Experimental Investigation of Four-Point Flexural Behavior of Textile Reinforcement in Geopolymer Mortar

Hiep Le Chi and Petr Louda

Abstract—**This paper describes an investigation of four-point flexural behavior of geopolymer composite specimens which made of textile reinforced geopolymer mortar. The two different types of mesh (basalt and carbon mesh) and their various aperture sizes were used as reinforcement. In this experimental work, only two mesh layers (for each type of textile) reinforced in geopolymer mortar are considered. All 21 plate specimens including reference specimens, each of size 360x180x20 mm^3, have been tested for four-point bending strength. Besides that, 15 samples with dimension 30x30x150 mm^3 and 15 samples of diameter size 45 mm x length 90 mm have been measured for evaluating the mechanical properties of geopolymer mortar matrix. The results have shown that geopolymer composite specimens with carbon meshes have both the flexural strength and deflection higher than those with basalt meshes. Besides, the decrease of aperture size of mesh improves significantly the flexural strength due to increase specified number of yarns.**

Index Terms—**Geopolymer, four-point flexural strength, textile, compressive strength, carbon mesh, basalt mesh.**

I. INTRODUCTION

Textile-reinforced concrete (TRC) is a composite material composed of a fine-grained matrix with textile materials such as alkali-resistant glass, carbon, basalt or polymer replacing usual steel reinforced bars. The major advantages of TRC are its high tensile strength and pseudo-ductile due to its tolerance of multiple cracking [1]. The further advantages of these materials such as reinforcement have the ability to withstand corrosion, aggressive environments and therefore does not require strong covering layers in contrast to classical steel-reinforced concrete, where required cover layer should be enough thickness to protect the corrosion of steel-reinforcement during the lifetime of the structure. Due to these reasons, it is resulting in thinning and reduction of the mass of the whole structure. Thanks to their excellent material properties, the TRC composites are used in a wide range of applications such as strengthening and repair in structural elements, thin-walled elements, façade elements, bridges and also freeform and lightweight structures [2]–[7]. However, the TRC is not an environmentally friendly composite due to the use of the cement rich binder. The production of Portland cement is responsible for around 5% of the global CO_2 emissions. The appearance of the new material called geopolymer presents a promising technology direction for the construction industry.

Geopolymers are considered as an environmentally favorable choice due to the production of its raw materials may reduce CO_2 emission by up to six times [8]. Moreover, geopolymers are believed to display good mechanical strength in elevated temperature due to their ceramic structure. Therefore, concretes produced using geopolymers may obtain greater fire resistance as compared to conventional concretes produced using Portland cement. Daniel L. Y. Kong [9] showed that metakaolin-based geopolymers displayed more severe degradation compared to fly-ash based geopolymer at a high temperature above 700°C. Nevertheless, at a lower temperature than 500°C, these materials exhibit the similar mechanical properties and provide enough stability without showing signs of spalling [10]. Geopolymers are ceramic-like inorganic polymers produced at lower temperature, generally below 100°C [11]. These materials are produced by activating the solid aluminosilicate source with an alkaline solution, which is usually alkaline hydroxides and/or silicate solution based on sodium or/and potassium [12]. The process of the formation geopolymer composes the dissolution of the solid aluminosilicate framework, followed by the condensation of free silicates and aluminates, which forming a 3D configuration. This structure consists of cross-linked SiO_4 and AlO_4 tetrahedra, where the negative charge is balanced by the positive charges of the alkali ions (Na^+, K^+) [11].

This paper presents information on the impact of four-points flexural test of geopolymer composite panels after the addition of basalt and carbon fibers in the form of networks into the geopolymer mortar.

II. EXPERIMENTAL PROCEDURE

A. Geopolymer Mortar Matrix

Baucis LNa alumino-silicate geopolymer binder based on metakaolin was purchased from Ceske Lupkove Zavody, a.s. Czech Republic (in weight percent: SiO_2 – 47.4; Al_2O_3 – 29.7; CaO – 14.5; MgO – 2.6; TiO_2 – 1.8; Fe_2O_3 – 0.5; K_2O – 0.3; Na_2O - 1) along sodium silicate activator of modul 1.73 (in weight percent: SiO_2 – 20.72; Na_2O – 12.33; H_2O – 66.68). The metakaolin geopolymer was synthesized from calcined kaolin and shale clay residues with Si/Al ratio of 2.0. the kaolin was mainly composed of kaolinite with small amounts of quartz, whereas shale clay was composed of kaolinite with low amount of quartz and anatase. At first, kaolin and shale clay were passed in a rotary kiln to obtain in 30-70% loss of kaolinitic structure due to dehydroxylation. Further, it was converted to metakaolin by additional calculations at 750°C

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for 10h in bath oven.

Two different types of silica sand were used as the fine aggregates for geopolymer mortar matrix (grain size: 0 – 0.063 mm and 0.6 – 1.25 mm).

The geopolymer mixture was prepared as a two-component system using aluminosilicate source and sodium silicate solution in a liquid-to-solid ratio (0.8:1) by mechanically stirring for 4 min. In the next step, the micro-silica sand was added to the geopolymer mixture and the mixture was stirred for an additional 2 min. Finally, second silica sand was added to the mixture and the mixture was mixed for more 1 min. The detail of geopolymer matrix mixture was shown in Table I.

TABLE I. MIXTURE OF GEOPOLYMER MORTAR MATRIX

Mix ratio (by wt.%)			
Metakaolin	Activator	Sand (grain size of 0 – 0.065 mm)	Sand (grain size of 0.6 – 1.25 mm)
1	0.8	0.15	1.85

The mechanical properties of the plain geopolymer matrix were obtained by the compressive, three-point bending, and splitting tensile tests. The three-point bending tests were conducted on 40×40×160 mm^3 prism specimens with test span 100 mm, and then the compressive strengths were measured on the far edge of both residual pieces obtained from the flexural test. The splitting tensile tests were conducted on cylinder specimens with the diameter of 45 mm and length of 90 mm. A total of 15 specimens for each test were prepared and tested at the age of 1, 14, and 28 days.

B. *Textile Reinforcements*

Six different types of textile (carbon mesh and basalt mesh) were used as a reinforcement, applied variants were shown in Fig. 1. The three different types of basalt mesh and carbon mesh corresponding to mesh sizes of 16x12 mm, 25x25 mm, and 37x37 mm were used in this study. The yarns in both directions of basalt textiles were composed of 2400 individual filaments and density of 2.75 g/cm^3. The carbon meshes with open size 16x12 mm were made up of 48000 individual filaments for the yarns in the longitudinal direction and 12000 individual filaments for yarns in the transverse direction, while the other two types of carbon mesh were made up of 48000 individual filaments for yarns in both directions, and density of 1.8 g/cm^3. The yarns of textiles were arranged in two orthogonal directions (0^o/90^o) to form textile and they were coated with styrene-butadiene binder.

C. *Manufacturing of Geopolymer Composite Plates*

In order to evaluate the four-point bending strength for geopolymer composite plates with embedded meshes (basalt and carbon meshes), specimens with a rectangular form with the dimensions of 360×180×20 mm^3 (length, wide, thickness) were prepared. The two layers of the same type of textiles were fixed in mold with the desired position, which mean that the cover mortar layer of thickness 5 mm was applied to the bottom and top surface of the mold and between them the rest of mortar layer of thickness 10 mm was placed. The fresh prepared mortar matrix was poured into molds, vibrated for 1 min on the vibration table to remove air voids and covered with a thin plastic film to prevent the evaporation of water. The total number of samples tested was 21 including nonreinforced reference samples (see Fig. 2). The samples prepared for test had a maturation period of 28 days.

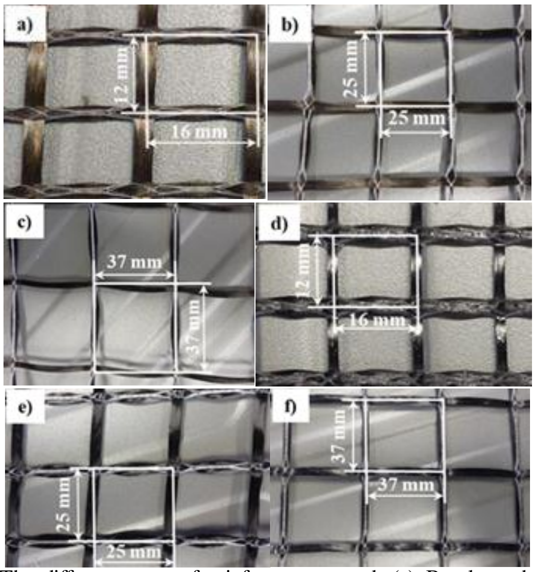


Fig. 1. The different types of reinforcement used: (a) Basalt mesh with aperture size of 16 x12 mm; (b) Basalt mesh with aperture size of 25 × 25 mm; (c) Basalt mesh with aperture size of 37 × 37 mm; (d) Carbon mesh of aperture size of 16 x 12 mm; (e) Carbon mesh of aperture size of 25 × 25 mm; (f) Carbon mesh of aperture size of 37 × 37 mm

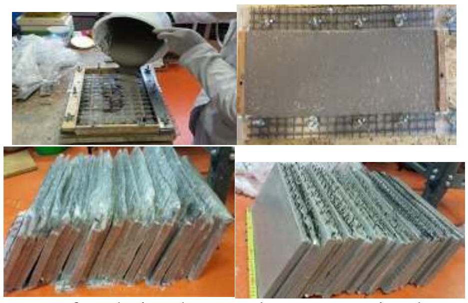


Fig. 2. Process of producing the geopolymer composite plates reinforced with textiles for four-points bending test.

A four-point bending test with constant bending moment zone was used to determine the bending strength of the panels. The illustration of the sample attachment and its fixation on the instrument was shown in Fig. 3. Three samples from each of the examined mesh types and mesh size were tested. For the safety reasons during the test, each sample was packaged with a foil (see Fig. 3). The calculation of the measured data and the evaluation of the test results were made using the following equation (3).

$$\sigma \frac{Fl}{bh^2} \text{ [MPa]} \quad (3)$$

where σ is the flexural strength in MPa; F is load at a given point on the load deflection curve in N; b is the width of the tested sample in mm; h is the thickness of tested sample in mm; l is the support span in mm.

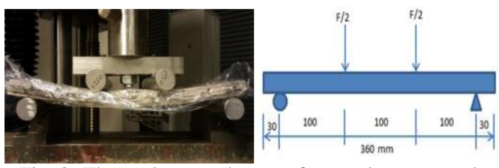


Fig. 3. Flexural strength test of geopolymer panels

III. Results and Discussion

A. The Mechanical Properties of Geopolymer Matrix

Table 2 shows the mechanical properties of geopolymer mortar matrix at a time period of 1, 14 and 28 days. It can be seen that the geopolymer mortar matrix cured at the room temperature reaches relatively high mechanical strengths at the age of 1 day after casting and its strength value gradually increases with increasing the curing age. After 28 days, the geopolymer mortar matrix has the compressive strength of 60.23 MPa, the flexural strength of 11.08 MPa, and the splitting tensile strength of 4.8 MPa.

TABLE II. Results of the Mechanical Properties of Geopolymer Matrix

Type	1 day	14 days	28 days
Flexural strength [MPa]	4.41±0.38	8.9±.63	11.08±0.48
Compressive strength [MPa]	27.66±1.01	40.67±3.78	60.23±3.79
Splitting tensile strength [MPa]	1.82 ±0.33	4.27±0.52	4.8±0.25

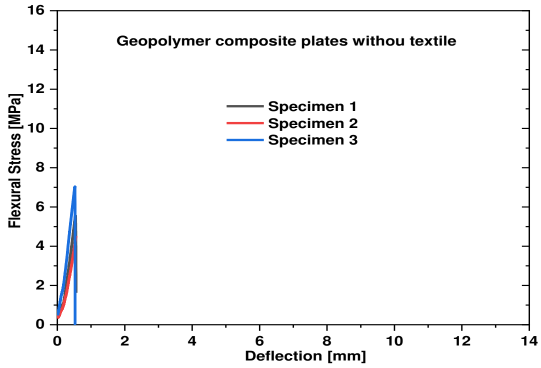


Fig. 4. Flexural stress and mid-span deflection curves of geopolymer plates without textiles.

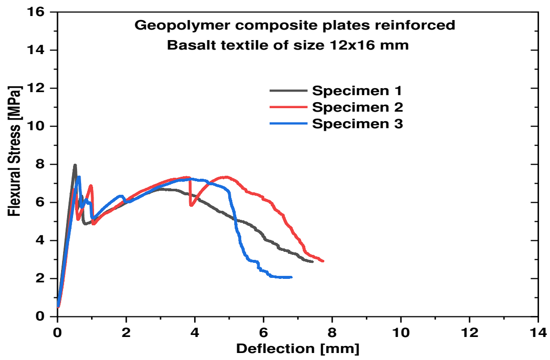


Fig. 5. Flexural stress and mid-span deflection curves of geopolymer plates reinforced basalt meshes of open size 12x16 mm.

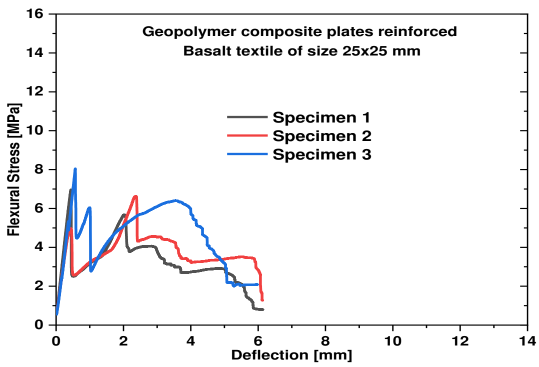


Fig. 6. Flexural stress and mid-span deflection curves of geopolymer plates reinforced basalt meshes of open size 25x25 mm.

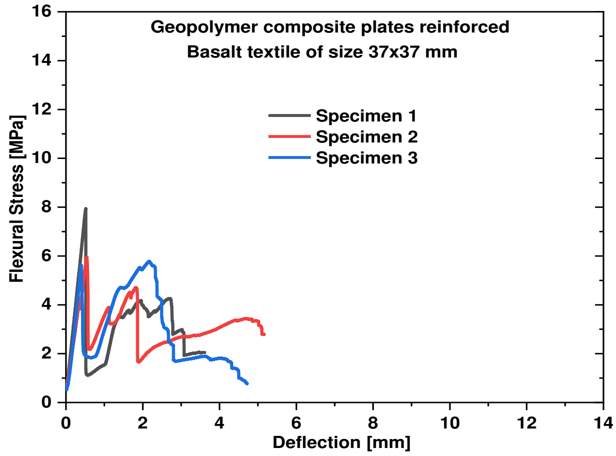


Fig. 7. Flexural stress and mid-span deflection curves of geopolymer plates reinforced basalt meshes of open size 37×37 mm.

B. Flexural Behavior of Textiles Reinforced Geopolymer Composite Specimens

An illustration of the course of four-point flexural tests of geopolymer composite panels has shown in the Fig. 4 – 10. Fig. 4 shows the flexural stress-deflection curves of geopolymer panels without the meshes. The result shows a linear increase in measured values until the first crack is formed, followed by a sharp degradation of the samples. This result is due to the fact that geopolymer material without added fiber reinforcement is very brittle. The obtained average ultimate bending strength of this specimen is 5.78 MPa (see Fig. 11).

In Fig. 5, 6 and 7 shows the flexural stress-deflection curves of geopolymer composite panels with basalt meshes of aperture size 16x12 mm (Fig. 5), of aperture size 25x25 mm (Fig. 6), and of aperture size 37x37 mm (Fig. 7). Basalt textile reinforced geopolymer composites show a similar course in the flexural stress-deflection curve. It can be seen that the effect of two-layer basalt meshes reinforced in geopolymer mortar on the flexural strength of composite panels is not significant. After the first cracking, which is attributed to degradation of geopolymer matrix, therefore, its flexural strength decreases suddenly. Then, the flexural strength increases again with increasing in deflection. This behavior can be attributed to the basalt textiles. However, instead of forming multiple cracks in the conventional way of the composites of TRC, the first crack continues developing widen with increasing in deflection, then followed by breaking out of the yarns of the basalt textiles (see Fig. 15). This behavior can be explained by fact that the use of two layers of basalt textile performs insufficient distribution of the yarns in given thickness of geopolymer plate specimens. From Fig. 11 shows that the use of the basalt mesh with an aperture size 12 × 16, 25 × 25, and 37 × 37 reinforced geopolymer composite specimens has an ultimate flexural strength of 7.31 MPa, 6.59 MPa, and 6.48 MPa, respectively.

Fig. 8, 9 and 10 shows the flexural stress-deflection behavior of geopolymer composite panels with carbon mesh of aperture size 16x12 mm (Fig. 8), of aperture size 25x25 mm (Fig. 9), and of aperture size 37x37 mm (Fig. 10). In contrast to basalt textile reinforced geopolymer specimens, carbon textile reinforced composite specimens shows the similar flexural stress-deflection behavior in the conventional way of the composites of TRC. The conventional behavior of TRC concrete is conducted in three stages. The first stage represents the linear uncracked state where the cementitious matrix takes the load. Then, as the load increases, the stress transfers from the cementitious matrix to the textile, which is represented by the multi-cracking process of the matrix. At the point or stage where the first crack takes the place is called the transition point. Then, the specimens continue to undergo a multi-cracking process, in which all of the stresses are transferred from matrix to textile. At this stage, the textile is only carrying until it fails by rupturing or by slipping [13]. In Fig. 8 – 10 it can be seen that the flexural stress-deflection curves greatly depend on the type of mesh size of the reinforcing carbon textile. The specimens with a textile of smaller mesh size have higher flexural strength than those with textile of bigger mesh size, due to more distribution of the yarns in the same thickness size of composite specimens. Furthermore, at the multicracking-formation state, the stiffness of composite thin plates with carbon textile of 12x16 mm aperture size is stronger and that can be seen on the crack-widening state in Fig. 8, 9, 10, and 15. From the results obtained, it is apparent that the use of a carbon mesh with an aperture size of 16x12 mm increases ultimate bending strength by 673.65%; a carbon mesh with an aperture size 25 ×25mm increases ultimate bending strength by 258.23% and a carbon mesh with an aperture size 3×37 mm increases ultimate bending strength by 205.37% compared to nonreinforced reference specimens. However, mid-span deflection capacity at the average peak load of the specimens with three different mesh sizes is similar 10.34 mm, 10.25 mm and 10.10 mm, respectively (see Fig. 12 and 13).

The reinforcement efficiency of specimens can be evaluated by a factor indicating the ratio of the ultimate flexural strength of reinforced composite to the flexural strength of nonreinforced reference composite. The results obtained are shown in Fig. 14. As can be seen from data, the reinforcement efficiency depends on both types of textile and aperture size of textile. The excellent performance in the reinforcement efficiency obtained belongs to composite specimens with carbon mesh of aperture size 12 ×16 mm.

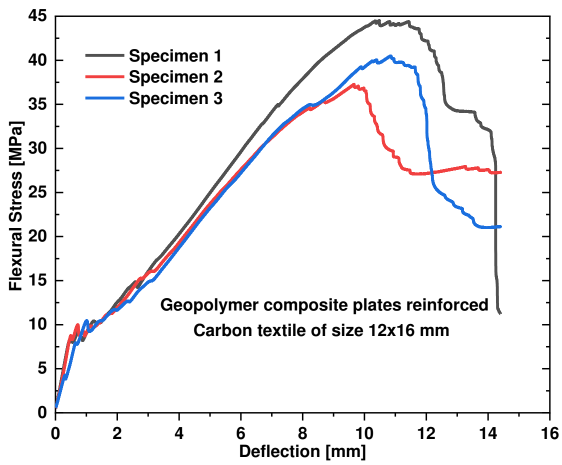


Fig. 8. Flexural stress and mid-span deflection curves of geopolymer plates reinforced carbon meshes of open size 12 × 16 mm.

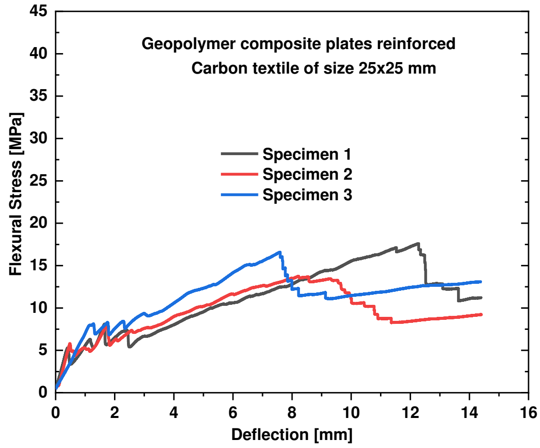


Fig. 9. Flexural stress and mid-span deflection curves of geopolymer plates reinforced carbon meshes of open size 25 × 25 mm.

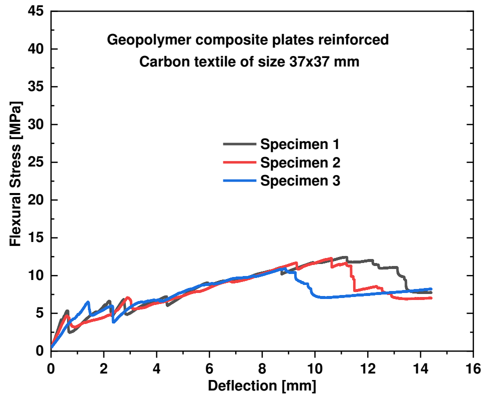


Fig. 10. Flexural stress and mid-span deflection curves of geopolymer plates reinforced carbon meshes of size 37 × 37 mm.

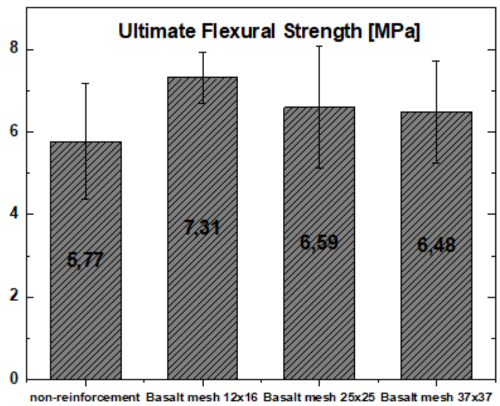


Fig. 11. Summary of four-point flexural strength of unreinforced specimens and basalt textiles reinforced composite specimens.

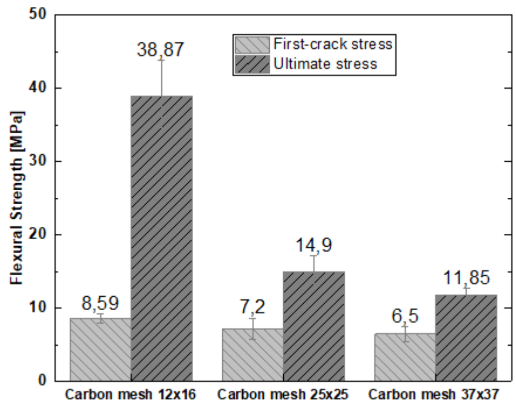


Fig. 12. Summary of four-point flexural strength of carbon textiles reinforced composite specimens.

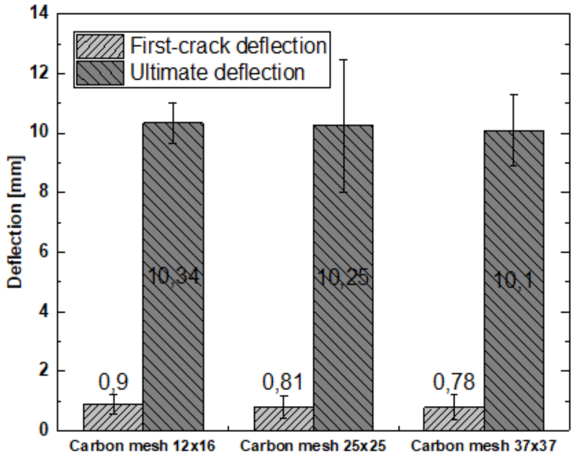


Fig. 13. Summary of deflection of carbon textiles reinforced composite specimens

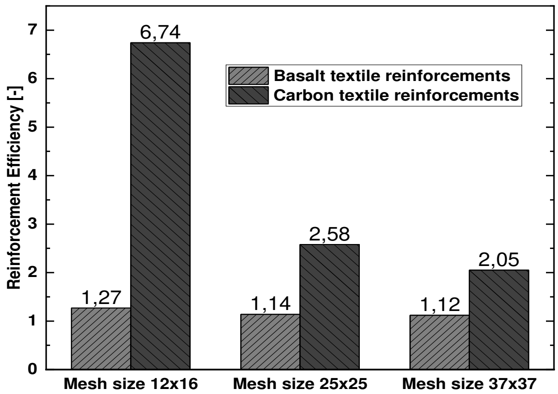
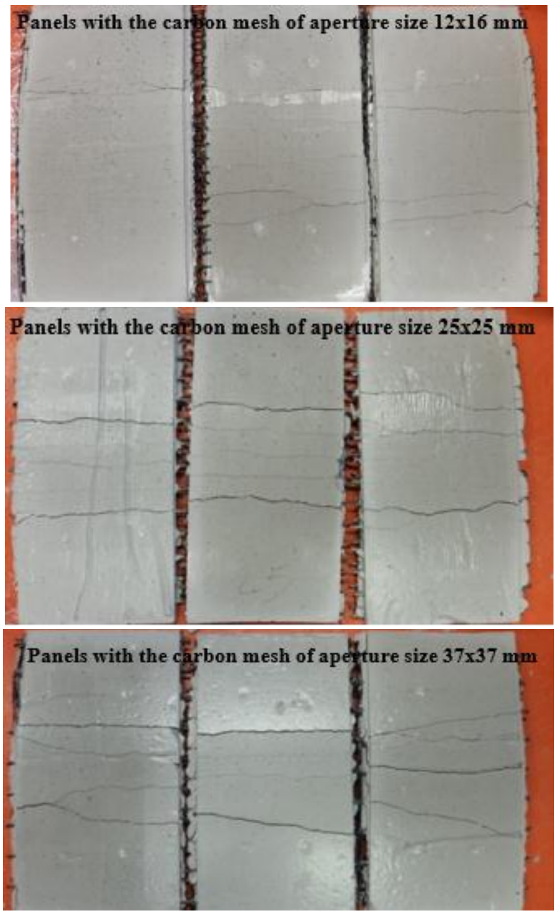


Fig. 14. The reinforcement efficiency of composite specimens.



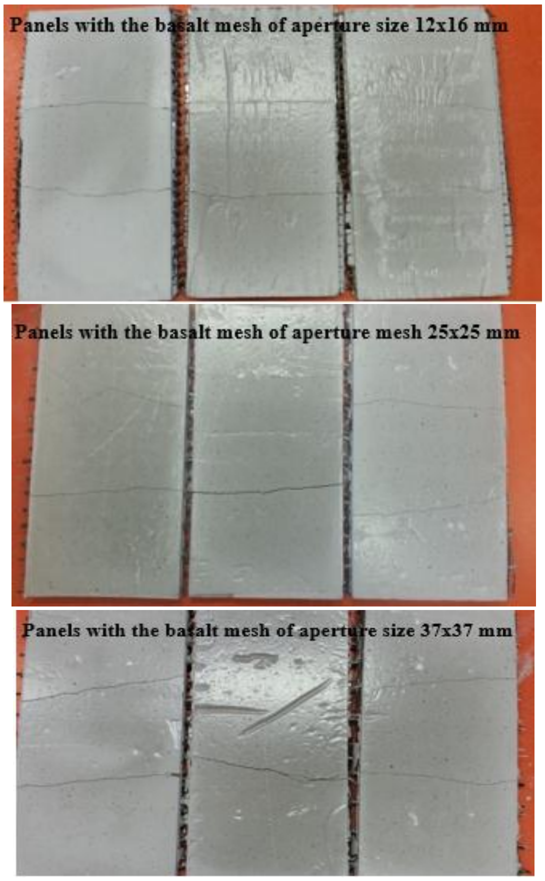


Fig. 15. Bottom surface crack patterns of the plate specimens after the end of testing.

IV. CONCLUSION

In this research, the flexural strengthening of geopolymer composite thin plates reinforced with the different types of textile is represented. The paper focused on an experimental investigation of the effect of applying the two layers of basalt and carbon textiles obtained the different aperture sizes on the four-point flexural strength. From the results obtained, it can be concluded that:

Basalt meshes including the different three types of aperture size have no significant impact on the flexural strength of composite specimens as compared to control specimen without reinforcement. It can be explained that the use of two layers basalt textile reinforced in geopolymer matrix makes insufficient distribution of the yarns in the given thickness of composite specimens.

Carbon meshes have a significant impact on both the flexural strength and deflection of composite specimens. The composite specimens with smaller mesh size have stronger flexural strength than those with bigger mesh size. This is mainly due to more contribution of the yarns in the given same thickness of the specimens.

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