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Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC

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Abstract

This paper describes an experimental investigation into the relationship between the splitting tensile strength and compressive strength of glass fiber reinforced concrete (GFRC) and polypropylene fiber reinforced concrete (PFRC). The splitting tensile strength and compressive strength of GFRC and PFRC at 7, 28 and 90 days are used. Test results indicate that the addition of glass and polypropylene fibers to concrete increased the splitting tensile strength of concrete by approximately 20–50%, and the splitting tensile strength of GFRC and PFRC ranged from 9% to 13% of its compressive strength. Based on this investigation, a simple 0.5 power relationship between the splitting tensile strength and the compressive strength was derived for estimating the tensile strength of GFRC and PFRC.

Keywords: GFRC; PFRC; Splitting tensile strength; Compressive strength

1. Introduction

The use of fiber reinforced concretes (FRC) has increased in building structures because the reinforced fibers in concrete may improve the toughness, flexural strength, tensile strength, impact strength as well as the failure mode of the concrete. It has also been known that addition of fibers in concrete has little or no effect on the compressive strength and the modulus of elasticity [1]. However, fiber reinforced concretes have considerably increased toughness and strain at the peak stress due to bonding forces at the fiber–matrix interface. During the past three decades, a number of works pertaining to experimental and analytical methods for evaluating the strength characteristics of FRC have been published under varied specimen types, fiber types, fiber contents, curing time and testing methods [2]. Although, concrete behavior is governed significantly by its compressive strength, the tensile strength is important with respect to the appearance and durability of concrete. The tensile strength of concrete is relatively much lower than its compressive strength because it can be developed more quickly with crack propagation. Generally, tensile strength of concrete is often assumed proportional to the square root of its compressive strength [3]. However, there has been very few published works dealing with experimental and analytical investigations of the relation of splitting tensile strength and compressive strength of fiber reinforced concretes. The objective of this investigation is to provide an experimental investigation into the relationship between the tensile strength and compressive strength of glass fiber reinforced concrete (GFRC) and polypropylene fiber reinforced concrete (PFRC).

Shaaban and Gesund [4] investigated the splitting tensile strength and compressive strength of steel fiber reinforced concrete (SFRC). A total of 96 cylinder specimens were made by rodding and vibrating. The authors found that the external vibrating of tested cylinders has resulted in a considerable increase in the splitting tensile strength of SFRC compared to the rodded cylinder specimens. Vibrating consolidation, however, did not have a similar effect on

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the compressive strength. Unfortunately, the authors did not attempt to analyze the relationship between splitting tensile and compressive strengths.

Nataraja et al. [5] investigated the splitting tensile strength of steel fiber reinforced concrete (SFRC) using a typical 100 mm cube specimen. From the results of flexural, compression and splitting tensile tests, authors found that the splitting tensile strength of SFRC was 0.67 times of its flexural tensile strength, and 0.09 times of its compressive strength. In addition, empirical equations on splitting tensile strength were proposed from the linear regression analysis as a function of the fiber reinforcing index (RI). A linear relationship between the splitting tensile and flexural tensile strengths was also proposed.

2. Experimental program

The experimental program was designed to evaluate the relationship between the splitting tensile and compressive strengths of GFRC and PFRC. The fiber contents considered in this investigation were 1.0% and 1.5% of the mixed concrete by volume. Generally, a relatively low content of fibers (less than 1%) seems to have a small positive influence on the concrete, and the fiber content more than 2% may have a difficulty in mixing and uniform distribution of fibers. The fiber contents used in this study seem to be reasonable fiber content for practical applications.

2.1. Materials and mix proportions

The materials used in the present study were: (1) Type I Portland cement which meets ASTM C150 specifications, (2) 25 mm maximum size of coarse aggregate with a density of 1.47×10^3 kg/m^3, (3) natural sand with a specific gravity of 2.66 and a fineness modulus of 2.78, (4) glass fiber with a specific gravity of 2.7, and (5) polypropylene fiber with a specific gravity of 0.91. The glass fiber is a monofilament fiber had 0.013 mm in diameter and 19 mm in length with high-quality alkali-resistant. The glass fiber is designed to reinforce cementitious and other alkaline matrices with non-combustibility characteristics and corrosion resistance. The polypropylene fiber is a monofilament fiber had 0.90 mm in diameter and 50 mm in length. The polypropylene fiber has a “wavelength” shape and is collated in small bundles for rapid introduction into wet and cementitious mixtures. The mix proportions used in this study were applicable to concrete that has a normal weight and a moderate compressive strength of 27.5 MPa at 28 days. A series of five concrete mixes were prepared using with and without fibers. The fiber weights are 27.5 and 55 kg/m^3 for glass fiber, and 9.5 and 19 kg/m^3 for polypropylene fiber corresponding to the fiber contents of 1.0% and 1.5% by volume, respectively. The GFRC and PFRC were mixed in a 0.25 m^3 laboratory mixer under the following steps [8]: First, coarse and fine aggregates were mixed for approximately 1 min. Cement and fiber were added, and then mixed for an additional 2 min. The mixing was continued while about 50% of the water was added. Finally, the remaining water was added and the mixing was continued for an additional 3–4 min. The details of materials and mix proportions used in this investigation are given in Table 1. The mix designations given in Table 1 are represented by the fiber type and the fiber content. For example, GFRC1.0 represents a mix of 1.0% glass fiber reinforced concrete and PFRC1.0 represents a mix of 1.0% polypropylene fiber reinforced concrete, and PC represents plain concrete without any fibers. During mix of concrete, the increase of fiber content seems to decrease its workability. The slump was measured for each mix using a mold, which has the shape of truncated cone with a base diameter of 204 mm, a top diameter of 102 mm, and a height of 305 mm. The measured slump values are also given in Table 1. The casting and finishing of the cylinder specimens in both 1.0% of GFRC and PFRC were not difficult in this study. However, a number of defects were observed in the 1.5% of GFRC in which the fibers formed a ball-like shape with cement paste.

2.2. Test specimen and procedure

A typical plastic cylinder mold of 150 mm in diameter and 300 mm in height was used for test specimen. The casting and finishing of specimens were made in a laboratory with a temperature of 20±1.5 °C. The specimens were demolded approximately 24 h after its casting, and then cured in the moist room at a temperature of 23±2 °C and 100% relative humidity until tested. A total of 18 cylinder specimens were made from each mix for compression and splitting tensile tests. Approximately 2–4 h before

Table 1
Material and mix proportions

Mix	Cement (kg/m^3)	Water (kg/m^3)	Coarse aggregate (kg/m^3)	Fine aggregate (kg/m^3)	Fiber content (kg/m^3)	Slump (mm)
PC	418.0	200.0	998.0	724.0	0.0	102.0
GFRC 1.0	418.0	200.0	998.0	724.0	27.5	13.0
GFRC 1.5	418.0	200.0	998.0	724.0	55.0	2.50
PFRC 1.0	418.0	200.0	998.0	724.0	9.50	38.0
PFRC 1.5	418.0	200.0	998.0	724.0	19.0	6.50

Fig. 1. Test setup for splitting tensile strength.

testing, the specimens were capped with a sulfur plaster on the cast faces. Compression tests were conducted on a Material Testing System (MTS) with a load capacity of 1800 kN. A total of 45 cylinder specimens of GFRC, PFRC and plain concrete at 7, 28 and 90 days were tested in accordance with ASTM C-39 standards [6]. The load was applied at a rate of 0.02 mm/s with a preload of about 200 N. The peak load and the load–axial displacement were recorded during the test by an acquisition system.

Split-cylinder tests were carried out in accordance with ASTM C-496 standards [7] at the same ages and numbers of specimens of concrete used for the compression test. Commonly, three test methods are used to measure tensile strength of concrete [9]: (1) the direct tension test, (2) the modulus of rupture or flexural test, (3) the split-cylinder test. The direct tension test can be attributed to the difficulty of insuring that the load is truly axial in direct tension when some eccentricities of the load may underestimate the tensile strength. The flexural (modulus of rupture) test is used to determine the tensile strength by using the maximum load obtained to cause failure. Although, the flexural tensile strength from a flexural test may show the true tensile strength of concrete, many researchers have indicated that the true tensile strength is approximately 65–70% of the flexural tensile strength [9,10]. The split-cylinder test is relatively simple and seems to provide a reliable test result to calculate the tensile strength of concrete under uniform stresses at the top and bottom across the diameter of the tested cylinder specimens [10]. Therefore, the split-cylinder test is preferred in this investigation. Each cylinder specimen was placed on its side and loaded in compression along a diameter of specimen. The load was applied at a rate of 0.01 mm/s for split-cylinder test with a preload of about 50 N. The splitting tensile strength, $f_{(\mathrm{st})}$ (MPa), was calculated using the following equation:

$$f_{(st)} = \frac{2P}{\pi LD} \tag{1}$$

where P is the peak load in the test, L is the length of the cylinder specimen and D is the diameter of the cylinder specimen. A typical split-cylinder test set-up used in this study is shown in Fig. 1.

3. Test results and discussions

The average compressive strengths of GFRC, PFRC and plain concrete at 7, 28, and 90 days are given in Table 2. During compression test, plain concrete specimens failed under explosive sound at the peak load while GFRC and PFRC specimens failed under some vertical cracks on the surface of the specimen at the peak load. Normally, these vertical cracks were appeared on the surface of the specimen at about 70–85% of the peak load. Also, the spallings were not significantly greater in the PFRC than in the GFRC. This result may be due to their different fiber length. The average compressive strengths given in Table 2 show that the addition of glass and polypropylene fibers to concrete does not seems to increase the compressive strength when compared to those of plain concrete. However, the strains corresponding to peak load mostly increased, and the toughness also increased considerably. Furthermore, both the ascending and descending portions of the stress–strain curves were affected by the reinforcing fibers. These results are shown in the stress–strain curves of compression test in Fig. 2.

The average splitting tensile strengths of GFRC, PFRC and plain concrete are given in Table 3. Generally, it has been suggested that the peak load (P) at the first crack from the test can be used for determining of the splitting tensile strength [11]. The splitting tensile strengths in Table 3 were calculated using Eq. (1) where the peak load was obtained at the first crack. Test results show that the addition of glass or polypropylene fibers in concrete increased the splitting tensile strength by approximately 20–50%. This result may be due to the reinforcing fiber's role to resist cracking and spalling across the failure plains. Furthermore, the addition of both glass and polypropylene fibers significantly

Table 2
Experimental compressive strength

Time (day)	GFRC1.0	GFRC1.5	PFRC1.0	PFRC1.5	PC
$f'_{c\text{-}7}$ (MPa)	20.19	21.55	31.92	31.54	35.41
	22.79	19.59	31.20	30.99	33.12
	24.67	23.01	32.03	28.78	33.60
Ave.	22.55	21.38	31.72	30.44	33.84
$f'_{c\text{-}28}$ (MPa)	26.72	23.57	35.73	32.84	36.72
	29.63	23.77	34.71	28.46	30.96
	23.30	26.33	35.82	30.93	37.42
Ave.	26.55	24.56	35.42	30.74	35.03
$f'_{c\text{-}90}$ (MPa)	28.10	26.12	39.42	32.77	39.62
	26.03	27.00	37.97	31.45	39.70
	29.10	28.03	36.98	31.65	38.58
Ave.	27.74	27.05	38.12	31.96	38.30

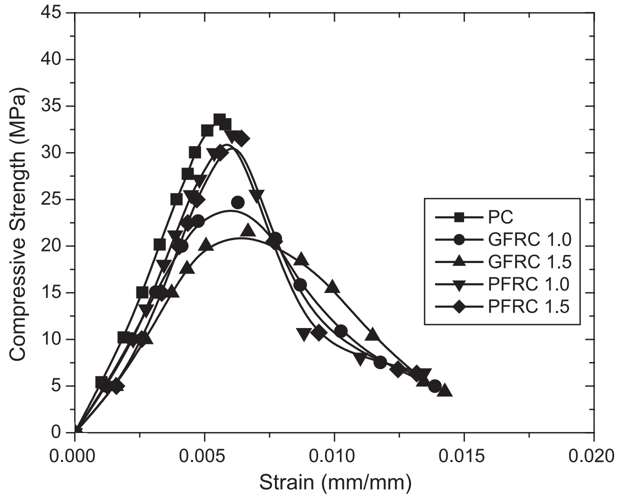

Fig. 2. Stress–strain curves on compression test.

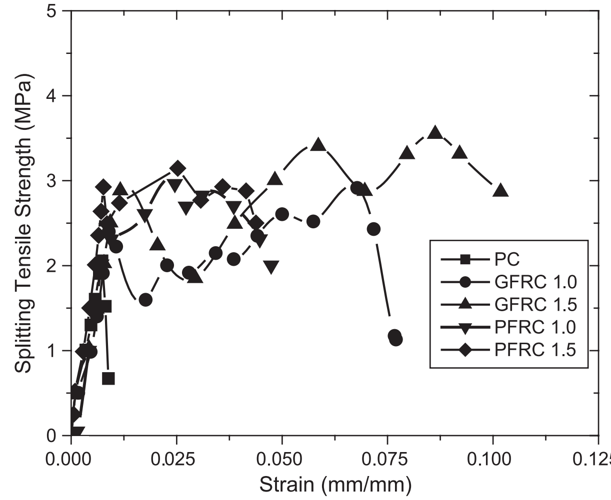

Fig. 3. Stress–strain curves on splitting tensile test.

increased the concrete's ductility, which is defined as the amount of strain exceeding the proportional limit up to the point of failure. These results are shown in the stress–strain curves of split-cylinder test in Fig. 3. It was observed that the stress–strain curves of GFRC and PFRC are both linear up to the first crack, known as the proportional limit, which essentially coincides with the first crack that occurred. The stress then suddenly drops, while the strain continues to increase, the stress then climbs again to a second peak. This process can be repeated several times, until the specimen collapsed. Unlike plain concrete, these phenomena may be due to the reinforcing fibers that provide additional roles in tensile strength and ductility to the fiber reinforced concrete. The test results also showed that the average splitting tensile strength of GFRC and PFRC ranged from 9% to 13% of its compressive strength. This range is similar to that found for SFRC by Nataraja et al. [5].

3.1. Analysis of test results

In order to estimate the effect of fiber on the splitting tensile strength of GFRC and PFRC, a regression analysis (curve fitting technique) was used. From a large number of tests, a simple 0.5 power law model has become one of the most widely used analytical models for describing the relationship between the splitting tensile strength and compressive strength of concrete. In this study, the tensile strengths of GFRC and PFRC are assumed to proportional to the square root of their compressive strength. The general form of the 0.5 power law model is given as:

$$f_{(st)_i} = K(f_c')_i^{0.5} \tag{2}$$

where $f_{(st)_i}$ and $(f_c')_i$ are the splitting tensile and compressive strengths at the ßth day of GFRC and PFRC, respectively. The intercept K represents the value of the constant at each age from regression analysis. Eqs. (3) and (4) have been derived for describing a relationship between the splitting tensile and compressive strength of GFRC and PFRC at all ages in this study:

$$f_{(st)} = 0.60(f_c')^{0.5}, \text{ for GFRC, and} \tag{3}$$

$$f_{(st)} = 0.55(f_c')^{0.5}, \text{ for PFRC} \tag{4}$$

These equations are plotted in Fig. 4 with the experimental data. It can be seen that the regression lines from Eqs. (3) and (4) showed a relatively good relationship between the splitting tensile strength and compressive strength with a largest scatter of 90-day test data. The coefficient of determination (COD=R^2), which indicates how much of the total variation in the dependent variable can be accounted for by the regression equation, was obtained as 0.81 and 0.87 for Eqs. (3) and (4) in this study, respectively. Most statisticians consider a COD of 0.7 or higher for a reasonable model [12]. Therefore, the derived 0.5 power equations may successfully used to represent the

Table 3
Experimental splitting tensile strength

Time (day)	GFRC1.0	GFRC1.5	PFRC1.0	PFRC1.5	PC
$f_{(st)\text{-}7}$ (MPa)	2.40	2.88	3.29	3.37	2.06
	2.98	2.92	2.86	2.95	2.01
	2.74	2.79	3.03	2.93	2.03
Ave.	2.71	2.86	3.06	3.08	2.03
$f_{(st)\text{-}28}$ (MPa)	2.87	3.05	3.00	3.29	2.22
	3.06	3.06	3.52	3.10	2.51
	3.04	3.07	3.12	3.21	2.07
Ave.	2.99	3.06	3.21	3.21	2.23
$f_{(st)\text{-}90}$ (MPa)	3.47	3.38	3.65	3.56	2.65
	3.14	3.68	3.16	3.16	2.90
	3.01	3.41	3.25	3.39	3.16
Ave.	3.21	3.49	3.35	3.37	2.89

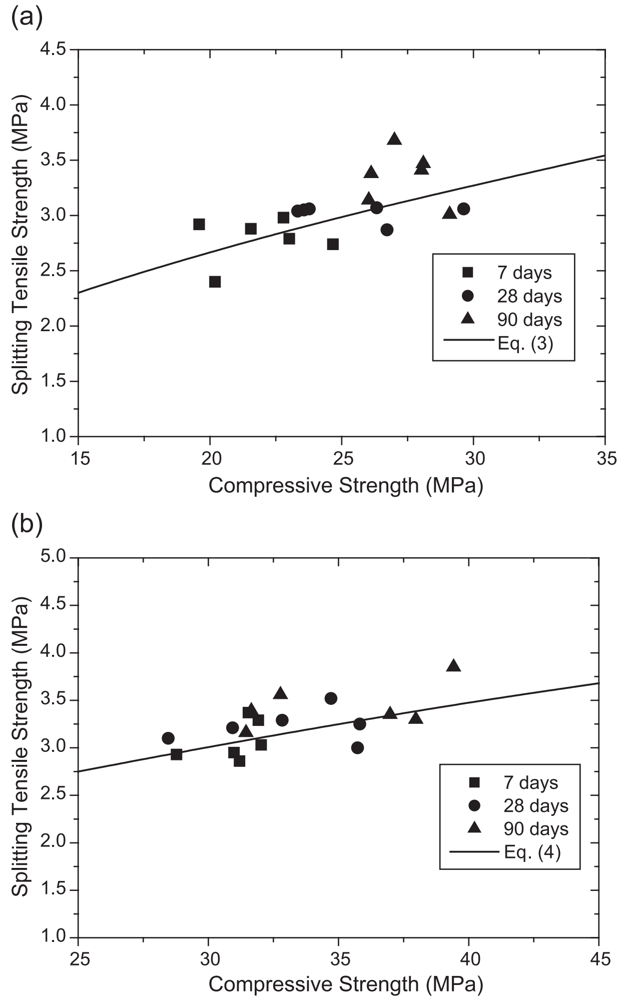

Fig. 4. Proposed equations with experimental data; (a) GFRC, (b) PFRC.

relationship between the tensile strength and compressive strength of GFRC and PFRC. Actually, it is noted that the tensile strength of concrete without fiber could be affected by the same factors as its compressive strength such as aggregate type, W/C ratio, curing time, specimen size and the testing method used [2–5]. In addition to these factors, tensile strength of FRC could be affected by the many other factors such as the types of fiber, fiber content, length of fiber, directions of embedded fibers, aspect ratio of fiber. Furthermore, the number of test data is important because the more test data may provide the better statistical validation for various factors. However, the proposed equations in this investigation for GFRC and PFRC are given only as a function of their compressive strength using a relatively small number of experimental data. Therefore, further research is needed to verify the proportional relationship derived in this study, and to determine the effects of fiber types, fiber contents, numbers of test data, curing time and other factors.

4. Conclusions

Based on the experimental and analytical results of the glass fiber reinforced concrete and the polypropylene fiber reinforced concrete in this study, the following conclusions were made:

(1) The splitting tensile strength of GFRC and PFRC approximately ranged from 9% to 13% of its compressive strength.
(2) The addition of glass and polypropylene fibers in concrete increases the splitting tensile strength by approximately 20–50%.
(3) Based on a relatively small number of experimental data, a simple 0.5 power relationship between the splitting tensile strength and the compressive strength of GFRC and PFRC can be successfully used to estimate its splitting tensile strength.
(4) Further research is needed to verify the derived proportional relationship including other types of fibers, more number of test data, different fiber contents, curing time and other factors.

References

[1] ACI Committee 544, Measurements of properties of fiber reinforced concrete, ACI Mat. J. 85 (6) (1988) 583–593.
[2] K. Ramesh, D.R. Seshu, M. Prabhakar, Constitutive behavior of confined fiber reinforced concrete under axial compression, Cem. Concr. Compos. 25 (3) (2003) 343–350.
[3] A.O. Francis, G.B. Edwin, J.H. Deatherage, Splitting tensile strength and compressive strength relationship at early ages, ACI Mater. J. 88 (2) (1991) 115–121.
[4] A.M. Shaaban, H. Gesund, Splitting tensile strength of steel fiber reinforced concrete cylinders consolidated by rodding or vibrating, ACI Mater. J. 90 (4) (1993) 366–369.
[5] M.C. Nataraja, N. Dhang, A.P. Gupta, Splitting tensile strength of SFRC, Indian Concr. J. 75 (4) (2001) 287–290.
[6] ASTM C-39-02, Standard test method for compressive strength of cylindrical concrete specimens, Annual Book ASTM Standards, 4 (04.02), 2002.
[7] ASTM C496-02, Standard test method for splitting tensile strength of cylindrical concrete specimens, Annual Book ASTM Standards, 4 (04.02), 2002.
[8] ASTM C-1116-00, Standard specification for fiber-reinforced concrete and shortcrete, Annual Book ASTM Standards, 4 (04.02), 2000.
[9] M.F.M. Zain, H.B. Mahmud, Ade Ilham, M. Faizal, Predicting of splitting tensile strength of high-performance concrete, Cem. Concr. Res. 32 (10) (2002) 1251–1258.
[10] C. Rocco, G.V. Guinea, J. Planas, M. Elices, Review of the splitting-test standards from a fracture mechanics point of view, Cem. Concr. Res. 31 (3) (2001) 73–82.
[11] F.L. Carneiro, A. Barcellos, Tensile strength of concretes, RILEM Bull. (13) (1983) 97–123.
[12] B. Ostle, K.V. Turner, C.R. Hicks, G.W. Mcelrath, Engineering Statistics: The Industrial Experience, Duxbury Press, Pacific Grove, CA, 1999.