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Tensile Strength of Green Self-Consolidating Concrete

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Abstract. The environmental footprint of the construction industry in general must be reduced. The process of manufacturing cement involves the release of appreciable amounts of CO_2 into the atmosphere. This paper summarizes the findings of an experimental study aiming at assessing the splitting tensile strength of self-consolidating concrete (SCC) in which 90% of the cement was replaced with various amounts of the industrial by-products including silica fume, fly ash, and ground granulated blast furnace slag (GGBS). Due to the high replacement ratio of cement with recycled industrial by-products, the produced SCC is referred in this study as *green concrete*. The compressive strength ranged between 30 MPa and 50 MPa and was produced with water/cementitious material ratios of 0.33 and 0.36. The splitting tensile strength was determined and a correlation was developed using regression analysis between the splitting tensile strength and compressive strength.

Introduction

Global warming is attributed to increased emission of CO_2 gas caused by human activity. International awareness of the problem led to the adoption of the 1997 Kyoto *Protocol* [1]. The process of producing cement involves the emission of significant amounts of CO_2, therefore, it is essential to decrease the usage of cement in the construction industry to the minimum practicable. Self-consolidating concrete (SCC) mixes developed and assessed in this study use significantly less cement than would typically be needed in similar conventional concrete. The SCC mixes developed in this study were produced in two sets, one set of mixes uses a water/cementitious (w/c) material ratio of 0.33 and a second set of mixes uses w/c ratio of 0.36. In both sets of mixes 90% of the cement was replaced with various combinations of recycled industrial by-products, namely, fly ash, silica fume, and ground granulated blast furnace slag (GGBS).

Mohamed et al. [2] studied fresh and hardened properties of sustainable SCC mixes in which 80% of the cement was replaced with combinations of recycled fly ash, silica fume, and GGBS and developed relationships to predict the splitting tensile strength of these sustainable SCC mixes [3,4]. These splitting tensile strength formulas were validated using data published in the literature and compared to prediction expressions published in three international codes published by the Japanese Society of Civil Engineers (JSCE), the Japanese Concrete Institute (JCI), and the American Concrete Institute (ACI) [5,6]. It was noted that ACI318 prediction formula was the most conservative of the three codes.

In order to enhance sustainability of SCC mixes, this study involves replacement of 90% of the cement with various combinations of fly ash, silica fume, and GGBS. The general format for splitting tensile strength prediction formulas used in various codes and will be adopted in this study is described by Eq. 1.

$$f_{spt} = k \times (f_c')^n \tag{1}$$

Oluokun [7] studied splitting tensile strength using 566 conventional concrete data sets collected from literature and concluded that the formula published by the ACI code overestimates the splitting results.

Gaedicke et al. [8] studied concrete cores and casted concrete samples to determine the relation between the splitting tensile strength and the compressive strength of low strength concrete. The splitting tensile strengh of core samples was related to 0.979 power of the compressive strength while the casted cylinders related to the 0.875 power of the compressive strength. Table 1 summarizes some of the findings from the previous studies.

Table 1: Different sources for the splitting-compressive relationship coefficients

Source	k	N	Remarks
JSCE,2007 [9]	0.23	2/3	conventional concrete with strength between 20 and 50 MPa and validated for strength up to 80 MPa
JCI,2008 [10]	0.13	0.85	conventional concrete with strength between 20 and 50 MPa and validated for strength up to 80 MPa
ACI318-14 [11]	0.56	0.5	Conventional normal weight concrete
Mohamed et al. [4]	0.34	0.57	SCC with fly ash, GGBS, and silica fume.
Mohamed et al. [3]	0.86	0.36	SCC with with GGBS
Oluokun [7]	0.294	0.69	normal weight

Experimental Study

In this study, a total of 18 green SCC mixes in addition to two control mixes were developed to assess the compressive strength and splitting tensile strength. In each of the green SCC mixes, 90% of the cement was replaced with combinations of fly ash, silica fume, and GGBS. Half of the green SCC mixes were prepared with w/c ratio of 0.33 and the other half was prepared with w/c ratio of 0.36.

The mechanical properties of the 20 concrete mixes mentioned above were determined by preparing and testing five samples for each mix for a total of 100 test samples. Two of the five samples prepared from each mix were tested and averaged to determine the compressive strength and three samples were tested and averaged to determine the corresponding splitting tensile strength. The two samples per mix tested to determine the 28-day compressive strength were standard 100 mm x 100 mm x 100 mm cubes. The three samples per mix tested for splitting tensile strength were standard 100 mm x 200 mm cylinders. The average of the three samples was taken to represent the splitting tensile strength of the mix. All samples were water-cured for 28-days under room temperature.

A high range water reducer (HRWR) marked by BASF Corporation under the commercial name *Master Glenium Sky 504* was used to prepare all of the green SCC mixes. All SCC mixes were designed to achieve a flow diameter of 550 mm $\pm$ 50 mm.

Each of the green SCC mixes studied contained a fixed amount of 480 kg/m^3 cementitious materials of which only 10% is conventional Portland cement. The remaining 90% of the cementitious material is combinations of fly ash, silica fume, and GGBS. The same amounts of fine and course aggregates were used in all SCC mixes. 10-mm diameter crushed course aggregates in the amount of 800 kg/m^3 were used in each concrete mix. Fine aggregates used in each mix consisted of 582.4 kg/m^3 black sand and 313.6 kg/m^3 dune sand. Table 2 lists all the mixes with the variables constituents along with the corresponding cube compressive strength.

The compressive strength testing was done according to BS EN 12390-3:2009 [12], while the splitting tensile strength test was conducted according to BS EN 12390-6:2009 and ASTM-C496 [13, 14]. All testing was conducted with machine having total compressive capacity of 3000 kN.

Experimental Results

The 28-days compressive strength test showed that all green SCC mixes developed lower compressive strength compared to the control mix as expected. However, any green mixes developed compressive strength suitable for practical structural engineering applications. For example, a green SCC mix achieving a high strength of 48.42 contained 5% fly ash, 15% silica fume and 70% GGBS. Similarly a mix achieving high compressive strength of 52.98 MPa contained 10% fly ash, 5% silica fume, and 75% GGBS. As shown in Fig. 1a and 1b, the splitting tensile strength followed the same trend of the compressive strength data.

Table 2: Green SCC mixes design

No.	Name	Cement %	Fly Ash %	MicroSilica %	GGBS %	Compressive Strength [MPa]	W/C
1	G1	100	0	0	0	63.30	0.36
2	G1.1	10	5	5	80	37.53	
3	G1.2	10	5	7.5	77.5	41.41	
4	G1.3	10	5	10	75	41.23	
5	G1.4	10	5	12.5	72.5	45.58	
6	G1.5	10	5	15	70	48.42	
7	G1.6	10	10	5	75	34.35	
8	G1.7	10	15	5	70	36.97	
9	G1.8	10	20	5	65	36.28	
10	G1.9	10	25	5	60	32.28	
11	G2.0	100	0	0	0	61.20	0.33
12	G2.1	10	5	5	80	30.54	
13	G2.2	10	5	7.5	77.5	39.86	
14	G2.3	10	5	10	75	40.00	
15	G2.4	10	5	12.5	72.5	50.42	
16	G2.5	10	5	15	70	47.62	
17	G2.6	10	10	5	75	52.98	
18	G2.7	10	15	5	70	49.74	
19	G2.8	10	20	5	65	48.34	
20	G2.9	10	25	5	60	30.93	

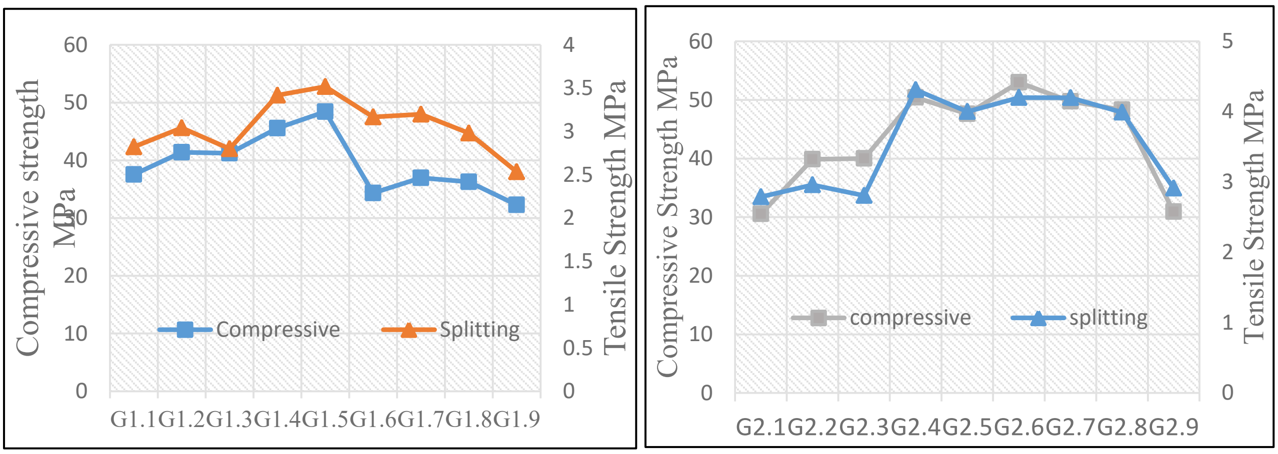

Fig. 1: a) compressive vs splitting for 0.36 w/c ratio mixes b) compressive vs splitting for 0.33 w/c ratio mixes

Correlation Study

It is desired in this study to develop a relationship between splitting tensile strength of green SCC mixes and the 28-day compressive strength based on concrete cylinders. However, the compressive strength tested and reported in this paper was based on standard cubes. Eq. 2 developed by Mansur [15] was used to convert the cube compressive strength determined in this study and reported in Table 2 to cylindrical compressive strength.

$$\left(f_{cu}\right)_{150} = \left(f'_c\right)_{100x200} + 6.41 \tag{2}$$

Regression analysis was conducted to determine a correlation between the splitting tensile strength to the 28-day compressive strength. Reliability of the correlation was assessed by calculating the Integral Absolute Error (IAE), using Eq. 3:

$$IAE\% = \sum \frac{[(O_i - P_i)^2]^{1/2}}{\sum O_i} \times 100 \tag{3}$$

where:

O_i: is the experimental tensile strength

P_i : is the predicted tensile strength from regression analysis.

Regression analysis was used to derive Eq. 4, which represents the best fit relationship between the splitting tensile strength, f_{spt}, and the 28-day compressive strength with a corresponding IAE value of 8%. Fig. 2 is the representation of the relationship between the splitting tensile strength and concrete compressive strength.

By comparing the results with the previous study of Mohamed et al. [4], the 90% cement replacements increased the power *n* from 0.57 to 0.66, this increase in power is a result of an increase in the tensile to compressive strength ratio resulted from the extra replacement of cement.

$$f_{spt} = 0.32 \times (f'_c)^{0.66} \tag{4}$$

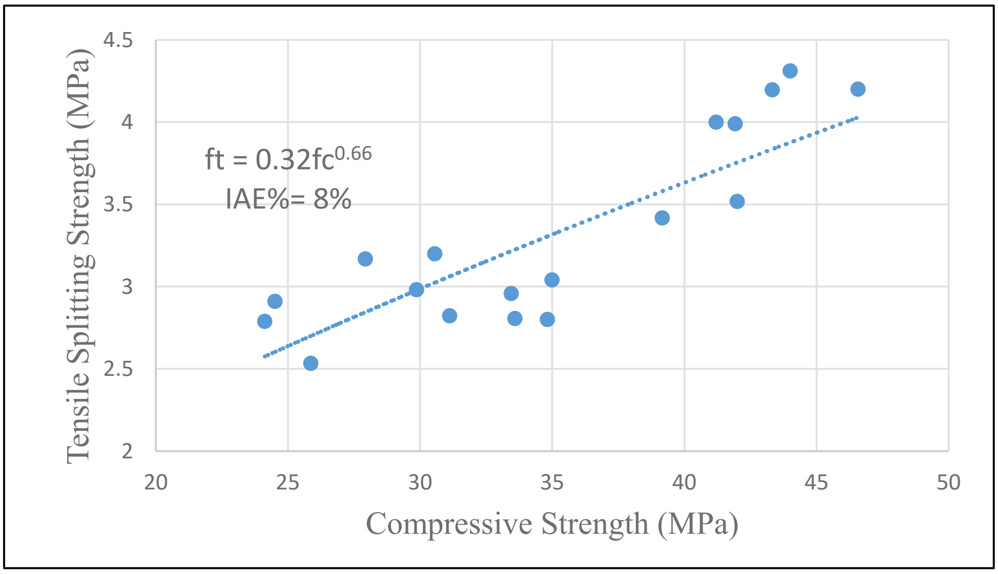

Fig. 2: Splitting Tensile strength to compressive strength correlation

Summary

This study presented sustainable self-consolidating concrete mixes where 90% of the cement was replaced with various combinations of fly ash, silica fume, and slag. Two sets of SCC mixes were examined, one with w/c of 0.33 and a second set of mixes prepared with w/c ratio of 0.36. Many of the developed green mixes produced compressive strength that is high enough for many structural design applications. The 90% replacement mix containing 75% GGBS, 10% fly ash, and 5% silica fume with w/c of 0.33 reached cube compressive strength of 52.98 MPa.

Regression analysis of test data was conducted and a relationship was developed between the tensile and compressive strength with parameters n = 0.66 and k = 0.32. Green mixes introduced in this study with 90% cement replacements showed higher power of the parameter n=0.66 compared to the 80% cement replacement SCC mixes reported by the authors in a previous study, where n = 0.57. This indicates that green SCC mixes with 90% replacement of cement results in higher splitting tensile strength.

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