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The Relationship between Splitting Tensile Strength and Compressive Strength of Fiber Reinforced Concretes

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Abstract

This paper presents experimental and analytical results of glass fiber-reinforced concrete (GFRC) and polypropylene fiber-reinforced concrete (PFRC) to investigate the relationship between tensile strength and compressive strength based on the split cylinder test (ASTM C496) and compressive strength test (ASTM C39). Experimental studies were performed on cylinder specimens having 150 mm in diameter and 300 mm in height with two different fiber contents (1.0 and 1.5% by volume fraction) at ages of 7, 28 and 90 days. A total of 90 cylinder specimens were tested including specimens made of the plain concrete. The experimental data have been used to obtain the relationship between tensile strength and compressive strength. A representative equation is proposed for the relationship between tensile strength and compressive strength of fiber-reinforced concrete (FRC) including glass and polypropylene fibers. There is a good agreement between the average experimental results and those calculated values from the proposed equation.

Keywords: glass fiber-reinforced concrete (GFRC), polypropylene fiber-reinforced concrete (PFRC), compressive strength, splitting tensile strength

1. Introduction

Recently, the development of fiber reinforced concrete (FRC) has been increased in the concrete structures because the reinforced fibers possibly add flexural, tensile, impact strengths, ductility and failure mode by the effects of fibers used. A number of researches have been conducted on FRC including steel, glass and polypropylene fibers for structural applications in which cost is the primary concern. The available literatures in the area of strength evaluations for FRC may be defined by the member types, reinforced fiber, fiber content, curing time and testing methods.

It has been widely known that an addition of fibers has no significant effects or marginal increasing on the compressive strength of concrete, and has significant increases in flexural performance in terms of ductility, load carrying capacity, shear resistance and damage tolerance by crack width and spalling of FRC. Regarding on tensile strength of concrete, many of the published investigations performed on split-cylinder testing about high-strength concrete (HPC) because HPC is a relatively new product and its characteristics differ from that of normal concrete.[2] Tensile strength of concrete is relatively much lower than compressive strength because it develops more quickly with crack propagation.

However, few researches have been done on splitting tensile strength of FRC and its relationship between compressive strength and splitting tensile strength.

Shaaban M. and Gesund H.[6] reported the test results of splitting tensile strength of steel fiber reinforced concrete (SFRC) cylinders consolidated by rodding or vibrating. Authors pointed out that the external vibrating of tested cylinders resulted in considerable increase in the split-cylinder tensile strength of SFRC compared to rodded cylinder specimens. Vibrating consolidation, however, did not have a similar effect on the compressive strength. Unfortunately, the authors did not attempt to analyze the relation-

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ship between splitting tensile strength and compressive strength based on test results. This paper presents the test results of an experimental study of glass fiber reinforced concrete (GFRC) and polypropylene fiber reinforced concrete (PFRC) using cylinder specimens according to the split-cylinder test and compressive strength test, and predicts the relationship between splitting tensile strength and compressive strength from the experimental data.

2. Experimental program

2.1. Materials

The materials used in this investigation were: Type I/II of Portland cement, 9.5 mm maximum size of crushed stone, natural sand and two types of fibers. Type 1 fiber, glass fiber, is 19 mm long monofilament fiber with diameter of 0.013 mm and a high-quality alkali-resistant fiber which is designed to reinforce cementitious and other alkaline matrices with non-combustibility characteristics and corrosion resistance. Type 2 fiber, corrugated polypropylene fiber, is 50 mm long monofilament fibers manufactured in "wavelength" shape with diameter of 0.90 mm and is collated in small bundles for rapid introduction into wet and cementitious mixtures.

2.2. Mix proportions

The mix proportions chosen in this investigation is applicable to normal weight concrete for moderate column strength with a 27.5 MPa of compressive strength at 28 days. The fiber contents were 1.0 and 1.5 % of mixed concrete by volume fraction. The corresponding fiber weights are 27.5 kg/m^3 and 55 kg/m^3 for glass fibers, and are 9.5 kg/m^3 and 19 kg/m^3 for polypropylene fibers. The fibers used in this study assumed randomly distributed in concrete because they are not place one at a time in a straight line. The basic ingredients of concrete mixture and the details of fiber mixes are given in Table 1.

2.3. Casting and curing

The concrete was mixed in a 0.25m^3 laboratory mixer using the following steps. First, coarse and fine aggregates were mixed for approximately 1 min. Cement and fiber were added next, and then mixed for an additional 2 min. The mixing continued for further while about 50 % of water was added. Finally, the remaining water was added and the mixing was continued for an additional 3-4 min.[1] The addition of fibers and increasing of fiber content decreased the workability of fiber reinforced concrete. The slump values were measured at each mixing using a mold which has the shape of truncated cone of base diameter 204 mm, top diameter 102 mm, and height 305 mm. The measured slump values are given in Table 2. Based on the measured values in Table 2, the slump values of PFRC are higher than GFRC under same fiber content even though the length of polypropylene fiber is longer than glass fiber as many as 2.5 times. In Table 2, mix designation represented by used fiber type and fiber content. For example, GFRC1.0 represents that a glass fiber reinforced concrete cylinder specimen including 1.0 % of fiber content by volume fraction. PFRC1.0 represents that a polypropylene fiber reinforced concrete cylinder specimen including 1.0 % of fiber content by volume fraction.

During the casting and finishing of cylinder specimens in 1.0% of fiber content for both fibers were not difficult in this study. However, in the mix design of GFRC with 1.5% of fiber content showed some balling of fibers between cement paste and fibers as shown in Fig. 1, and it was not shown in PFRC with 1.5% of fiber content.

For each mix, a total of 24 cylinder specimens with dimensions of 150 x 300 mm were made. After casting, the specimens were stored in a temperature range between 22 to 25°C with polyethylene sheets for preventing moisture loss. Approximately after 28 hours, the specimen were demolded and cured in the moist room at a temperature of 23 ± 2°C and 100 percent relative humidity until tested. Table 3 shows the summary of experimental program in this investigation.

Table 1 Mix proportions for fiber reinforced concrete

Content	Weight (kg/m^3)	Volume (m^3)
Water	200	0.141
Cement	418	0.092
Coarse agg.	998	0.264
Fine agg.	724	0.191
Air	0	0.040
Total	2,340	0.729

Table 2 Experimental measured slump values

Fiber	Mix design	W/C	Slump (mm)
Plain con.	PC	0.48	102
Glass	GFRC1.0	0.48	13
	GFRC1.5	0.48	2.5
Polypropylene	PFRC1.0	0.48	38
	PFRC1.5	0.48	6.5

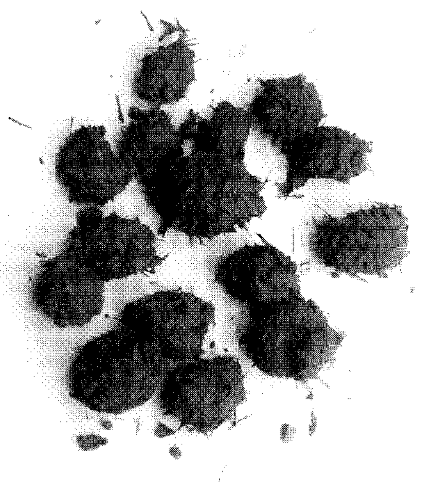


Fig.1 Mixing defects on GFRC at 1.5 % fibers

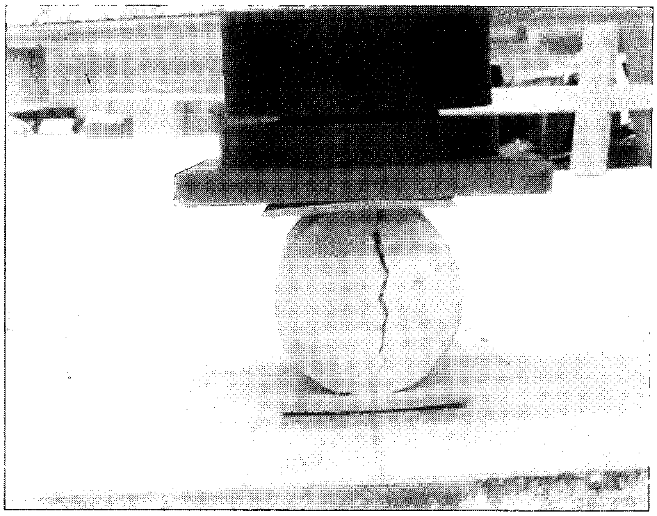


Fig. 2 Test setup for split-cylinder test

Table 3 Details of experimental program

Fiber	Mix design	Fiber (kg/m^3)	W/C	No
Glass	GFRC1.0	27.5	0.48	24
	GFRC1.5	55	0.48	24
Poly-propylene	PFRC1.0	9.5	0.48	24
	PFRC1.5	19	0.48	24
Plain Con.	PC	0	0.48	24

2.4 Test procedures

A total of 45 cylinder specimens having 150 mm in diameter and 300 mm in height were tested under axial compression in accordance to ASTM C-39 standards at 7, 28 and 90 days with a real-time plotting of test data and a rate of loading controller. Before 2-4 hours of testing, the compressive cylinders were capped with a sulfur plaster on the cast faces. The load was applied at a rate of 0.02 mm/sec with a preload of about 200N. The deformations were taken at every 1 sample/sec for the duration of the test by the acquisition system. The peak loads and stresses were obtained at the failure of specimens.

In general, three test methods are usable for estimating the tensile strength of concrete: (1) the direct tension test, (2) the modulus of rupture or flexural test, and (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, and some eccentricities of load have resulted in underestimation of tensile strength, particularly in brittle materials. The flexural (modulus of rupture) test is used to determine the tensile strength, and the maximum load obtained at the failure on the tension face. Although flexural tensile strength from a flexural test shows the true tensile strength of concrete, many researchers have indicated that the true tensile strength is approximately 65% - 70% of the flexural tensile strength.[3,8,9] It is widely known from many investigations that the split-cylinder test is relatively simple and seems to provide the reliable test data to measure the tensile strength of concrete under uniformly stresses at the top and bottom across the diameter of the tested cylinder specimens.[3,8,9,10] The split-cylinder test was used in this investigation. A total of 45 cylinder specimens were placed on it side and loaded in compression along a diameter in accordance to ASTM C-496 standards for the splitting tensile strength at 7, 28 and 90 days with a real-time plotting of test data and a rate of loading controller. The load was applied at a rate of 0.01 mm/sec with a preload of about 50N. The splitting tensile strength, f_{st}, from a split-cylinder test was computed from the following equation:

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

where, f_{st} is the splitting tensile strength (MPa), P is the maximum applied load in the test, L is the length of cylinder specimen and D is the diameter of cylinder specimen. The typical split-cylinder loading test used in this study is given in Fig.2.

3. Test results and discussions

GFRC and PFRC cylinder specimens with two different fiber contents were tested to investigate splitting tensile strength and compressive strength of FRC. The uniaxial compression test results for GFRC and PFRC at 7, 28, and 90 days are given in Table 4. The average values in Table 4 are showed approximately 10 % of deviation in compressive strength. It was observed that an axially loaded plain concrete cylinder specimen was failed explosively at the

Table 4 Summary of FRC compressive strength

Time(d)	GFRC1.0	GFRC1.5	PFRC1.0	PRRC1.5	PC
	20.19	21.55	31.92	31.54	35.41
$f'_{fc\text{-}7}$ (MPa)	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
	26.72	23.57	35.73	32.84	36.72
$f'_{fc\text{-}28}$ (MPa)	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
	28.10	26.12	39.42	32.77	39.62
$f'_{fc\text{-}90}$ (MPa)	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

Table 5 Summary of FRC splitting tensile strength

Time	GFRC (1.0)	GFRC (1.5)	PFRC (1.0)	PRRC (1.5)	PC
	2.40	2.88	3.29	3.37	2.06
$f_{st\text{-}7}$ (MPa)	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
	2.87	3.05	3.00	3.29	2.22
$f_{st\text{-}28}$ (MPa)	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
	3.47	3.38	3.65	3.56	2.65
$f_{st\text{-}90}$ (MPa)	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

point of maximum load, but an axially loaded FRC cylinder specimen was failed under non-explosively at the point of maximum load which demonstrates the reinforced fibers acts as a crack arrestor to change failure mode less brittle than plain concrete. The test results show that compressive strengths of PFRC in accordance to curing time are slightly higher than those of GFRC under same fiber content. It was also observed that compressive strengths of both GFRC and PFRC having 1.5% of fiber content ranged approximately from 85% to 95% of those values of 1.0% of fiber content.

Test results in Table 4 show that the use of glass and polypropylene fibers did not seem to have a increasing of compressive strength of FRC compared to plain concrete. However, the strains corresponding to peak stress mostly increased compare to plain concrete, and considerably increase in toughness. Also both ascending and descending

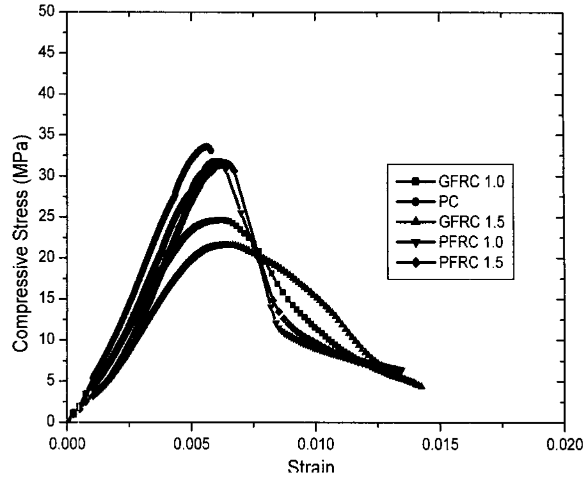


Fig. 3 Stress-strain curves of compressive strength

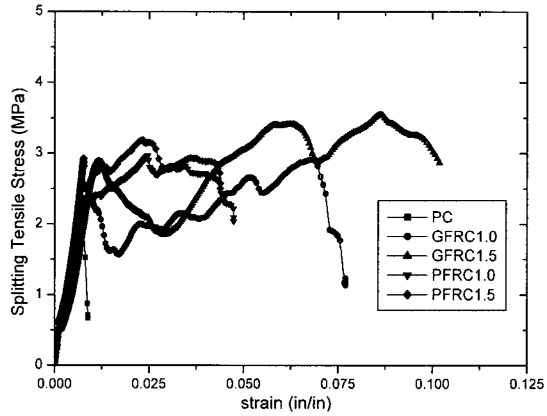


Fig.4 Stress-strain curves of splitting tensile strengths

portion of the stress-strain curves are affected by the added fibers. These results showed in Fig.3 in terms of stress-strain curves on compressive strength. The average and experimental values of splitting tensile strength (f_{st}) of GFRC and PFRC are summarized in Table 5. It has been suggested that the maximum load (P) from the test can be used the applied load at the first crack occurred in cylinder specimens for determining the splitting tensile strength.[6] The splitting tensile strengths in Table 5 were obtained based on the load at the first crack detected by a computerized data acquisition system.

The addition of glass or polypropylene fibers in concrete increased the splitting tensile strength of concrete since the reinforcing fibers provided the role to resist cracking and spalling crossing the failure plains. In addition, the addition of both glass and polypropylene fibers on split-cylinder specimens significantly increased the concrete's ductility which is defined as the amount of strain exceeding proportional limit up to the point of failure.

Fig. 4 shows typical stress-strain curves from the split-cylinder tests of FRC. These stress-strain curves show a straight line relationship up to a point known as the proportional limit, which essentially coincides with the first crack occurred, then the stress suddenly dropped with increasing of strain, and picked up again up to another maximum point until the specimen terminated. Furthermore, unlike plain concrete, these phenomena come from the effects of reinforced fibers which provide additional roles in tensile strength and ductility of FRC.

3.1 Analysis of test results

An analytical work between splitting tensile strength and compressive strength of fiber reinforced concrete (FRC) were discussed. According to many researchers, splitting tensile strength of concrete closely related to that of compressive strength. The relationship between tensile strength and compressive strength of concrete without fibers can be represented by nonlinear equations because the tensile strength of concrete increases with an increase in the compressive strength, and the ratio of tensile strength to the compressive strength decreases as the compressive strength increases.[3,4,5)] In this study, however, test results show that the splitting tensile strength of GFRC and PFRC increases with an increase in the compressive strength, the ratio of tensile strength to the compressive strength of GFRC and PFRC remains steadily as the compressive strength increases.

This implies that the splitting tensile strengths of GFRC and PFRC are assumed to be linear relationship of compressive strength. It is necessary to validate this trend for the fiber reinforced concrete with a much larger test data because the number of tested specimens was relatively small in this study. The tensile and compressive strength data on GFRC and PFRC in Table 4 and 5 were used to develop their relationship. The splitting tensile strengths at 7, 28 and 90 days are plotted versus corresponding compressive strength of GFRC and PFRC in Fig.5, respectively. The linear relationship between splitting tensile strength and compressive strength was adopted as following form:

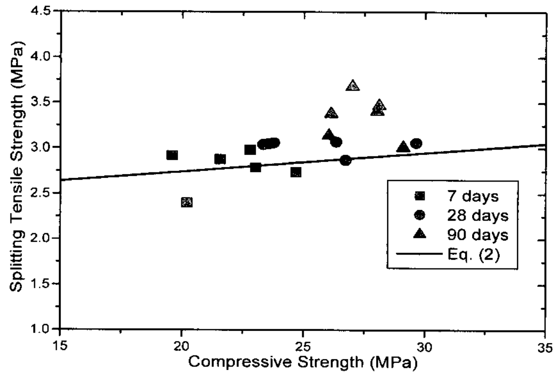
$$f_{(st)_i} = A + Bf'_{(fc)_i} \qquad (1)$$

where, $f_{(st)_i}$ and $f'_{(fc)_i}$ are the values of splitting tensile and compressive strengths, respectively, at i days of FRC. A and B are coefficients that can be obtained from regression analysis. In order to establish a potential relationship between the tensile strength and compressive strength of FRC, the regression analysis conducted on the experimental data. The following two equations were obtained with test data:

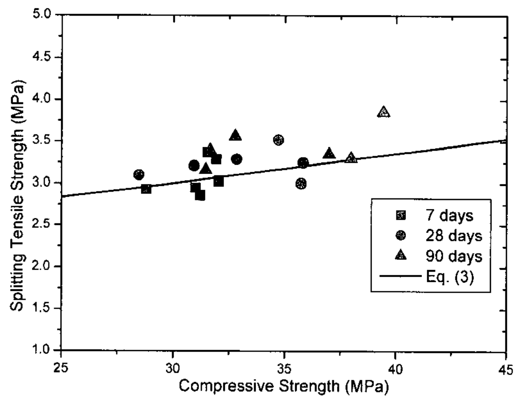
$$f_{(st)} = 2.338 + 0.0203(f'_{fc}), \quad \text{for GFRC, and} \qquad (2)$$

$$f_{(st)} = 1.945 + 0.0353(f'_{fc}), \quad \text{for PFRC} \qquad (3)$$

The coefficients of determination, R^2, were obtained between test data and regression equation. It is a measure of the portion of the total variability of the test data explained by the particular equation. When R^2 is unity, all data points lies exactly or closely on the regression equation, whereas a value of zero means there is no correlation between data points and regression equation.[7)] The value of $R^2 = 0.71$ and 0.66 were obtained in Eq. (2) and Eq. (3), respectively, in the present work. The resulting predicted curves for splitting tensile strength of GFRC and PFRC from Eqs. (2) - (3) are shown in Fig.5 with actual experimental data. With the exception of some of the test data points at early testing time (7 days), the resulting linear equation curves in Fig.5 are below the test data. Obviously, the predicted splitting tensile strength curves result in a slightly more conservative, but it can be acceptable as considered the lower bound criterion. In practice, using of this lower bound limit is acceptable because it minimizes the effects of tested specimens, machine and etc.



(a) GFRC



(b)PFRC

Fig. 5 Linear relationship of tensile strength and compressive strength for FRC; (a) GFRC, (b) PFRC

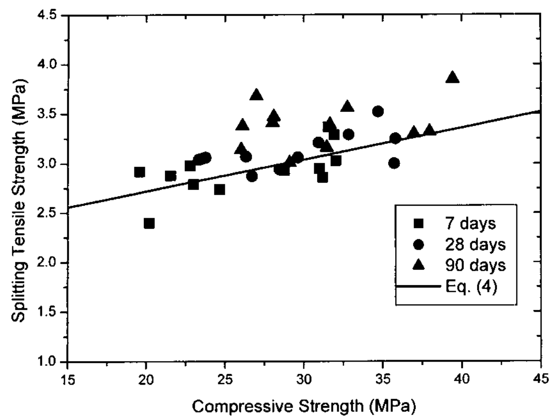


Fig. 6 Proposed equation versus experimental results

Finally, Fig. 5 indicates the simplicity of relationship between splitting tensile strength and compressive strength of GFRC and PFRC regardless of reinforced fiber types. This simplicity can easily lead to single regression equation for tested FRC cylinder specimens. The resulting single regression equation is given by following equation:

$$f_{(st)} = 2.08 + 0.032(f'_{fc}) \text{, for GFRC and PFRC} \quad (4)$$

In Eq. (4), R^2 = 0.72 was obtained which explains that 72 % of test data is correlated to the regression equation. This value is better than any of the equation reported in this study. The single regression equation (Eq. 4) with actual experimental data is shown in Fig. 6.

Fig. 6 indicates that the linear relationship between tensile strength and compressive strength of single regression equation (Eq. 4) well represents the lower bound criterion with the exception of some data point at 7-days. The proposed Eq. (4) was applied to the average experimental data from Table 4 and 5 to compare its validity.

Table 6 shows the estimated splitting tensile strength from the proposed equation to average splitting tensile strength from test. The ratio of average experimental values and estimated values in Table 6 shows a very good agreement in which the difference ranged from 2% to 10 % (except only one data point which has 18%).

Actually, the tensile strength of concrete without fibers could be affected by the same factors as the compressive strength such as aggregate type, W/C ratio, curing time, size effects of tested specimen and testing method. In addition to these factors, the tensile strength of FRC would be affected by the many factors such as type of fibers, fiber content, fiber length, directions of embedded fibers and aspect ratios of fiber. Also the number of tested specimens is important because a much larger test data shows a more statistical validation for various factors. In this study, however, the splitting tensile strength of FRC was estimated only as a function of compressive strength based on the relatively small test data. It is necessary that further works are needed for improving of prediction between splitting tensile strength and compressive strength of FRC regarding to above factors.

Table 6 Comparison of Proposed Splitting Tensile Strength and Test Data

Time(day)	GFRC 1.0	GFRC 1.5	PFRC 1.0	PFRC 1.5
7	2.71(2.80)	2.86(2.76)	3.06(3.09)	3.08(3.05)
28	2.99(2.93)	3.06(2.87)	3.21(3.19)	3.21(3.06)
90	3.21(2.98)	3.49(2.96)	3.35(3.30)	3.37(3.11)

Parenthesis values are obtained by Eq. (4)

4. Conclusions

Based on the experimental and analytical results, the following conclusions can be drawn:

1) The splitting tensile strength of GFRC and PFRC increases as the fiber content and curing age increases.
2) Based on the experimental data, a new relationship (Eq.4) between the splitting tensile and compressive strengths of fiber-reinforced concrete was proposed.
3) The estimated splitting tensile strength from the proposed equation showed a good agreement with the average experimental results
4) Further researches are needed for improving estimation between splitting tensile and compressive strengths of FRC regarding to type of fibers, fiber content, number of specimens and curing time.

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