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Comparative Performance of SF, PPF and Hybrid Fiber-Reinforced Self-Compacting Lightweight Concrete Under Fire Exposure

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ABSTRACT

This study endeavors to interrogate the fire resistance properties of self-compacting lightweight concrete reinforced with Steel Fibers (SF), Polypropylene Fibers (PPF), and a hybrid combination of the two. Exposure to fire flame can significantly compromise the mechanical properties of concrete, leading to deterioration and spalling, which in turn, jeopardizes the structural integrity and performance of the material. In this investigation, concrete specimens, cured for 28 days, were subjected to fire temperatures of 300℃, 450℃, and 600℃, in line with ISO-834 practical curve. The heating environment was controlled by twenty-seven burners strategically positioned to ensure uniform heating. The thermal gradients across the specimens' cross-sections were monitored through thermocouples embedded inside at various locations. The experimental variables considered were the type and volume dosage of fiber reinforcements. Steel fibers were dosed at 0.25 and 0.5 volumes, while polypropylene fibers were introduced at 0.15 volume. Hybrid combinations of SF and PPF were also examined. For comparative purposes, a reference mix devoid of fiber reinforcements was prepared. The study revealed that at 600℃, the incorporation of steel fibers alone contributed to enhanced residual strengths—compressive, splitting tensile—and ultrasonic pulse velocity, outperforming both the hybrid fiber combination and the polypropylene fibers. It was observed that PPF began to melt, initiating a volume reduction at 160℃, and leading to increased porosity and microcrack development as the temperature approached 600℃. The best resistance to spalling was evidenced in the lightweight concrete reinforced with the hybrid fibers. This research provides crucial insights into the fire resistance of self-compacting lightweight concrete and the role of fiber reinforcement in enhancing structural resilience under high-temperature conditions. These findings have significant implications for the design and construction of fire-resistant structures.

1. INTRODUCTION

Self-compacting lightweight aggregate concrete (SCLWC) is a distinctive building material that amalgamates the merits of lightweight aggregate concrete (LWAC) with self-compacting concrete (SCC). This material possesses the capacity to self-disperse and occupy the desired location within formwork, enveloping reinforcement efficiently and obviating issues such as bleeding or segregation. Primarily, its application is found in the reinforcement-intensive structural components and elements designed for seismic resilience, owing to its lightweight and self-flowing properties. The material is particularly beneficial in building construction where high compressive strengths for concrete are not mandated, but reduced weight is a necessity [1].

Lightweight expanded clay (LECA) has been extensively employed in numerous studies [2-5]. An experimental investigation conducted by Sonia and Subashini [2] aimed at partially replacing the coarse aggregate in M25 grade concrete, with the mix design grounded on IS 10262:1982, with LECA. The creation of five distinct mixes, with replacement percentages ranging from 20% to 100%, demonstrated a linear decrease in the density and strength of the concrete as the replacement percentage escalated. The compressive strength of the concrete dipped below 25 N/mm^2 when the coarse aggregate was replaced by 60%, while the concrete containing 100% LECA retained a strength surpassing 17 N/mm^2, indicating its potential utility as a lightweight structural material [2].

Echoing these findings, research conducted by Yew et al. [3] further elucidated the properties of fresh and hardened concrete with an increased percentage of light expanded clay aggregates replacing conventional aggregates. This work revealed a decrease in concrete density and an enhancement in workability as the replacement percentage increased, albeit at the expense of the compressive, split tensile, and flexural strength of the concrete [3].

Concrete, without reinforcing fibers, is inherently fragile, exhibiting low tensile resistance and reduced toughness. To augment toughness, fatigue resistance, concrete cover spread, resistance to abrasion, and flexural strength, fibers possessing superior mechanical properties can be introduced, thereby altering the failure mechanisms of the composite [6]. The concept of fiber hybridization, mixing multiple types of fibers to generate a combination of properties unattainable from the original material, has garnered recent interest. Hybrid composite materials are bifurcated into two categories: a mixture employing varied quantities of the same fiber material or a fiber combination of different materials with diverse moduli of elasticity [7].

High temperatures are notorious for inflicting severe damage on both the macroscopic and microscopic structures of concrete, resulting in substantial mechanical degradation and concrete spalling. The main cause of concrete deterioration at elevated temperatures is damage to the binder or aggregate; their effects on the mechanical properties of the concrete at high temperatures have already been studied by the study [8]. Concrete's exposure to elevated temperatures induces significant alterations in its physical structure and chemical composition. Dehydration occurs above 110℃, leading to the release of chemically bound water from calcium silicate hydrate, which in turn generates internal stresses due to matrix dehydration and aggregate thermal expansion. At temperatures exceeding 300℃, microcracks begin to form within the material. The crucial compound of cement paste, Ca(OH)2, dissociates at around 530℃, causing concrete shrinkage. These transformations in concrete's composition and structure can have significant implications for its overall strength and durability in high-temperature environments [9].

Fire can induce the loss of concrete's load-bearing capacity and heighten the risk of collapse due to the evaporation of entrapped water at high temperatures. Fires in residential and public buildings can reach temperatures up to 1000-1200℃, and over 1300℃ in industrial structures, persisting for several hours, leading to concrete chipping and flaking. Fire temperatures are often calculated indirectly by melting concrete materials [10].

It has been proposed that incorporating 1.5 kg/m^3 of 12.5 mm long PPF could prevent spalling with low water-to-cement (W/C) ratio in concrete. Moreover, the compressive strength of SCC was notably improved by using 0.1% PPF, and the optimal results for splitting tensile strength, impact resistance, and heat resistance were achieved with 0.3% PPF [11]. The combination of fibers significantly boosts residual tensile strength and toughness at elevated temperatures, whereby the presence of steel fibers appears to provide the best post-cracking behavior [12].

While the impact of elevated temperature on the properties of self-compacting concrete (SCC) and SCLWC reinforced with fibers using an electric furnace has been considered in the literature, the effect of real fire flame on SCLWC reinforced with fibers remains unexplored. As such, this study aims to investigate the spalling characteristics, residual compressive and splitting tensile strength, and residual ultrasonic pulse velocity of SCLWC reinforced with steel fibers and hybrid (steel+polypropylene) fibers after exposure to real fire flames. This investigation will provide a deeper understanding of the fire resistance characteristics of SCLWC and theeffectiveness of reinforcing fibers on enhancing fire resistance in real-world scenarios.

2. RESEARCH SIGNIFICANCE

With the growing utilization of SCLWC in structural contexts and its associated advantages, a thorough comprehension of the core response of SCLWC under elevated temperatures becomes crucial. This understanding is vital for ensuring the safety of structural fire design when employing fiber-reinforced SCLWC. In most papers the effect of high temperature on concrete has been studied by subjecting concrete to elevated temperature in furnace without a fire flame. Since this cannot simulate the real situation, the present study applies a direct fire flame at temperature levels 300,450 and 600℃ for 1 hour on SCLWC reinforced with fibers. The experimental work involves the evaluation of compressive strength, splitting tensile strength and spelling of this concrete. Steel fibers and hybrid fibers (steel + polypropylene) are used in different percentages for this demonstration such as0.25SF, 0.5SF, (0.25SF+0.15PPF) and (0.5SF+0.15PPF) in order to study the impact of fibers on the fire resistance of SCLWC.

3. EXPERIMENTAL WORK

This section details the experimental program that has been followed in the present study and the reason for choosing the specific materials for the study is the availability of these materials and their appropriate cost, as well as their application in practice for many buildings.

3.1 Materials

3.1.1 Cement and limestone

In this study, ordinary Portland cement type 1 (AL MASS) was used which complied with IQS No.5 [13] while limestone powder (LP) known locally as "Al-Gubra" was brought from the local market and used as filler in SCLWC. The chemical composition of cement and limestone is listed in Table 1.

Table 1. Chemical composition of AL MASS cement and limestone powder

CaO(%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3(%)	L.O.I.(%)	Item
64.78	21.1	4.78	3.19	1.76	2.45	1.78	Cement
56.1	1.38	0.72	0.12	0.13	0.21	40.56	Limestone

Table 2. Chemical composition of LECA.

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	L.O.I.	TiO_2	MnO_2	Na_2O	K_2O
3.78	61.58	16.99	7.62	2.56	2.45	0.2	0.8	0.1	1.03	2.34

Table 3. Properties of steel and polypropylene fibers

Fiber Type	Length (mm)	Diameter(mm)	Tensile Strength(MPa)	Aspect Ratio (l/d)	Relative Density
Steel	13	0.2	2400	65	7825
Polypropylene	12	0.018	300-400	375	910

Table 4. Mix proportions of SCLWC

Mixtures	Material kg/m³ – SP by wt. of Cement							
	Cement	LP	Water	SP	Sand	LECA	Fibers	
							SF	PPF
SCLWC	480	70	175	1.45	820	373	0	0
SCLWC0.25SF	480	70	175	1.45	820	373	19.56	0
SCLWC0.5SF	480	70	175	1.9	820	373	39.1	0
SCLWC(0.25SF+0.15PPF)	480	70	175	1.6	820	373	19.56	1.36
SCLWC(0.5SF+0.15PPF)	480	70	175	2	820	373	39.1	1.36

LP: Limestone powder
SP: Superplasticizer

Figure 1. (A) LECA was drained in the laboratory air; (B) LECA was soaked in water

Figure 2. Micro steel and polypropylene fibers used in this study

3.1.2 Aggregate

Natural local fine aggregate with a maximum particle size of (4.75) mm a fineness modulus of (2.8) and specific gravity 2.65 was utilized. The sand meets the requirements of IQS No.45 [14]. Lightweight expanded clay aggregate (LECA) see Figure 1, was used in this research with regular sizes ranging from 0.475 cm to 1 cm, and it was imported from the north of Tehran, Iran. The specific gravity, water absorption and density of LECA were 1.26, 12% and 700kg/m^3 respectively. Table 2 depicts chemical composition of LECA.

3.1.3 Superplasticizer

Throughout the study, a superplasticizer (SP) commercially known as GLENIUM® 54 was used. This SP met the ASTM-C494 [15] requirements.

3.1.4 Fibers

Dramix straight-shape steel fiber SF and polypropylene fibers PPF shown in Figure 2 were used in this study. Table 3 shows the characteristics of these fibers as given by the manufacturer.

3.2 Mix proportions

Designing self-compacting lightweight concrete (SCLWC) to attain the desired fresh and hardened properties often involves conducting multiple trials mixes with varying material proportions, For SCLWSC, the trial mixture approach is best for selecting proportions because there is no standard method for designing such new type of concrete up to now. To obtain target compressive strength, air dry density of less than 2000 kg/m^3 and target fresh properties, it is of importance to use a low water to binder ratio and high binder content according EFNARC (2005). As shown in Table 4 Five mixtures were prepared in the current study, the first mixture was normal SCLWC without fibers, while the other four mixtures were incorporated a single or hybrid fibers of steel and polypropylene in different proportions in terms of volume, namely as shown in Table 4. A code was given for each mixture, as an example the code for the fourth mix is SCLWC (0.25SF+0.15PPF) where SCLWC designate lightweight self-compacting concrete, 0.25SF and 0.15PPF represent the volume fraction proportion of steel and polypropylene fibers respectively.

3.3 Test specimens and curing

After the preparation of mixes, two sorts of specimens were casted: cubes having the dimension of (10×10×10) cm for the ultrasonic pulse velocity and compressive strength measures, cylinders of dimensions of (10×20) cm for the splitting tensile strength measure. The use of cubes of a smaller size than the size specified in the specifications leads to the use of a smaller quantity of concrete. Also cubes with dimensions of (10×10×10) (10×20) cm are widely available in the building materials lab.

After 24 hours of casting, the sample were demolded and then cured in water tank for 28 days with 21℃+2℃ water temperature. Because water curing is the most efficient method compared with other methods.

3.4 Description of a fire test furnace

This furnace is designed to generate typical conditions, such as temperature and heat transfer, to which concrete might be exposed during an actual fire incident. specific materials and dimensions were used to design the furnace in order to control the firing procedure and raise the temperature levels of the samples to the target temperature and maintain a constant temperature for the required period. The furnace's internal dimensions measure 2200 mm in length, 450 mm in width, and 650 mm in height. Comprising three layers constructed from distinct refractory materials, the insulation for both the furnace floor and walls is depicted in Figure 3. This design guarantees accurate thermal insulation and consistent internal conditions within the furnace.

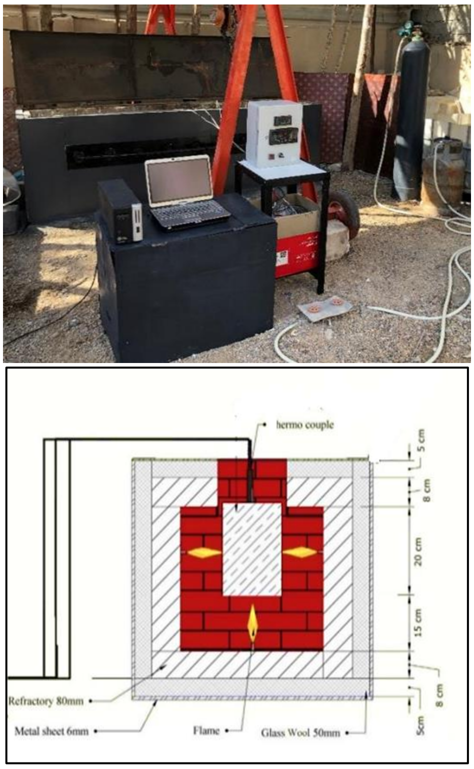

Figure 3. Site burning furnace details

The uniform wall thickness on all sides remains at 136 mm, comprising a primary structure constructed from thermal bricks and mortar. A minor aperture is present to facilitate the inflow of essential fresh oxygen for the burners. Additionally, the furnace lid, as depicted in Figure 3, consists of an insulating plate, 8 mm thick, aimed at maintaining a consistent temperature. The burner network consists of three lines, one in the bottom and one in each lateral side. All methane burners were connected together to an electrical regulator which connected to two valves controlling the discharge of gas coming from oxygen and methane bottles. The aim of the fire-flame bars was to simulate the heating condition in a realistic fire.

The study involved subjecting the samples to different temperatures (300, 450, and 600°C) for a duration of 1 hour. The ultrasonic pulse velocity and compressive strength were tested using three cubes, while the splitting tensile strength was tested using three cylinders at each temperature level and for each mix. Additionally, three reference samples were used for each test in each mix, which were maintained at room temperature (25°C).

The furnace temperature closely conforms to the ISO 834 fire curve with less than 10% variation until the target temperature (600°C) is reached. In order to control the Digital temperature controller, an electric gas regulator with thermocouples was connected to a digital gauge.

It is observed that the first part of the fire curve at figure 4 is similar to the standard fire curve up to 600°C., the samples were kept at this maximum temperature for 1 hour at (300, 450 and 600°C). In a controlled laboratory setting, the samples were subsequently subjected to a cooling process. The experimental curve's heating rate and the maximum temperature of fire exposure remain below the ISO-834 recommendation, owing to the constraints imposed by the available equipment.

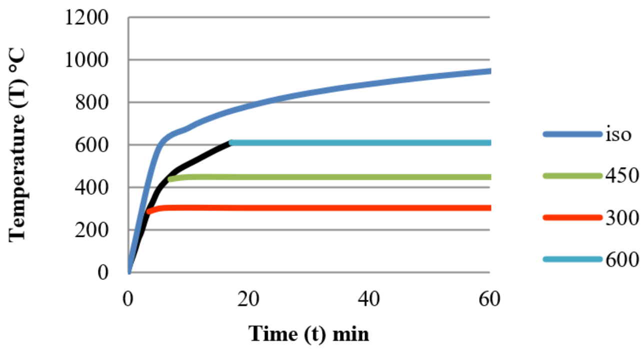

Figure 4. Experimental and ISO-834 Standard recommended temperature-time curves

3.5 Testing methods

3.5.1 Fresh properties tests

Fresh density of SCLWC was measured immediately after casting according to ASTM C138, 2017 [16]. The workability characteristics of SCLWC were assessed by four tests which following the recommendation of EFNARC [17], namely: slump flow, T50 cm, L box and V funnel. Regarding slump flow test the cone is put on flat steel with a leveled and non-absorbing surface with at least 900 mm x 900 mm plane area, filled with mixture, and lifted to a height of 15 to 30 mm in 2 to 4 sec; under the influence of gravity the mixture flows out. On the other hand, the T50 was measured as the duration from when the cone departed the base to the point of contact between the concrete and the 50 cm diameter circle. The L-box test was utilized in this study to evaluate the filling and passing ability of the self-compacting concrete SCLWC, which represents its capacity to pass through obstacles such as reinforced bars without causing segregation or blockage. In this test, the vertical section of the L-box is first filled with SCLWC, and then the gate is raised to allow the concrete to flow into the horizontal part after passing through the rebar obstructions. Two measurements are taken: H1, representing the height of the concrete at the beginning, and H2, representing the concrete height at the end of the horizontal section. The H2/H1 ratio is calculated to determine the filling ability, with a desirable value ranging from 0.8 to 1.

V-funnel test is designed to evaluate the filling ability and viscosity of SCLWC. The funnel is filled with concrete and the time of flow through the apparatus is measured for discharging all fresh mixture.

3.5.2 Strength tests

The compressive and splitting tensile strength of all mixes were measured at the age of 28 days. The guideline of B.S 1881: Part 116 [18] was utilized to determine the value of compressive strength by cubes samples, while the ASTM C469 [19] was followed to measure the splitting tensile strength by cylinder samples.

3.5.3 Ultrasonic pulse velocity test

The ultrasonic pulse velocity was executed according to ASTM C597 [20].

3.5.4 Oven dry density test

Following ASTM C642/ C642 M [21], the 28 days oven dry density was assessed after the 100 by 100 cubical specimens had been dried at 100 ± 2°C in the furnace for 24 hours.

4. RESULTS AND DISCUSSION

4.1 Fresh properties

Figure 5 depicts the value of fresh density of all SCLWC mixes. The fresh density value ranged from (1890-1922) kg /m^3. It can be observed from this figure that the addition of micro steel fibers resulted in a slight increase in the fresh density of SCLWC, this is in line with the result in this study [21], while in the hybrid mixes, the PPF has very little effect on the fresh density. This may be due to the fact of the low specific gravity of polypropylene fibers [22].

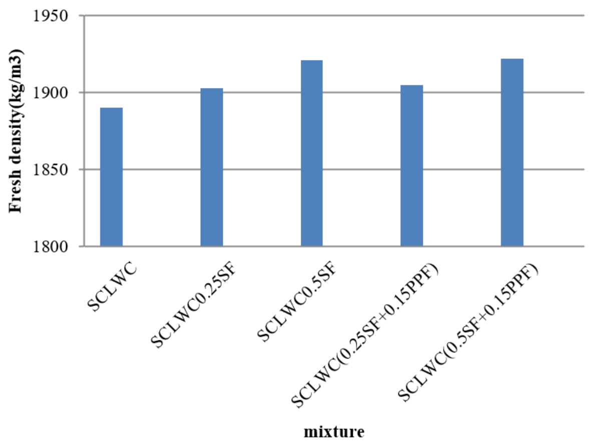

Figure 5. Fresh density of SCLWC mixes

Based on Figure 6, it can be observed that mixes with fibers have less slump flow results in comparison with the reference mix without fibers. Actually, to maintain a slump flow within the range of 709-725mm a higher dosage of superplasticizer SP was used for mixes with fibers. For example, the dosage of (SP) used in plain SCLWC was 1.45% by weight of cement to get a slump flow of 725 mm, while for SCLWC(0.5SF+0.15PPF) mix, the dosage of SP was 2% by weight of cement to get a slump flow of 709 mm. This is because, during the mixing process, the movement of aggregates caused the fibers to disperse and open up into a network of linked filaments, which were then mechanically anchored to the cement paste. It should be noted that this anchoring mechanism occurred without any need for compaction, as reported in literature [11].

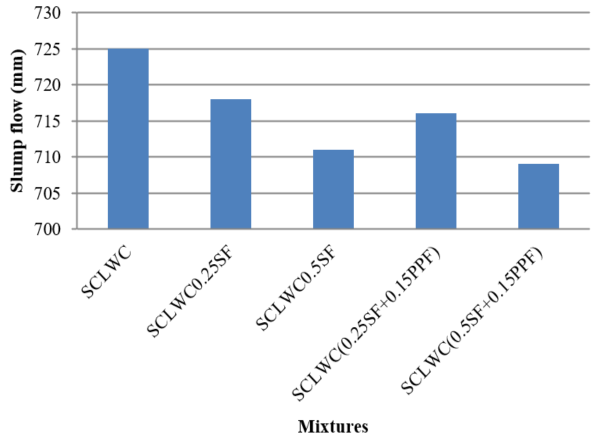

Figure 6. Slump flow for SCLWC mixes

As shown in Figure 7, the T50cm values for various SCLWC mixtures range from 3.5 to 4 seconds. It can be observed that the addition of fibers increased the T50cm values, indicating an increase in the viscosity of the SCLWC. For instance, the SCLWC mixture without fibers had a T50cm value of 3.5 seconds, while the SCLWC (0.5SF+0.15PPF) mixture had a value of 4 seconds. This increase in viscosity can be attributed to the greater interlocking and friction that occurs between particles in mixtures containing fibers [22].

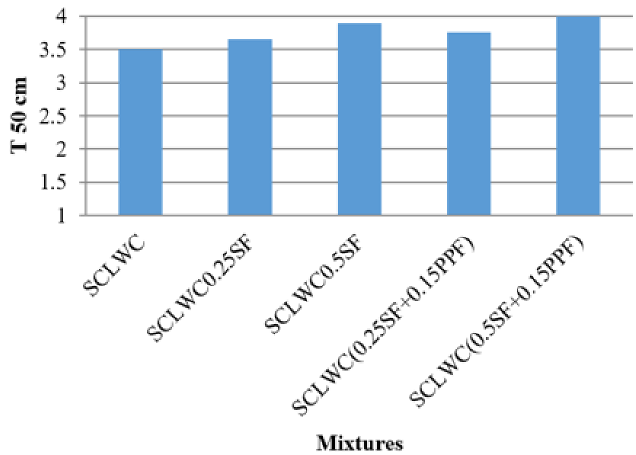

Figure 7. T50 cm for SCLWC mixes

Figure 8 demonstrates that the SCLWC mixes with micro steel and hybrid fibers had longer V-funnel flow times compared to those without fibers, with longer times corresponding to higher fiber percentages. This trend is due to an increase in viscosity, resulting in a more cohesive and interlocked concrete mixture due to fiber reinforcement, which delays the flow of SCLWC from the V-funnel apparatus [23].

The outcomes of the L-Box test are displayed in Figure 9. Notably, the introduction of micro-steel and hybrid fibers resulted in a reduction in the L-Box height ratio. Among the SCLWC mixtures, the highest ratio, H2/H1 of 0.94, was recorded for the fiber-free composition, while the SCLWC(0.5SF+0.15PPF) blend exhibited the lowest H2/H1 of 0.87. It is evident that the inclusion of fibers in SCLWC contributes to a decrease in its workability; nevertheless, the test results remained within the recommended limits stipulated by the EFNARC committee and aligned with results in this investigation [24].

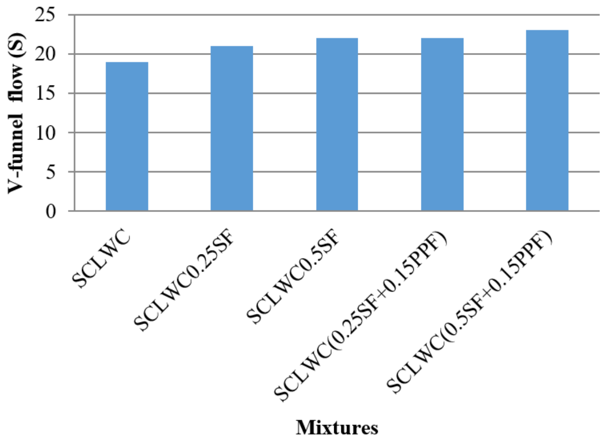

Figure 8. V-funnel flow for mixes

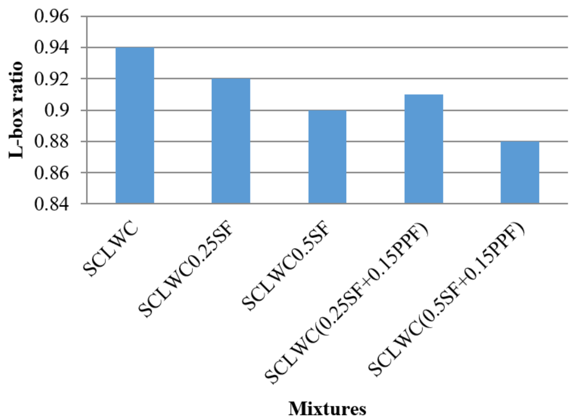

Figure 9. L-box ratio for SCLWC mixes

In order to compare these results with certain closed and related tests results previously performed by others in reference [22], an investigation was conducted to explore the impact of incorporating steel (SF) and polypropylene (PPF) fibers on the fresh properties of self-compacting lightweight concrete (SCLWC). The study examined combinations of SF and PP fibers across four volume fractions (SF/PP)=[0.5%/0, 0.5%/0.5%, 0.5%/0.75%, 0.5%/1%]. The self-compacting characteristics of the concrete were assessed using slump flow, T500, v-funnel, and L-box tests. Slump flow diameters were observed within the range of [750-660] mm, classifying as SF2, except for the case of SCLC with 0.5SF/1PP Hybrid fibers, which exhibited a mere 5% reduction in slump flow from [680-645] mm. The v-funnel, T500, and L-box tests for all mixtures yielded results within the ranges [11.2-19.35], [1.9-4.55], and [0.85-0.98], respectively. the recorded results were indicated semi-identical behavior with the present study as recommended by EFNARC.

4.2 Spalling characteristics

For the SCLWC specimens incorporating 0.25% and 0.5% micro steel fibers by volume, spalling was observed when they were subjected to fire flame 600°C see Figure 10. This confirmed the findings of previous investigations that showed that the steel fiber was not effective enough to totally prevent spalling during the fire test even with volume fraction 0.5 steel fiber [25]. This phenomenon can be ascribed to variances in thermal expansion, stemming from the interplay between the thermal gradient and dissimilar expansion coefficients.

While the polypropylene and micro steel fibers in hybrid mixes resisted the risk of spalling of SCLWC sample after exposure to fire flame, as shown in Figure 10. The particular characteristics of PPF help to enhance the durability of concrete and make it more resistant to fire damage. When exposed to high temperatures, these fibers create empty spaces within the concrete, allowing moisture in both liquid and vapor forms to escape more easily. This lowers internal pressure and prevents the surface of the concrete from cracking or flaking due to the build-up of moisture [11].

Figure 10. Spalling characteristics

4.3 Hardened properties

Test results of the hardened properties of SCLWC reinforced with fibers for all mixes exposed to fire flame were given in Figures 11-14. For comparison purposes the result are expressed as the percentage of the reference values i.e., values at room temperature 25°C.

4.3.1 Compressive strength

The impact of fire flame at different fire temperature levels on the residual compressive strength of specimens without and with fibers are depicted in Figure 11. The results demonstrate that the compressive strength of each of the SCLWC without fibers or with fibers decreased with the increase in the fire flame temperature, and that the percentage of the added fibers and their type affected the extent of the compressive strength loss. This phenomenon occurs because higher temperatures diminish the connection between cement paste and aggregate, resulting in the deterioration of the cement gel structure. This, in turn, leads to a subsequent reduction in load-bearing capacity, as stated in reference [26].

The finding of the test revealed that when the samples were exposed to temperature below 450°C , the presence of steel fibers had negligible effect on the fluctuation of compressive strength .However , as the temperature reached 600°C, the residual compressive strength of steel fibers reinforced SCLWC increased with the increase in amount of fibers , As shown at 600°C the residual compressive strength of (SCLWC0.25SF) and (SCLWC0.5SF) mixes were higher than values corresponding to the reference mix (the SCLWC mix) by (9%) and (13%) respectively. This can be imputed to the fact that the existence of steel fibers in the concrete help limit crack growth and propagation in this temperature range, the same conclusion was reached by the reference [27]. However, for the mixes with hybrid fibers the behavior is changed. The residual compressive strength of SCLWC (0.25TH+0.15PPF) and SCLWC (0.5SF+0.15PPF) mixes were less than the residual strength of reference mix by [7% and 5%] and [6% and 4%] at temperatures 300°C and 450°C respectively. On the other hand, at 600°C residual strength was higher than those of the reference mix by (6%) and (9%) respectively this is in line with reference [23].

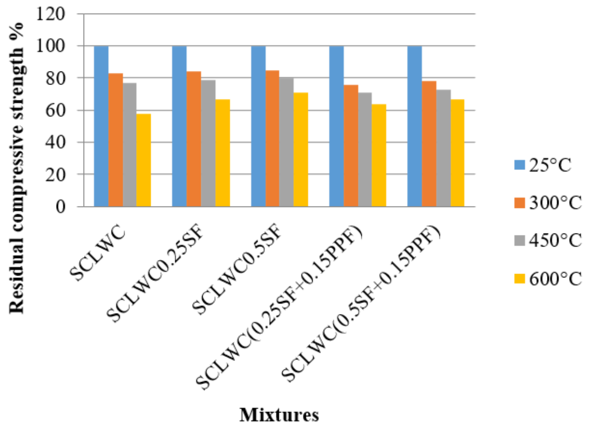

Figure 11. Residual compressive strength after fire flame exposure as a percentage of that at room temperature (at 25°C)

4.3.2 Splitting tensile strength

As anticipated, the impact of the steel and polypropylene fibers on the splitting tensile strength of concrete is considerably greater than their effect on the compressive strength of concrete. This can be attributed to the behavior of concrete when it undergoes tensile cracking, wherein the fibers intersecting the crack plane become engaged and offer resistance against failure resulting from splitting [28]. Under splitting tension test, the plain SCLWC cylinders were split into two parts, suggesting a brittle failure, whereas the fiber reinforced the fiber reinforced SCLWC cylinders kept their integrity, indicating a ductile failure as shown in Figure 12.

According to Figure 13 the presence of steel fibers did not significantly affect the residual splitting tensile strength of concrete when subjected to temperatures up to 450°C. However, beyond this temperature, the splitting tensile strength of steel fiber reinforced SCLWC increased as the steel fiber content increased, compared to the tensile strength of plain SCLWC at the same exposure temperature. The increase in fiber content led to an increase in the number of fibers, which improved the ability of fiber bridging and interception at the crack surface. At 600°C, the residual splitting tensile strength of steel fibers reinforced SCLWC increased as the amount of fiber increased. Where the residual strength results of SCLWC0.25SF and SCLWC0.5SF mixes were higher than the residual splitting tensile strength of reference mix (the SCLWC mix) by (8%) and (14%) respectively. the same conclusion was reached by reference [7].

In contrast, the residual splitting tensile strength SCLWC (0.25SF+0.15PPF) and SCLWC(0.5SF+0.15PPF) mixes were less than the residual splitting tensile strength of reference mix by [3% and 4%] and [17% and 14%] at temperature 300°C and 450°C respectively. However, at 600°C the results for these mixes where higher than those of the reference mix by (7%) and (9%) respectively, which is in agreement with the reference [27]. In order to compare these results with certain closed and related tests results previously performed by نهلة هلال ناجي. [27] studied the performance of lightweight concrete containing fibers exposed to high temperatures the results showed that after exposure to 600°C, the residual compressive strength of LWC was about 50-72 of the room temperature strength. However, in this study, the residual strength of the two groups of SCLWC after exposure to 600°C was about 57%–71% of the initial strength. Rephrase the sentence. The recorded results were indicated semi-identical behavior with the present study.

(a) (Ductile failure) (b) (Brittle failure)

Figure 12 Mode of failure under splitting tension test (a) Without steel fiber, (b) With steel fiber

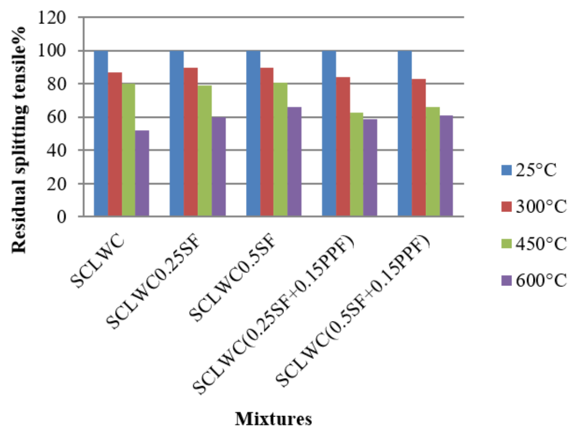

Figure 13. Residual splitting tensile after fire flame exposure as a percentage of that at room temperature (at 25°C)

4.3.3 Ultrasonic pulse velocity (UPV) test

In general, SCLWC incorporating steel fibers showed a lesser degree of UPV loss than the plain SCLWC as shown in

Figure 14. However, with further increase in exposure temperature the residual UPV of steel fiber reinforced SCLWC increased in comparison with residual values of plain SCLWC. As shown at 600°C, the residual UPV of (SCLWC0.25SF) and (SCLWC0.5SF) mixes were higher than the value corresponding to the reference mix by (10%) and (13%) respectively. This can be attributed to the fact that the presence of steel fibers in concrete repress crack formation and consequently they can reduce deterioration of concrete.

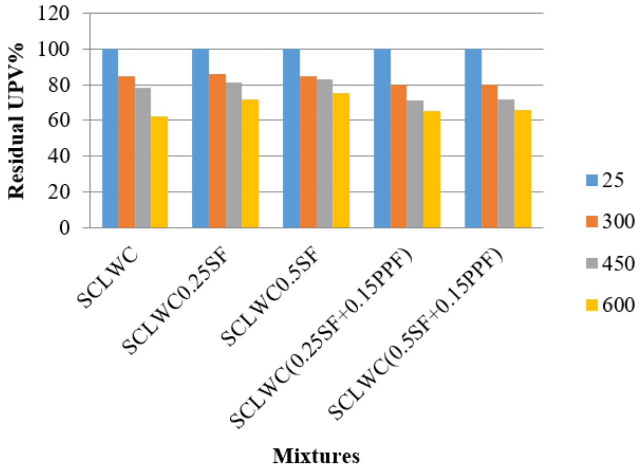

Figure 14. Residual ultrasonic pulse velocity after fire flame exposure as a percentage of that at room temperature (at 25°C)

Also, Figure 13 reveals that the residual UPV of hybrid mixes were lower than that the residual UPV of reference mix at 300°C and 450°C. In fact, at a temperature of 160°C, the volume of polypropylene fibers commences diminishing due to the onset of melting. As the temperature further rises, the fibers undergo degradation, initiating the ignition process at temperatures nearing 360°C. This is leading to increased porosity and microcracking [27].

In contrast, at 600°C the results for these mixes were higher than those of the reference mix (the SCLWC mix) by (3%) and (4%) respectively. In order to compare these results with certain closed and related tests results previously performed by Sadrmomtazi et al. [29], an investigation was carried out on the impact of high temperatures on the microstructure of fiber-reinforced self-compacting concrete. The results from UPV testing of cubic specimens when subjected to elevated temperatures indicated a reduction in UPV for all configurations at 600°C. It becomes evident that the propagation of pulse waves through the SCC mass was notably influenced by the presence of microcracks within the SCC. the recorded results were indicated semi-identical behavior with the present study.

4.3.4 Oven dry density

Figure 15 displays the test outcomes of 28-day oven dry density for all SCLWC blends. The discernible divergence in this characteristic across the mixtures can be attributed to the quantity of micro steel fiber. The reduction in dry density when compared to fresh density was given in Figure 5 primarily due to the improved binding ratio. In fact, a significant portion of the decrease may have been owing to LECA's greater water absorption (12%) that contributed to the increased loss of moisture throughout oven drying [21]. In order to compare these results with and related tests results previously performed by Nahhab and Ketab [21] studied influence maximum size of light expanded clay aggregate and steel fiber on oven dry density of self-compacting lightweight aggregate, The oven dry density ranged from 1657 to 2044 kg/m^3, exhibiting a notable disparity among different mixtures. This variation primarily stemmed from differences in LECA content, maximum aggregate size, and micro steel fiber content While the current study of Oven Dry Density ranged between 1810 - 1835 kg/m^3 the relatively variation was due to variation in volume fraction of (0.25 and 0.5) steel fiber.

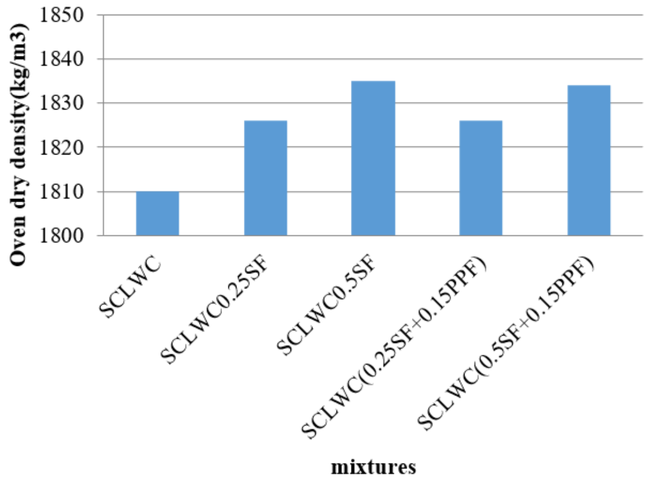

Figure 15. Oven dry density of SCLWC mixes

5. CONCLUSIONS

(1) The addition of fibers resulted in an increase in the fresh density and oven dry density of SCLWC. On the other hand, the inclusion of polypropylene fibers in hybrid fibrous concrete did not result in any significant reduction in fresh density when compared with plain SCLWC.

(2) As the volume fraction of fibers increased, the required dosage of SP to achieve the target slump flow also increased. Additionally, both T50cm and V-funnel flow time became longer, indicating an increase in viscosity, which is imputed to the fact that fiber reinforcement causing more interlocking and friction between particles.

(3) The presence of volume fraction (0.25 and 0.5) steel fibers did not influence the variation of compressive and splitting tensile strengths of SCLWC below 450°C. At 600°C, the residual (compressive and splitting tensile) strengths of steel fiber reinforced SCLWC mixes were higher than the value corresponding to the plain SCLWC mixes.

(4) Incorporating mixed steel and polypropylene fibers into SCLWC resulted in enhanced residual (Compressive strength, splitting tensile strength and ultrasonic pulse velocity) of the SCLWC when exposed to fire temperature of 600°C, in comparison with plain SCLWC mix.

(5) The steel fibers were not effective to totally prevent spalling during the fire test even with large quantities while the use of polypropylene (even with only 0.15% by volume) and steel fibers in hybrid SCLWC improves the resistance to spalling. The mechanism of polypropylene fibers is to mitigate the potential for spalling by either forming pathways within the concrete when they melt, thereby alleviating water vapor pressure, or by addressing microcracking that may arise in the concrete when subjected to heat.

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