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EFFECT OF THE HEIGHT OF REINFORCED CONCRETE LAYER ON THE MECHANICAL PROPERTIES OF FUNCTIONALLY GRADED CONCRETE INCORPORATING FLY ASH AND POLYPROPYLENE FIBER

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Abstract

The present research aims to investigate the influence of the ratio of reinforced concrete layer height to total height (h/H) on the mechanical properties of functionally graded concrete (FGC) containing fly ash (Fa) and polypropylene (PP) fiber. All FGC samples were prepared with a constant water-to-cementitious materials ratio of 0.36 and ordinary Portland cement was replaced with Fa at 20% by mass. The reinforcement layer of FGC was enhanced with PP fiber inclusion (0.3% by volume of concrete). The effect of various h/H ratios of 0.25, 0.50, and 0.75 on the mechanical properties of the FGC samples was evaluated. The results show that flexural strength, flexural toughness, and compressive strength values of the FGC with PP fiber were higher than those of FGC without PP fiber at the age of 28 days regardless of Fa replacement. The experimental results also pointed out that the FGC samples prepared using an h/H ratio of 0.50 were beneficial in terms of mechanical properties.

Keywords: functionally graded concrete; fly ash; polypropylene fiber; compressive strength; flexural strength; flexural toughness.

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1. Introduction

Concrete is the most widely used material in construction works in the world due to its useful characteristics such as high mechanical properties and durability, and flexible shape [1]. It was used to build many popular constructions that served human demand such as houses, schools, hospitals,

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buildings, roads, railways, ports, and so on. It is reported that over 10 billion tons of concrete are being produced all over the world every year [1]. In the United States, the annual production of over 500 million tons of concrete implies about two tons for each person. Such volumes require vast amounts of natural resources for aggregate and cement productions [1]. The production process of ordinary Portland cement (OPC), which is the main material in the composition of concrete releases a large amount of carbon dioxide into the atmosphere, resulting in a negative environmental impact [2]. To develop eco-friendly sustainable concrete and reduce carbon dioxide emission, supplementary cementitious materials such as fly ash (Fa) and ground granulated blast furnace slag were used to substitute OPC [2]. Fly ash, a by-product of coal-burning power plants, contains large amounts of siliceous and aluminous minerals which react with calcium hydroxide in the presence of water to produce the additional C–S–H [3]. This chemical reaction is called the pozzolanic reaction of Fa. When Fa was used to partially replace OPC at a relative ratio from 10% up to 40% by mass, the mechanical properties and durability of concrete incorporating Fa could be improved at later ages [4]. However, the pozzolanic reaction of Fa is slower than the hydration of cement, resulting in lower mechanical properties of the concrete than those of reference concrete without Fa at the early ages [4]. Normally, the conventional concrete using OPC has high compressive strength but low tension performance. Hence, the fibers were added to the concrete mixture to improve the tensile strength, toughness and increase fracture energy [5, 6]. The addition of fibers such as carbon fiber, steel fiber, polymer fiber, and rubber fiber could improve the flexural performance of concrete [6–9]. The role of fibers in the concrete mixture is considered as a reinforcement, bridging the cracks and further prevent their propagation. An excess of fibers should not be used because a large number of fibers caused poor fiber dispersion and fiber balling, leading to the reduction of the efficiency of fibers [5, 6]. Meanwhile, the low content of fibers was recommended due to the influence of aggregate size on fibers in the concrete mixture, leading to the reduction of workability as well as generation of the balling phenomenon [6].

Functionally graded concrete (FGC) is a new type of concrete material created from multiple concrete layers, as shown in Fig. 1. Generally, FGC was developed with higher compressive strength, flexural strength, fracture energy, and water resistance compared to conventional concrete with a single layer [6–10]. Functionally graded concrete was applied in many projects such as skateboarding areas, river tunnels, piers, etc. [5]. Based on the recommendation of previous studies [4, 5, 10–13], the replacement of OPC with Fa at 20% by mass of cementitious materials and the addition of polypropylene fiber at 0.3% by volume of concrete were carried out in this research to reduce the use of OPC as well as improve the flexural performance of FGC. On the other hand, an important aspect of FGC is the thickness (height) of double-layer concrete which was previously mentioned by Torelli et al. [10] and Chan et al. [6]. The thickness of double-layer concrete could be relative to the interfacial bond, the delamination (casting the top layer on the hardened bottom layer), or wavy layers (casting the top layer on the bottom layer that was not hardened). Therefore, this research was conducted to investigate the proper time for casting the top layer on the bottom layer to prevent the delamination, or wavy layers, or the

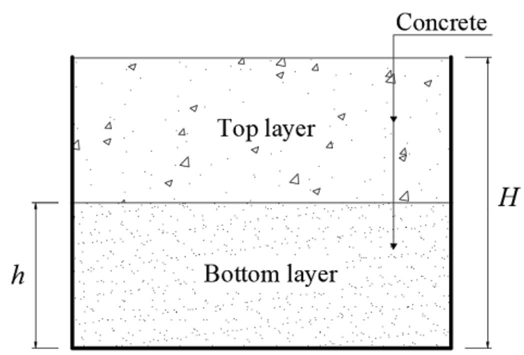


Figure 1. Typical functionally graded concrete (2 layers)

weak interfacial bonding between two layers. In addition, the ratio of the height of reinforced concrete layers (h) to the total height (H) of the FGC sample (h/H ratio) was investigated to find an optimal ratio that gives the best mechanical properties in terms of flexural strength, flexural toughness, and compressive strength.

2. Materials and methods

2.1. Materials

The cementitious materials used in this research were type-I OPC (as per TCVN 2682:2009 [14]) supplied from Nghi Son cement company and type-F Fa (as per TCVN 10302:2014 [15]) supplied from Duyen Hai thermal power plant. Their physical properties and chemical compositions are shown in Table 1.

Table 1. Physical properties and chemical compositions of OPC and Fa

Constituent	Item	Cementitious materials	
		OPC	Fa
Physical properties	Density (g/cm^3)	3.1	2.2
	Compressive strength at 28 days (MPa)	59.2	–
	Percentage passing through 0.09-mm sieve (%)	0.3	7.0
Chemical compositions (% by mass)	SiO_2	24.0	45.5
	Al_2O_3	4.0	20.5
	Fe_2O_3	2.0	17.4
	CaO	63.0	5.4
	K_2O	0.6	5.7
	Na_2O	0.1	0.3
	SO_3	2.4	0.5
	MgO	1.5	0.5
	LOI	2.7	4.8

LOI: loss on ignition; –: not measured.

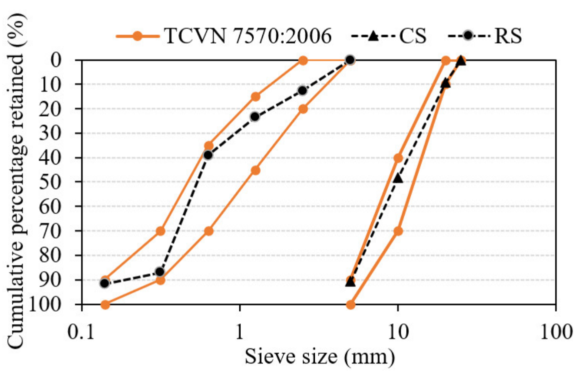


Figure 2. Grading curve of aggregates compared with TCVN 7570:2006

River sand (RS) taken from the Dong Nai river was used as fine aggregate. The fineness modulus, density, and water absorption of RS were 2.55, 2.65 g/cm^3, and 0.82%, respectively. Meanwhile, coarse aggregate was crushed stone (CS) with a maximum size of 20 mm. Density and water absorption of CS were 2.69 g/cm^3 and 0.35%, respectively. Fig. 2 shows the particle size distributions of RS and CS compared with TCVN 7570:2006 [16].

Polypropylene (PP) fiber used in this research (Fig. 3) was a polymer fiber with high mechanical strength (tear and tensile strength), conforming to TCVN 12393:2018 [17]. Characteristics of PP fiber are shown in Table 2.

Figure 3. PP fiber

Table 2. Properties of PP fiber

Properties	Value
Diameter (mm)	0.02
Length (mm)	6-12
Density (g/cm^3)	0.91
Tensile strength (MPa)	500

Tap water (W) was used for casting all concrete mixtures. In addition, the lignosulfonate-based Sikament R4 superplasticizer (SP) supplied by the Sika group was applied in all concrete mixtures to improve the workability.

2.2. Mixture proportion and specimen preparation

The normal concrete with a water-to-cementitious materials ratio (W/C) of 0.36 was designed according to ACI 308R-01 [18]. The target slump and compressive strength at 28 days were 8 ± 2 cm and 70 MPa, respectively. According to the previous studies [4, 12, 13], Fa was used to replace OPC at 20% by mass of cementitious materials in the concrete mixtures. Moreover, PP fiber with a content of 0.3% by volume of concrete which was the optimal content for structural and economic aspects according to previous research [5, 6] was used. A total of four concrete mixtures was produced in this research, including normal concrete (N), concrete with 20% Fa replacement (FA), normal concrete combined with 0.3% PP fiber (NP), and concrete with 20% Fa replacement and 0.3% PP fiber (FAP).

Table 3. Mixture proportion of all concretes

	Unit: kg						PP (% V_{con})	SP (L)
Mixture	W/C	W	C	Fa	CS	RS		
N	0.36	183	508	0	969	772	0	4.06
FA	0.36	183	406	102	969	742	0	4.06
NP	0.36	183	508	0	969	772	0.3	4.06
FAP	0.36	183	406	102	969	742	0.3	4.06

% V_{con}: % volume of concrete.

Table 3 shows the mixture proportions of all FGC samples. The concrete with a single layer without Fa and PP fiber (100N) was considered as the reference concrete in this research.

The codification of all FGC mixtures was denoted as AX/BY. Where, A and X are the height and concrete mixture of the top concrete layer, respectively; B and Y are the height and concrete mixture of the bottom concrete layer, respectively. For example, mixture 25NP/75FAP means that height and concrete mixture of the top concrete layer are 25 cm and normal concrete containing PP fiber, whereas height and concrete mixture of the bottom concrete layer are 75 cm and concrete containing Fa and PP fiber, respectively. On the other hand, various h/H ratios of 0.25, 0.50, and 0.75 were evaluated in this research, as described in Fig. 4.

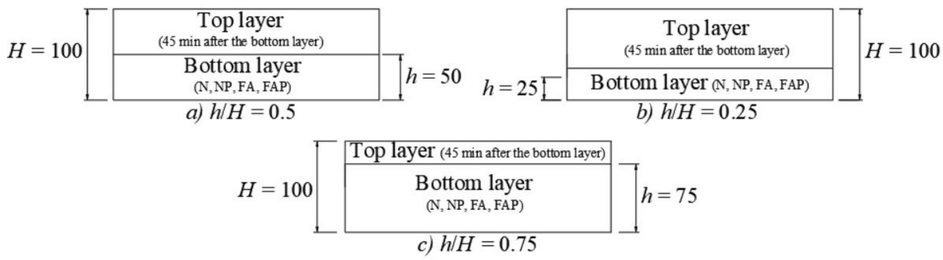


Figure 4. Typical cross-sections of FGC considered in this research (values in mm)

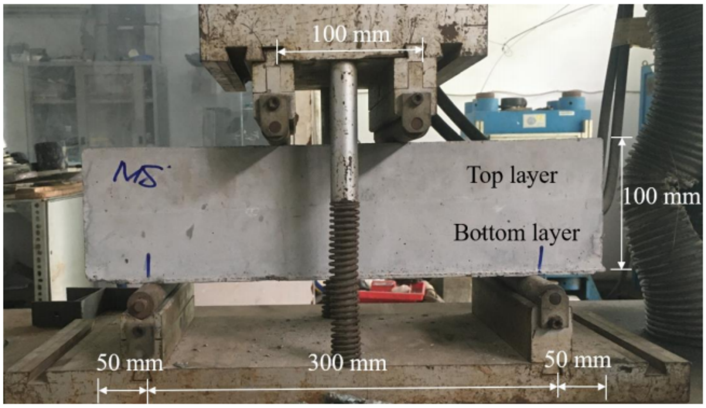
The setting time of the reinforced concrete mixture was measured by penetration resistance of fresh concrete using the HG80s device following TCVN 9338:2012 [19] and GB.T 50080:2016 [20]. Based on experimental results of the setting time, for the production of FGC in this research, the top concrete layer was cast approximately 45 min after finishing the bottom concrete layer to eliminate the effect of casting time on the bonding between two layers of FGC samples as well as prevent the coarse aggregate in top concrete layer entering into the bottom concrete layer. The proposal time for casting the top layer was also recommended by Li and Xu [21] (i.e., the later concrete layer should be cast about 60 min after the first concrete layer).

The mixing process could be briefly described as follows: (1) fine aggregate and cementitious materials were firstly mixed for 30 seconds; (2) 80% water containing SP was then added and mixed for another 30 seconds; (3) the coarse aggregate was put into the mixer and kneaded for 60 seconds; (4) PP fiber and the remaining amount of water containing SP were added and mixed for 60 seconds (note: the mixing process was not more than 180 seconds). After mixing and slump testing, fresh concrete was poured into the cubic molds with a size of 150×150×150 mm for determining compressive strength and prismatic molds of 100×100×400 mm for measuring flexural strength and toughness of FGC. All samples were covered with plastic sheets and damp clothes for 24 hours after casting. These samples were then de-molded and cured in water until the designated ages under TCVN 3105:1993 [22].

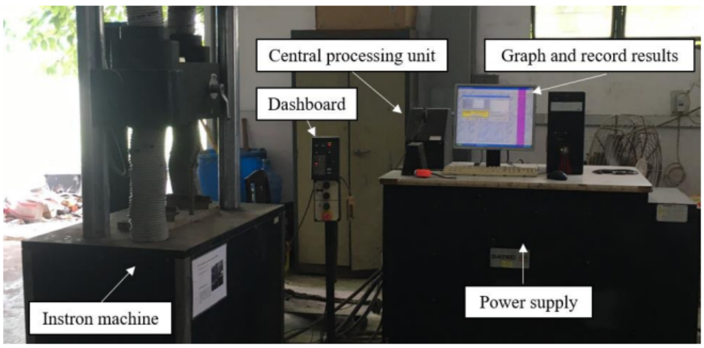
2.3. Test methods

Slump: After mixing, the slump of all concrete mixtures was immediately determined according to TCVN 3106:1993 [23].

Flexural strength and flexural toughness: Flexural strength was conducted for concrete beam samples with a dimension of 100×100×400 mm after 28 days using an Instron multi-function machine in accordance with TCVN 3119:1993 [24]. The loading rate was controlled by an increase in load/time with a value of 0.5 kN/s instead of the increase in deflection/time. It is due to the limitation of equipment. However, it is believed that the tendency of results was not affected because the same loading rate was applied for all tests. Fig. 5(a) shows the setup of the flexural strength test as guidance by ASTM C1609 [25]. During the test, the applied load and deflection were automatically recorded by the Instron multi-function machine, as shown in Fig. 5(b). The flexural toughness of FGC was then derived from the result of the load-deflection curve according to ASTM C1609 [25].



(a) Flexural strength test of concrete beam



(b) Instron multi-function machine

Figure 5. Flexural strength test and Instron multi-function machine

Flexural toughness is one of the most important characteristics of concrete structures subjected to static strains, earthquakes, or dynamic loads. It reflects the energy absorption capacity, crack resistance, and ductility of concrete. Flexural toughness can be measured based on the typical load-deflection curve from the flexural test, as shown in Fig. 6. Based on the graph between the load and deflection curve, the load (A) corresponding to the occurrence of the first crack or first peak load (P_1) was measured. Point δ_1 was identified as an intersection point of the horizontal axis and the perpendicular line from point A. Then, O was the intersection of the horizontal axis and load P axis and it was the intersection of the horizontal axis and curve of flexural strength. The load (B) corresponding to the occurrence of the peak load ($P_{\max}$) was measured. Point δ_p was identified as an intersection point of the horizontal axis and the perpendicular line from point B as shown in Fig. 6. Similarly, point L/600 and L/150 could be determined as the intersection points of the horizontal axis and residual load P_{600} and P_{150}, respectively. Referring to a previous study [26], the flexural toughness (in

J/m^2) was calculated by the integral area of load-deflection under first peak load (P_1) defined as first crack - flexural toughness, while that was calculated by the integral area of load-deflection under peak load (P_{max}) defined as peak flexural toughness, and that was determined by the total integral area of load-deflection referred to limit flexural toughness, see Fig. 6.

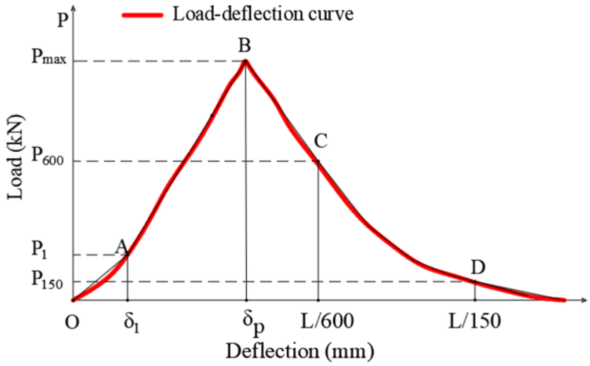


Figure 6. The diagram for calculating the toughness of concrete beams

Compressive strength: The compressive strength of concrete was tested at the ages of 3, 7, and 28 days using the automatic loading compressor according to TCVN 3118:1993 [27]. The value was the average of three cubic samples (150×150×150 mm) of each concrete mixture at each age. To eliminate the effect of delamination, the direction of the compression test was conducted as longitudinal with the direction of the bonding between two concrete layers (top and bottom layers), as shown in Fig. 7.

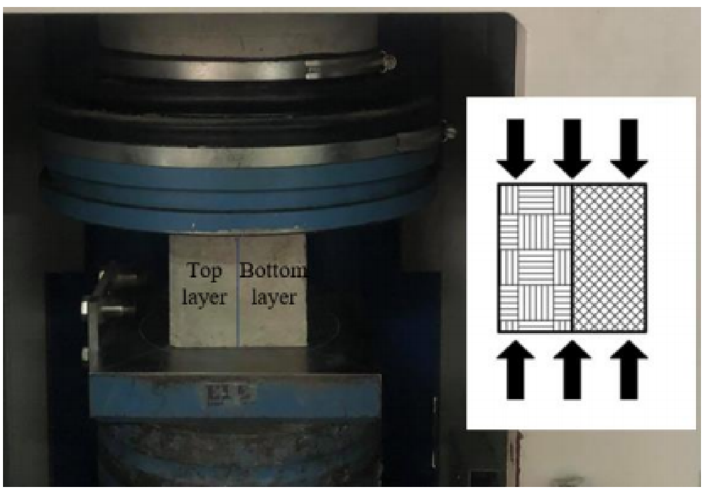


Figure 7. Experimental setup for compressive strength test

3. Results and discussion

3.1. Slump

Fig. 8 shows the slump values of all concrete mixtures in the research. It is found that the slump of normal concrete ranged from 6 to 10 cm, and was consistent with the designed slump of 8 ± 2 cm. The addition of Fa to normal concrete resulted in an increase in slump value due to the spherical shape of Fa, which contributed to the reduction of friction among particles in the cement matrix [3, 4]. However, the slump of concrete was significantly reduced when PP fiber was used due to its effect on the mobility of aggregates in the concrete mixture. As a result, the interlocking and friction between PP fiber and aggregates were increased [5, 9]. Moreover, the addition of PP fiber led to an increase in water demand. Further, the free water for lubricating the cementitious particles was reduced [5, 9].

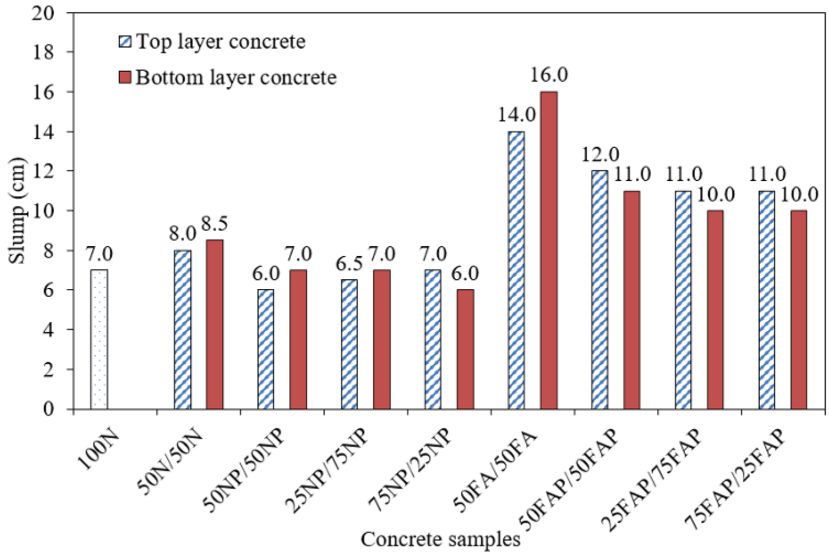


Figure 8. Slump values of all concrete specimens

3.2. *Flexural strength and flexural toughness*

Fig. 9 shows the flexural strength of FGC samples at 28 days. Flexural strength was found to be affected by the h/H ratio. It can be seen that the flexural strength of almost FGC specimens was higher than that of reference specimen, except for 50FA/50FA. Flexural strength values of FGC using normal concrete and PP fiber (50NP/50NP, 25NP/75NP, and 75NP/25NP) were about 9–16% higher than that of corresponding FGC without PP fiber (50N/50N). The inclusion of Fa slightly reduced the flexural strength of FGC. However, the reduced strength could be improved by adding PP fiber to the FGC samples. For instance, the FGC using Fa concrete and no PP fiber (50FA/50FA) was 8% lower in flexural strength than the corresponding FGC using normal concrete (50N/50N). However, the flexural strength of FGC using Fa concrete was increased and slightly higher than that of the FGC using normal concrete (50N/50N) when PP fiber was used. It is due to the distribution of PP fiber in FGC samples, creating a connection network and thus increasing the flexural strength of the FGC sample. This is in good agreement with the previous study [6].

Moreover, the flexural strength of the FGC using normal concrete and PP fiber with the h/H ratio of 0.50 (50NP/50NP) at 28 days was 6.7% and 3.6% higher than that with the h/H ratios of 0.75 (25NP/75NP) and 0.25 (75NP/25NP), respectively. The same tendency was also observed for FGC using Fa concrete and PP fiber. In particular, FGC containing Fa and PP fiber with the h/H ratio of 0.50 (50FAP/50FAP) at 28 days had 3.1% higher in flexural strength than that with the h/H ratios of 0.75 (25FAP/75FAP) and 0.25 (75FAP/25FAP). From the results, it can be found that the highest value of flexural strength corresponded to the FGC sample with an h/H ratio of 0.50.

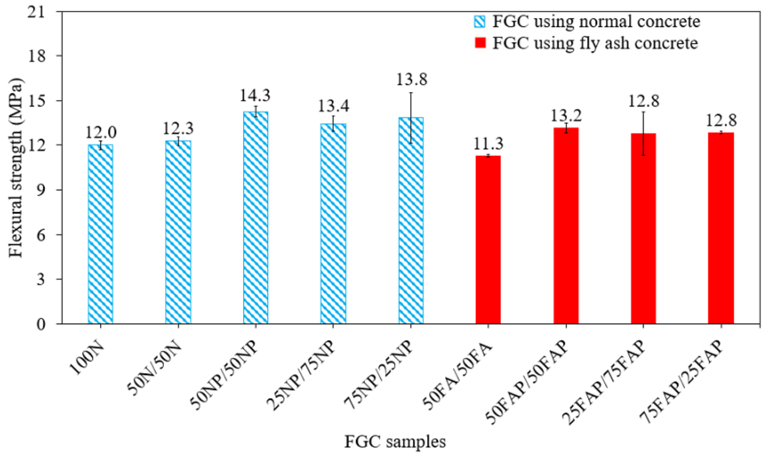
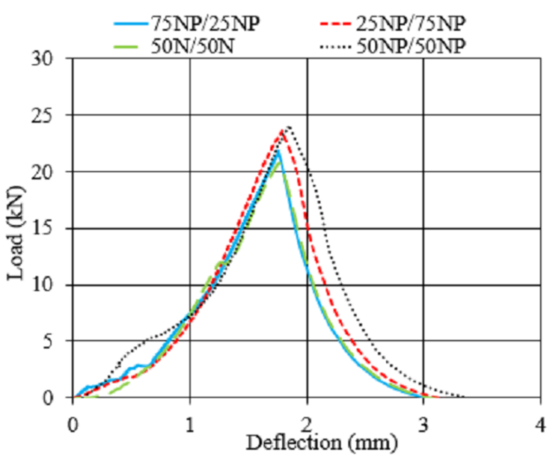
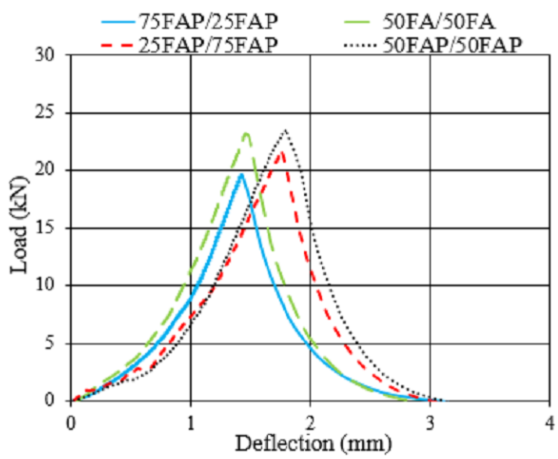


Figure 9. Flexural strength of FGC at 28 days

The relationship between load and deflection is plotted in Fig. 10. The load-deflection curve of FGC using normal concrete and PP fiber with the h/H ratio of 0.50 (50NP/50NP) had a gentler slope than that of corresponding FGC with the h/H ratios of 0.75 (25NP/75NP) and 0.25 (75NP/25NP) (see Fig. 10(a)). The same tendency was also observed for FGC containing Fa, as shown in Fig. 10(b). Fig. 10 also reveals that the FGC containing PP fiber with the h/H ratio of 0.50 exhibited the highest deflection and maximum failure stress as compared to the others.



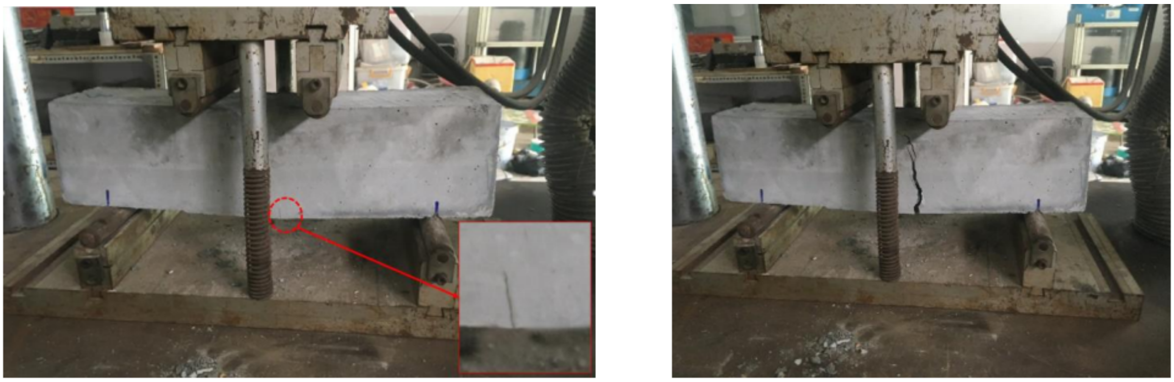
(a) FGC using normal concrete



(b) FGC using fly ash concrete

Figure 10. Effect of h/H ratios on load-deflection curve of FGC

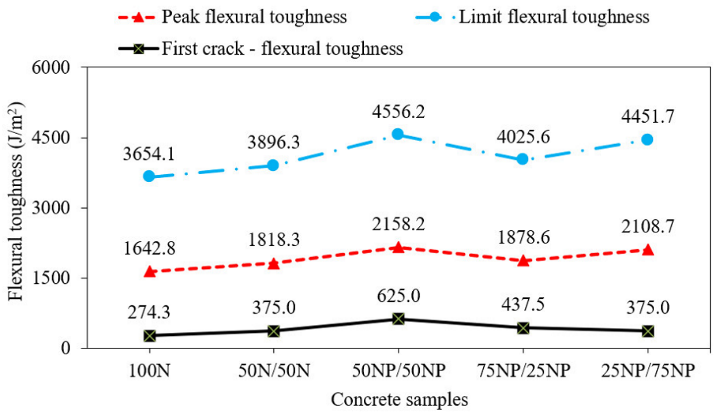
Fig. 11 shows the development of crack in tension area of FGC beam with PP fiber. When the load exceeds the bearing capacity of the concrete beam, the first crack would occur from the tension area of concrete and spread slowly (see Fig. 11(a)). Since FGC beam contained PP fiber, the load and deflection were still increased and the beams were not immediately destructed (see Fig. 11(b)). The stress in FGC was transformed to PP fiber since the load was increased. Therefore, microcracks were bridged by fiber, further preventing the crack development [28, 29].



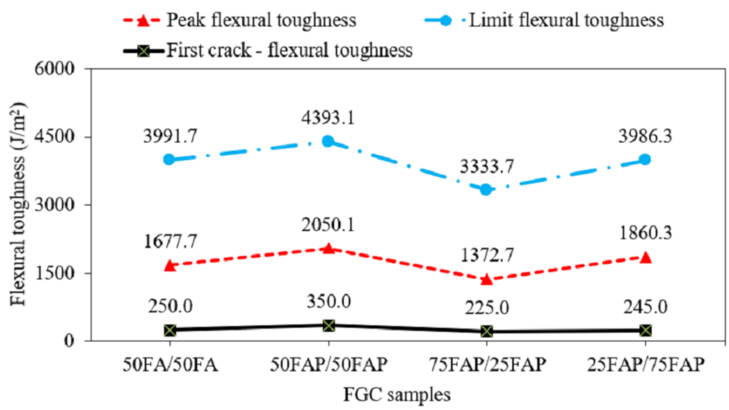
(a) Occurrence of first cracking

(b) Formation and slow extension of cracks from the tension area

Figure 11. The development of crack in tension area of FGC beam with PP fiber



(a) Flexural toughness of FGC using normal concrete



(b) Flexural toughness of FGC using fly ash concrete

Figure 12. Effect of the h/H ratios on the flexural toughness of FGC

Fig. 12 shows the effect of h/H ratios on the flexural toughness of FGC. For the same h/H ratio of 0.50, the FGC samples containing PP fiber showed higher in first crack - flexural toughness, peak flexural toughness, and limit flexural toughness than FGC samples without PP fiber regardless of Fa replacement. It is due to the contribution of PP fiber to the enhancement of bearing capacity after cracking. When FGC incorporating PP fiber, the value of first crack - flexural toughness, peak flexural toughness and limit flexural toughness of FGC with the h/H ratios of 0.75 and 0.25 was lower than that with the h/H ratio of 0.50. In particular, the peak flexural toughness and limit flexural toughness of FGC incorporating PP fiber with the h/H ratio of 0.50 (50NP/50NP) were 2158.2 and 4556.2 J/m^2 (see Fig. 12(a)), whereas those with the h/H ratio of 0.25 (75NP/25NP) were 1878.6 and 4025.6 J/m^2, and those with the h/H ratio of 0.75 (25NP/75NP) were 2108.7 and 4451.7 J/m^2 (see Fig. 12(a)), respectively. The same tendency was also found for FGC using Fa concrete, as shown in Fig. 12(b). This result was consistent with the observation of Dong et al. [26]. It could be clarified that the FGC samples with an h/H ratio of 0.50 were stable and effective. Therefore, this ratio was chosen for verifying the compressive strength in Section 3.3.

3.3. Compressive strength

Fig. 13 shows the compressive strength of FGC with the h/H ratio of 0.50 at the ages of 3, 7, and 28 days. Moreover, the normal concrete samples with a single layer (100N) were produced for comparison. It can be seen that the compressive strength of all FGC samples was higher than that of normal concrete with a single layer (100N), except FGC containing Fa (50FA/50FA). For example, the compressive strength of the FGC specimens without Fa and PP fiber (50N/50N) was 1.1% and 2.7% higher than that of concrete with the single layer (100N) at 3 and 7 days, respectively. Meanwhile, the compressive strength of FGC incorporating Fa was lower than that of concrete with the single layer (100N) and FGC without Fa at the early ages (3 and 7 days), regardless of PP fiber addition. It is due to the dilution effect and slow reactivity of Fa [12, 30]. However, the compressive strength of FGC specimens containing only Fa (50FA/50FA) was almost the same as that of normal concrete with the single layer (100N) at 28 days. The reason is probably due to the pozzolanic reaction of Fa, which generated the additional C–S–H and C–A–S–H [12, 30] and enhanced the compressive strength of FGC. On the other hand, the inclusion of PP fiber was found to positively increase the compressive

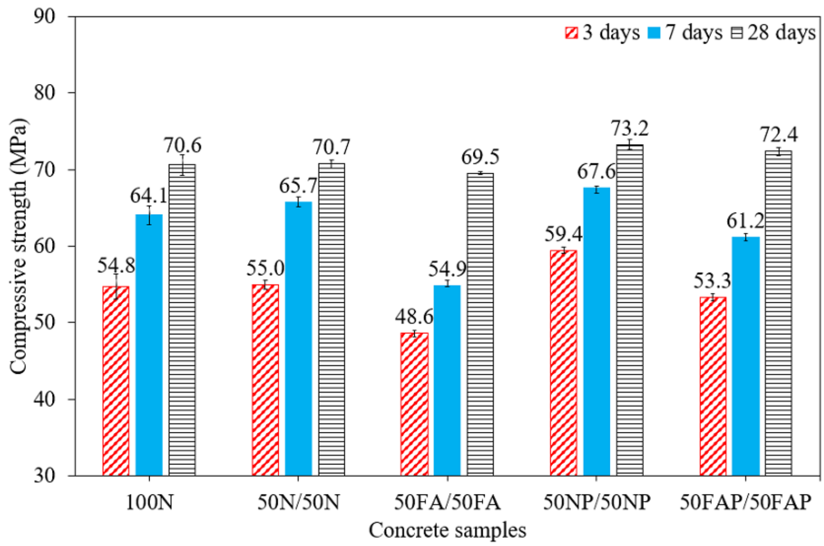


Figure 13. Compressive strength development of all FGC mixtures

strength of the FGC samples. For instance, the compressive strength of FGC samples containing only PP fiber (50NP/50NP) at 28 days was approximately 3.7% higher than that of normal concrete with a single layer (100N). This is in good agreement with the previous studies [6, 7, 9].

After the compression test, the visual inspection of the fractured surface of FGC samples was done (see Fig. 14). It can be observed that the bonding between the two layers of the FGC was not destroyed or broken and the fracture surface of the FGC was the same as that of the normal concrete with a single layer after compression test. It means that the capable bonding between two layers of FGC samples was realizable. A similar observation was previously done by Río et al. [8]. This could be clarified that the mixing procedure and fabrication of FGC based on the setting time of the bottom concrete layer in this research were workable and acceptable.

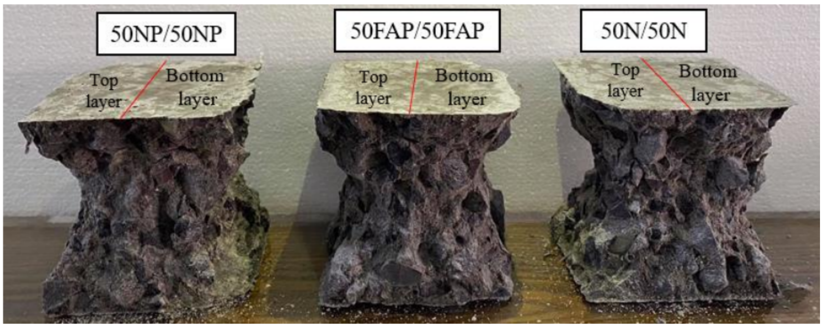


Figure 14. The visual inspection of the fractured surface of FGC samples after compression test

A relationship between flexural strength and compressive strength of the concretes at 28 days is plotted in Fig. 15. The high coefficient of determination (R^2 = 0.89) implies that the flexural strength had the linear correlation with compressive strength. The flexural strength increased with an increase in compressive strength.

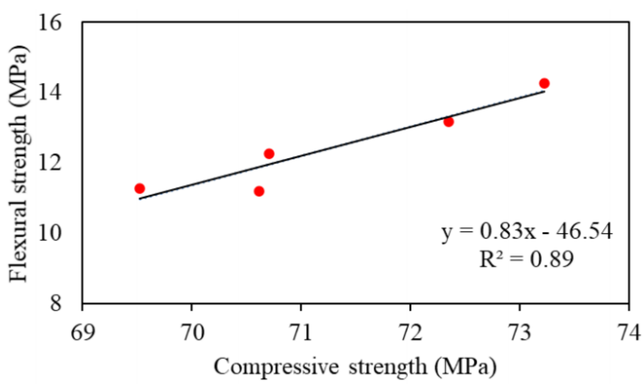


Figure 15. The relationship between flexural strength and compressive strength of the concretes at 28 days

4. Conclusions

The influence of the h/H ratios on the mechanical properties of FGC incorporating Fa and PP fiber has been investigated in the present research. Based on the experimental results, some conclusions can be drawn as follows:

- The FGC with the presence of PP fiber exhibited the better performance, in terms of flexural strength, flexural toughness, and compressive strength, in comparison with the FGC without PP fiber at the age of 28 days regardless of Fa replacement.

- The FGC samples incorporating 20% Fa replacement and 0.3% PP fiber demonstrated the better mechanical properties than the conventional concrete with a single layer (100N).

- The h/H ratio of 0.50 was suggested as an optimal ratio for FGC, where the FGC samples earned good mechanical properties and were more stable than the samples prepared with other h/H ratios. This finding was proved through the tests of flexural toughness and flexural strength of FGC.

- The capable bonding between the top and bottom layers of FGC samples prepared with the h/H ratio of 0.50 was the best among the samples. It could be clearly observed through compressive strength test.

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