

Mechanical Behavior of High Strength Concrete Reinforced with Glass Fiber Reinforced Polymer

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Abstract— Effects of alkali resistant glass fiber reinforced polymer (AR-GFRP) with various proportions on the mechanical behavior of high strength concrete (HSC) were investigated on this study. Concrete mixtures were prepared with various proportions of AR-GFRP typically 0.3, 0.6, 0.9, and 1.2 by weight of cement. The mixtures were cast and tested for compressive, splitting tensile and flexural strengths in accordance to ASTM standards. The experimental results showed that the strengths increase as fiber percentage increases; the compressive strength increased from 57.85 to 66.6 MPa, the splitting tensile strength increased from 3.06 to 4.92 MPa, and the flexural strength increased from 4.84 to 7.27 MPa when fiber percentage increased from 0.0 to 1.2 respectively. In comparison with plain HSC control specimens that showed destructive sudden failure, the formation of cracks that led to failure in the specimens with AR-GFRP was gradual as the fiber percentage increases. Hence it can be concluded that the presence of fibers in the matrix has contributed towards prevent sudden crack formation and thus enhancing concrete ductility.

Index Terms—HSC, GFRC, AR-GFRP, HSGFRC, Mechanical behavior, Mechanical properties, Mode of failure.

I INTRODUCTION

It has been recognized that high strength concrete (HSC) has a brittle behavior at ultimate limit state of loading. The addition of closely spaced and uniformly dispersed small fibers to concrete would act as crack arrester and would substantially improve its mechanical behavior and ductility. The addition of fibers results in a product, which has higher flexural and tensile strengths compared with normal concrete [1].

The conventional fiber reinforced concrete (FRC) made by adding fibers in normal strength concrete (NSC) only exhibits an increase in ductility compared with the plain matrix, whereas high strength fiber reinforced concrete (HSFRC) made by adding fibers in HSC exhibits substantial strain hardening type of response which leads to a large improvement in both strength and toughness compared with the plain matrix [2].

Many types of fibers are available in practice; glass fiber reinforced polymer (GFRP) is preferred than other types due to high ratio of surface area to weight and high strength properties to unit cost ratio. However, glass fiber which is originally used in conjunction with cement was found to be affected by alkaline condition of cement. The alkali resistant glass fiber reinforced polymer (AR-GFRP), which is used recently has overcome this defect and can be effectively used in concrete [3].

For new materials like high strength glass fiber reinforced concrete (HSGFRC), studies on mechanical behavior are of paramount important for initializing confidence in engineers. Most of the carried out research on mechanical behavior of FRC, was made with steel, carbon, and natural fibers. However, few attempts were made with glass fibers. In addition, the literature indicates that most of available studies were made with normal strength concrete (NSC) reinforced with insufficient proportions of glass fibers. Therefore, the undertaken

study was conducted to investigate the mechanical behavior of HSC reinforced with various percentages of glass fibers. The aim of this research is to study the effect of the addition of AR-GFRP with various proportions on the mechanical behavior of HSC. Strength characteristics and mode of failure of HSGFRC were compared with plain HSC, by performing laboratory tests on compressive strength, splitting tensile strength, flexural strength, and density.

II EXPERIMENTAL PROGRAM

A Materials

HSGFRC constituent materials used in this research include ordinary Portland cement, coarse aggregate, fine aggregate, normal range water reducer (NRWR) and GFRP. Proportions of these constituent materials have been chosen carefully in order to optimize the packing density of the mixture. Ordinary Portland cement CEM II 42.5R was used. The cement met the requirements of ASTM C150 specifications [4]. According to the local market surveying, the available fine aggregate is dune sand type which is finer than required by standard specifications of ASTM C33 [5] and its gradation does not fall within the limits. However, many researchers mentioned that the role of FM and gradation of the fine aggregate in HSC is not as crucial as in conventional strength mixtures [6] [7]. The grain distribution of fine aggregate is shown in Table 1. The coarse aggregate was natural crushed lime stone of 12.5 mm nominal maximum size. The sieve analysis of the coarse aggregate according to ASTM C33 [5] is shown in Figs.1. The specific gravities of coarse and fine aggregates were 2.66 and 2.63 respectively. NRWR confirming ASTM C494 [6] Type A specification was used with dosage of 2 Lit./m³ according to manufacturer's suggestion. According to manufacture data sheet, the properties of AR-GFRP used are shown in Table 2.

Table 1
Grain Distribution of Fine Aggregate.

Sieve Size (mm)	% Passing
4.75	100
2.36	100
1.18	95.99
0.6	87.33
0.425	73.14
0.3	39.33
0.15	1.50
0.075	0
Fineness Modulus FM	1.75

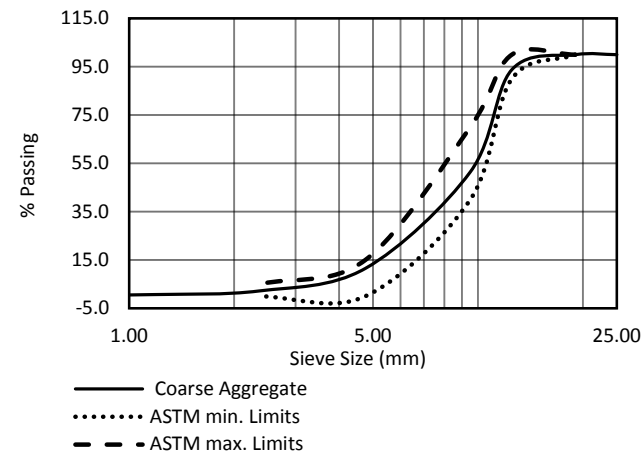


Figure 1 Coarse Aggregate Sieve Analysis According to ASTM C33 [5].

TABLE 2
Properties of AR-GFRP.

Fiber Properties	Quantity
Fiber Length	Hybrid 8 to 30 mm
Diameter	14μ
Density	2.7 t/m ³
Modulus of Elasticity	72 GPa
Tensile Strength	1,700 MPa
Chemical Resistance	Very high
Electrical Conductivity	Very low
Softening Point	860 °C
Zro2 Content	15-20 %
Material Alkali Resistant	Alkali Resistant Glass

B Mix Proportioning

The reference concrete mix (without GFRP) was developed on a trial and error basis to obtain 28-day cylinder compressive strength for design of 50 MPa. The first trail mixture

was based on Kosmatka et al. [8], then modifications were applied to obtain the best determinable mix design proportions that achieved the target design strength.

Five fiber percentages were used, i.e. 0.0, 0.3, 0.6, 0.9, and 1.2 by weight of cement. Accordingly, the five mixes shown in Table 3 were used to evaluate the effect of AR-GFRP on the mechanical behavior of plain HSC. These percentages were chosen in a range that can give better observation and evaluation on the mechanical behavior of HSGFRC when contain a small amount of fiber and when contain a large amount of fiber. For the reference mixture M50 F0 (without fibers), mixing procedures was applied in accordance with ASTM C192 [7]. However, for addition of the glass fibers; special attention was applied. The glass fibers were always added last and mixed for the minimum time required to achieve uniform dispersion and to prevent their damage by excessive mixing.

TABLE 3
HSGFRC Mixtures for 1 m³ of Concrete.

IN	%AR-GFRP by Weight of Cement	C (kg)	FA (kg)	CA (kg)	NRWR (Lit.)	W/C
M50 F0	0	600	484	1068	2	0.37
M50 F1	0.3	600	484	1068	2	0.37
M50 F2	0.6	600	484	1068	2	0.37
M50 F3	0.9	600	484	1068	2	0.37
M50 F4	1.2	600	484	1068	2	0.37

C Test Specimens and Method

Compressive strength, splitting tensile strength, flexural strength, and density tests were carried out to evaluate the strength properties of HSGFRC using MATEST C104 Servo Plus with a capacity of 2000 KN. Each test was carried out at ages 7 and 28 days, except for the density which was determined at 28 days. Cylinder specimens of 150 x 300 mm were prepared for testing the adopted HSC mix proportions that carried out in the trial mix stage which achieve the target design strength at 28 days of 50 MPa. The test of compressive strength was made according to ASTM C39 [8]. The specimens were loaded under compressing at a constant stroke rate of 1.4 MPa/min. confirming to the standard requirements. Cube specimens of 150 x150 x150 mm were prepared for compressive strength test and density. The test of compressive strength was made according to BS 1881, Part 108 standard test method [9]. The specimens were loaded at a constant stroke rate of 0.34 MPa/sec. confirming the standard requirements. Cylinder specimens of 150 x 300 mm were prepared for splitting tensile strength test in accordance to ASTM C496 standard test method [10]. The specimens were loaded at a constant stroke rate of 1.4 MPa/min. confirming the standard requirements. Prism speimens of 100 x 100 x 500 mm were prepared for flexural strength test using center-point loading in accordance to ASTM C293 [11]. The specimens were loaded so that the extreme fiber stress increases at rate of 1 MPa/min. confirm-

ing the standard requirements.

For each mix, three specimens were made for testing for each test for period of 28 days and two specimens were made for testing for each test for period of 7 days. The mean value of the test results of the specimens was considered as the test result of the experiment.

III TEST RESULTS AND DISCUSSION

A Mix Design Compressive Strength Test Results

The average 28 days' compressive strength of three cylinder specimens for the adopted HSC mix proportions that carried out in the trial mix stage was 51.15 MPa which obviously achieve the target design strength of 50 MPa.

B Size Effect

The results of 7 and 28 days' compressive strength are shown in Table 4. The average 28 days' cylinder compressive strength of plain HSC specimens (without fiber) obtained from adopted mix proportion was equal to 51.149 MPa, however, the average 28 days' cube compressive strength of plain HSC specimens as shown in Table 4 was equal to 57.85MPa. Therefore, the ratio of cylinder to cube compressive strength was equal to 0.88 which is obviously higher than for normal strength grade. It should be mentioned that this ratio increases as concrete strength increases until approaching 1 for ultrahigh strength concrete [12]. The compression test assumes a state of pure, uniaxial compression. Which is untrue because of the friction between the ends of the specimen and the bearing plates of the test machine. Through friction, the bearing plates act to restrain the lateral expansion of the ends of the specimen and to introduce a lateral confining pressure near the specimen ends. This confining pressure is greatest right at the specimen end and gradually dies out forward the middle of the specimen [12]. It is believed that the restraining effect of the bearing plates of the testing machine may extends over the entire height of a cube specimen, however, it leaves unaffected part of cylinder specimen. It is, therefore, to be expected that the strength of cubes specimen is greater than for cylinder specimen made from the same concrete. For NSC, the ratio of cylinder to cube compressive strength is around 0.8, but, in reality, there is no simple relation between the strength of the specimens of two shapes. However, for HSC, the effect of specimen's size and shape on the compressive strength is insignificant as for NSC. The ratio of cylinder to cube compressive strength increases strongly with an increase in strength and is nearly one at strength of more than 100 MPa [13].

This increasing in the ratio can be explained such that the lateral expansion in HSC is small and thus the plate confining effect will be insignificant in both the cube and the cylinder. Both specimens will be subjected in this case to uniaxial state of stress.

Table 4
Compressive Strength Test Results.

IN	% GFRP	Average Compressive Strength (MPa)				% Increase Over the Reference Mix - 28 Days
		7 Days	28 Days	S 28 Days	CV % 28 Days	
M50 F0	0	46.05	57.85	1.49	2.58	0
M50 F1	0.3	47.96	61.05	2.48	4.06	5.238
M50 F2	0.6	50.73	66.01	2.86	4.33	12.36
M50 F3	0.9	49.65	66.34	1.95	2.94	12.79
M50 F4	1.2	49.58	66.60	2.60	3.90	13.14

C Effect of AR-GFRP on the Compressive Strength of HSC

From Table 4, it is observed that with increase in fiber percentage, the compressive strength also increases. As shown in Figure 2, the 28 days' compressive strength increases sharply from 57.85 to 66.01 MPa with increase in fiber percentage from 0.0 to 0.6 respectively. Then, a very slight increase is observed in the compressive strength from 66.01 to 66.6 MPa when fiber percentage increases from 0.6 to 1.2 respectively.

In general, as shown in Figure 3, the percentage of increase over the reference mix at fiber percentage of 0.6 and 1.2 is 12.36 and 13.14 percent respectively, hence it is established that fiber percentage of 0.6 can be consider the optimum value of fiber addition for compressive strength enhancement since the difference between those values of fiber percentage is insignificant.

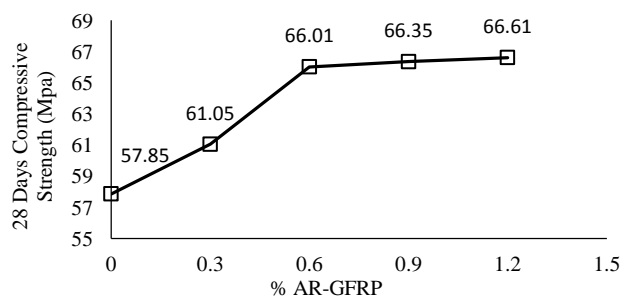


Figure 2 Effect of AR-GFRP on 28 Days Compressive Strength of HSC.

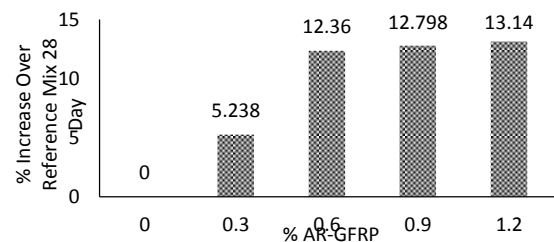


Figure 3 The Percentage of Increase in Compressive Strength Over the Reference Mix Due to Addition of AR-GFRP on HSC.

The behavior shown in Figure 2, can be explained such that according to Li [14], the reinforcement provided by fibers can work at both a micro and macro levels. At a micro level fibers arrest the development of micro cracks. The ability of the fiber to control micro cracking growth depends mainly on the number of fibers. Whereas at a macro level, fibers control crack opening and increasing the energy absorption capacity of the composite. Hence, a higher number of fibers in the ma-trix leads to a higher probability of a micro crack being in-tercepted by a fiber leading to higher compressive strengths as can be seen in Figure 2 where a sharp increase in the compressive strength is observed as fiber percentage in-crease from 0.0 to 0.6. Whereas at a macro level, the mode of failure will be enhanced due to the great amount of energy that consumed by fibers and due to postponing the formation of the first major crack in the matrix. On the other hand, fiber addition causes some perturbation of the matrix and appear strongly at high percentage of fibers, which can result in higher voids during the micro level due to fiber de-bonding and pullout process as long as there is no fiber frac-ture. When the macro level starts, voids can be seen as de-fects where macro cracking starts. In addition, as the amount of fiber exceeded the optimal value, larger surface area of coarse aggregate particles will be surrounded be fibers which is soft polymeric material could weaken the aggregate interlock thereby reducing the compressive strength of the concrete. It is safe then to say that the influence of fibers on the compressive strength at higher percentages could not enhance or increase the compressive strength as discussed and as can be seen in Figure 2 where a very slight increase is observed at fiber percentage from 0.6 to 1.2.

Test result show good agreement with other researchers studied the effect of addition of GFRP on structural concrete, Swami et al. [15] and Ghorpade [16] show that the concrete compressive strength can increased obviously when small amount of fiber used, however, there was no additional significant enhancement in compressive strength when fiber percentage increased upper the optimum value as shown in Figure 4 Ghorpade -whose use very high strength concrete (VHSC) to study the effect of addition of GFRP- show that the optimum amount of fiber addition can be achieved at 1 percent, while when using HSC -such this research- the optimum amount of fiber addition can be achieved at 0.6 percent, frequently, using lower strength -such Swami- the optimum amount of fiber addition could decrease to 0.3 percent. Hence, it was established that as concrete strength in-crease, the optimum amount of fiber addition for compressive strength enhancement also increase as shown in Figure 4.

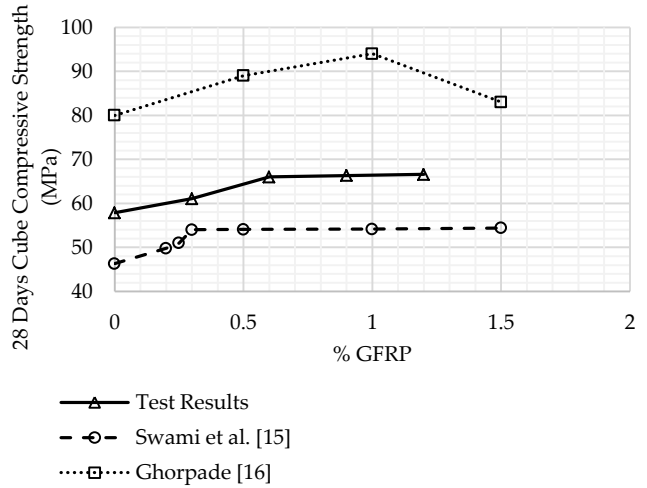


Figure 4 Comparisons of compressive strength test results with other related researches.

D Effect of AR-GFRP on the Strength Gain with Age of HSC

Figure 5 illustrates the strength gain with age for each mix. Figure 6 illustrates the relative strength gain at 7 and 28 days with percentage AR-GFRP. In reference to Figure 6, it is obvious that the ratio of 7 days' to 28 days' compressive strength for the reference mix (M50 F0) is higher than for normal strength grade, typically 79.6 percent. However, according to ACI committee 363 [17], it has been recognized that HSC shows a higher rate of strength gain at early ages compared to NSC. The higher rate of strength development of HSC at early ages is caused by an increase in the internal curing temperature in the concrete mixtures due to a higher heat of hydration and shorter distance between hydrated particles due to low water-cement ratio. However, as shown in Figure 6, the ratio of 7 days to 28 days' compressive strength has decreased from 79.6 to 74.43 as fiber percentage increased from 0.0 to 1.2, respectively. This can be explained by that fibers may have absorbed part of increased temperature and can make the distance between hydrated particles wider, which will in turn result in less internal curing temperature in the concrete mixtures.

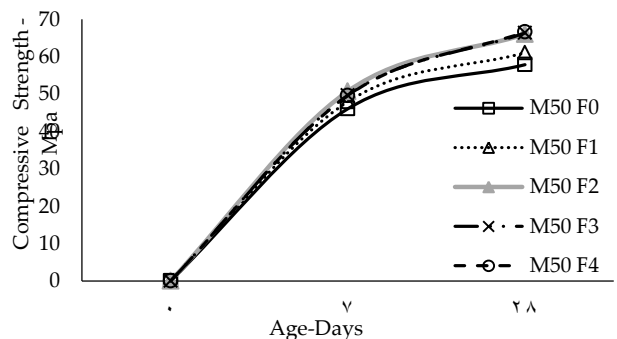


Figure 5 Effect of AR-GFRP on the Strength Gain with Age of HSC.

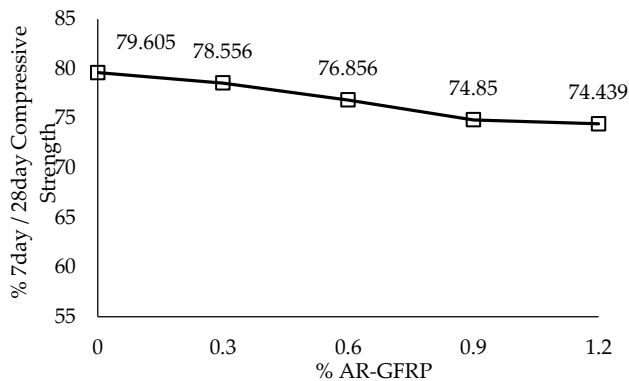


Figure 6 Effect of AR-GFRP on %7days / 28days Compressive Strength.



Figure 8 Mode of Failure and Crack Pattern of Plain HSC Specimens (Without Fiber).

(a)

E Effect of AR-GFRP on the Density of HSC

Figure 7 shows the effect of AR-GFRP on the concrete density. It is observed that with increase in fiber percentage, the density increases very slightly. This can be explained due to the extremely light weight and high ratio of surface area to weight of AR-GFRP.

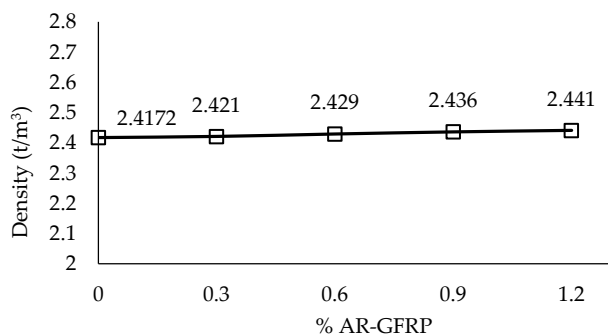


Figure 7 Effect of AR-GFRP on Density of HSC.



(b)

F Crack Pattern and Mode of Failure During Compressive Strength Test

Observation of specimens during compressive strength tests showed that in the case of plain HSC specimens; Figure 8, the failure was sudden, brittle and destructive with loud sound. However, with addition of fiber by 0.3 percent on HSC specimens, the failure became normal similar to normal strength concrete as shown in Figure 9. HSC specimens with 0.6 and 0.9 fiber percentage showed finer cracks and less dispersion compared with HSC specimens with 0.3 fiber percentage as shown Figure 10 and Figure 11, respectively. At highest fiber percentage of 1.2, the specimens after failure remained intact as shown in Figure 12 and the cracks were extremely fine.

In conclusion, it is observed that as fiber percentage increases, failure takes place gradually with the formation of cracks and can arrest sudden crack formation. Moreover, although the higher fiber percentage could not enhance the compressive strength -as explained before- at a macro level, fibers at higher percentages can control crack opening, consume a great amount of energy, and postponing the formation of the first major crack in the matrix, hence changing the failure mode from brittle to quasi-ductile.



Figure 9 (a) and (b) Mode of Failure and Crack Pattern of HSC Specimens with 0.3 Fiber Percentage.



Figure 10 Mode of Failure and Crack Pattern of HSC Specimens with 0.6 Fiber Percentage.



Figure 11 Mode of Failure and Crack Pattern of HSC Specimens with 0.9 Fiber Percentage.



Figure 12 Mode of Failure and Crack Pattern of HSC Specimens with 1.2 Fiber Percentage.

G Effect of AR-GFRP on The Splitting Tensile Strength of HSC

Table 5 show the results of 7 and 28 days splitting tensile strength, respectively. According to ACI Committee 363 [17], Equation (1) was recommended for the prediction of the splitting tensile strength (F_{sp}) of HSC with 28 days' cylinder compressive strength (f'_c) within 21 to 83 MPa.

$$F_{sp} = 0.59\sqrt{f'_c} \quad (1)$$

The 28 days' cylinder compressive strength of plain HSC was equals to 51.149 MPa; which makes the predicted splitting tensile strength F_{sp} using Equation (1) equals to 4.21 MPa.

This value is very close with the average experimental value of plain HSC specimens (M50 F0) of 4.12 MPa shown in Table 5. The difference is 2.1% only! showing good agreement.

Table 5
Splitting Tensile Strength Test Results.

IN	% GFRP	Average Split Tensile Strength (MPa)				% Increase Over the Reference Mix (28 Day)
		7 Days	28 Days	S 28 Day	CV % 28 Day	
M50 F0	0	3.066	4.124	0.22	5.5	0
M50 F1	0.3	3.579	4.777	0.55	11.6	15.83
M50 F2	0.6	3.917	5.538	0.33	6.1	34.28
M50 F3	0.9	4.177	5.845	0.45	7.8	41.73
M50 F4	1.2	4.924	6.731	0.39	5.8	63.22

It is observed from Table 5 that with increase in fiber percentage, the splitting tensile strength increases significantly. As shown in Figure 13, the splitting tensile strength increased from 3.06 to 4.92 MPa with the increase in the fiber percentage from 0.0 to 1.2, respectively for 7 days. For 28 days, the strengths increased from 4.12 to 6.7 MPa when the fiber percentage increased from 0.0 to 1.2, respectively. It is observed from Figure 14 that, the percentage of increase in the splitting tensile strength over the reference mix due to addition of fibers is much higher than for the compressive strength. Moreover, the increasing trend in splitting tensile strength due to addition of fibers continued ascending until the highest value of 6.73 MPa at (28 Days) at the highest fiber percentage of 1.2 as shown in Figure 13.

In comparison with the increase in compressive strength Figure 2 shows continuous ascending just until 0.6 fiber percentage and then at fiber percentage from 0.6 to 1.2, the increasing rate reduced slightly. This difference between the increasing mode of compressive strength and splitting tensile strength curves shown in Figure 2 and Figure13 can be explained simply that the defects that caused by higher fiber percentages during the micro level, which are as discussed before, the voids due to fiber de-bonding and pullout process, and the weakness of the aggregate interlock due to softening and polymeric characteristic of fibers, appear strongly when the concrete fail due to compressive stress. While in splitting tensile test, although the cylinder specimen subjected to compressive load, the specimen fails due to the induced tensile stresses before reach its ultimate compressive strength capacity (i.e. for the same mixture of M50F4, in the compression test, the maximum average applied compressive load at 28 days is 1505.4 KN. While in the splitting tensile test, the maximum average applied compressive load at 28 days is only 473.18 KN).

It is safe then to say that with higher percentage of fibers, according to Li [16] it is possible that micro cracks formed in the matrix at micro level will be stabilized due to the interaction between the matrix and fibers through bonding, hence postponing the formation of the first major crack in

the matrix. Thus, the apparent tensile strength of matrix can be increased. Hence it is established that AR-GFRP inclusion in HSC mixtures is more powerful for enhancing the tensile strength than compressive strength.

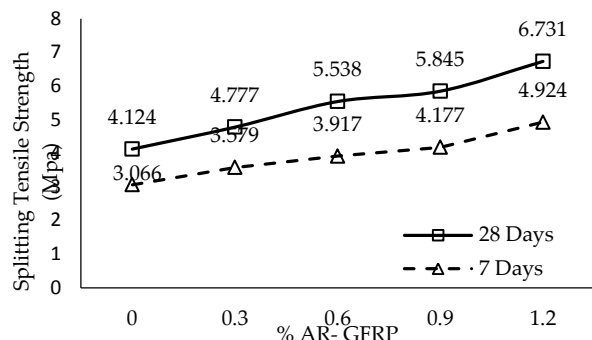


Figure 13 Effect of AR-GFRP on Splitting Tensile Strength of HSC.

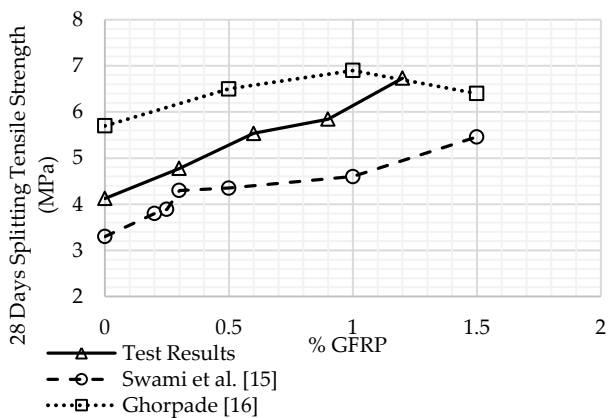


Figure 14 Comparisons of Splitting Tensile Strength Test Results with Other Related Researches.

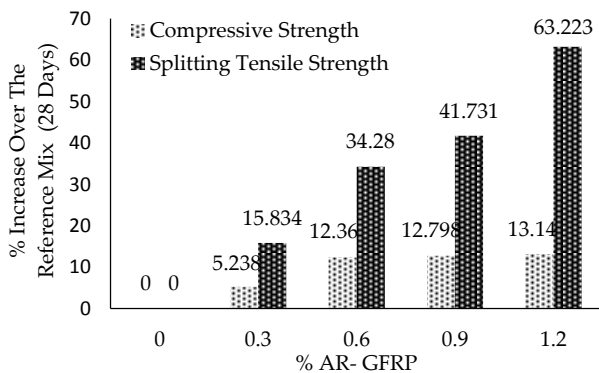


Figure 15 The Percentage of Increase Over the Reference Mix Due to Addition of AR-GFRP on HSC: Comparison between Compressive Strength and Splitting Tensile Strength.

Test result show good agreement with Swami et al [15]. and Ghorpade [16] who showed that the concrete splitting tensile strength can be increased significantly with addition of glass fiber even when large amount was used. However, Ghorpade who used VHSC, reported that the splitting tensile strength was de-created at fiber percentage larger than 1 percent as shown in Figure 15.



Figure 16 Mode of Failure of Plain HSC Specimens (Without Fiber).

H Crack Pattern and Mode of Failure During Splitting Tensile Strength Test.

Observations of specimens during splitting tensile strength test showed in the case of plain HSC that the failure was brittle and occurred by sudden complete splitting accompanied by loud sound, Figure 16. With addition of fiber by 0.3 percent on HSC specimens, the mode of failure remained sudden similar to plain HSC specimens as shown in Figure 17. However, HSC specimens with 0.6 and 0.9 fiber percentages showed less sudden splitting failure and remained intact as shown in Figures 18 and 19. At highest fiber percentage of 1.2, the HSC specimens remained standing after failure and the crack was fine as shown in Figure 20.

In conclusion, as fiber percentage increased the splitting crack occurred progressively, arrested sudden crack formation, and overcame the brittle characteristic of HSC.



Figure 17 Mode of Failure of HSC Specimens with 0.3 Fiber Percentage

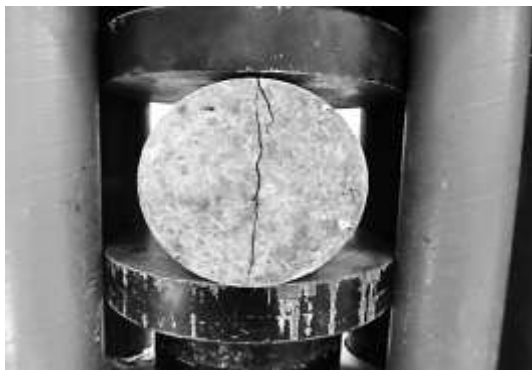


Figure 18 Mode of Failure and Crack Pattern of HSC Specimens with 0.6 Fiber Percentage.



Figure 19 Mode of Failure and Crack Pattern of HSC Specimens with 0.9 Fiber Percentage.



Figure 20 Mode of Failure and Crack Pattern of HSC Specimens with 1.2 Fiber Percentage.

$$F_r = 0.94\sqrt{f_c'} \quad (2)$$

The 28 days' cylinder compressive strength of plain HSC (without fiber) was equals to 51.149 MPa. The prediction of F_r using Equation 2 equals to 6.72 MPa in comparison with measured average value of 6.35 MPa for plain HSC specimens (M50 F0) shown in Table 6 with a deference of 5.5% only! showing good agreement.

Table 6

Flexural Strength (Modulus of Rapture) Test Results.

IN	% GFRP	Average Flexural Strength (MPa)				% Increase Over the Reference Mix (28 Day)
		7 Days	28 Days	S	CV %	
M50 F0	0	4.84	6.35	0.49	7.79	
M50 F1	0.3	5.28	7.53	0.20	2.63	18.50
M50 F2	0.6	6.26	8.28	0.31	3.75	30.41
M50 F3	0.9	6.68	8.79	0.37	4.24	38.35
M50 F4	1.2	7.27	9.68	0.47	4.85	52.36

It is observed from Table 6 that with the increase in fiber percentage, F_r increased significantly. As shown in Figure 21, the flexural strength increased continuously from 4.84 to 7.27 MPa with increase in fiber percentage from 0.0 to 1.2 respectively for 7 days, and 6.35 to 9.68 MPa when fiber percentage increase from 0.0 to 1.2 respectively for 28 days.

Therefore, it concluded that the percentage of increase in the flexural strength over the reference mix due to addition of fibers is much higher than for the compressive strength; but little less than for splitting tensile strength, except at 0.3 fiber percentage where flexural strength shows the highest percentage of increase as shown in Figure 22. The rate of increasing in flexural strength due to addition of fibers is the same as for splitting tensile strength, which was also ascending until the highest value of 9.68 MPa (28 Days) at the highest fiber percentage of 1.2 as shown in Figure 21. In comparison with the increase in the compressive strength, Figure 2 shows continuous ascending just until 0.6 fiber percentage and then at fiber percentage from 0.6 to 1.2, the increase turned was very slight. This difference between the increasing mode of compressive strength and flexural strength curves shown in Figures 2 and 21 can be explained similarly as for the splitting tensile strength. Hence it is established that AR-GFRP inclusion in HSC mixtures is more effective in enhancing the tensile strength than compression strength.

I Effect of AR-GFRP on The Flexural Strength (Modulus of Rapture, F_r) of HSC

The results of 7 and 28 days' flexural strengths (modulus of rapture, F_r) are shown in Table 6. According to ACI Committee 363 [17], Equation. 2 was recommended for the prediction of F_r of HSC with 28 days' cylinder compressive strength f_c' within 21 to 83 MPa.

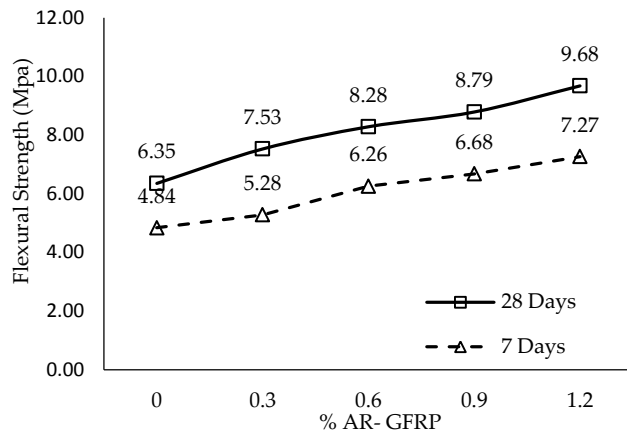


Figure 21 Effect of AR-GFRP on Flexural Strength (Modulus of Rapture) of HSC.

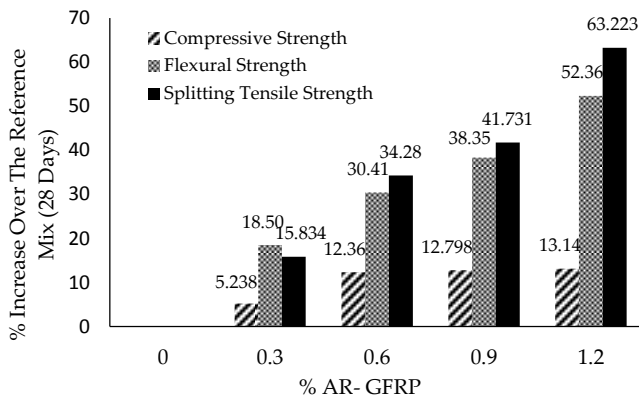


Figure 22 The Percentage of Increase Over the Reference Mix Due to Addition of AR-GFRP on HSC: Comparison Between Compressive, Flexural and Splitting Tensile Strength.

Test result show good agreement with Swami et al [15]. and Ghorpade [16] as discussed earlier and as shown in Figure 23 for 1 percent fiber.

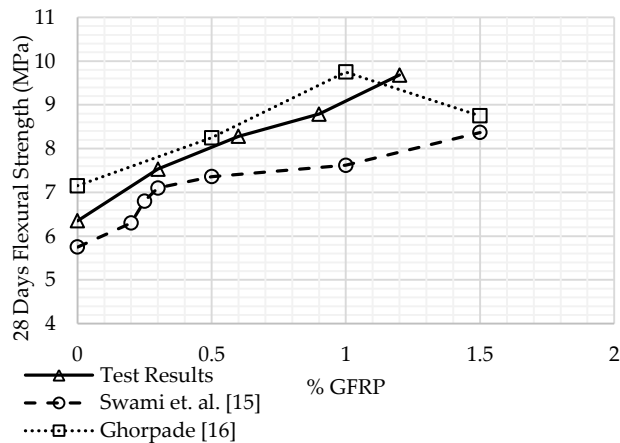


Figure 23 Comparisons of flexural strength test results with other related researches.

IV CONCLUSION

The effects of addition of alkali resistant glass fibers reinforced polymer (AR-GFRP) on the strength and mode of failure of high strength concrete (HSC) up to 51 MPa cylinder compressive strength were experimentally investigated. The following conclusions were made based on the results of compressive strength, splitting tensile strength, flexural strength, and density tests carried out at 7 and 28.

- i. Maximum compressive strength of HSC was obtained at 1.2 percentage of fiber and achieved 13.14% increase over the reference mix without fibers. With 0.6% fiber 12.36% strength increase was recorded.
- ii. The ratio of 7 days to 28 days' compressive strength decreased from 79.6% to 74.43% as fiber percentage increased from 0.0 to 1.2 respectively.
- iii. The density of HSC increased slightly from 2417 to 2441 kg/m³ as fiber percentage increased from 0.0 to 1.2%.
- iv. The splitting tensile strength of HSC increased continuously reaching 63.22% increase at 1.2% fiber.
- v. The flexural strength (modulus of rapture) increased continuously reaching 52.36% increase with 1.2% fiber.
- vi. It was observed that the percentage of increase in the splitting tensile and flexural strengths over the reference mix due to addition of fibers is much higher than for the compressive strength. Hence, it is established that AR-GFRP inclusion in HSC mixtures is more significant for enhancing the tensile strength than compression strength of HSC.
- vii. The specimen failure in compressive and splitting tensile strength tests was gradual as fiber percentage increased. On the other hand, the failure of plain HSC specimens was sudden, brittle and completely destruction with sound (Loudly). Hence it is established that the presence of fibers in the matrix has contributed towards prevent sudden crack formation.
- viii. Test result show good agreement with ACI committee 363 and other relevant researches.

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