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Evaluation of Steel Fiber Reinforced Geopolymer Concrete Made of Recycled Materials

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A B S T R A C T

In the last few decades, the geopolymer concrete presented an evolution in civil engineering field. The current study aims to produce a low cost steel fiber reinforced geopolymer concrete with an exceptable tensile properties. The experimental program aims to investigate the tensile behaviour of geopolymer concrete reinforced with steel fiber and made of recycled materials. The primary ingredients of the steel fiber reinforced geopolymer concrete in this study were waste materials. The recycled steel fiber was extracted from tires and chopped into tiny fibers with an average length of 20 mm and an average diameter of 0.7 mm. The geopolymer concrete in this study consisted of coarse aggregate, which was crushed recycled concrete. Also, the fine aggregate was crushed waste glass. In addition to the compressive strength, tensile test procedures such as splitting tensile strength, double punch tensile strength, and flexural tensile strength were all investigated in this study. Recycled steel fiber was compared to a new hooked-end steel fiber and hybrid steel fiber (50% new + 50% recycled) with three different volumetric percentages of steel fiber (0.5%, 1.0%, and 1.5%). The new steel fiber geopolymer concrete mix with 1.5% of steel fiber showed the highest test results among other mixes, as the tensile strength was increased by nearly 50% in the case of the double punch test. This conduct could be explained as the new steel fiber having a uniform, straight shape with hooked ends, increasing the anchorage between the fly ash binder and the steel fiber. In addition, the recycled steel fiber was contained some rubber crumbs that could be another reason that negatively affected the tensile properties of the geopolymer concrete.

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1. INTRODUCTION

Conventional concrete is the most used construction material worldwide for its cost effectiveness and reliable mechanical properties. This very high consumption of the general purposes cement concrete, more than 8.8 billion tons per year [1], is now considered one of the carbon dioxide emission sources to the atmosphere that causes dramatic climate changes. Thus, geopolymer concrete (GC) was introduced by Davidovits in 1994 [2] to be an alternative to Portland cement concrete for environmental considerations. Instead of Portland cement, by-product materials such as fly ash or new materials such as metakaolin were used to develop an inorganic alumina-silica polymer that works as cementing material [3-5]. Both ordinary concrete and GC are weak under tensile stresses and for this reason, the concrete in tension is neglected in many international codes [6]. However, in some structural applications (such as hydraulic structures and airport pavements), tensile strength could be a critical mechanical property of GC, and then it should be taken into account [7]. One solution to enhance the tensile behaviour of the GC is to add a steel fiber to the concrete mix. The cracking triggering and propagation behavior of fiber-reinforced geopolymer concrete (FRGC) can be controlled by using the optimum dose of steel fiber that depends on many factors such as shape and aspect ratio (length/diameter) of steel fiber and aggregate/binder ratio of GC. In the current study, some recycled materials were used to enhance the tensile

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properties of the GC in order to produce a low cost building material with reliable mechanical properties.

To assess the tensile behaviour of concrete, several test methods have been adopted for this purpose. The most widely used test procedure: the splitting test or the Brazilian test. Many international standards have adopted this method, such as American Standard for Testing Materials C 469-04 [8]; Australian Standard (AS) 1012.10 [9], because of its ease to perform and reliable results of tensile strength for plain concrete. The splitting test procedure is also applicable for steel fiber reinforced concrete (SFRC), as stated by many studies [10-13]. On the other hand, Olesen et al. [14], Goaiz et al. [15] and Goaiz et al. [16] stated that the splitting test procedure is not recommended to evaluate the tensile strength of SFRC because of the overestimated results recorded by this test method in comparison with the results of the direct tensile test method. Another indirect tensile strength test was suggested by Chen [17], commonly called Double Punch Test (DPT). Several studies were then assessed the Double Punch Test procedure reported in literature [18-21]. The DPT has the advantage of a smaller size of concrete sample and a more straightforward test procedure than the splitting test. Goaiz et al. [16] found that the results of the DPT and the direct tensile test were closer to each other. Thus, the tensile behaviour of the GC that reinforced with different types of steel fiber in this study was evaluated by three different test procedures.

Recently, many experimental studies were conducted in order to investigate the behaviour if fiber reinforced geopolymer concrete [22-24]. However, for the Steel Fiber Reinforced Geopolymer Concrete (SFRGC) to be valuable construction material, it must compete economically with the existing reinforcing system. The current study aims to produce a low cost steel fiber reinforced geopolymer concrete with an acceptable tensile properties. Therefore, one of the best options for getting low-cost SFRGC is to find recycled materials that could be used to produce this type of concrete.

2. EXPERIMENTAL PROGRAM

The experimental program included three different test procedures (splitting test, double punch test, and flexural test) that have been conducted to evaluate the tensile behaviour of the SFRGC specimens. In addition to the reference concrete mix made of plain GC, nine SFRGC mixes have been prepared with volumetric steel fiber percentages 0.5%, 1.0%, and 1.5%. Also, the experimental program of this work included three different types of steel fiber; new steel fiber, recycled steel fiber, and hybrid steel fiber (50% new + 50% recycled).

2. 1. Materials Ten GC mixes were prepared using class F fly ash. This type of fly ash was chosen in this study due to the better performance compare to other types when cured at 60 °C. The coarse aggregate of recycled crushed concrete (5-20 mm), the fine aggregate of recycled crushed glass with a grade of Zone No. 3, according to the Iraq standard No. 45:1985 [25]. In addition, alkaline solution ($NaOH+Na_2SiO_3$), water, a water-reducing admixture (superplasticiser), and steel fiber were used. Table 1 shows the mixed design of the fly ash-based GC used in this study. The steel fiber was in two types; the first type was end-hooked steel fiber of 25 × 0.5 mm (long × diameter). The second type was recycled steel fiber extracted from cars tier, with an average length of 20 mm and average diameter of 0.7 mm; some of the materials used in this study are shown in Figure 1. The SFRGC included 0.5%, 1.0%, and 1.5% steel fiber by volume of concrete for all mixes. The hybrid mix contains 50% of new steel fiber and 50% recycled steel fiber.

2. 2. Mixing of SFRGC Specimens In this study, sodium hydroxide was prepared with a molarity of 10 by dissolving the NaOH flakes in distilled water. Then, sodium hydroxide solution was mixed with sodium silicate for several minutes to form the alkali liquid left for 24 hours before use. The recycled crushed gravel, crushed glass, and fly ash were mixed in a dry condition for 2-3 minutes by a pan-type concrete mixer. Then, the alkali liquid was mixed with additional water and for 4-5 minutes until homogeneity is reached. The reference mix (0% steel fiber) was ready to be cast. In the case of SFRGC, the steel fiber was added little by little to the fresh GC mix and in order to avoid any blockage of the steel fiber during the last 3 minutes of mixing. All of the GC samples were cured at a temperature of 60 ˚C in the oven for 28 days.

TABLE 1. Concrete mix design adopted for the current study

Component	Dosage			
	GC	**S0.5X***	**S1.0X***	**S1.5X***
Fly ash (FA) [kg/m^3]	350	350	350	350
Alkaline solution by wt.% of FA	0.5	0.5	0.5	0.5
Recycled coarse aggregate [kg/m^3]	1050	1050	1050	1050
Recycled fine aggregate [kg/m^3]	900	900	900	900
NaOH molarity	10	10	10	10
Superplasticiser by wt.% of FA	2.25	2.25	2.25	2.25
Steel Fibres [kg/m^3]	-----	40	80	120
Water by wt. % of FA	0.1	0.1	0.1	0.1
Na_2SiO_3/NaOH	1:1.5	1:1.5	1:1.5	1:1.5

*Note: X letter refers to any type of steel fiber reinforcement

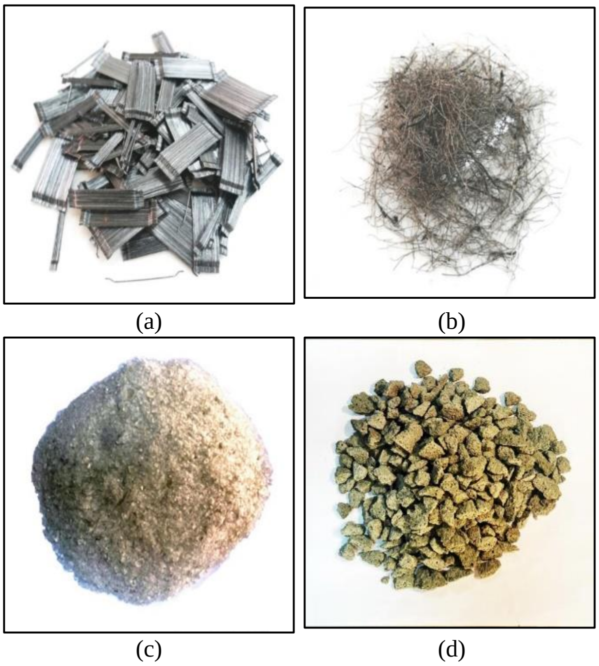


Figure 1. Some materials: (a) New steel fiber; (b) Recycled steel fiber; (c) Recycled crashed glass and (d) Recycled crashed concrete

2. 3. Test setup and Procedure

2. 3. 1. Compression Test To determine the compressive strength of the GC cubes, a Matest compression testing machine with a loading capacity of 1500 kN was used. For each mix, three cubes were tested under a constant loading of 20 MPa/min according to BS EN 12390-3:2019 [26] at the age of 28 days.

2. 3. 2. Splitting Tensile Test The American standard ASTM C496-02 [2] was adopted to evaluate the splitting strength of the GC cylinders. For each mix, three cylinders were prepared with 150 mm × 300 mm (diameter × height). According to the standard, the load must be applied at a rate of 1.5 MPa/min. Therefore, the splitting tensile strength of the specimens can be calculated according to ASTM C496-02 [2].

2. 3. 3. Double Punch Test (DPT) The DPT was conducted according to the test method proposed by Chen [17], see Figure 2. Based on this test method, the tensile strength of GC specimens can be determined by preparing three cylinders with 150 mm ×150 mm (diameter × height). The applied load is transferred from the loading heads of the compression machine to the specimens through steel punches with 37.5 × 25 mm (diameter × height) located between the loading plates and the two surfaces of the specimen. Two-dimensional guides were used to ensure that the steel punches were located at the center of the specimens to prevent any loading eccentricity during the test. The load was applied at a 1.4 MPa/min rate on the specimen until the maximum load was reached. The tensile strength can be calculated according to Chen [17].

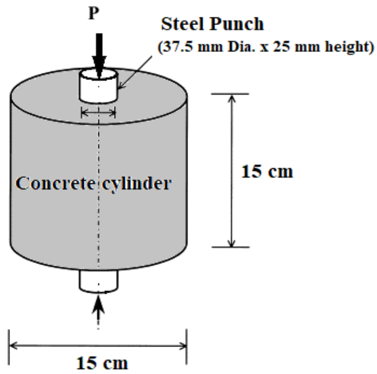


Figure 2. Double Punch Test as suggested by Chen [17]

2. 3. 4. Flexural Test The flexural strength in this study is conducted according to ASTM C 78-16 [27] to calculate the modulus of rupture by using simple beam with a third-point loading test procedure. The flexural strength of the geopolymer concrete is obtained by averaging the results of two specimens since the values obtained are very close. Test prisms of SFRGC are made with dimensions of 100 × 100 × 500 mm.

3. RESULTS AND DISCUSSION

3. 1. Concrete Compressive Strength Table 2 shows the test results for the compressive strengths of the plain GC mix and SFRGC with new steel fiber, recycled steel fiber, and hybrid steel fiber. The results showed an average strength of the four concrete mixes between 31 MPa to 36 MPa. Also, it can be seen that the type of the steel fiber had a considerable impact on the strength of SFRGC.

Mixes S0.5N, S0.5R, and S0.5H were achieved an increment of 7%, 0%, and 5% higher compressive strength than Mix GC. It can be seen that there is no increment of the compressive strength was recorded for GC mix with 0.5% of recycled steel fiber or even slight decrease and this could be attributed to the presence of the rubber crumbs within the recycled steel fibers. Mixes S1.0N, S1.0R, and S1.0H were achieved an increment of 12%, 1%, and 9% higher compressive strength than Mix GC. For example, mixes S1.5N, S1.5R, and S1.5H were achieved an increment of 16%, 3%, and 13% higher compressive strength than Mix GC. The higher average 28-d compressive strength was obtained by Mix S1.5N (SFRGC made with new steel fiber) which is 36 MPa, see Figure 3.

To demonstrate the effect using recycled aggregate, the results of this study were compared to another study conducted by Zhang et al. [24] which had nearly the same aggregate/cementitious materials ratio but with natural river aggregate. For the same content of steel fiber ranging from 0% to 1.5%, Zhang et al. [24] obtained GC mixes with compressive strength between 43 MPa to 50 MPa. Taking in consideration other differences between the mixes of the two studies, it can be seen that the use of recycled aggregate lead to a reduction of nearly 30% of the compressive strength of the GC mixes.

3. 2. Splitting Tensile Strength Test Figure 4 presents the splitting strength of GC mix and SFRGC mixes with different types of steel fiber. The splitting strength of mixes S0.5N, S0.5R and S0.5H was respectively increased by 49%, 9% and 30% compared to GC mix. Mixes S1.0N, S1.0R and S1.0H was respectively increased by 61%, 28% and 44% compared to GC mix. Also, the splitting strength of mixes S1.5N, S1.5R and S1.5H was respectively increased by 85%, 46% and 56% compared to GC mix. Mix S1.5N that included new steel fiber had recorded the highest splitting strength of 4.9 MPa which contained the highest compressive strength and new steel fiber.

3. 3. Double Punch Test Figure 5 shows the DPT failure pattern of the GC samples with new, recycled, and hybrid steel fiber. Figure 5(a) present the failure mode of GC specimens (no steel fiber added). It can be observed that the failure pattern showed three radial cracks on the upper and the lower surfaces of the specimen that having an angle of 120° between each crack. According to previous studies, this pattern of

TABLE 2. Average strength results of all mixes.

Mix ID	Compressive [MPa]		Splitting [MPa]		DPT [MPa]		Flexural [MPa]	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
GC	31.3	1.1	2.65	0.23	2.24	0.22	4.86	0.44
S0.5N	33.6	1.88	3.95	0.35	2.91	0.28	6.92	0.75
S0.5R	31.2	2.66	2.88	0.41	2.36	0.33	5.08	1.06
S0.5H	32.8	2.42	3.44	0.44	2.5	0.38	6.11	0.97
S1.0N	35.1	2.32	4.28	0.48	3.18	0.36	8.15	0.93
S1.0R	31.7	3.28	3.4	0.36	2.55	0.46	6.19	1.31
S1.0H	34.1	2.94	3.82	0.38	2.8	0.39	6.83	1.18
S1.5N	36.2	3.14	4.9	0.42	3.31	0.43	8.36	1.26
S1.5R	31.9	4.2	3.86	0.61	2.65	0.44	6.51	1.68
S1.5H	35.4	3.44	4.12	0.54	3.16	0.49	7.10	1.38

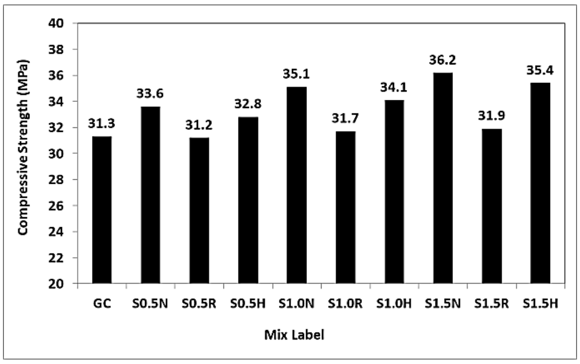


Figure 3. 28-day results of compressive strength

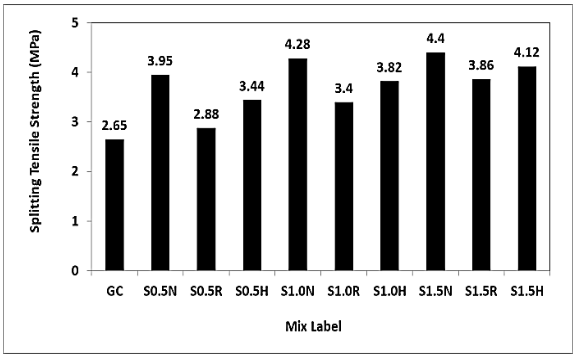
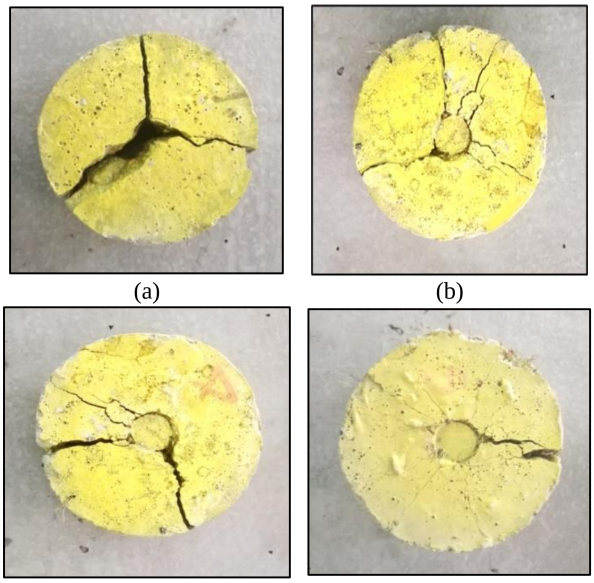


Figure 4. 28-day results of splitting strength

failure was commonly reported in the literature [15-21]. However, as the percentage of the steel fiber increased up to 1.5%, more radial cracks can be seen. On the other hand the width of the radial cracks was reduced, as presented in Figures 5(b) and 5(c). Therefore, by using steel fibre in the GC mixes, more minor radial failure cracks can be seen in different directions of the surface of the specimens.

Figure 6 shows the DPT results, according to this figure, the tensile strength of S0.5N, S0.5R, and S0.5H was increased by 30%, 5%, and 17%, respectively, compared to GC. Also, the DPT tensile strength of S1.0N, S1.0R, and S1.0H was increased by 42%, 14%, and 25%, respectively, compared to GC. Finally, the tensile strength of S1.5N, S1.5R, and S1.5H was increased by 48%, 25%, and 41%, respectively, compared to PC. The highest tensile result of 3.31 MPa was recorded by S1.5N that had the highest GC compressive strength and contained the new steel fiber. This behaviour is quite similar to the splitting strength test because of the influence of the increment in steel fiber content.

3. 4. Flexural Strength Test Figure 7 shows the flexural failure modes of the GC samples with new, recycled and hybrid steel fiber. Figure 7(a) present the failure pattern of plain GC samples (no steel fiber added).



(a) (b)

(c) (d)

Figure 5. Failure pattern of double punch test for different steel fiber content

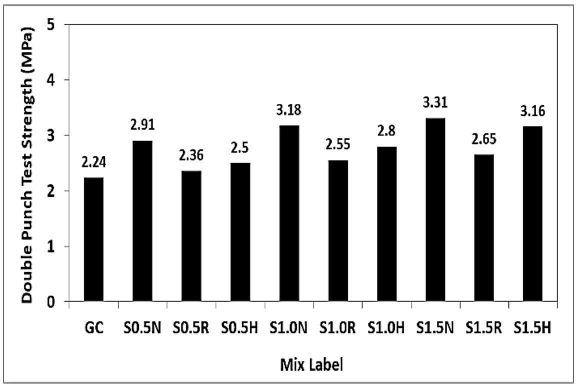


Figure 6. 28-day results of DPT tensile strength

As shown in this figure, the prism sample was utterly split into two parts near the centerline of the specimen by one crack. This mode of failure is reported as a standard failure mode of the flexural strength test. The failure mode was tended to show more cracks near the centerline of the specimen due to the increase of the steel fiber percentage up to 1.5%. The two parts of the specimen in this case, however, were still attached to each other by the presence of the steel fiber, as shown in Figures 7(b), 7(c), and 7(d). Thus, using of steel fiber in the GC could be the reason to see more centerline cracks in the failure mode.

The results of the flexural strength are presented in Figure 8. This figure shows an increase of the flexural strength of mixes S1.5N, S1.5R, and S1.5H was respectively increased by 72%, 34%, and 44%, in comparison with the GC mix. The highest flexural tensile strength (8.36 MPa) was recorded by mix S1.5N,

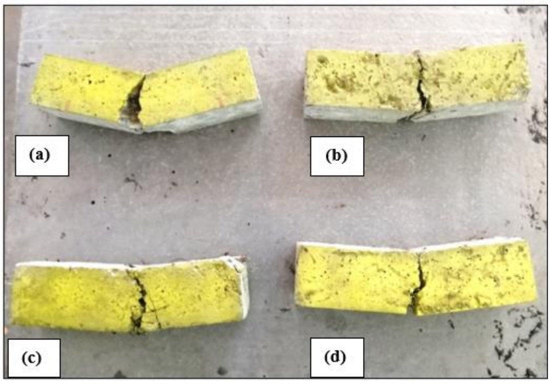


Figure 7. Failure mode of flexural test for different steel fiber content

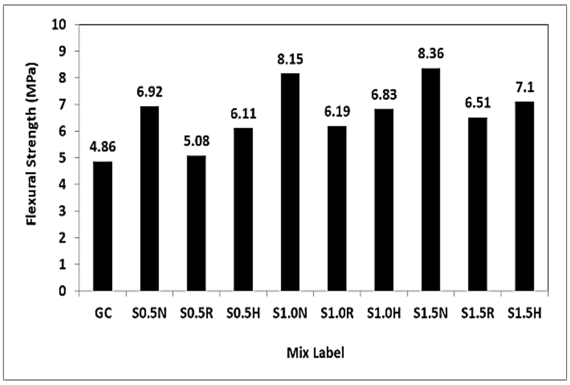
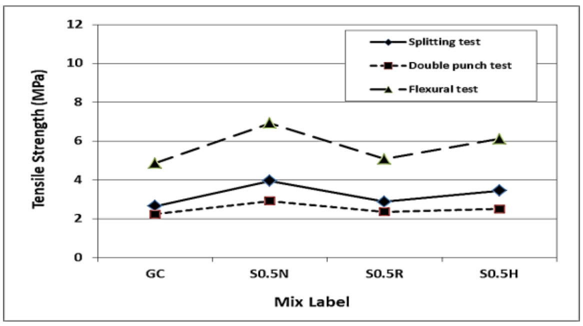


Figure 8. 28-days results of flexural tensile strength

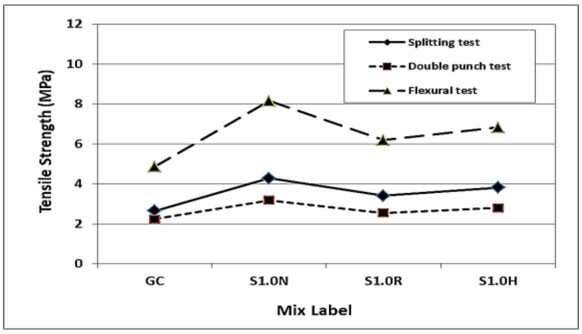
where the highest steel fiber content and the new steel fiber were used.

3. 5. Comparison of Tensile Strength Tests

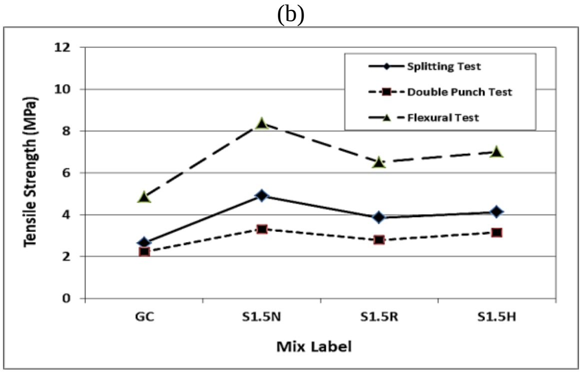
Figure 9 shows the tensile test results for three different test procedures (splitting test, double punch test, and flexural test). As expected, the Flexural test shows the highest tensile results among other test methods, and mix S1.5N obtained the highest tensile strength of 8.36 MPa. On the other hand, splitting and double punch tests are both indirect tensile test methods, although the splitting test is not appropriate for SFRGC mixes because the



(a)



(b)



(c)

Figure 9. Tensile strength results of different test methods and different steel fiber content: (a) 0.5% steel fibre content; (b) 1.0% steel fibre content and (c) 1.5% steel fibre content

failure crack was not visual and the SFRGC samples was intact post the ultimate failure was achieved. The presence of the steel fiber is the only reason for this ductile behaviour because the applied load was spread along multiple surfaces of failure which prohibited the splitting failure. Also, the applied load was non-uniformly extended in the direction of load due to the compressive zone that created under the loading strip. Also, according to the tensile test results of different test procedures that were used in this study, it can be seen the type and the amount of the steel fiber had a dramatic effect of the tensile behaviour. The recycled steel fiber has the lower effect on tensile strength compared to the new steel fiber and the hybrid steel fiber. The main reason behind this behaviour was the small amount of the rubber that attached to the surface of the recycled steel fiber which affects the bond between the steel fiber and the surrounded GC matrix. Another reason could be the non-uniform shape and distribution of the recycled steel fiber within the GC mix which causes weak bonding between the steel fiber and the GC mix.

4. COMPRESSIVE-TENSILE STRENGTH RELATIONSHIP

The tensile strength could be an important design parameter in different types of structures such as hydraulic structures or airports pavement. For this reason, international building codes suggested some equations to predict the value of the tensile strength by only knowing the compressive strength of the concrete. However, these empirical equations are limited to Portland cement concrete with a specific range of compressive strength. In this study, two equations, Equations (1) and (2) proposed by the ACI 363R-92 [28] and CEB-FIP 199 1[29] respectively were used to verify the experimental tensile strength of the steel fibre geopolymer concrete.

$$f_t = 0.59\, {f_c}^{0.5} \tag{1}$$

$$f_t = 0.3\, {f_c}^{0.66} \tag{2}$$

Then, the predicted tensile strength was compared to the experimental results of each individual test procedure in Table 3 shown below. From this table, it can be seen that Equation (2) shows a lower predicted values of the tensile strength than Equation (1) and this conservative model could be more suitable and preferable in the structural design. Moreover, Equation (2) yielded predicted values of the tensile strength which are very close to the experimental values of the double punch test procedure as can be seen in Table 4. As mentioned above in many previous studies [15-21], the double punch test showed very reliable results in terms of determining the tensile strength of steel fibre reinforced concrete. For this reason, an equation was suggested to show the relationship between the compressive strength and the double punch tensile strength of SFRGC. Although, the equation is limited number of data in this study but it could be a promising start for future studies to find a reliable model for the relationship between the compressive and the tensile strength of SFRGC. A polynomial equation from the second order was obtained using MS Excel program to represent the best fit with the higher R-squared value of 0.91 for the double punch tensile strength, see Figure 10. In addition, Equation (3) is shown below:

$$f_t = 0.0016\, {f_c}^{2.0} + 0.084\, f_c - 1.83 \tag{3}$$

5. COST EFFECTIVENESS

In general, the cost of a geopolymer concrete vary from country to another around the world depending on many factors such as the target compressive strength of the concrete, prices of the raw materials, the labor cost and the regulations of the country due to carbon taxation. Locally in Iraq, the cost of ordinary Portland cement concrete production for compressive strength of 30s MPa is nearly \$80 per cubic meter and it can be up to \$120 for steel fiber reinforced concrete. However, the cost of the GC production is unknown because there is no constructional demand on this type of concrete yet. One advantage of any new proposed material is the cost effectiveness so that it can be potentially used the construction industry. Table 4 shows the estimated cost of GC locally produced per cubic meter. The total price of nearly $107 per cubic meter of can be expected to locally produce a recycled steel fiber reinforced geopolymer concrete. This price is 12% lower than those of conventional concrete with advantage of using friendly environment construction material.

TABLE 3. Experimental and predicted values of the tensile strength

Mix ID	Splitting [MPa]	Double Punch [MPa]	Flexural [MPa]	Predicted Strength Eq. (1)	Predicted Strength Eq. (2)
GC	2.65	2.24	4.86	3.30	2.97
S0.5N	3.95	2.91	6.92	3.42	3.12
S0.5R	2.88	2.36	5.08	3.30	2.97
S0.5H	3.44	2.5	6.11	3.38	3.07
S1.0N	4.28	3.18	8.15	3.50	3.21
S1.0R	3.4	2.55	6.19	3.32	3.00
S1.0H	3.82	2.8	6.83	3.45	3.15
S1.5N	4.9	3.31	8.36	3.55	3.28
S1.5R	3.86	2.65	6.51	3.33	3.01
S1.5H	4.12	3.16	7.10	3.51	3.23

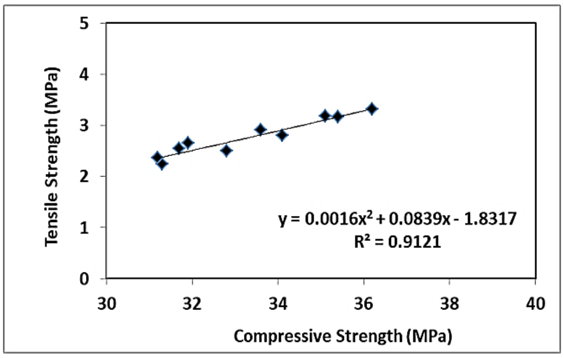


Figure 10. Compressive-tensile relationship of SFRGC based on double punch tensile test procedure

TABLE 4. Cost per cubic meter for locally produced GC

Component	Price per (kg)	Amount (kg/m^3)	Cost per (m^3)
Fly ash (class F) [kg/m^3]	0.1	350	35
Alkaline solution [kg/m^3]	0.05	175	8.75
Recycled coarse aggregate [kg/m^3]	0.01	1050	10.5
Recycled fine aggregate [kg/m^3]	0.05	600	30
Superplasticiser [kg/m^3]	0.4	7.8	3.12
Steel Fibres [kg/m^3]	0.5	40	20
		Total	$107.4

6. CONCLUSIONS

This study experimentally investigated the tensile behaviour of three different types of steel fiber geopolymer concrete (SFRGC) mixes. A total number of 120 specimens were tested under compression, splitting tensile, double punch and flexural tests. Each result shown in this study was an average of three individual readings. The SFRGC mixes were compared to a reference plain geopolymer concrete (GC) mix to examine the efficiency of using recycled steel fiber in making concrete.

1. In this study, geopolymer concrete was produced with reliable compressive strength of nearly 30 MPa by using waste filler (recycled crashed concrete, and recycled crushed glass). Accordingly, with more research work on the durability of this type of concrete, it can be recommended to use it as a reinforced concrete in the construction field. However, compared to a previous research, the replacement of natural river aggregate with recycled aggregate could lead to a compressive strength reduction of nearly 30%.
2. The compressive strength of concrete was slightly increased by using recycled steel fiber (an increment of 3% for 1.5% of recycled steel fiber concrete). However, an increment of 16% was achieved for the compressive strength when new steel fiber is used with 1.5% volume content. Also, attention should be given to the geopolymer concrete's workability by using the proper amount of alkaline solution and superplasticiser. The higher average 28-d compressive strength was obtained by SFRGC made with new steel fiber which is 36 MPa.
3. The highest splitting tensile strength of GC of 4.9 MPa was achieved by using new steel fiber with 1.5% of steel fiber content. Because this type of steel fiber has some advantages such as uniform aspect ratio (length/diameter) and straight shape with a hooked end to increase the anchorage with the cement paste. On the other hand, the highest splitting tensile strength of GC with recycled steel fiber was 3.86 MPa. This is because that the recycled steel fiber was contained some rubber crumbs which may negatively affected the mechanical properties of the geopolymer concrete.
4. The splitting test method was inadequate to evaluate the tensile strength of SFRGC in both cases of new steel fiber and recycled steel fiber. This is because the failure surface of the specimen was more than one and it is a conflict with the equation used to calculate the tensile strength in this method. However, for tensile strength assessment of SFRGC, a double punch test procedure can be adopted with reliable adequacy.
5. The highest flexural strength (8.36 MPa) of GC mixes was achieved by involving 1.5% of steel fiber content. New steel fiber recycled steel fiber, and

hybrid steel fiber was respectively increased by 72%, 34%, and 44%, in comparison with the GC without steel fiber. Also, as expected, the flexural test method obtained the highest tensile strength results among other tensile strength test procedures, nearly 16% of the compressive strength.

6. In terms of cost effectiveness, locally the cost of producing recycled steel fiber geopolymer concrete is nearly 12% lower than the cost of conventional steel fiber reinforced concrete.

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Persian Abstract

چکیده

در چند دهه اخیر، بتن ژئوپلیمری تحولی در زمینه مهندسی عمران ارائه کرده است. هدف مطالعه حاضر تولید یک بتن ژئوپلیمری تقویت شده با الیاف فولادی کم هزینه با خواص کششی قابل قبول است. هدف این برنامه آزمایشی بررسی رفتار کششی بتن ژئوپلیمری تقویت شده با الیاف فولادی و ساخته شده از مواد بازیافتی است. مواد اولیه بتن ژئوپلیمری تقویت شده با الیاف فولادی در این مطالعه مواد زائد بودند. الیاف فولادی بازیافتی از لاستیک ها استخراج و به الیاف ریز با طول متوسط ۲۰ میلی متر و قطر متوسط ۰,۷ میلی متر خرد شد. بتن ژئوپلیمری در این مطالعه شامل سنگدانه های درشت بود که بتن بازیافتی خرد شده بود. همچنین، سنگدانه ریز خرد شده شیشه زباله بود. علاوه بر مقاومت فشاری، روش‌های تست کششی مانند استحکام کششی شکافتن، مقاومت کششی دو پانچ و استحکام کششی خمشی همگی در این مطالعه بررسی شدند. الیاف فولادی بازیافتی با الیاف فولادی با انتهای قلاب‌دار جدید و الیاف فولادی هیبریدی (۵۰٪ جدید + ۵۰٪ بازیافت شده) با سه درصد حجمی مختلف الیاف فولادی (۰,۵٪، ۱,۰٪ و ۱,۵٪) مقایسه شد. مخلوط بتن ژئوپلیمر الیاف فولادی جدید با ۱,۵ درصد الیاف فولادی بالاترین نتایج آزمایش را در میان سایر مخلوط ها نشان داد، زیرا مقاومت کششی در مورد آزمایش پانچ دوبل افزایش یافته است. این رفتار را می توان به این صورت توضیح داد که الیاف فولادی جدید دارای یک شکل یکنواخت و مستقیم با انتهای قلاب شده است که باعث افزایش لنگر بین چسب خاکستر بادی و الیاف فولادی می شود. علاوه بر این، الیاف فولادی بازیافتی حاوی خرده های لاستیکی بود که می تواند دلیل دیگری باشد که بر خواص کششی بتن ژئوپلیمری تأثیر منفی می گذارد.