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Effect of Silica Fume on the Properties of Steel-Fiber Reinforced Self-compacting Concrete

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Abstract**—**Implementing significant advantages in the supply of self-compacting concrete (SCC) is necessary because of the, negative features of SCC. Examples of these features are the ductility problem along with the very high cost of its constituted materials. Silica fume with steel fiber can fix this matter by improving the ductility and decreasing the total cost of SCC by varying the cement ingredients. Many different researchers have found that there have not been enough research carried out on the steel fiber-reinforced self-compacting concrete (SFRSCC) produced with silica fume. This paper inspects both the fresh and the mechanical properties of SFRSCC with silica fume, the fresh qualities where slump flow, slump T_{50} and V- funnel. While, the mechanical characteristics were the compressive strength, ultrasound pulse velocity (UPV) and elastic modulus of the concrete samples. The experimental results have proven that steel fiber can enhance the mechanical features. In addition, the silica fume within the entire hybrid mix may possibly adapt the fiber dispersion and strengthen deficits due to the fibers. It could also improve the strength plus the bond between the fiber and the matrix with a dense calcium silicate-hydrate gel in SFRSCC. The concluded result was predicted using linear mathematical models and was found to be in great agreement with the experimental results.

Keywords**—**Self-compacting concrete, silica fume, steel fiber, fresh and mechanical properties.

I. Introduction

SELF–COMPACTING Concrete (SCC) is the rapid revolution in concrete production which provides a high, fresh quality as well as hardened characteristics. The SCC mix has the ability to resist segregation and to flow easily by it is own weight [1], [2]. The properties of SCC have been studied in many researches due to their importance and the ability to solve the problems of a concrete mix [2]. To develop the SCC-mix required to reduce the aggregate content with as high binder content as possible in order to maintain excellent fresh properties, it is recommended to minimize the water content and use a chemical admixture, such as superplasticizer or Glenium [3], [4]. An increase in cement content will lead to the brittleness of the concrete and increase the total cost. To avoid these two problems, steel fiber with a cement replacement material (CRM) can be used. This is because the fiber can bridge the cracks and enhance the ductility of the concrete. While, the RCM can replace part of the cement and hence, reduce the total cost [5]. Much research has been conducted to investigate the properties of fiber-reinforced self-compacting concrete (FRSCC) [6]-[8].

The disadvantages of fiber in a concrete mix are clumping. This is because the fibers may clump together before they are added to the mix; the normal mixing action will not break down these clumps [9], [10]. Silica fume is a type of CRM that can be applied to replace the cement content in the concrete and can increase the workability properties of the SCC mix [11], [12]. Silica fume with different levels of replacement in the SCC mix have been studied to ensure the effectiveness and optimum degree of replacement that can be used [13]. The ultrasonic pulse velocity can be consider as an indicator to check the reliability of strength gain for concrete with 95% confidence limits of ±20% on the predicted strength [14]. Today's method to measure the None Destructive Test (NDT) parameters is based on the years-old ultrasonic method. Similar combinations include other qualities of the ultrasonic measurement, such as UPV, and the damping constant [15]. Assessment of the concrete quality using the UPV test was found in literature as hardened properties of the concrete sample at different curing times [16]. The objectives of this work have been first to study the effect of steel fiber and silica fume on the properties of SFSCC. Second is to find out the relationship between the compressive strength with the ultrasonic pulse velocity (UPV) and the elastic modulus of SFSCC respectively.

II. The Experimental Program

A. Materials and Methods

ASTM, type-1 ordinary Portland cement (OPC) was applied in the experiment. Its chemical composition was tabulated and presented in Table I. Silica fume was provided by Elkem Materials in a dry densified form of Grade 920E with LOI less than 4% and a particular area (Bet) of 15-35 m^2/gram verified with the specification of ASTM C-1240. The chemical composition of the silica fume has been proven as presented in Table I.

The fine aggregate in the experiment was clean natural sand with a specific gravity of 2.61 and fineness modulus of 2.76; the largest size was only 3.35mm. Since the coarse aggregate was applied as (10-5)mm crushed granite stone according to the BS: 812-103.2-1989, a particular gravity of 2.66 in SSD was obtained. HRWR superplasticizer from SIKA- KIMIA, Malaysia was tried for the enhancement of the workability of the concrete. It is a highly effective liquid-based superplasticizer for the production of free-flowing concrete that complies with the requirements of BS 5075. WSF0220 high-strength steel fiber of the diameter of 0.2mm and 20mm in length with an aspect ratio of 100 was used in this experiment to replace the cement by weight. Its tensile

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strength of more than 2300 MPa confirmed the ASTM A820 and EN 14889. Steel fibers coated with brass and possessing very smooth surfaces reduced the energy loss during the movement of the particles.

TABLE I
CHEMICAL COMPOSITION

Chemical Composition	Percentage %	
	OPC**1**	Silica fume**2**
SiO_2	20.3	96.36
Al_2O_3	4.2	0.21
Fe_2O_3	3	0.77
CaO	62	0.24
MgO	2.8	0.52
SO_3	3.5	0.55
K_2O	0.9	0.102
Na_2O	0.2	0.12

1OPC; the data provide by Shafiq et al. [17], **2**Silica fume; the data provides by M. F. Nuruddin et al. [18].

B. Test Setup of the Experiment

One of the main characteristics of SCC is the workability. The experimental test was started by conducting the fresh properties, which consisted of slump flow, slump T_{50} and V-funnel. Fresh test results were governed by the Specification of the European Federation of Producers and Applicators of Specialist Products for Structures – EFNARC [19]. The methodology of the experiment first, examined the new qualities and after that, the hardened qualities, for example the compressive strength, ultrasonic pulse velocity (UPV), density and elastic modulus. The SCC mixes were prepared using a drum mixer. The mixer was first of all cleaned with water to make sure that there was no moisture inside. Next the two aggregates were combined with half of the water and left for just two minutes to allow the water to completely absorb with the aggregate. After that, the cement and mineral admixture was added (as needed) with the mixture of the remaining water and superplasticizer for 4 minutes to permit the result of the chemical admixture to be completed. Lastly, the mixer was left for 4-minutes to permit the elements to distribute evenly within the concrete mixer. Each sample was examined to look for the compressive strength at various stages after going through the water curing. Every cube was stored at 70 degrees of 20°C for 24 hours after casting. After remolding, the cubes were moved towards the water tank for more curing until the age for the test. The cubes then were examined based on BS 1881: Part 114. The compressive strength was examined at 7, 28, and 90 days with cubes of 100mm^3 immediately after acquiring their densities based on BS1881: Part 116 for every test age. The axial compressive load was put on 100 mm^3 cube samples using a universal testing machine (UTM) having a capacity of 1000 KN.

C. Mix Proportions

There were twelve mixes of FRSCC developed based on three groups. They were 100% OPC in group one, and 5% and 10% of silica fume were used to replace the cement in group two and three, respectively. Each group contained 4- mixes according to the volume ratio of the steel fiber which were 0%, 1%, 1.5% and 2% by weight of the cement. Group one was kept as the control to compare it with the other groups to highlight the effect of the steel fiber associated with the silica fume. Mix proportioning was tabulated and presented in Table II. It shows the arrangement of the mixing according to the silica fume content. SCC-mixtures have been labeled based on their groups, binder and steel percentage's respectively.

TABLE II
MIX PROPORTIONING

Groups	CODE MIX	OPC Kg/m^3	Silica fume Kg/m^3	Water Kg/m^3	Steel fiber Kg/m^3
GROUP ONE	G1- 100% OPC-0. 0%	600	0	200	0
	G1- 100% OPC-1. 0%	600	0	200	6
	G1- 100% OPC-1. 5%	600	0	200	9
	G1- 100% OPC-2. 0%	600	0	200	12
GROUP TWO	G2- 5.0 % S. F- 0. 0%	570	30	196	0
	G2-5.0 % S. F - 1.0%	570	30	196	6
	G2-5.0 % S. F - 1. 5%	570	30	196	9
	G2-5.0 % S. F - 2. 0%	570	30	196	12
GROUP THREE	G3-10.0 % S. F - 0. 0%	540	60	192	0
	G3-10.0 % S. F - 1. 0%	540	60	192	6
	G3-10.0 % S. F - 1. 5%	540	60	192	9
	G3-10.0 % S. F - 2. 0%	540	60	192	12

III. EXPERIMENTAL TEST RESULTS

A. Fresh Properties

Table III shows the result of the experimental test on the fresh stage, which included slump flow, slump T_{50} and V-funnel. The trend of the result proved that the addition of steel fiber will cause a reduction in the workability of SCC as in the movement and time of the slump. In group one, the slump flow was high because the binder was totally cemented. But with an increase in the steel fiber, the slump was decreased gradually, moreover, the replacement of the cement by 5% and 10% of silica fume in groups two and three, respectively, prevented the SCC mix to loss their slump flow due to the graphical behavior of the silica fume particles. The slump T_{50} represented the time of the fresh mix to reach the 500mm diameter. All of the groups showed times of discharge within the specification of EFNARC, between 2 to 5 seconds. The V-funnel test was performed to assess the viscosity of the SCC mix. This can be accomplished through the V-funnel shape starting by keeping the fresh mix of SCC inside the funnel and finishing by calculating the time required for the mix to come out through the outlet. The result of the V-funnel was located within the range of EFNARC

B. Compressive Strength

The compressive strength test was conducted for 7, 28 and 90 days. Three molds were cast for each one and the average was calculated. The results were tabulated and are presented in Table IV. The result in Table IV indicates that the steel fiber increased the compressive strength per each group at different curing times.

According to the result, the 2.0% steel fiber was found as the optimum steel fiber for group one while the 1.0% and

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1.5% were the optimum values for groups two and three, respectively.

TABLE III
FRESH TEST RESULT

Groups	Code Mix	Slump flow mm	Slump T_{50} Second	V-Funnel Second
GROUP ONE	G1- 100% OPC-0. 0%	760	5	10
	G1- 100% OPC-1. 0%	750	5	11
	G1- 100% OPC-1. 5%	720	4	12
	G1- 100% OPC-2. 0%	670	5	12
GROUP TWO	G2- 5.0 % S. F- 0. 0%	690	4	7
	G2-5.0 % S. F - 1.0%	680	2	6
	G2-5.0 % S. F - 1. 5%	650	4	11
	G2-5.0 % S. F - 2. 0%	600	4	12
GROUP THREE	G3-10.0 % S. F - 0. 0%	695	3	7
	G3-10.0 % S. F - 1. 0%	670	5	6
	G3-10.0 % S. F - 1. 5%	650	4	6
	G3-10.0 % S. F - 2. 0%	630	4	12
Guidelines	EFNARC	650-800	2-5	6-12

C. Ultrasonic Pulse Velocity

The ultrasonic pulse velocity (UPV) test is a non-destructive test which is actually carried out by delivering a high-frequency wave (over 20 kHz) throughout the media. Utilizing the theory that a wave moves quicker in a denser media than in the looser one, a manufacturer can figure out the level of the quality of the material by the velocity of the wave. This could be applied to numerous types of materials like concrete, wood, etc. The objective of the UPV test was to study the effect of the steel fiber and the silica fume on the relationship between the compressive strength and UPV. It was also used to produce a general equation which related the UPV and compressive strength. The test was performed on a PUNDIT instrument according to BS-1881: Part203: 1986 while the methodology of the test was performed by the direct method of the UPV test. The test result is shown in Table IV and Fig. 1. The result of group (1) recorded high values of UPV as compared with the other groups; nevertheless, the result proved that the combination of silica fume with steel fiber can enhance the UPV properties of SCC.

D. Stress –Strain Relationship

The main objective for using fibers in concrete mixes is to enhance the ductility characteristics of the mix [20]. The ductility can be evaluated by the value of the modulus of the elasticity which can be derived from the stress – strain curve. The axial compressive load was applied to the 100mm cube sample by using a universal testing machine (UTM) with a capacity of 100 KN, the strain gauge was fixed at the center of the cube's surface while it was connected with a data logger and software called Execute UCS-60A MEAS. Table IV and Fig. 2 explain the result of the elastic modulus per each mix group. From the result, it was found that the ductility of the SCC mix according to the elastic modulus was improved with the additional steel fiber content. The concrete sample after reaching the cracking load did not crash totally but looked similar to that at the beginning of the test. Silica fume can also improve the elastic properties of concrete because the strength development of SCC with silica fume is similar or less than the strength of concrete using Portland cement as the only cementing material, depend on the surface area of silica fume and their percentage added to concrete the slow reaction of silica fume may affect the strength gain of SCC.

TABLE IV
HARDENED TEST RESULT

Code Mix	Compressive Strength KN/m^3			UPV m/sec	Elastic Modulus KN/m^3
	7-Days	28-Days	90-Days	28- Days	28-Days
G1- 100% OPC-0. 0%	71.10	89.80	94.62	4166	22.15
G1- 100% OPC-1. 0%	73.82	91.92	105.70	4760	28.36
G1- 100% OPC-1. 5%	77.7	94.04	108.15	5020	35.50
G1- 100% OPC-2. 0%	80.63	101.48	110.55	5250	37.13
G2- 5.0 % S. F- 0. 0%	60.36	77.42	89.76	3800	28.60
G2-5.0 % S. F - 1.0%	71.88	82.78	97.05	4600	43.30
G2-5.0 % S. F - 1. 5%	70.07	80.37	94.52	4358	37.70
G2-5.0 % S. F - 2. 0%	67.67	79.92	90.68	3936	34.60
G3-10.0 % S. F - 0. 0%	57.81	75.09	83.19	3780	30.50
G3-10.0 % S. F - 1. 0%	59.13	85.73	88.28	4470	35.30
G3-10.0 % S. F - 1. 5%	62.17	89.25	93.38	4918	39.10
G3-10.0 % S. F - 2. 0%	60.91	86.81	90.47	4827	3.60

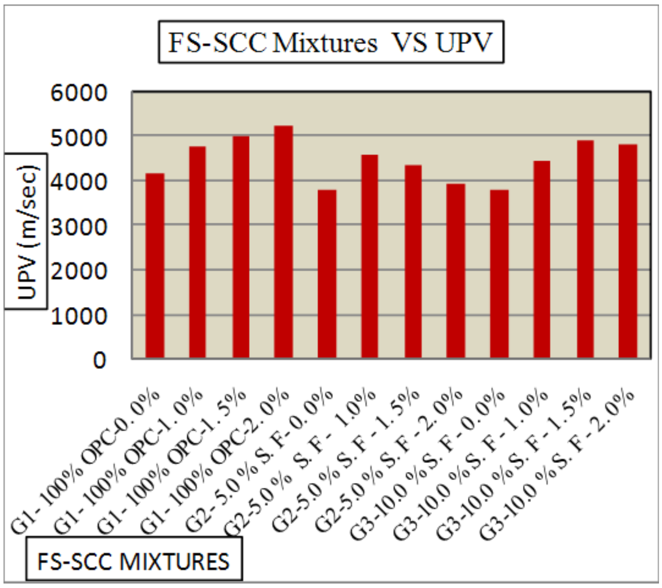

Fig. 1 Groups VS UPV

IV. ANALYSIS OF THE RESULT

A. Relative Change in Compressive Strength

Table V refers to the relative change in compressive strength result. The highest increase in value occurred on day 7 with the 1.0% steel fiber for group two. While the lowest value was found in group two at 90 days with the 2.0% steel fiber.

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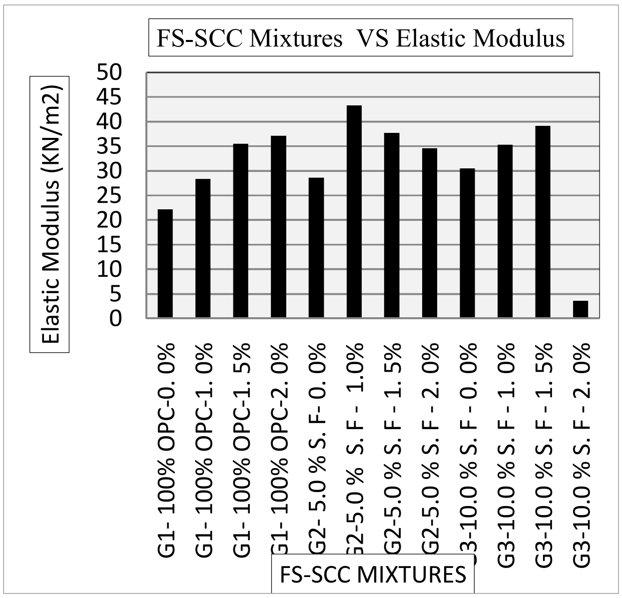


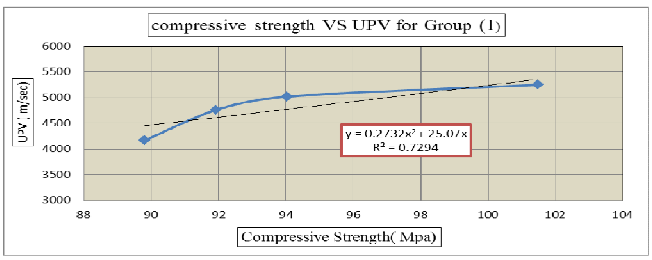
Fig. 2 Groups VS Elastic Modulus

TABLE V
RELATIVE CHANGE IN COMPRESSIVE STRENGTH

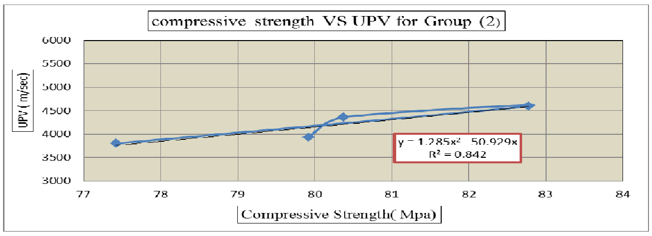
Code Mix	7-Day	28-Day	90-Day
G1- 100% OPC-0. 0%	0	0	0
G1- 100% OPC-1. 0%	3.83	2.25	11.71
G1- 100% OPC-1. 5%	9.28	4.61	14.30
G1- 100% OPC-2. 0%	13.40	12.99	16.84
G2- 5.0 % S. F- 0. 0%	0	0	0
G2-5.0 % S. F - 1.0%	19.08	6.92	8.12
G2-5.0 % S. F - 1. 5%	15.57	3.81	5.30
G2-5.0 % S. F - 2. 0%	12.11	3.23	1.03
G3-10.0 % S. F - 0. 0%	0	0	0
G3-10.0 % S. F - 1. 0%	2.28	14.17	6.12
G3-10.0 % S. F - 1. 5%	7.54	18.86	12.25
G3-10.0 % S. F - 2. 0%	5.36	15.61	8.75

B. Correlations between the Compressive Strength and UPV

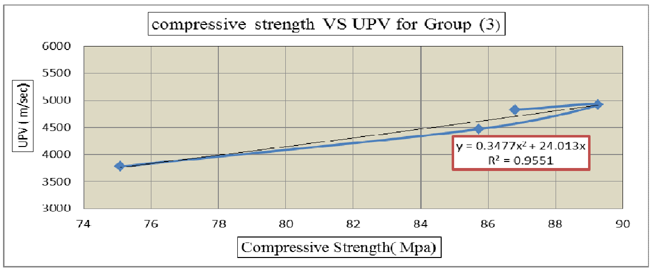
Fig. 3 concludes the correlations between the compressive strength and UPV, three statistical models were proposed to predict the compressive strength of the concrete based on the groups. Group (3) possessed a higher correlation than the other groups while the UPV value was increased by the combination of the steel fiber and the silica fume.



(A)



(B)

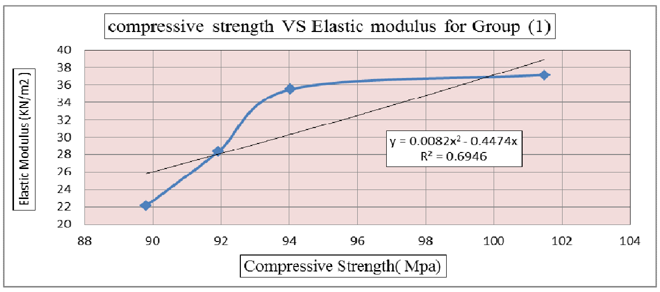


(C)

Fig. 3 (A), (B), (C) Correlation between the compressive strength and the UPV for SCC mix

C. Correlations between the Compressive Strength and the Elastic Modulus

Different researches have been carried out to develop a relationship between the compressive strength and the elastic modulus of steel fiber-reinforced concrete [21]. Some of them have concluded that the elastic modulus did not correlate well with the compressive strength and that of their constitute materials. Other researches have proven the trend of a good correlation because they applied different conditions, and because of the combination of fiber with the cement replacement material (CRM) [22]. The correlation of this experimentation is shown in Fig. 4 and can be classified as being good between the compressive strength and elastic modulus. In addition, this has been attributed to the steel fiber which increased the ductility of the SCC mix.



(A)

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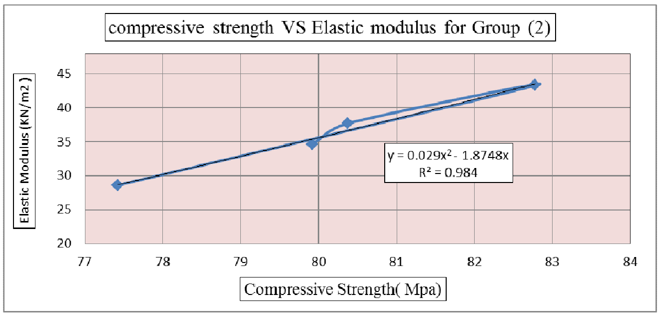

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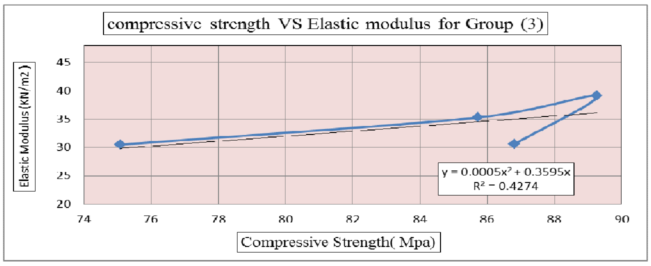

(C)

Fig. 4 (A), (B), (C) Correlation between the compressive strength and elastic modulus for each group

V. Conclusion and Discussion

Based on the experimental work of steel fiber-reinforced self-compacting concrete containing silica fume, the following conclusions have been arrived at:

SCC can be produced by steel fiber and silica fume with high quality of fresh and mechanical properties.

Steel fiber at early age did not increase the compressive strength due to the degree of reactivity of silica fume, the strength was less than that of control mix. In other hand, the application of steel fiber reduced the workability properties of SCC but the silica fume will increase the ability of mixture to flow easily within short time due to it is fineness particles.

2.0% of steel fiber by weight of cement was found as the optimum steel fiber for group one while the 1.0% and 1.5% was the optimum values for groups two and three respectively. Regarding to the compressive strength result, SCC sample of the experimental work shows the steel fiber increase the compressive strength slightly. Result have been an analysis by the correlation between the compressive strength and UPV as well as the elastic modulus, the correlation was agreement with the experimental result.

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