DEVELOPMENT OF DUCTILE FIBRE REINFORCED GEOPOLYMER COMPOSITES

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Abstract: *This paper reports the development of ductile fibre reinforced geopolymer composites (DFRGC) where the cement binder is replaced by fly ash based geopolymer binder. In this study, three types of fibres are considered namely steel and two types of polyvinyl alcohol (PVA) fibres having different diameters, lengths and elastic modulus. The fibres are used in mono as well as in hybrid forms in the development of DFRGC. Comparison is also made with its cement based counterpart the ductile fibre reinforced cement composites (DFRCC). The effects of two different sand sizes (1.18mm, and 0.6mm) and sand/binder ratios (0.5 and 0.75) on the deflection hardening and multiple cracking behaviours of DFRGC containing hybrid fibres are also evaluated and compared with DFRCC. Results reveal that the deflection hardening and multiple cracking behaviours can be achieved in DFRGC similar to that of cement based DFRCC. For a given sand size, fibre content and sand content, comparable ultimate flexural strength and deflection at peak load are observed in both DFRGC and DFRCC. The results also show that the hybrid steel-PVA fibre reinforced DFRGC exhibited better deflection hardening behaviour compared to its cement based counterpart. The proposed development of DFRGC exhibits a significant benefit over cement based system (DFRCC) as the former one is* **green** *in terms of* **no cement use**.

1 INTRODUCTION

The need for environmentally friendly construction materials for sustainable development is an important issue in the present time. The concrete industry is said to be one of the contributors of global warming. This fact is due to the use of Portland cement as the main component in making concrete and cement based composites. The cement industry is responsible for about 6% of the CO_2 emission. However, the use of concrete and cement based composites, as the most widely used construction materials, are still unavoidable in the foreseeable future. In this respect, the efforts of using supplementary cementitious materials or finding alternatives to Portland cement in cement based binders are necessary. Recent years have seen a great development in new types of inorganic cementitious binders called "geopolymeric cement" around the world. This prompted its application in concrete, which improves the

greenness of normal concrete at the same time maintains comparable and even better properties [1].

High performance fibre reinforced cementitious composites (HPFRCC) have been steadily developed in the last two decades. One of the salient features of HPFRCC is its strain hardening and multiple cracking behaviours in both tension and bending [2]. It is a short fibre (metallic and/or non-metallic) reinforced cement based composites where fibre content between 2% and 3% by volume appears to be the most attractive due to ease of processing. Great interest in this area is observed through the development of engineered cementitious composites (ECC) [3] and ductile fibre reinforced cementitious composites (DFRCC) [4]. The DFRCC is cement based composite reinforced with short random fibres which exhibits deflection-hardening and multiple-cracking behaviours in bending. It is a special class of HPFRCC that has higher deflection capacity than that of regular fibre reinforced concrete and exhibit deflection hardening and multiple cracking behaviours. However, current version of DFRCC is limited to cement rich matrix, although the replacement of cement with fly ash is reported in few studies (e.g. [5]).

Considerable research has been conducted on geopolymer concrete [6]. Very little research is reported on the fibre reinforced geopolymeric composites [7-10]. However, none of the above studies reported the deflection hardening or strain hardening behaviour in bending or tension, respectively in the fibre reinforced geopolymeric composites.

This paper reports some preliminary results on the development of ductile fibre reinforced geopolymer composite (DFRGC) exhibiting deflection hardening in bending where the cement binder is replaced by fly ash based geopolymer binder. The fly ash is activated by alkaline liquids (sodium hydroxide and sodium silicate). This newly developed DFRGC is the first of its kind in the field of HPFRCC where Portland cement is completely replaced by class F fly ash.

2   EXPERIMENTAL PROGRAM

The experimental program is divided into two parts. In the first part (Part A), cement based DFRCC containing steel and PVA fibres in mono and hybrid forms are considered. The second part (Part B),   the geopolymer based DFRGC series, is similar to the first part in every aspect, except the matrix where the cement is replaced by the class F fly ash and is activated by the alkaline activators (Sodium hydroxide and sodium silicate). The total volume fraction of fibre is limited to 2% for all fibre types and hybrid combinations of steel-PVA fibres. The properties of fibres are given in Table 1.

Table 1. Properties of fibre

Types of Fibre	Length (mm)	Diameter (mm)	Modulus of elasticity (MPa)	Fibre Strength (MPa)	Density (gm/cm^3)	Elongation (%)
PVA-1	8	0.04	40,000	1,600	1.3	6
PVA-2	12	0.10	25,000	1,100	1.3	10
Steel	10	0.12	200,000	2,500	7.8	-

In each part five series are considered. The first series evaluated the deflection hardening behaviour of mono fibre reinforced composites, while the rest four series evaluated the same for hybrid combinations of steel-PVA fibres with two different sand sizes (maximum sand sizes of 0.6mm and 1.18mm) and sand/binder ratios (0.5 and

0.75). Detail experimental program is shown in Table 2.

For each fibre type and combination, three prismatic specimens of 20X75X300 mm in dimension are cast. All specimens are tested in four-point bending using an Instron testing machine under displacement control with a loading rate of 0.5mm/min. A schematic of the bending test setup is shown in Fig. 1.
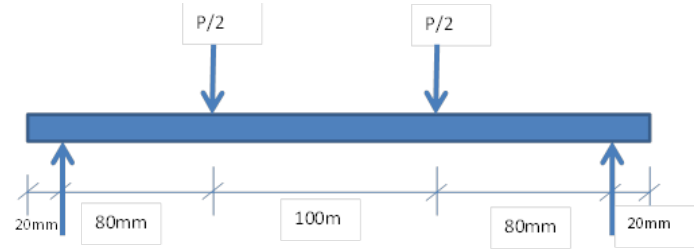

Figure. 1. Bending test setup

Table 2. Experimental program and mix proportions

	Series no.	Fibre types (by volume)			Mix proportions by wt. ratio						
		Steel	PVA-1	PVA-2	Cement	Class F fly ash	Sand/Binder		Water/cement	Alkali activator/fly ash	
							d_{max} = 1.18 mm	d_{max} = 0.6mm		NaOH (8M)	Na_2SiO_3
DFRCC – Part A (Hybrid combination)	1	2%	-	-	1	-	-	0.5	0.45	-	-
		-	2%	-							
		-	-	2%							
	2	1%	1%	-	1	-	0.5	-	0.45	-	-
		1%	-	1%							
	3	1%	1%	-	1	-	0.75	-	0.45	-	-
		1%	-	1%							
	4	1%	1%	-	1	-	-	0.5	0.45	-	-
		1%	-	1%							
	5	1%	1%	-	1	-	-	0.75	0.45	-	-
		1%	-	1%							
DFRGC – Part B (Hybrid combination)	6	2%	-	-	-	1	-	0.5	-	0.13	0.32
		-	2%	-							
		-	-	2%							
	7	1%	1%	-	-	1	0.5	-	-	0.13	0.32
		1%	-	1%							
	8	1%	1%	-	-	1	0.75	-	-	0.13	0.32
		1%	-	1%							
	9	1%	1%	-	-	1	-	0.5	-	0.13	0.32
		1%	-	1%							
	10	1%	1%	-	-	1	-	0.75		0.13	0.32
		1%	-	1%							

Note: Binder = Cement or fly ash

3 MATERIALS, MIXING, CURING AND MIX PROPORTIONS

The cement used in the study is general purpose (GP) Portland cement which corresponds to ASTM type I. The fly ash used is originated from Collie power station in Western Australia and satisfies ASTM class F classification. The fly ash consists of an amorphous part about 60% by wt. and a crystalline part about 40% by wt. The chemical composition of fly ash is shown in Table 3. The crystalline part of the fly ash has low reactivity and acts as fine aggregate in the binder system. The activating solutions used are sodium silicate (Na_2SiO_3) with a chemical composition of (wt.%): Na_2O=14.7, SiO_2=29.4 and water=55.9. The other characteristics of the sodium silicate solution are specific gravity=1.53 g/cc and viscosity at 20^OC=400 cp. The sodium hydroxide (NaOH)

solution is prepared from analytical grade sodium hydroxide pellets. The mass of the NaOH solids in the solution varied depending on the concentration of the solution expressed in terms of molar, M. In this study, the NaOH solution with a concentration of 8M is considered and consisted of 8X40=320gms of NaOH solids per liter of the solution, where 40 is the molecular weight of NaOH. The NaOH (Sodium Hydroxide) is first mixed with de-ionized water with the ratio of 0.32:1 and produce sodium hydroxide solution. During the mixing of sodium hydroxide solution, the white sodium hydroxide pellets were slowly dissolved by the addition of de-ionized water. A rise of temperature occurred as the sodium hydroxide pellet slowly dissolved in the solutions. The alkali activator is prepared by mixing NaOH solution with Na_2SiO_3 (Sodium Silicate) with the ratio of 0.4:1. The alkali activator solution is then used in the mixing of geopolymer based cementitious composites.

The mixing of DFRCC and DFRGC is carried out in a Hobart Mixer. First sand and cement or fly ash (in case of geopolymer matrix) are dry mixed for approximately 2 minutes and then water or alkaline activator solution (in case of geopolymer matrix) is slowly added into the mix and continues to mix for another 3 minutes. The fibres are then slowly added to the wet mix and continued mixing until the fibres are well dispersed in the mix.

The DFRGC specimens subjected to stream curing for a day at 60°C immediately after casting. The stream curing is carried out in the stream curing room in the laboratory. The specimens are then demolded after 24 hours and stored in the laboratory in open air until the date of testing. The DFRCC specimens are demolded after 24 hours and stored in the curing tanks where they are subjected to standard wet curing conditions. All specimens are tested after 28 days of casting. Table 2 shows the mix proportions of DFRCC and DFRGC.

Table 3. Chemical compositions of fly ash

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI
51.5%	23.63%	15.3%	1.74%	1.2%	0.28%	0.38%	0.84%	1.78%

4   RESULTS AND DISCUSSIONS:

4.1   Deflection hardening behaviour of mono DFRCC and DFRGC

Fig. 2 shows the deflection hardening behaviour of both cement based and geopolymer based mono fibre reinforced composites and comparison between the two can also be seen in the same figure. Generally, the composite containing 2% steel fibre exhibited much higher modulus of rupture (MOR) than
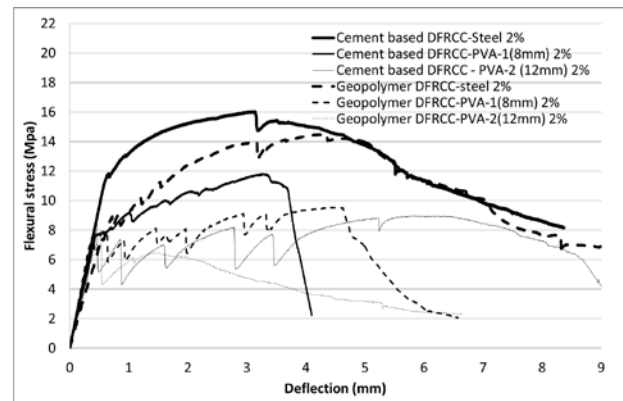

Figure. 2. Deflection hardening behaviour of mono fibre reinforced DFRCC and DFRGC

those containing PVA-1 and PVA-2 fibres of same volume fraction. However, its deflection capacity (deflection at peak load) is much lower than those containing PVA fibres. The higher MOR and smaller deflection capacity of steel fibre reinforced DFRCC and DFRGC compared to its counter parts PVA-1 and PVA-2 fibres systems is due to the high modulus of steel fibres. The lower MOR with considerable higher deflection capacity of PVA fibre reinforced composites is due to the low modulus of PVA fibres. Other researchers also observed similar behaviour in both steel and PVA fibre reinforced cement based composites (e.g. [5]). The geopolymer based DFRGC exhibits comparable deflection hardening behaviour to cement based system with only exception in the composite containing PVA-2 fibre, where no deflection hardening behaviour is noticed. It should be noted that PVA-2 fibre is about 33% longer and about 31% weaker than that of PVA-1 fibre. Research suggests that the fibre having length greater than the critical fibre length exhibits fibres rupture rather than pull out in cement based composites [11]. Research also suggests that, in addition to friction bond, chemical bond also develops between PVA fibre and cement matrix [12]. Therefore, the poor behaviour observed in PVA-2 fibre reinforced DFRGC could be attributed to the longer length and lower strength of PVA-2 fibre than that of PVA-1 fibre. In the case of DFRGC, the chemical bond might be higher than that of cement based matrix and affected the deflection hardening behaviour of the composite containing PVA-2 fibre. However, it is not in the case of DFRGC containing PVA-1 fibre, whose deflection capacity is higher than that of cement based system, which is still not clear and need to be thoroughly investigated through measuring the frictional bond of PVA fibres in the geopolymeric matrix.

4.2 Deflection hardening behaviour of hybrid DFRCC and DFRGC

The effect of geopolymeric matrix on the deflection hardening behaviour of hybrid steel-PVA fibre reinforced DFRGC composites and its comparison with that of cement based DFRCC is shown in Figs. 3-6. Generally, the hybrid fibre reinforced DFRGC exhibited comparable deflection hardening behaviour in terms of MOR and deflection at peak load to that of DFRCC, even better in the case of DFRGC containing 1% steel (ST) and 1% PVA-1 fibres. In this study, two hybrid combinations are considered, one contained 1% ST and 1% PVA-1 fibres and the other contained 1% ST and 1% PVA-2 fibres. The DFRGC containing the former hybrid combination exhibited better deflection hardening behaviour than that of DFRCC. In the case of second hybrid combination, the DFRGC exhibited similar deflection hardening behaviour to that of DFRCC. It is interesting to note that, by replacing 1% PVA-2 fibre with ST fibre in 2% PVA-2 fibre reinforced DFRGC (series 6), the deflection hardening behaviour can be reinstated, which was not observed in mono fibre system.

The effects of sand contents and its sizes on the deflection hardening behaviour of DFRCC and DFRGC can also be seen by comparing Figs. 3-6. It can be seen that, for a given sand/binder ratio (S/B), the increase in sand size (from 0.6mm to 1.18mm in this study) adversely affected the deflection
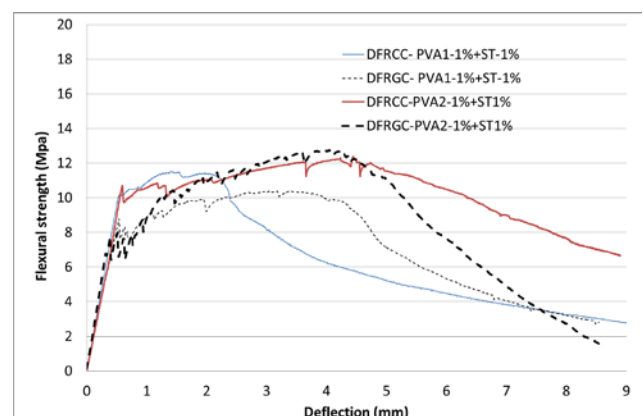

Figure. 3. Deflection hardening behaviour of hybrid fibre reinforced DFRCC and DFRGC containing S/B ratio of 0.5 and maximum sand size of 0.6mm
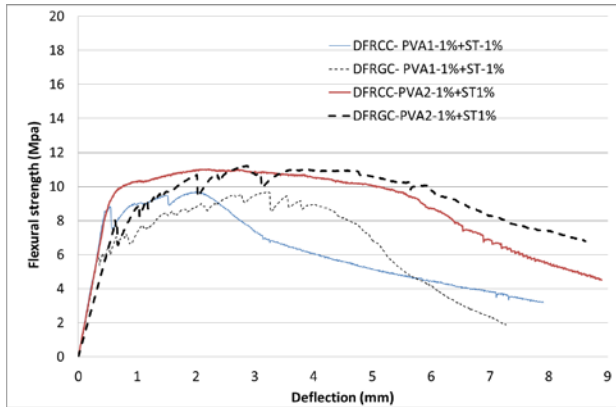
Figure. 4. Deflection hardening behaviour of hybrid fibre reinforced DFRCC and DFRGC containing S/B ratio of 0.75 and maximum sand size of 0.6mm
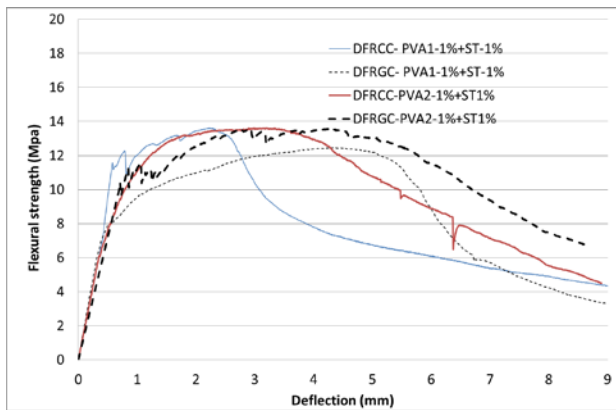

Figure. 5. Deflection hardening behaviour of hybrid fibre reinforced DFRCC and DFRGC containing S/B ratio of 0.5 and maximum sand size of 1.18 mm
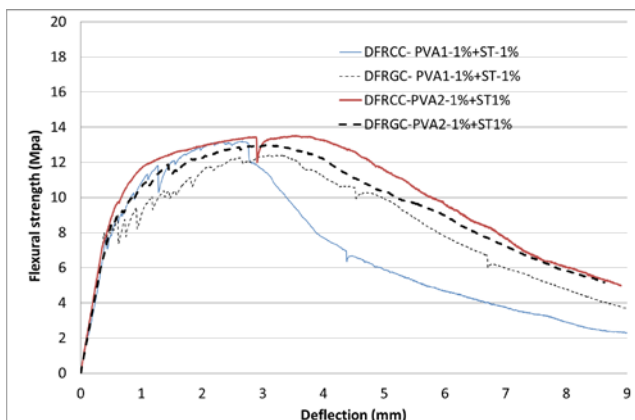

Figure. 6. Deflection hardening behaviour of hybrid fibre reinforced DFRCC and DFRGC

containing S/B ratio of 0.75 and maximum sand size of 1.18mm

capacity at peak load and the deflection hardening behaviour, where the MOR increased and the deflection at peak load decreased with increasing sand size. The geopolymer based DFRGC also exhibited similar trend to that of DFRCC in terms of deflection at peak load and deflection hardening behaviour. The effect of sand contents on the deflection hardening behaviour of both DFRGC and DFRCC can also be seen in above figures. The adverse effect of increasing the amount of sand on the deflection at peak load can be seen in DFRCC and DFRGC composites, which is also reported in other studies [13-14]. The DFRGC also exhibited comparable multiple cracking to that of DFRCC (compare Fig. 7 with Fig. 8).

Figure. 7: Multiple Cracking Patterns in DFRCC (Left, PVA-1; right, ST+PVA-1)

Figure. 8: Multiple Cracking Patterns in DFRGC (Left, PVA-1; right, ST+PVA-1)

4.3 Effect of geopolymer matrix on the hybrid mechanism of fibres

The hybrid mechanism of high and low modulus fibres in cement based fibre composite is well established [5]. The fibre reinforced cement composite containing high modulus fibres (such as steel fibre) exhibits high ultimate strength and low ductility,

whereas that containing low modulus fibres (such as PVA or polyethylene) exhibits low ultimate strength and high ductility. The hybrid fibre composite containing proper volume ratio of high and low modulus fibres exhibits simultaneous improvement in strength and ductility. In this study, the similar hybrid mechanism between steel and PVA fibres in geopolymer composite (i.e. in DFRGC) is also observed (see Fig. 9), which is comparable to that observed in cement based composite in this study (see Fig. 10) or elsewhere [5].
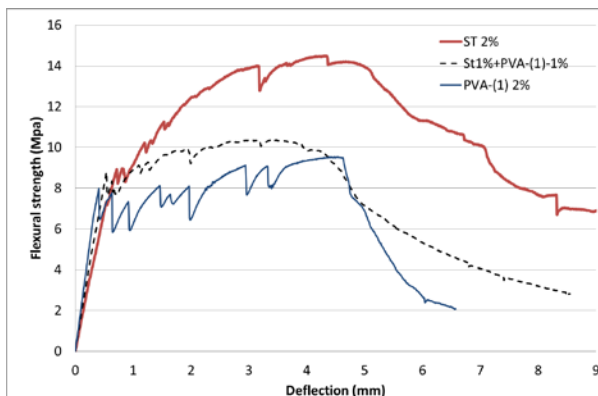

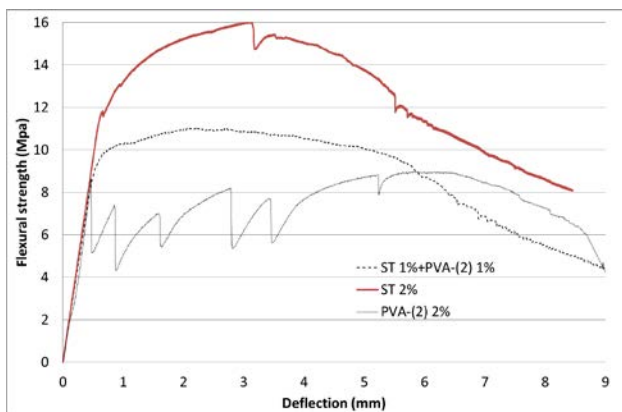Figure 9. Influence of hybrid fibres on flexural behaviour of DFRGC

Figure 10. Influence of hybrid fibres on flexural behaviour of DFRCC

CONCLUSIONS:

Within limited variability in terms of fibre types, fibre combinations, sand sizes and sand contents the following conclusions can be made for the newly developed DFRGC composites:

- Deflection hardening behaviour is achieved in the DFRGC containing 2% steel fibre by volume.

- Deflection hardening behaviour is also achieved in the DFRGC containing 2% PVA-1 fibre by volume.

- No deflection hardening behaviour is noticed in the DFRGC containing PVA-2 fibre. This could be due to the long length and the low strength of PVA-2 fibre. The high bond of fibre/matrix interface could also influence in this case, but need to be confirmed with bond test.

- Deflection hardening behaviour is also achieved in the DFRGC containing hybrid combinations of 1% ST+1% PVA-1 and 1% ST+1% PVA-2 fibres (by volume).

- The deflection hardening and multiple cracking behaviour of hybrid DFRGC is comparable to that of DFRCC.

- The hybrid mechanism between high and low modulus fibres observed in DFRGC is very similar to that in conventional cement based DFRCC.

- The increase in sand content and sand size adversely affected the deflection hardening behaviour of DFRGC composites, similar to that of observed in cement based DFRCC system.

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