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Mechanical Properties of Self-Compacting Lightweight Concrete Containing Organic Waste Ash

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Abstract

The fresh and mechanical properties of self-compacting lightweight concrete (SCLWC) prepared by scoria and organic waste ash (OWA) were investigated, in which the OWA replaced limestone powder with different percentages. Besides, the effects of steel fiber on the mechanical properties of mix designs containing 15% OWA replaced limestone powder were also investigated. To examine the fresh properties, slump flow, J-ring, and V-funnel tests were considered on fresh SCLWC, whereas compressive and splitting tensile strength were concerned with mechanical properties assessment. The results confirmed that the mix design containing 15% OWA replaced limestone powder achieved the lowest weight; however, its compressive and splitting tensile strength decreased by 28% and 20%, respectively, compared to the SCLWC made with limestone powder. Meanwhile, the inclusion of 1% steel fiber to this optimum mix design with 15% OWA replaced limestone powder increased the splitting tensile strength by 20%.

Keywords: Self-compacting lightweight concrete, Organic waste ash, Scoria, Mechanical properties, Steel fibers.
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1. Introduction

Self-compacting concrete (SCC) is an innovative concrete that can flow under its own weight to achieve full compaction without any external vibration. Ozawa and Okamura[1] did preliminary studies on SCC performance at the University of Tokyo in Japan. SCC has specific workability that enables it to be placed and compacted under its own weight without segregation or bleeding. The advantages of SCC in the construction industry are summarised as reducing the manpower, reducing the noise level, diminishing the effect on the environment, and enhancing the quality of the final product. On the other hand, the advantage of lightweight concrete is improving the seismic behavior of structures and reducing the overall cost of the project.[2] Although self-compacting lightweight concrete mix designs can provide uniform concrete without segregation, previous research indicated that the lightweight materials used in the SCC couldn't create enough energy to move in thin concrete sections with high reinforcement density.[3,4]

A wide range of substances can be used as filler, and so many experimental studies on the different fillers used in SCC manufacturing have been done, such as pozzolanic fillers (silica fume, and metakaolin) and non-pozzolanic fillers (limestone powder, granite dust and marble dust).[5,6] Khaleel *et al.*[7] reported that concrete mixes made with crushed limestone achieved higher strength than those made with crushed gravel or uncrushed gravel. Memon *et al.*[8] studied the mechanical properties of SCC containing different percentages of rice husk ash as filler and concluded that this substance improves the flexural strength, compressive strength, and elasticity of SCC. Several research also confirmed that the type of filler has a significant effect on the fresh and mechanical properties of SCC.[9,10] Mucteba Uysal *et al.*[11] investigated the effectiveness of various mineral admixtures, including fly ash, granulated blast furnace slag, limestone powder, basalt powder, and marble powder in producing self-compacting concrete (SCC). They concluded that replacing 20% of Portland cement (PC) with GBFS resulted in strength of more than 78 MPa at 28 days. One of the main weaknesses of concrete is in tension; using steel reinforcements improves the tensile strength of concrete, but

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still, hairline cracks due to the creep would be inevitable. Therefore, the solution is to make isotropic sections resistant to cracking and plasticity using fibers.[12] In research by Zheng,[13] it has been observed that adding fibers has little effect on the compressive strength of concrete. Gencel *et al.*[14] proved that fibers in concrete could reduce and control cracking in concrete. Ramesh[15] showed that fiber-reinforced concrete has more toughness and improved mechanical strength than normal concrete. Parveen[16] showed that steel fibers have more positive effects on concrete's compressive and tensile strength than polypropylene fibers.

There is no systematic study in the open literature study the fresh and mechanical properties of self-compacting lightweight concrete (SCLWC) containing scoria and organic waste ash (OWA). Therefore, the first phase of this research investigates developing SCLWCs prepared by OWA to find a mixed design with optimum weight. Fresh and mechanical properties of all developed mixes were examined and compared against mix design prepared by limestone powder. In the second phase of the study, mechanical features of optimum SCLWC containing 0.5, 0.75, and 1% of steel fibers were investigated.

2. Materials and methods

The properties of coarse aggregate were examined against American standard testing methods (ASTM) standards. This specification defines the requirements for grading and quality of fine and coarse aggregate for use in concrete. The specifier should ascertain that aggregates specified are or can be made available in the area of the work, with regard to grading, physical or chemical properties, or a combination thereof. Particle-size distribution is important for various uses of aggregate. Aggregate is classified into two general sizes: coarse grained and fine grained. Coarse aggregate is rock retained on a 3/8-inch (#4 U.S. sieve). Fine aggregates pass the 3/8-inch sieve and are retained on a #200 U.S. sieve.

Coarse aggregate: This study used scoria with a saturated density of 1550 kg/m^3 as coarse aggregate following ASTM standards,[17] as shown in Fig. 1. Following ASTM standard 95% to 100% of coarse aggregate should pass through a 25 mm sieve, which addresses in this research.

Fine aggregate: Saturation density of sand used as fine aggregate in this study was 2440 kg/m^3, and it complies with ASTM standards, as shown in Fig. 2. Following ASTM standard, 95% to 100% of fine aggregate should pass through a 4.75 mm sieve, which addresses in this research.

Super-plasticizer (SP): This lubricant used in this study was a naphthalene super-plasticizer with a density of 950 kg/m3. Naphthalene super-plasticizer is a high-range water reducing agent. In the production of flowing concrete, the use of naphthalene super-plasticizer not only reduces the water-cement ratio, but also hardens the strength of the concrete material.[18]

Cement consumption: Cement used in the manufacturing of all mix designs was type 2 with a specific gravity of 3500 kg/m3.

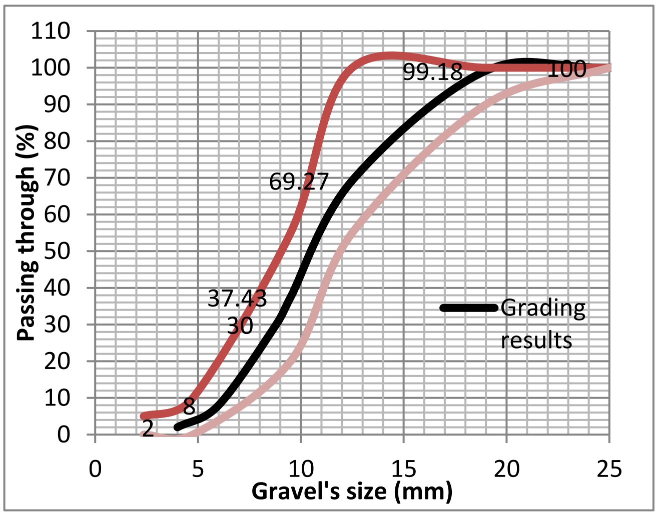

Fig. 1 Coarse aggregate compliance with ASTM standards.

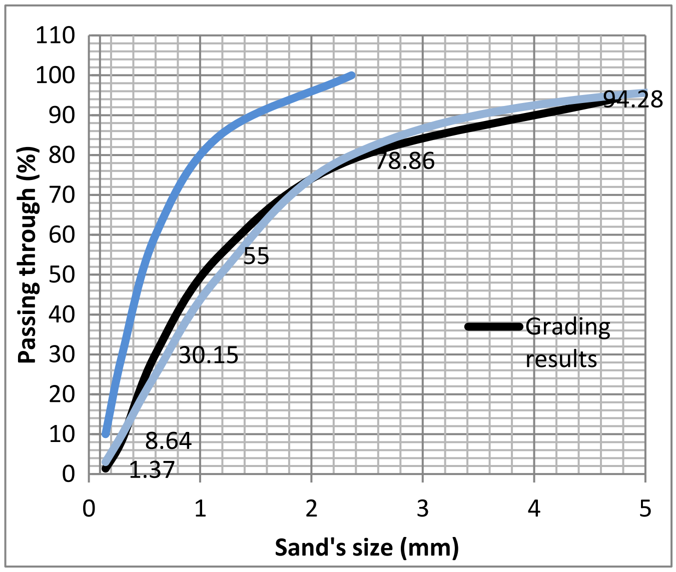

Fig. 2 Fine aggregate compliance with ASTM standards.

Limestone powder as filler: The density of limestone powder (CaCO3) used in the experiments was 1990 kg/m3. Fiber Used: Steel fiber used in this study was made of steel with a length of 35 mm and a diameter of 0.5 mm.

Organic waste ash (OWA) as filler: The OWA used in this study is a mixture of milk vetch ash, oak and almond wood ash, and animal waste ash with a density of 890 kg/m3. Using X-ray fluorescence (XRF) test, the chemical composition of the OWA used in this study is shown in Table 1. XRF is a non-destructive elemental analysis method for qualitative and quantitative determination of the chemical composition of solids and liquids. For many years the cement industry has been relying on XRF for the elemental analysis of cement and related raw materials. Sample preparation by pressing powders into pellets was commonly and widely used for decades, but borate fusion has become more important and increased in popularity for the last decades. Typically, a sample preparation process will involve preliminary size reduction, sample division, fine size reduction, and, depending on the subsequent analysis, pellet pressing.

Table 1. Chemical analysis results on the OWA.

Analysis Parameters	OWA
SiO_2 (%)	37.5
CaO (%)	16.7
Al_2O_3 (%)	7.8
K_2O (%)	6.7
Fe_2O_3 (%)	5.3
MgO (%)	4.1
Cl (%)	1.3
P_2O_5 (%)	1.2
SO_3 (%)	1.0
TiO_2 (%)	0.42
SrO (%)	0.13
Na2O, Available alkali (%)	1.1
L.O.I (at 1000 C) (%)	16.79
La&Lu (%)	<1.0

Based on the obtained results, 29.8% of OWA is based on aluminum, silicon, and calcium oxides. Also, chemical analysis results (Table 1) showed that the significant oxides in the OWA are silicon dioxide (SiO_2), lime (CaO), aluminum oxide (Al_2O_3), potassium oxide (K_2O), and iron oxide (Fe_2O_3), respectively.

SCC mixtures often contain high amounts of powdered materials, and this is because of the viscosity and flow properties of concrete. Due to the high cost of cement and high temperature during the production of concrete, in addition to cement, limestone and silica powders are used in SCC. The volumetric method is used to produce SCC mixtures, and the following criteria should be taken into account, as shown in Eqs. (1) to (4).

$$\text{Size of aggregate} = 1 - \text{powder volume} - \text{water volume} - (0.02) \times \text{air volume} \quad (1)$$

$$0.28 < \frac{volume\ of\ gravel}{volume\ of\ concrete} < 0.35 \quad (2)$$

$$\frac{volume\ of\ sand}{volume\ of\ concrete} > 0.4 \quad (3)$$

$$\text{Sand weight} > 0.5 \times \text{total weight of aggregates} \quad (4)$$

Many experiments showed that better results would be obtained by manufacturing SCLWC with the same portions of scoria and sand by volume.[19] This is because in a high percentage of scoria to sand due to being less fine aggregate material to make a uniform concrete, a higher amount of limestone powder is needed, which will cause to rise in concrete's weight. Scoria has a high roughness coefficient and low density, which means it would not increase the flow and viscosity of concrete. Therefore, in this study same portions of scoria and sand were used as aggregation.

Following the self-compacting concrete regulations,[20] 400 kg of cement per cubic meter for all mix designs was considered in this study. Besides, the ratio of water to cement in all mix designs was considered between 0.4 and 0.45 (160 to 180 liters in m^3).

The ratio of water to the powder (cement & limestone powder) by volume following the SCC regulations[20] must be between 0.8 to 1.1. However, since scoria was used as gravel in this study, different amounts of filler were used in manufacturing SCC. The naphthalene super-plasticizer used in the experiment was in the range of 1.5 to 3% by weight of powdered materials. Table 2 illustrates the properties of all studied mix designs.

3. Tests program

Segregation resistance refers to concrete's ability to remain in the same state throughout the placement setting. It also involves static and dynamic stabilities. The resistance of the new blends was tested in this study by implementing a V-shaped funnel completely filled with concrete (volume 0.01 m^3) that had not been tapped or compacted. Subsequently, a trapdoor located at the bottom was opened to enable the concrete to flow out; the flow times were then documented. The test apparatus, shown in Fig. 3, consists of a V-shaped funnel with a height of 425 mm, a top width of 500 mm, bottom width, and a thickness of 75 mm. At the bottom of the

Table 2. Properties of all studied mix designs.

No.	cement (kg)	Water (kg)	w/c	SP[1]	Limestone Powder (kg)	OWA[2] (%)	Scoria/ Aggregates	Sand/ Aggregates	Overall weight (kg/m^3)	slump (mm)
1	400	172	0.43	1.5%	250	0	0.6	0.4	2000	540
2	400	172	0.43	1.75 %	250	0	0.6	0.4	2000	550
3	400	172	0.43	2%	218.5	12	0.6	0.4	2020	720
4	400	160	0.4	1.5 %	163	35	0.5	0.5	2100	700
5	400	172	0.43	1.5 %	191.33	23	0.5	0.5	2010	720
6	400	172	0.43	1.5 %	218.5	12	0.7	0.3	2000	520
7	400	172	0.43	1.5 %	191.33	23	0.52	0.48	2080	600
8	400	180	0.45	1.5 %	210	15	0.5	0.5	1990	730
9	400	160	0.4	3%	163	35	0.48	0.52	2100	730

[1] from the overall weight of mix design

[2] OWA replaced limestone powder

V-shape, a rectangular section extends downward 150mm. According to relevant standards, the funnel flow time should be between 6 and 12 seconds. The measurement of the mixtures' filling capacity assesses any shape changes caused by weighting, impacting the flow time. Thus, to determine the flow capacity, slump flow tests were performed using bottom diameter: 20 cm, top diameter: 10 cm, height: 30 cm. Data pertaining to the concretes' T50 slump flow lengths were documented until they reached 500 mm. The T50 time is a secondary indication of flow in which a lower time indicates greater flowability. Additionally, J-ring tests were carried out using four unique J-rings. In concrete production, passing capacity and independent spreading ability are two different things. The latter refers to the mixture's ability to pass through restricted spaces. Typically, the passing capacity of concrete is enhanced through increased filling capacity. The J-Ring test apparatus is used for determining the passing ability, the flow spread and t500 flow time of the self-compacting concrete as the concrete flows through the J-Ring. The apparatus consists of a stainless steel crown with 16 bars 18 mm dia. Fig. 3 presents the slump, J-ring, and V-funnel test devices used in this study.

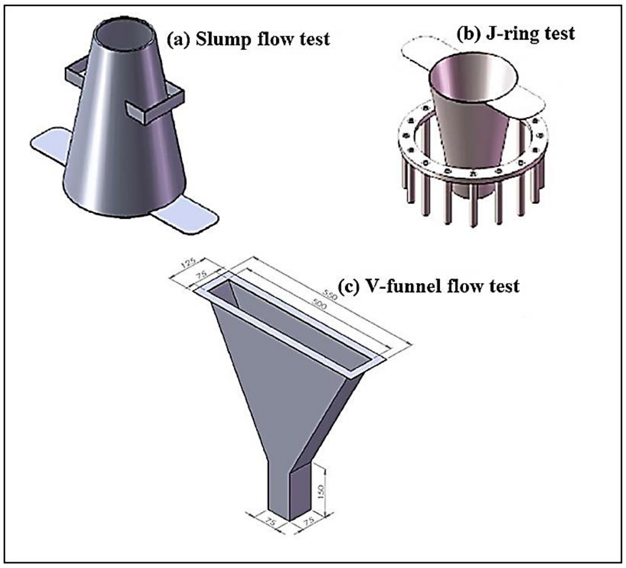

Fig. 3 Different Rheological tests to assess the fresh properties of SCC, (a) slump test, (b) J-ring test, and (c) V-funnel flow test.

The J-ring and slump test results in the construction of SCLWC are shown in Fig. 4. To test the compressive strengths (CS) and splitting tensile strengths (TS), of the new blends, ASTM C109,[21] and ASTM C496,[22] guidelines were followed, respectively, and the average value for three tested specimens was adopted. To measure the compressive and tensile strength, cubic specimens with 15 × 15 × 15 cm and cylindrical specimens with a diameter of 15 and height of 30 cm, respectively, have been used. The loading rate for CS and TS test was limited to 0.2 to 0.3MPa/sec. This helps ensure consistency within and among laboratories.

4. Test results and discussion

4.1 Fresh properties

Table 2 illustrates the slump test of all mix designs in which mix design number 8 contains 210 kg/m^3 limestone powder and 15% OWA achieved the height slump and the lowest weight; selected as an optimum mix design. Table 3 summarizes the fresh properties of SCLWCs made with limestone powder (mix No.1) and with 15% OWA (Mix No.8). As it can be seen, the values obtained for the selected mix design with limestone and OWA as filler are in the standard range of SCLWC.

Results for selected mixes containing OWA in SCC showed that the properties of concrete are in the standard range of SCC regulations. Slump-flow value describes the flowability of a fresh mix in unconfined conditions. It is a sensitive test that will normally be specified for all SCC, as the primary check that the fresh concrete consistence meets the specification. As indicated in Table 3, Slump flow 650-800 mm is suitable for many normal applications (*e.g.* walls, columns). The T50 time is secondary indication of flow. A lower time indicates greater flowability. The Brite EuRam research[23] suggested that a time of 3-7 seconds is acceptable for civil engineering applications and 2-5 seconds for housing applications. V-Funnel Test is designed to assess the flowability and also segregation resistance of Self Compacting Concrete. The time required to empty the funnel completely in seconds, introduced T0, and per the present guidelines,[24] T0 from the test should be in the range of 6 to 12 seconds. The J-ring test can be used to determine the passing ability of SCC.

Fig. 4 Illustration of the slump and J-ring test.

Table 3. Fresh properties of studied SCLWC.

SCLWC made with limestone powder (Mix No.1)		
Test	Results	Standard range[22]
Slump	730(mm)	650-800(mm)
Slump T_{50cm}	2(sec)	2-5(sec)
J-ring	10(mm)	0-10(mm)
V-funnel	11.5(sec)	6-12(sec)
SCLWC made with 15% OWA (Mix No.8)		
Slump	710(mm)	650-800(mm)
Slump T_{50cm}	2(sec)	2-5(sec)
J-ring	13(mm)	0-10(mm)
V-funnel	11.9(sec)	6-12(sec)

The measured flow is certainly affected by the degree to which the reinforcing bars block the concrete movement. The extent of blocking is much less affected by the flow characteristics, and it can say that clearly, the greater the difference in height, the less the passing ability of the concrete.

The obtained results prove that by using OWA as filler, the ability for filling and segregation resistance of concrete has been decreased, but it is still in the standard criteria for SCC. J-ring results showed that using OWA instead of limestone powder would reduce concrete's flowing ability because the ash used in concrete contains greater coarse particles with more roughness than limestone powder.

4.2 Hardening properties

When assessing the compressive strength of concrete, three test cylinders are required for each test from the same sample of concrete. This may be reduced to two specimens when analysis of strength results shows that the within test coefficient of variation is less than 4%.

Table 4 illustrates the CS development of SCLWC made with limestone powder and 15% OWA. The results confirm that SCLWC made with 15% OWA addressed the minimum CS requirement of 25 MPa recommended by ASTM C109.[21]

4.3 Mechanical properties of SCLWC containing steel fibers

This section investigates the mechanical properties of SCLWC prepared with 15% OWA (mix No.8) and containing different percentages of steel fibers, 0.5, 0.75, and 1%. Table 5 confirms that the maximum CS achieved by mix design containing 1% steel fibers indicates around a 50% increase compared to mix No.8.

Figure 5 illustrates the correlation between steel fiber percentage and the CS, and as it cleared, no strong correlation exists. Besides, the inclusion of steel fiber in SCLWC made with limestone powder (Mix No.1) had minor effects on improving the CS. Wasim Abbass *et al.*[12] indicated that the addition of different content and lengths of steel fibers with increasing water-to-cement ratios caused a change in the mechanical properties of concrete, with an increase of about 10–25% in compressive strength and about 31–47% in direct tensile strength. Shahid Iqbal *et. al.*[25] investigated mechanical properties of steel fiber reinforced high strength lightweight self-compacting concrete (SHLSCC). They investigated five concrete mixes of SHLSCC with different fiber contents (0%, 0.5%, 0.75%, 1% and 1.25%) to examine the change in its fresh and hardened properties. Results showed that there was a strong influence on the workability of SHLSCC with a steel fiber content of 1% or more. In addition, there was around 12% reduction in compressive strength, 37% and 110% increase in splitting tensile strength and flexural strength, respectively, with an increase of steel fiber content from 0% to 1.25%, while the modulus of elasticity remaining unchanged.

Table 4. CS of SCLWC made with limestone powder and 15% OWA.

Mix design	Average CS (MPa)
7 days	
SCLWC made with limestone powder (Mix No.1)	27.31
SCLWC made with 15% OWA (Mix No.8)	16.88
28 days	
SCLWC made with limestone powder (Mix No.1)	32.13
SCLWC made with 15% OWA (Mix No.8)	25.16
Tensile strength at the age of 28 days (MPa)	
SCLWC made with limestone powder (Mix No.1)	3.09
SCLWC made with 15% OWA (Mix No.8)	2.65

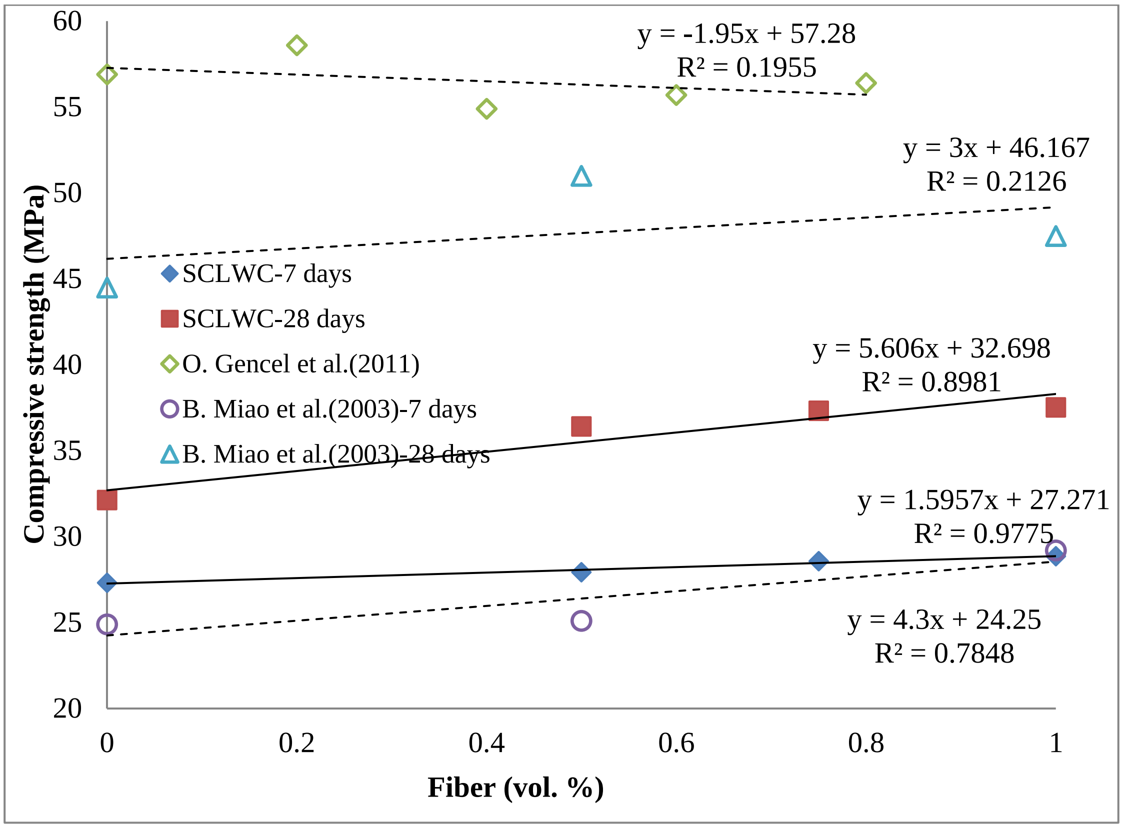

Fig. 5 Correlation between CS and steel fiber ratio.

Table 5. CS of SCLWC made with 15% OWA and different steel fibers percentage.

Fiber percentage[1]	Average CS (MPa)
7 days	
0.5%	27.9
0.75%	28.5
1%	28.8
28 days	
0.5%	36.4
0.75%	37.3
1%	37.5

[1] from the overall weight of concrete

Table 6 shows the splitting tensile strength of SCLWC made with 15% OWA and different steel fiber percentages at 28 days. The results confirm that the steel fiber ratio did not have major effects on average splitting tensile strength.

The splitting tensile strength test consists of applying a diametric compressive load along the entire length until failure occurs. Fig. 6 illustrates the correlation between steel fiber percentage and the splitting tensile strength, and as it cleared, a relatively strong correlation exists; although increasing steel fiber percentage does not significantly improve the splitting tensile strength. The other researchers also indicated almost similar results.[25] Nevertheless, the inclusion of 1% steel fiber in the mix design contains 15% OWA (mix No.8), increasing its splitting tensile strength by only 36%. As explained in reference,[25] there was a 37% increase in splitting tensile strength with an increase in steel fiber content from 0% to 1.25%.

Table 6. splitting tensile strength of SCLWC made with 15% OWA and different steel fibers percentage at 28 days.

Steel fiber percentage	Average splitting tensile strength (MPa)
0.5%	3.42
0.75%	3.52
1%	3.62

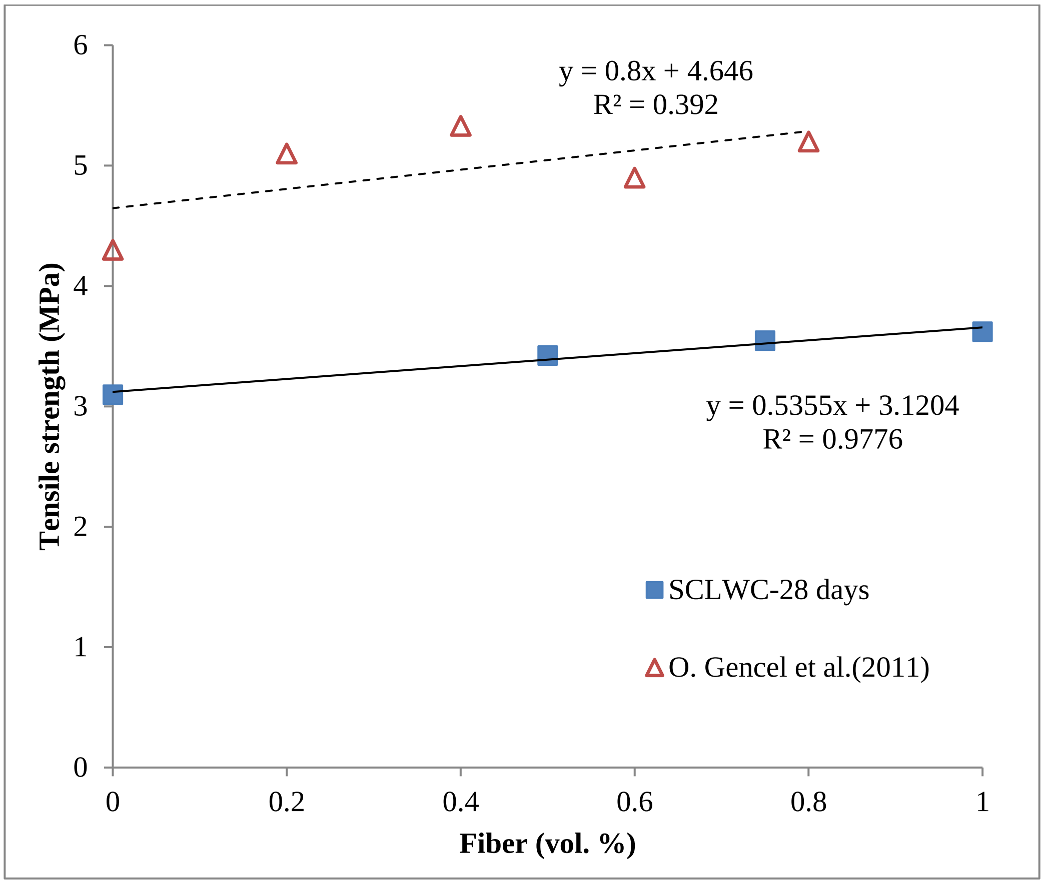

Fig. 6 A Correlation between splitting tensile strength and steel fiber ratio.

4.4 Relationship between compressive and tensile strength

The relationship between compressive and splitting tensile strength is one of the main characterizations of concrete. C Chhorn *et al.* showed that this relationship could be defined as a simple exponential equation 26.[26] A comparison between the equation obtained from the results of this study and other equations obtained by other researchers is shown in Fig. 7. As can be seen, the results from this experiment are placed within the standard range of CEB regulations.[27]

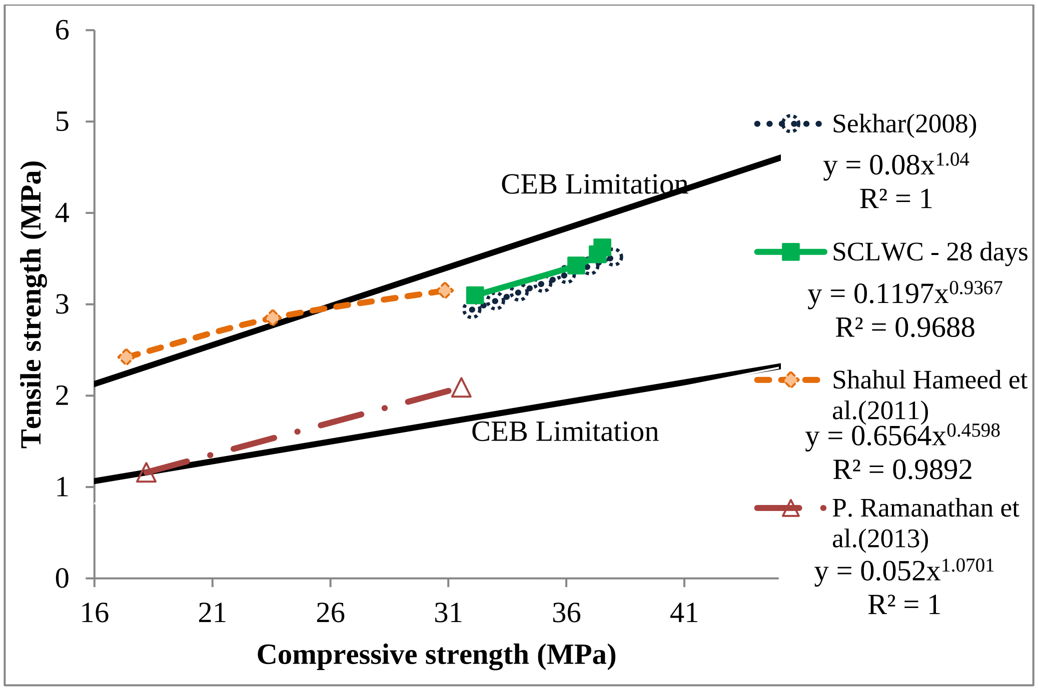

Fig. 7 Relationship between compressive and splitting tensile strength.

5. Conclusion

This study investigated the fresh and mechanical behavior of self-compacting lightweight concrete (SCLWC) prepared by limestone powder and organic waste ash (OWA). Besides, the mechanical features of optimum SCLWC (with 15% OWA) containing 0.5, 0.75, and 1% of steel fibers were investigated. The results confirm that SCLWC contains 210 kg/m3 limestone powder, and 15% OWA achieved the heights slump and the lowest weight; selected as an optimum mix design. This mix design achieved 25 MPa which addressed the minimum CS requirement recommended by ASTM C109 21. Nevertheless, using OWA instead of limestone would have some odd effects on the compactibility of concrete due to OWA's greater size and higher roughness than limestone. The concrete's filling ability, segregation resistance, and flow would be within the standard range of SCC regulations; as this study recommended by maximum replacing 15% limestone powder by OWA. Meanwhile, replacing limestone powder with 15% OWA caused to decrease the CS and splitting tensile strength of SCLWC by 28% and 13%, respectively; however, such mechanical properties still remain in the acceptable range. The results also confirm that the inclusion of 0.5% steel fiber of the total aggregate weight led to achieving an optimum mix design as further percentage did not significantly improve either CS or splitting tensile strength.

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Conflict of Interest

The authors declare no conflict of interest.

Supporting information

Applicable.

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