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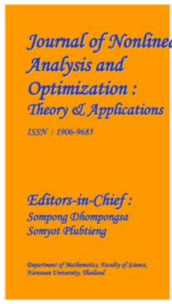

FLEXURAL SHEAR BEHAVIOUR OF GEOPOLYMER CONCRETE BEAMS WITH WEB REINFORCEMENT

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Abstract

This study investigates the shear behavior of slender steel-reinforced geopolymer concrete (GPC) beams with the shear span to effective depth ratio (a/d) of 4.5 and 5.0. To investigate the effect of shear reinforcement, two ordinary Portland cement concrete (OPC) beams and two GPC beams without shear reinforcement, and two OPC beams and two GPC beams reinforced with shear stirrups were cast. All beams were 150 mm wide and 225 mm deep with lengths of 1770 mm (a/d=4.5) and 1950 mm (a/d=5). The beams were tested under a three-point bending test. The experimental results showed that OPC and GPC beams without and with shear reinforcements exhibited similar crack propagation and failure mechanism. The midspan deflections of GPC beams were greater than OPC beams. The normalized shear resistance of OPC and GPC beams with a/d ratio 4.5 was greater than 4% and 30%, respectively, than beams with a/d ratio 5. OPC beams showed a greater decrease in shear resistance with an increasing a/d ratio compared to GPC beams. The shear resistances computed using empirical relationships available in various OPC design codes including AC1-318-14, AC1-318-19, fib-10 and JSCE-07 underestimated the experimental shear resistance of both OPC and GPC beams. In addition, the environmental assessment of OPC and GPC beams exhibited that GPC beams emit about 34% lower embodied CO2 emissions than OPC beams.

Keywords: geopolymer concrete; shear behavior; shear span; slender beams; estimated shear resistance

1. Introduction

Concrete remains the second most popular material globally, only after water [1,2]. In the construction industry, cement has been extensively used as the primary binding material in concrete [3,4]. Cement production releases about 5–7% of the total global CO2 emissions, which remains one of the main contributors of greenhouse gases (GHG) and rising temperature of the earth's surface, and hence global warming [5,6]. Moreover, the manufacturing of cement is a highly energy-consuming process that uses nearly 4 GJ of energy to produce one ton of cement, and about 3.6 billion tons of cement are manufactured annually [7]. The annual cement production is steadily rising by about 9% [8]. Hence, it is necessary to find environmentally friendly alternatives to cement to reduce GHG emissions and reduce the negative impacts of cement production on climate change.

In 1979, Davidovits introduced geopolymers, which belong to a class of inorganic polymers, and are formed by the chemical reaction between alumino-silicate precursors sourced from natural minerals or industrial waste products and an alkaline activator solution [9]. In geopolymerization, three-dimensional polymeric ring structures of alumina silicate (Si-O-Al-O) chains are formed. These polymeric chains condensed to form polymeric structures, which provide strength to the geopolymers [10,11].

GPC has great potential to substitute OPC in construction, as GPC shows improved characteristics than OPC, such as enhanced flexural and bond strengths [12,13]. Hussin et al. [14] and Jiang et al. [15]

also reported that GPC has a higher resistance to fire, chemicals and acid attacks. Hassan et al. [16] and Nawaz et al. [10] concluded that GPC attained the required mechanical characteristics to effectively substitute OPC in the construction industry.

Numerous research studies reported that GPC beams exhibited similar flexural behavior and strength as OPC beams with similar target compressive strengths [17,18]. It was found that initial flexure cracking load, size of the crack, load-displacement response, applied load and failure mechanisms of OPC and GPC beams were similar [19,20]. Mamdouh et al. [21] reported that slag-based ambient cured GPC beams exhibited 7.4% greater flexural strength and 17.5% reduced cracking moment than the OPC beams of similar compressive strengths. Zinkaah et al. [22] reviewed data from forty GPC beams and found that OPC and GPC beams exhibited similar flexure failures with similar crack width and crack propagation. GPC and OPC beams exhibited similar ductility. Tran et al. [23] concluded that fly ash (FA) and slag-based GPC has a lower modulus than OPC for similar strengths. Adak et al. [24] found that the flexural strength of nano-silica modified FA-based ambient cured GPC beams was greater than OPC beams. Kathirvel and Kaliyaperunal [25] noted that the flexural strength of slag-based ambient cured GPC beams was greater than OPC beams and both types of concrete beams exhibited similar failure modes. Kumaravel and Thirugnanasambandam [26] observed that FA-based heat cured (60 °C for 24 h) GPC beams exhibited 2.7% greater flexural strength than OPC beams. However, the deflection in GPC beams was 48.7% greater than that of OPC beams due to the lower stiffness of GPC.

Past studies mainly focused on the flexural strength of GPC beams while fewer research investigations evaluated the shear behavior of GPC beams. The beams are often classified into different groups based on the slenderness ratio. ASCE (2015) classifies beams based on the (a/d) ratio, i.e., very short, short, slender, and very slender beams having a/d ratios ≤ 1 to 2.5, 2.5 to 6, and ≥6, respectively [27]. Numerous research investigations reported the shear behavior of short and slender GPC beams with a/d ratios of less than 4. Wu et al. [28] concluded that FA with slag-based GPC beams under ambient and heat-cured conditions exhibited reduced shear strengths by 42.6–46.2% as the a/d ratio was increased from 1.5 to 2.5. In addition, the observed crack patterns and failure modes in GPC beams were identical to OPC beams. Yacob et al. [29] investigated the shear behavior of five FA-based heat cured (65 °C for 28 h) GPC beams and a control OPC beam having a/d ratios of 2 and 2.4. The shear resistance of OPC beam was 8% greater than that of the GPC beam for an a/d ratio of 2. The addition of stirrups in beams shifted the failure pattern of tested specimens from shear-dominant to shear-flexure. Visintin et al. [30] found that the shear resistance of FA-based ambient cured GPC beams decreased by 29.5% and 60.9% as the a/d ratios were increased from 2.5 to 3 and 2.5 to 3.5, respectively. The findings of the available experimental studies showed that the shear behavior of GPC beams was identical to OPC beams [31,32]. Yost et al. [33] and Chang et al. [34] found that both the cracking pattern and shear behavior of OPC and GPC beams were similar.

Hu and Wu, [35] reported that the shear resistance of OPC beams was reduced by 33.9% with an increase in the a/d ratio from 1.9 to 3.1. Deng et al. [36] found that in OPC beams the shear resistance was increased by 6–28% by decreasing the a/d ratio from 3 to 2.2. Moreover, shear resistance was enhanced with increasing aggregate size. Katkhuda and Shatarat, [37] reported that the shear resistance of OPC beams was reduced by 24% with increasing a/d ratio from 2 to 3 and tested beams failed due to diagonal tension cracking. Slowik [38] concluded that the shear resistance of OPC beams decreased by 58.6% as the a/d ratio was increased from 1.8 to 4.1. It is concluded from the review of the available studies that slenderness (a/d ratio) of beams negatively influenced the shear resistance of OPC and GPC beams.

Meanwhile, previous studies adopted empirical equations intended for OPC beams available in various design codes to compute the shear resistance of GPC beams. Darmawan et al. [39] reported that ACI 318-14 [40] underestimated the shear resistance of FA-based ambient cured GPC beams having an a/d ratio of 2.98 by 25%. Lee et al. [41] found that ACI 318-14 [40] underestimated the shear resistance of slag-based ambient cured GPC beams having a/d ratio 3 by about 27%. Wu et al. [28] reported that ACI 318-19 [42], also underestimated the shear resistance of FA with slag-based GPC beams having a/d ratios of 1.5, 2.5 and 4.0 by about 28%. Similarly, Maranan et al. [43] observed that JSCE-07 [44] underestimated the shear resistance of FA with slag-based ambient cured GFRP reinforced GPC beams having an a/d ratio of 1.8 by 41.9%. Visintin et al. [30] found that fib-10 [45] yielded conservative results of the shear resistance of FA-based ambient cured GPC beams with the a/d ratios of 2–3.5 by about 33%. It is concluded that the design equations intended for OPC beams underestimated the shear resistance of GPC beams having a/d ratios between 1.5 and 4.0 by about 42%.

The review of the existing studies exhibited that the majority of existing studies investigated the smaller a/d ratios. Limited studies investigated the shear behavior of FA-based GPC beams having a/d ratios greater than 4. Hence, it is important to investigate the slender beams having an $a/$ greater than 4 to fill the gap in the existing literature. This study investigates the shear behavior of slender GPC beams without and with shear stirrups. In addition, the failure mechanisms of GPC vs. OPC beams are also studied. It is important to investigate the shear capacity of GPC beams and also, to report the applicability of the design guidelines (ACI 318-14 [40], ACI 318-19 [42], JSCE-07 [44] and fib model code-10 [45]) for OPC beams to GPC beams. The findings of this study will help in understanding the shear behavior and failure mechanisms of GPC beams having a/d ratios greater than 4.

2. Experimental Program

The experimental program comprised four OPC beams and four GPC beams. The width and depth of all eight beams were 150 mm and 225 mm, respectively. Two OPC and two GPC beams of length 1770 mm (a/d ratio of 4.5), whereas the other two OPC and two GPC beams of length 1950 mm (a/d ratio of 5) were cast. The shear span (a), which is measured between the center of the support and the loading point, was 810 mm for an a/d ratio of 4.5, and 900 mm for an a/d ratio of 5. The effective depth (d) of all the beams was kept at 180 mm. The clear concrete cover to the bottom reinforcement was 35.5 mm and 25.5 mm, respectively, for the beams without stirrups and with stirrups. The longitudinal reinforcement comprising two deformed steel bars of 19 mm diameter was provided in all eight beams. The longitudinal reinforcement ratio of all beams was 2.1%, and beams were transition reinforced to ensure that beams failed in shear. The longitudinal reinforcing bars at the ends were bent at 90o to provide the required anchorage length. In two OPC and two GPC beams, no shear reinforcement was provided whereas in the other two OPC and two GPC beams, shear reinforcement comprising steel stirrups at the spacing of 90 mm ($d/2$) were provided. Three cylinders of 150 mm diameter and 300 mm depth corresponding to each beam were cast to determine the compressive strength (fc′) of the concrete. The cross-sectional and longitudinal reinforcement details of the beams are presented in Figure 1.

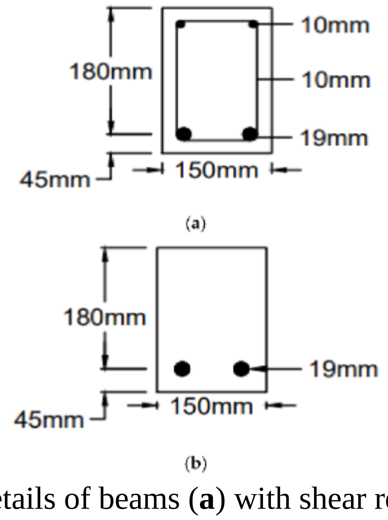

Figure 1. (**a**) Cross-sectional details of beams (**a**) with shear reinforcement and (**b**) without shear reinforcement, and longitudinal sectional details of beams

The FA was sourced from Sahiwal Coal Power Plant. The chemical analysis of FA was performed as per ASTM C114-19 [46] and is presented in Table 2. The sum of SiO_2, Al_2O_3, and Fe_2O_3 contents in FA was 82.95%, CaO content was 9.56%, SO_3 content was 1.30% and loss on ignition (LOI) was 2.0. The sum of SiO_2, Al_2O_3 and Fe_2O_3 was greater than 70%, SO_3 was less than 5%, CaO was less than 18%, and LOI was less than 6%. Based on ASTM C618-19 [47], the FA was classified as low-calcium Class F.

2.1.2. Aggregates

Locally available crush sourced from Margalla was used as coarse aggregates (CA). The sizes of CA ranged from 9.5 to 12 mm. The dry-rodded density of CA was 1542 kg/m3 and the loose bulk density of CA was 1427 kg/m3 as per ASTM C29-17 [48]. The specific gravity of CA was 2.71 as per ASTM C127-15 [49]. The aggregate impact value of CA was 17 as per BS 812-112 [50]. The aggregate crushing value of CA was 21 as per BS 812-110 [51].

Locally available sand sourced from Lawrencepur was used as fine aggregates. The fineness modulus (FM) of fine aggregate was 2.5 according to ASTM 33-18 [52]. The dry-rodded density of fine aggregates was 1778 kg/m3, and the loose bulk density of fine aggregates was 1626 kg/m3 as per ASTM C29-17 [48].

2.1.3. Alkaline Solution

The alkaline solution comprised sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) solutions. The solid pellets of NaOH were added to water to produce the NaOH solution. In this study, 16 M NaOH solution was prepared by mixing 640 g of NaOH pellets in 1000 mL of solution [5]. The Na2SiO3 solution comprising 52% liquid and 48% solids was obtained from a local vendor. The SiO2/Na2O ratio was 3:1. In this study, the ratio of Na2SiO3 solution to NaOH solution was kept at 1.5 [5]. The alkaline solution was prepared 24 h prior to the casting of concrete to cool down the excessive heat during dissolving.

2.1.4. Steel Reinforcement

The nominal diameter of the longitudinal steel reinforcing bar was 19 mm, whereas the nominal diameter of the shear reinforcing bar was 10 mm. A tension test was performed on steel bars using 200 tons Shimadzu Universal Testing Machine (UTM) as per ASTM A615-20 [53]. The average yield and ultimate tensile strengths of 19 mm diameter bars were 450 MPa and 649 MPa, respectively. The average yield and ultimate tensile strengths of 10 mm diameter bars were 395 MPa and 526 MPa, respectively.

2.2. Mix Design

The target fc′ of OPC was 21 MPa. The OPC mix comprised 380 kg of cement, 760 kg of fine aggregates, 1000 kg of CA and 209 kg of water per cubic meter. The water-to-cement ratio of the OPC mix was 0.54. The target fc′ of GPC was also 21 MPa. The GPC mix comprised 420 kg of FA, 620 kg of fine aggregates, 1150 kg of CA, 210 kg of alkaline solution, 21 kg of additional water, and 4.2 kg of superplasticizer per cubic meter. The alkaline solution comprised 126 kg of sodium silicates and 84 kg of sodium hydroxide solution. The ratio of FA to aggregates was 0.237 and the ratio of FA to alkaline solution was 0.5.

The preparation of OPC was divided into two steps. In the first step, the dry mixing of cement and aggregates was conducted in a high-speed mixer for a minute. In the second step, water was added to the dry mix and mixed for additional two minutes to achieve a homogenous mix. The preparation of GPC was also conducted in two steps. In the first step, the FA and aggregates were dry-mixed for two minutes. In the second step, the alkaline solution, superplasticizer, and additional water were added to the dry mix and mixed for additional two minutes to achieve a homogenous mix. The freshly prepared GPC mix was stickier than OPC due to the presence of an alkaline solution. The 1% superplasticizer and 5% additional water were mixed in the GPC mix to obtain a workability of 75 mm. The GPC beams were ambient cured at room temperature using hessian rugs [3,30]. Similarly, OPC beams were ambient cured at room temperature by covering them with wet hessian bags.

2.3. Testing Setup

All beams were tested under a three-point bending test as simply supported beams using 1000 kN Shimadzu UTM as per ASTM C78-18 [54]. The testing was performed at a 0.5 mm/minute controlled displacement rate. The test setup is shown in Figure 2. The cylinders corresponding to each beam were tested under compression in a 3000 kN Denison compression testing machine as per ASTM C39-20 [55] on the same day.

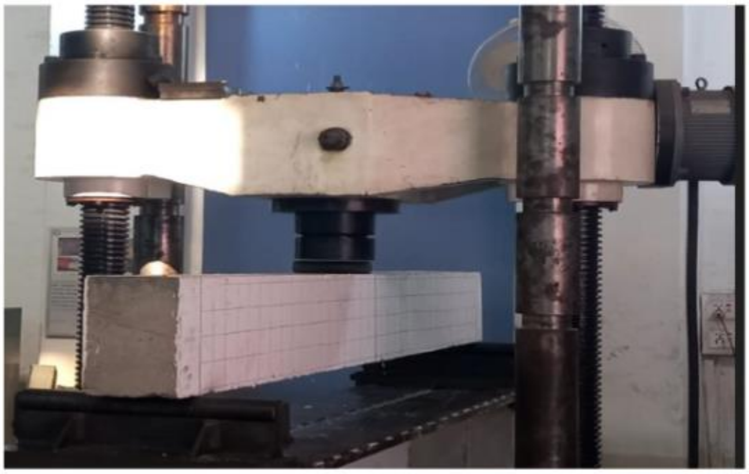

Figure 2. Test set up for three-point bending test.

3. Results and Discussions

The test results include failure modes, first inclined cracking load, peak flexural load (Pu), and maximum deflection at the mid-span of all the tested OPC and GPC beams.

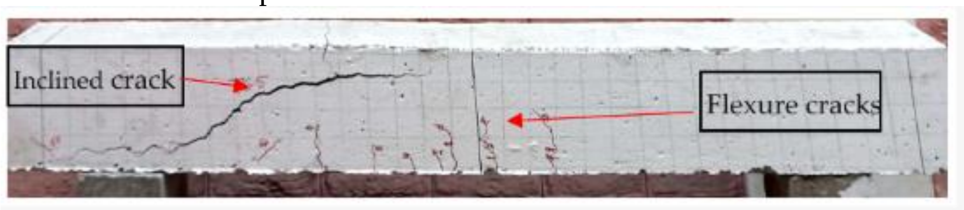

Figure 3. Failure mode of Beam ON-4.5.

3.1. Failure Mechanism of OPC and GPC Beams without Stirrups

The crack pattern and the failure mechanism of the tested OPC beams and GPC beams without shear reinforcement were similar. In Beams ON-4.5 and ON-5, and GN-4.5 and GN-5, the flexural cracks developed in the mid-span region at about 25–29% of Pu. The flexural cracks propagated vertically towards the point of application of load with increasing applied loads. The inclined cracks started to appear near the supports with increasing applied load. The first inclined crack both in OPC and GPC beams appeared around 65% of the Pu. The inclined cracks grew in width and length and propagated in the direction of the loading point with increasing load resulting in the shear failure of the beams. The failures in both OPC and GPC beams were brittle and a sudden drop in load was observed. The tested beams are shown in Figure 3, Figure 4, Figure 5 and Figure 6. Sinik and Arsalan, [56] and Lee et al. [41] reported similar cracking patterns and failure mechanisms of slender OPC and GPC beams. Deng et al. [36] reported that inclined cracking load in slender OPC beams was at about 62–79% of Pu.

Environmental Assessment

The environmental assessment of OPC beams and GPC beams with varying a/d ratios (4.5 and 5) was carried out based on embodied carbon dioxide (e-CO2) emissions. Based on previous studies, the considered e-CO2 emissions of OPC, FA, coarse aggregates, fine aggregates, sodium hydroxide, sodium silicate and water are 0.8300 kg/kg, 0.0090 kg/kg, 0.0459 kg/kg, 0.0139 kg/kg, 0.9355 kg/kg, 0.7873 kg/kg and 0.0003 kg/kg, respectively [62]. The computed e-CO2 of OPC beams (ON-4.5, OS-4.5) and GPC beams (GN-4.5, GS-4.5) were 22.22 kg and 14.699 kg, respectively. The computed e-CO2 of OPC beams (ON-5.0, OS-5.0) and GPC beams (GN-5.0, GS-5.0) were 24.488 kg and 16.190 kg, respectively. The e-CO2 emissions of GPC beams were 65.7% of OPC beams. Hence, the use of GPC as a substitute for OPC can reduce the e-CO2 emissions by one-third of the total e-CO2 emissions while maintaining comparable structural performances.

4. Conclusions

Four OPC beams and four GPC beams having a/d ratios of 4.5 and 5 were cast and tested under a three-point bending test. All beams were 150 mm wide and 225 mm deep with lengths of 1770 mm (a/d=4.5) and 1950 mm (a/d=5). The experimental shear resistance is compared to the estimated shear resistance computed using the available OPC design code equations in ACI 318-14 [40], ACI 318-19 [42], JSCE-07 [44], and fib-10 [45]. The following conclusions are drawn based on the experimental research works carried out in this research study.

i.The crack propagation and failure mechanisms of GPC beams without stirrups and with stirrups (shear reinforcement) were similar to corresponding OPC beams. The loads corresponding to the first inclined crack of the OPC beams and GPC beams were similar which, shows that GPC beams behaved similarly to the OPC beams.

ii.The normalized shear resistance of OPC and GPC beams with a/d ratio 4.5 was greater than 4% and 30%, respectively, than beams with a/d ratio 5. The Pu of shear-reinforced OPC and GPC beams decreased by about 5% and 9%, respectively, with an increase in the a/d ratio from 4.5 to 5. GPC beams exhibited about 18% higher midspan deflection at Pu than OPC beams.

iii.The shear resistance of GN-4.5 was underestimated by ACI 318-14 [40], ACI 318-19 [42], JSCE-07 [44], and fib-10 [45] by 34%, 32%, 76% and 45%, respectively. The shear resistance of GN-5 was underestimated by ACI 318-14 [40], ACI 318-19 [42], JSCE-07 [44], and fib-10 [45] by 34%, 31%, 80% and 44%, respectively. The results exhibited that ACI 318-19 [42] and ACI 318-14 [40] exhibited a good match with the experimental shear resistance. The JSCE [44] exhibited conservative results.

iv.All the design code equations computed the shear resistance for both OPC and GPC beams on the conservative side. The Pu of shear-reinforced beams which failed in flexure, were also underestimated by the available equations. Therefore, these equations are safely applicable for GPC specimens for design purposes. Furthermore, experimental testing on large-scale beams is needed to validate the applicability of the available equations.

v.Equation (15) after modifying ACI 318-14 [40] Equation has been proposed. The proposed equation computed shear resistances closer to experimental shear resistances.

5. Future Developments and Applications

FA-based GPC is a major advancement in the construction industry as GPC is environmentally friendly concrete with significantly reduced embodied CO2 emissions. The findings of this research study exhibited that the shear behavior of slender GPC beams is identical to OPC beams. Further, the design code equations intended for OPC are applicable to GPC. This makes GPC a promising alternative to OPC.

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