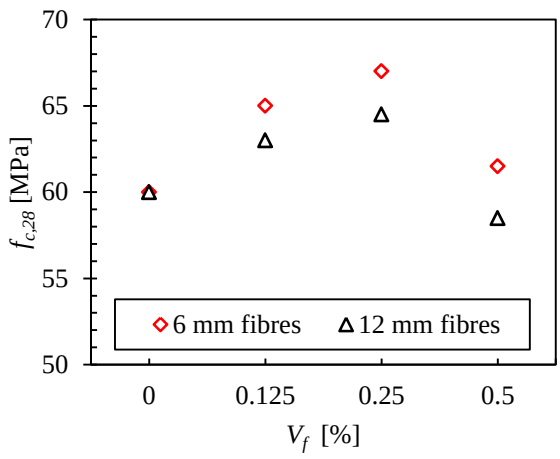


Figure 2: 28 days compressive strength of FRCs

3.2. Splitting tensile strength

As indicated in Table 3, splitting tensile strength at 28 days ($f_{ct.sp,28}$) of plain concrete is significantly enhanced by introducing PVA fibres to the mix. The $f_{ct.sp,28}$ values of all FRCs are higher than that of control concrete, ranging from 11% for FRC.6 to 32.5% for FRC.2 including 0.25% volume fraction of 6 mm fibres.

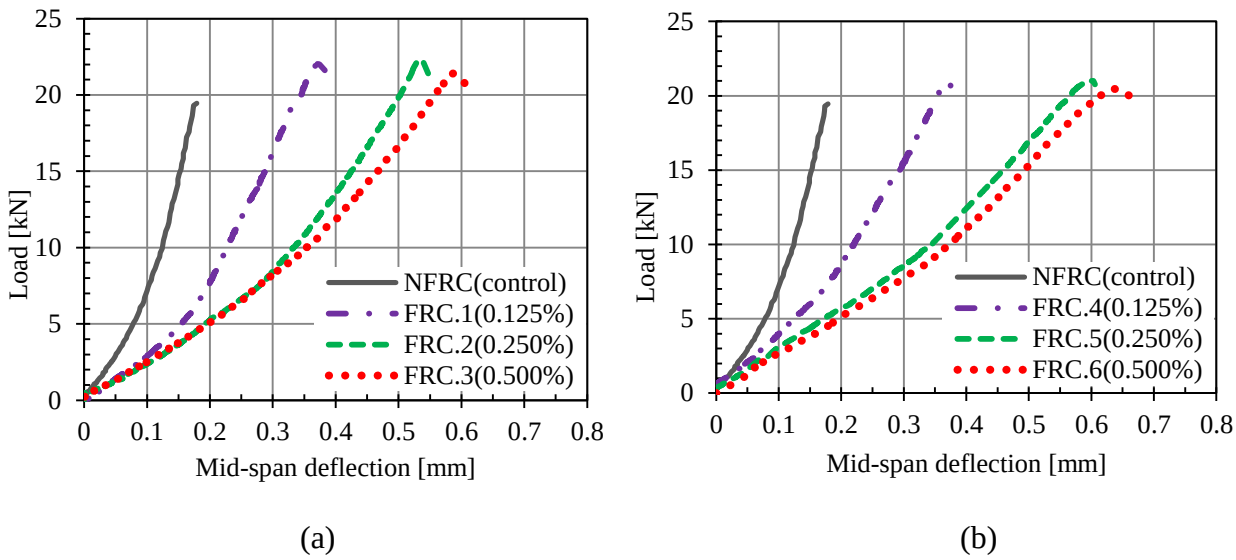
3.3. Flexural strength (modulus of rupture)

Similar to splitting tensile strength, results of flexural strength at 28 days ($f_{ct.f,28}$) of FRCs versus control show considerable improvement ranging from 11% up to 21.5%. Recurrently, in terms of flexural strength, optimum fibre content goes to 0.25% volume fraction. Up to this optimum value more fibres provide more bridging effects and enhance the multiple cracking process which leads to strength improvement, however, higher fibre content had reverse effects. This can be caused by the weak fibre distribution and improper orientation due to large number of fibres in the mix. Fibres which are not parallel to the cracks, can contribute to the stress bridging process by preventing a proper fibre orientation.

Furthermore, as it is inferred from the results, shorter fibres had a better effect on improving the mechanical properties of the concrete particularly the flexural strength. Higher aspect ratio of the fibres can be responsible for this effect. It is assumed that these fibres may bend and not stay

straight in the matrix, therefore, their total length cannot contribute in load bearing process and stress control mechanism.

Figure 3 illustrates the Load-mid span deflection of test specimens in flexure. It can be observed that, the load-deflection curves for composites vary significantly depending on the fibre content. FRCs show significantly larger deflections at the ultimate state as well as higher loads compared to the control concrete. This will result in a bigger area under the load-deflection curves which can be an indication of increasing toughness. As it has been stated in literature (Jastrzebski 1977; Low & Beaudoin 1994) the flexural toughness and ductility can be determined from the flexural load-deflection curves. The flexural toughness is calculated as the area under entire load-deflection curve and ductility is determined from deflection in post-peak region. Consequently, it can be stated that the flexural toughness of concrete enhances by introducing PVA fibres to the mix and it will be further increased if more fibres are added.



(a) (b)

Figure 3: Load-mid span deflection curves in 4-point bending test (a) FRCs with 6 mm fibres versus control (b) FRCs with 12 mm fibres versus control

3.4. Modulus of elasticity

Static Chord modulus of elasticity at 28 days ($E_{c,28}$) of FRCs and control are compared in Table 3. From the results it can be noted that PVA fibres in low volume fractions used in this study do not significantly affect the modulus of elasticity. However, it is explicable that within the FRCs incorporating the same fibre, 0.25% volume fraction shows the highest $E_{c,28}$ and in a same fibre content longer fibres have lower $E_{c,28}$.

4. CONCLUSIONS

The effect of adding PVA fibres to concrete were investigated in this study. The compressive strength of concrete is marginally increased with increasing fibre content and the optimum volume fraction goes to 0.25% for both geometric lengths, 6 and 12 mm, with approximately 10%

improvement compared to the plain concrete. The same trend for tensile and flexural strength is also observed with increasing fibre content. The average strength development of 20% in flexure and 30% in splitting tensile at 0.25% volume fraction shows to what extend fibres can improve the properties of plain concrete. Furthermore, FRCs showed lower flexural stiffness together with providing a higher load bearing capacity compared to the control. This results in a higher ultimate deflection for FRCs where the peak load values were remained constant.

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