

# Strengthening of plain concrete beams using Strain Hardening Geopolymer Composites (SHGC) layers

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## Abstract

In this paper the application of novel, environmentally friendly, Strain Hardening Geopolymer Composites (SHGC) for the structural upgrade of existing concrete elements has been examined. The binder of these cement-free materials (SHGC) is different from that used in conventional cement based systems. Ternary geopolymer binder is used instead of Portland cement, which is activated by a low concentration and content of alkaline liquids (Potassium Silicate). The addition of two types of fibres (steel and PVA) has been examined in order to provide enhanced ductility and energy absorption characteristics. These novel materials have been used for the strengthening of concrete prisms. SHGC layers have been applied to conventional concrete elements and composite prisms with 100 mm breadth and depth and 500 mm span length and have been tested through flexural tests. The experimental results indicate that the addition of SHGC layers to existing concrete elements can considerably improve the flexural response of normal concrete. The proposed technique can lead to significantly higher flexural loading carrying capacity, while at the same time the ductility can be considerably improved, especially by the addition of PVA fibres which can also provide strain hardening properties.

**Keywords:** Geopolymer, SHGC, PVA fibres, steel fibres, fly ash and slag.

## 1 Introduction

Improvement of the structural performance of many existing infrastructure elements is an urgent need worldwide, especially in earthquake prone areas. Several techniques have been proposed for the strengthening of existing structures using conventional materials (e.g. Reinforced Concrete), Fibre Reinforced Polymers (FRPs) and, recently, Ultra High Performance Fibre Reinforced Concrete

(UHPRC). These techniques have been proven to be relatively efficient but, as the need for sustainable development is becoming increasingly important, the application of new environmentally friendly materials for strengthening applications is becoming an area of growing interest.

Cement-based materials are characterised by an overall brittle behaviour with relatively low tensile strength and ductility [1]. One of the most widely used techniques for the enhancement of ductility,

apart from the use of steel bars, is the addition of fibre reinforcement [2]. Fibre-reinforced cementitious composites can be used to considerably improve the service life of civil infrastructures by improving mechanical properties and durability [2, 3]. The mechanical behaviour of strengthened elements with SHCCs under chloride exposure and accelerated corrosion has been examined in previous studies [4, 5] and superior performance has been reported. This is attributed to the fibre-bridging action and self-healing properties of SHCCs [6]. Several studies have also focused on the application of SHCCs for seismic and non-seismic structural applications [7-9]. Based on these studies [8-9], enhanced structural performance of SHCCs elements under cyclic loading has been highlighted and this is attributed to the development of a multiple cracks phase rather than the localisation of the damage and the development of single crack followed by structural failure of the elements [10].

In the last few years, the application of SHCC material for new structures has become quite popular especially in applications with increased load and ductility demands [11, 12]. However, a high cement content is normally required for the SHCC mixture design and subsequently these materials are more energy intensive than conventional concrete.

In this study, the application of Strain Hardening Geopolymer Concrete (SHGC) has been examined for the strengthening of existing concrete elements. Geopolymer concrete is one of the most promising sustainable alternative to Ordinary Portland Cement (OPC). Geopolymers are inorganic by-product materials, rich in silicon (Si) and aluminium (Al) that react with alkaline activators to form three dimensional polymeric chains of silicate and poly(silicate) (Si-O-Al-O) [13, 14]. Utilization of geopolymer materials can reduce 80% of greenhouse gas emissions associated with material production, and overcome issues related to cement production and unregulated disposal of industrial materials [14-16].

The aim of the current study is to investigate the mechanical properties of SHGC materials and the

flexural behaviour of SHGC layered concrete beams. An experimental investigation was conducted to evaluate the effectiveness of the application of SHGC layers for the structural strengthening of existing concrete elements. The effect of the incorporation of discontinuous steel (ST), and polyvinyl alcohol (PVA), fibres on flexural performance has been examined. The geopolymer matrix was produced using a ternary geopolymer binder (fly ash, slag and silica fume) mixed with a low content and concentration of potassium silicate alkaline activator.

## 2 Preparation of SHGC material and testing

The geopolymer mortar matrix adopted in the present work was based on geopolymer binder (fly ash, slag and silica fume) mixed with potassium silicate (with molar ratio equal to 1.25) and fine aggregate [17]. Silica sand of particle size less than 0.5 mm was used as the fine aggregate. The chemical compositions of the fly ash, slag and silica sand used are presented in Table 1.

*Table 1. Chemical compositions of FA, GGBS and Silica Sand*

Chemical compositions (%)	Fly ash	Slag	Silica Sand
Silicon Dioxide, SiO <sub>2</sub>	59	35	99.73
Aluminium Oxide, Al <sub>2</sub> O <sub>3</sub>	23	12	0.1
Calcium Oxide, CaO	2.38	40	--
Ferric Oxide, Fe <sub>2</sub> O <sub>3</sub>	8.8	0.2	0.051
Sulphur Trioxide, SO <sub>3</sub>	0.27	--	--
Sodium Oxide, Na <sub>2</sub> O	0.74	--	<0.05
Potassium Oxide, K <sub>2</sub> O	2.81	--	0.01
Magnesium Oxide, MgO	1.39	10	--
Loss on ignition, LOI	6.7	--	0.09

Four different mixtures were examined in this study (Table 2). Total binder and silica sand quantities of 775 kg/m<sup>3</sup> and 1054 kg/m<sup>3</sup> respectively were used for all the examined mixes. Steel fibres with 13 mm length and 0.16 mm diameter, and PVA fibres with 12mm length and 0.04 mm diameter, were used in the examined mixes (Figure 1).

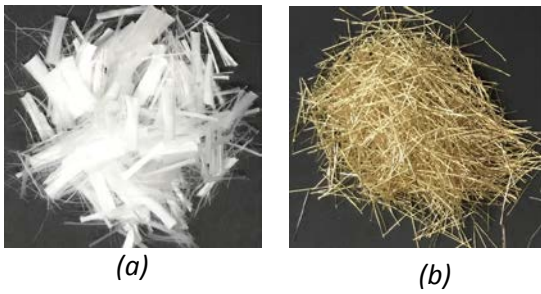


Figure 1. Fibres used in this study (a) steel fibres and (b) PVA fibres

Table 2. Mixture compositions

Mix ID	FA/ Binder	Slag / Binder	SF/ Binder	OPC/ binder	K <sub>2</sub> SiO <sub>3</sub> / Binder	Water/ Binder	Fibre Content	Sand (Kg/m <sup>3</sup> )	Gravel (Kg/m <sup>3</sup> )
PG	50%	40%	10%	-	12%	25%	0%	136%	-
PVAFRGC	50%	40%	10%	-	12%	25%	2% PVA	136%	-
SFRGC	50%	40%	10%	-	12%	25%	3% ST	136%	-
NSC	-	-	-	100%	-	50%	0%	240%	210%

For the Normal Strength Concrete (NSC) of the control specimens, Portland cement (380 kg/m<sup>3</sup>), gravel (920 kg/m<sup>3</sup>), sand (800 kg/m<sup>3</sup>) and water (190 kg/m<sup>3</sup>) were used. A Zyklos 75L mixer (Pan Mixer ZZ 75 HE) was used for the mixing of the materials. Geopolymer binder (Silica fume, fly ash and slag) was placed first in the mixing drum, followed by alkaline liquid, and sand. The materials were dry mixed for 5 min and then the liquid phase was added and the mixer run for another 5 min. After that steel fibre were gradually added to ensure uniform fibre dispersion in the geopolymer mix. Finally, silica sand was added to the mixer and the mixer was run for another 3 min to give a total mixing time of 13 min [17].

### 3 Experimental results of SHGC material

#### 3.1 Mechanical properties of SHGC material

Compressive and flexural strength tests were conducted to evaluate the mechanical properties of SFRGC. Compressive strength was evaluated through standard compressive tests on 50 mm side cubes. The examined specimens were tested

at 28 days since it has been found that the examined mixes reach almost 80-90% of their maximum strength at this age. Compressive tests were conducted in a Denison Avery 2000KN testing machine with loading rate 45 KN per minute [18] and four cubes per mix were tested. Flexural strength was determined through standard flexural tests of prism specimens (100\*100\*500mm) at 28 days using an Instron universal testing machine. Span length was taken equal to 450 mm and the distance between the loading points was set at one third of the span length (Figure 2).

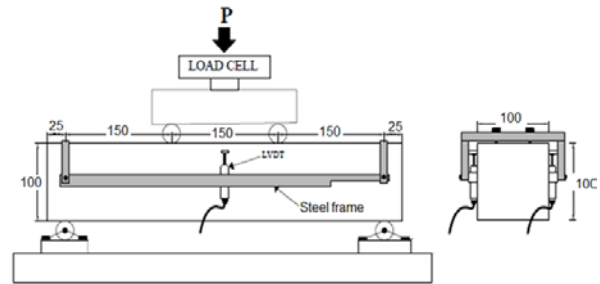


Figure 2. Bending specimen geometry and test set-up (dimensions in mm)

The testing machine was operated in a 'closed loop' at a fixed deflection rate of 0.24 mm/min. Two Linear Variable displacement Transducers (LVDTs) were attached to a 'yoke' (steel frame) which was used in order to eliminate any induced displacements at the supports during loading (Figure. 2). Load versus deflection results were obtained for the calculation of ultimate flexural strength, toughness and residual strength, based on ASTM C1609 [19]. The development of compressive strength and flexural strength for geopolymer mixes with and without fibres, are presented in Figure 3 and 4 respectively

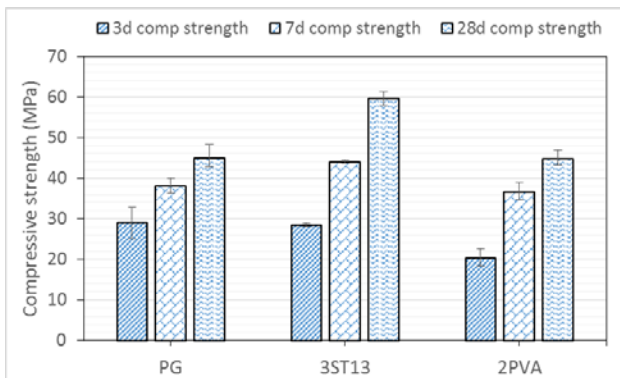
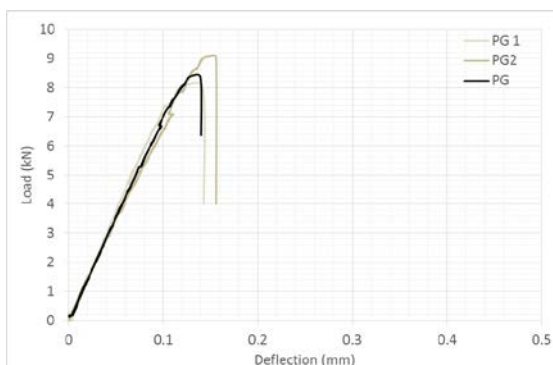
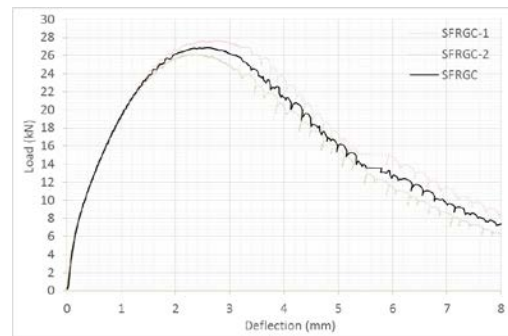


Figure 3. Compressive strength of plain geopolymer and FRGC mixtures

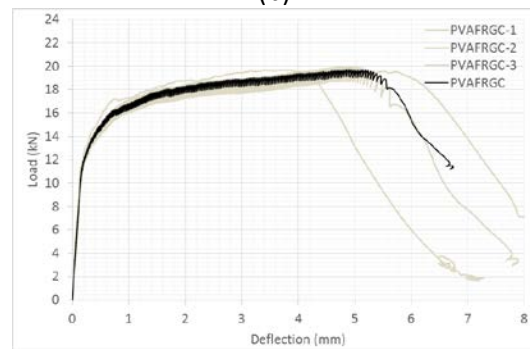
The results of Figure 3 indicate that the addition of fibres in the geopolymer material considerably impacted the compressive strength. The compressive strength of all the examined FRGCs was increased for longer curing periods. The 7 days compressive strength was enhanced by 31%, 52% and 80% for PG, SFRGC and PVAFRGC mixtures respectively, compared with the respective values at 3 days. This observation is in agreement with the behaviour of OPC concrete, which undergoes a progressive hydration process and strength is gradually developed over time. The maximum compressive strengths were achieved at 28 days. The mean compressive strength at this age was found equal to 44 MPa, 60 MPa, and 43 MPa for PG, SFRGC and PVAFRGC mixtures, respectively.



(a)



(b)



(c)

Figure 4. Flexural strength of (a) plain geopolymer, (b) SFRGC and (c) PVAFRGC mixture

Flexural load versus deflection behaviour of PG, SFRGC and PVAFRGC mixtures is illustrated in Figure 4. The load carrying capacity and the respective deflection values were considerably enhanced by the addition of fibres. The ultimate load capacity of plain geopolymer (PG) was increased by 140% and 240% for the mixture reinforced with steel fibre and PVA fibre, respectively. Also, the deflection at the peak load for SFRGC and PVAFRGC mixtures was almost 18 and 37 times higher compared to the respective value for the plain geopolymer (PG) mortar. The deflections at first cracking load and ultimate load were 0.6 mm and 2.5 mm for SFRGC. The PVAFRGC mixture showed significant deflection hardening behaviour and the respective characteristic points for first cracking and ultimate load were at 0.18 mm and 5.5 mm, respectively (Figure 4c). The load deflection diagram showed that after the initial cracking, load was further increased up to quite high deflection values, due to the fibre bridging action at the interface of the cracks. The ultimate flexural load value for SFRGC and PVAFRGC was found to be equal to 27 MPa and 20 MPa.

### 3.2 Drying Shrinkage behaviour

For repair and strengthening applications, the shrinkage of the new concrete is a crucial parameter for the response of the 'composite' elements [20]. In order to evaluate the shrinkage performance of SHGC, the drying shrinkage strain of SHGC, PVA-FRGC and OPC mortar was measured in accordance with ASTM C 490 [21]. A digital gauge was used and shrinkage measurements were taken at 1, 3, 5, 7, 14, 21, 28, 56, 90 and 120 days. Drying shrinkage measurements were started at 24 hrs after casting. A series of prismatic specimens with cross-sectional dimensions of 75 mm x 75 mm and length of 285 mm were used for the free shrinkage measurements. The specimens were stored in a room with relative humidity 42% and temperature 20 °C. The average drying shrinkage results of three replicate specimens for all the examined mixtures are presented in Figure 5.

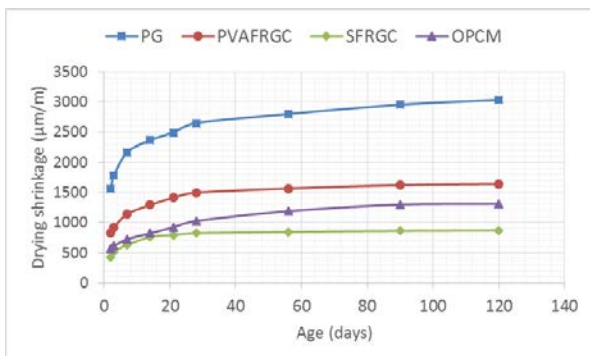


Figure 5. Dry shrinkage results up to 120 days

Based on the results of Figure 5 it is evident that the drying shrinkage strain of the plain geopolymer mortar (PG) is very high (around 3000 microstrains) at 120 days. This value is much higher than the respective strain value for plain OPC mortar (OPC) which was found to be around 1200 microstrains, a value which is in agreement with previous studies [22, 23]. The addition of fibres leads to significant reduction in shrinkage strain values in both cases (i.e. PVAFRGC and SFRGC), especially with the addition of steel fibres (SFRGC). In case of steel fibres (SFRGC) the shrinkage strain at 120 days was found equal to 850 microstrains, while in the case of PVA fibres (PVAFRGC) the respective value was found to be equal to 1600 microstrains. This reduction is

attributed to the physical restraint provided by the presence of the fibres in the geopolymer matrix, which is in agreement with previous studies on conventional fibre reinforced concrete [24, 25]. Li *et al.* [24] reported that the reduction of the drying shrinkage strain is considerably affected by the volume of the fraction of the fibres. Atis and Karahan [26] supported this finding and reported that the use of steel fibre restrained the movements at micro level in the case of fly ash and OPC based concrete by bridging and stitching the fine cracks.

### 4 Strengthening of conventional concrete prisms with SHGC layers

In all the examined specimens, concrete substrate was initially cast. One hour later, the surfaces of the initial prisms were roughened followed by the casting of 50mm thick SHGC (SFRGC and PVAFRGC) layers. Normal strength concrete prisms with the same dimensions (100 mm x 100 mm x 500 mm) were also cast and used as the control specimens. All the examined specimens were demoulded 48 hours after casting and wet cured (using water spraying) for the first two weeks to prevent shrinkage cracking and debonding at the SHGC-to-normal concrete interfaces. Flexural tests were conducted 6 months after casting (Figure 6). Standard four-point loading flexural tests were carried out according to the requirements of ASTM C1609 [19]. The testing setup is illustrated in Figure 6a and the failure modes of the strengthened samples with SFRGC layers are illustrated in Figures 6b and 6c. In the control concrete prisms, failure occurred with a single crack was developed and propagated under the loading point. Bending failure mode was also observed for SFRGC and PVAFRGC strengthened prisms, but in this case, multiple cracks were initially formed at the strengthening layer followed by propagation of one main crack to the initial conventional concrete prism. 'It should also be mentioned that even if quite high free shrinkage strain values have been measured for most of the examined specimens (Figure 5), shrinkage cracks were prevented in all the examined specimens by wet curing.





(a)



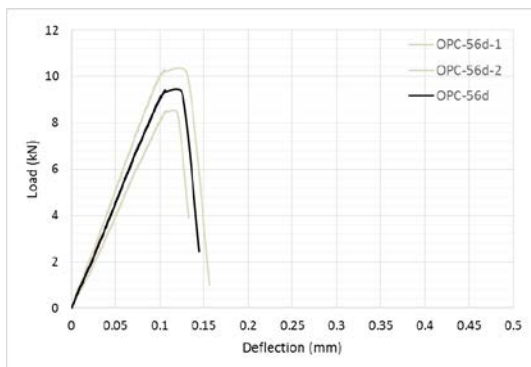
(b)



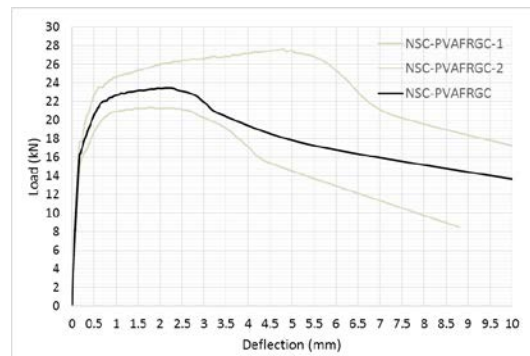
(c)

Figure 6. Concrete beam layered with 50mm SFRGC: (a) flexural test configuration, (b) SFRGC composite beams after testing and (c) PVAFRGC composite beams after testing

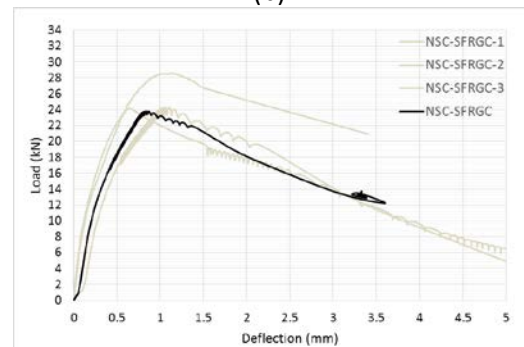
The flexural load-deflection results for the normal strength prisms, which have been used as the control specimens for comparison, and the strengthened prisms with PVAFRGC and SFRGC layers are presented in Figure 7a, 7b and 7c respectively. All the individual results together with the average curves are presented in Figure 7.



(a)



(b)



(c)

Figure 7. Flexural load versus deflection diagrams: (a) NSC prisms, (b) NSC prisms strengthened with PVAFRGC layers, and (c) NSC prisms strengthened with SFRGC

For plain normal strength concrete (NSC) beams, the average deflection at the peak load was found equal to 0.12 mm (Figure 7a). In the case of strengthened prisms with SFRGC layers (Figure 7c), the deflection at the peak load was increased to 0.87 mm, which is 7 times higher compared to the control specimens. From the results of the strengthened prisms with PVAFRGC layers (Figure 7b), it can be observed that the deflection at the peak load for these specimens was found to be equal to 2.3 mm which is almost 19 times higher compared to the control specimens' results. The considerably higher ductility of the composite/strengthened specimens was also evidenced by the failure mode of the examined specimens. In the case of the control specimens, cracks initiated at the mid span in the tensile side and propagated rapidly to the top of the compressive zone leading to fracture of the specimens into two pieces. The failure mode was completely different for the strengthened prisms with PVAFRGC/SFRGC layers, where crack-bridging by fibres gave high deflection values. Also, in the

case of strengthened prisms, the maximum flexural load was considerably increased. The flexural load of the control concrete beam was found equal to 8 kN, while the respective values for prisms strengthened with SHGC and PVAFRGC layers were 24 kN and 23.3 kN.

## 5 Conclusions

In this study the application of novel fibre reinforced geopolymer concretes for the strengthening of existing concrete beams was examined. The mechanical properties of SHGC materials were determined by compressive and flexural strength tests. The examined materials were found to have improved strain hardening performance under ambient temperature curing conditions. These materials were then applied for the strengthening of conventional concrete prisms and flexural tests were conducted in order to evaluate the efficiency of the proposed method. Based on these experimental results of the current study, the following conclusions can be drawn:

- The compressive strength of the examined specimens was increased by 15 MPa when steel fibres were added to the mix. The addition of PVA instead of steel fibres did not give the same pronounced improvement in compressive strength.
- The shrinkage strain of the plain geopolymer mix was reduced by 40% and 70% by the addition of PVA (PVAFRGC) and steel fibres (SFRGC) respectively.
- The strengthened prisms with SFRGC and/or PVAFRGC layers were found to have considerably improved ductility and maximum flexural strength capacity.
- The deflection at the peak load for the strengthened prisms, with SFRGC and PVAFRGC layers, was found to be almost 7 and 19 times higher than the respective value for the control specimens.
- The ultimate flexural strength of SFRGC strengthened specimens was similar to the ultimate strength of PVAFRGC strengthened elements. However, PVAFRGC strengthened elements exhibited significant deflection hardening behaviour and the ductility of these specimens was significantly improved.

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