Magazine of Civil Engineering. 2024. 17(5). Article No. 12806

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 69

DOI: 10.34910/MCE.128.6

Fire flame effect on some properties of hybrid fiber reinforced LECA lightweight self-compacting concrete

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Keywords: lightweight self-compacting concrete, LECA, fire flame, steel fiber, polypropylene fiber, hybrid fiber

Abstract. This research aims to produce lightweight self-compacting concrete (LWSCC) using lightweight expanded clay aggregate (LECA) as coarse aggregate. The additional aim is to study the influence of steel fiber and hybrid fibers (steel and polypropylene (PP)) on the properties of LWSCC in fresh and hardened state. Furthermore, compressive, tensile, and flexural strengths of LWSCC specimens (with and without fibers) are tested after being subjected to the fire exposure. In this study, four LWSCC mixtures with different fiber percentages (0 % fiber, 1 % steel, 0.75 % steel + 0.25 % PP, and 0.5 % steel + 0.5 % PP) are prepared and tested. The specimens were burned at temperatures 25, 300, 400, and 600 °C. The results show that all mixtures have excellent resistance to segregation and high ability to filling and passing. The presence of fibers slightly reduced the workability of LWSCC. The mechanical properties of LWSSC decrease with increasing temperature. The results show that mixtures containing fibers have good mechanical qualities and spalling resistance compared to mixtures without fibers when exposed to fire.

Acknowledgments: The experiments mentioned in this paper were conducted at the Building Materials Laboratory, College of Engineering, Baghdad University.

Citation: Al-Kabi, W.H, Awad, H.K. Fire flame effect on some properties of hybrid fiber reinforced LECA lightweight self-compacting concrete. Magazine of Civil Engineering. 2024. 17(4). Article no. 12806. DOI: 10.34910/MCE.128.6

1. Introduction

Self-compacting concrete (SCC) was first invented in 1986 in Japan by Prof. Okumara. This type of concrete is extremely fluid and does not require vibration or tamping after pouring, it can fill the space between the reinforcement and the corners of the molds [1]. Superior deformability and segregation resistance characterize this type of concrete. Advantages of using SCC include reduced construction time, labor costs, and noise pollution, as well as the ability to fill crowded and thin portions with ease [2].One of the drawbacks of SCC is its large cost, which is due to the usage of large amount of Portland cement and chemical additives. The SCC cost can be lowered if the mineral additions replace a portion of the Portland cement [3]. Mineral additives used in SCC production also have positive economical and environmental effects [4].

Many modern architectural projects are using increasingly structural lightweight concrete (LWC) due to its low density [5]. LWC has good heat insulation due to low thermal conductivity as well as superior sound insulation [6, 7]. Since the forces of earthquakes that influence civil engineering buildings and structures are proportional to the mass of those buildings and structures, it is essential to reduce their mass for earthquake sustainability [8]. Lightweight concrete can be produced in three ways:

1) by substituting the conventional mineral aggregate with lightweight aggregate (this type of concrete is known as lightweight aggregate concrete);

2) by incorporating gas or air bubbles into concrete (air-entrained concrete);
3) by excluding sand from the aggregate (no fines concrete).

Lightweight aggregate concrete is the most common type [9]. Despite its many benefits, LWC has some disadvantages due to the low density of lightweight aggregates, which causes the segregation of aggregate from the mixture [7]. Unsuitable vibration of LWC can cause inefficient distribution of lightweight aggregates, i.e. particles float to the surface of concrete, resulting in forming of a weak layer [10]. Since SCC does not require vibration, using lightweight particles in SCC can help to overcome this problem. Lightweight self-compacting concrete (LWSCC) is a novel concrete that combines the benefits of both SCC and LWC. Inclusion of lightweight aggregates in SCC helps to achieve better strength-to-weight ratio, thermal properties, and fire resistance when subjected to high temperature. Using lightweight aggregates also helps to reduce the dead load of buildings [11, 12]. LWSCC needs no external vibration and can spread into place, fill the formwork and encapsulate reinforcement without any bleeding or segregation [13]. When concrete is exposed to extreme temperatures, a common phenomenon known as spalling can occur, significantly reducing the stability and affecting the structural safety of concrete. Incorporating polypropylene (PP) or steel fibers into concrete is an effective method of preventing spalling [15]. The spalling resistance of concrete containing steel fiber has been shown to be lower than concrete containing PP fiber [16]. Al-Obaidey conducted research [32] to study the effect of steel fibers on fresh and some mechanical properties of LWSCC. According to the findings, using of steel fibers led to negative effects on fresh properties. The steel fibers had the marginal effect on compressive strength, while for both splitting and flexural tensile strengths significant increase was obtained with increasing of steel fibers content. Hachim and Fawzi studied the effect of the type of lightweight aggregate (Thermostone and Porcelinite) in production of LWSCC, the effect of using silica fume (SF) and high reactivity metakaoline (HRM), and the effect of using different ratios of w/cm ratio (0.32 and 0.35) on the properties of LWSCC in the fresh and hardened state. The results indicate that the air dry density for LWSSC of Porcelinite aggregate is 1964 kg/m^3 and the compressive strength is 29.57 MPa after 28 days for w/cm ratio 0.32. The air dry density for LWSCC of Thermostone aggregate is 1820 kg/m^3 and the compressive strength is 25.75 MPa after 28 days for w/cm ratio 0.32. The results demonstrated that the HRM performance, which is locally available, is better than SF in production of LWSCC [33]. Wu et al. in [15] studied the effects of PP fiber on the spalling characteristics and mechanical properties of LWSCC at elevated temperature. The results indicate that the addition of PP fibers greatly reduces the risk of LWSCC spalling. The thermal damage and the loss in residual mechanical properties of LWSCC with PP fibers are smaller compared with that without PP fibers. AL-Radi et al. investigate in [2] mechanical properties of SCC with PP, steel, and hybrid fibers at high temperatures. At temperatures below 200 °C, SCC reinforced with steel fiber shows significant improvement in mechanical properties; at temperatures over 200 °C, these properties begin to drop. Mechanical properties of SCC reinforced with PP fiber dropped at 200 °C. Occurrence of explosive spalling was reduced by using SCC reinforced with steel and PP fibers.

The purpose of this study was to evaluate the properties of LWSCC in fresh and hardened state employing light expanded clay aggregate (LECA) as coarse aggregate. This study also investigated the influence of hybrid fibers on the aforementioned properties. In addition, it evaluated the compressive, flexural, and splitting strengths of LWSCC specimens after being subjected to fire exposure at various temperatures (300, 400, and 600 °C).

2. *Methods and Materials*

2.1. *Materials*

2.1.1. Cement

Ordinary Portland Cement (OPC) was used in this research (CEM I-42.5R). The physical and chemical requirements were in accordance with the specifications of IOS.5 [17]. Tables 1 and 2 show the properties of OPC.

Table 1. Chemical properties of OPC.

Oxides	Test results (% by weight)	Limit of IOS.5 [17]

CaO	62.8	----
SiO_2	20.57	----
Al_2O_3	5.56	----
Fe_2O_3	3.32	----
MgO	2.91	5.0 (max)
SO_3	2.23	≤ 2.8 % for C_3A > 3.5 %
I.R	1.00	1.5 (max)
L.O.I	1.94	4.0 (max)
Main compounds of OPC		
C_3S	50.79	---------
C_2S	20.74	---------
C_3A	9.12	---------
C_4AF	10.10	---------

Table 2. Physical properties of OPC.

Physical properties	Test results	Limits of IQS.5 [17]
Specific surface area m^2/kg (Blain method)	381	≥ 280
Setting time (Vicat apparatus)		
Initial setting, min	165	≥ 45 min
Final setting, hr : min	4 : 30	≤ 10 hr
Soundness (Autoclave method), %	0.14	≤ 0.8
Comp. strength at 2 day, MPa	23	≥ 20
Comp. strength at 28 day, MPa	44	≥ 42.5

2.1.2. Fine Aggregate

In this research, natural sand from the region of Al-Ukhaidir was used as fine aggregate in accordance with IOS.45 specifications [18].

2.1.3. Lightweight Expanded Clay Aggregate (LECA)

In this study, LECA was used as lightweight coarse aggregate with maximum size 10 mm. Fig. 1 shows the dry LECA that was soaked in water for one day before being added to the concrete to obtain saturated surface dry LECA particles.

Figure 1. Lightweight expanded clay aggregate (LECA).

Table 3 shows properties of LECA.

Table 3. Properties of LECA.

Property	**Results**	**Limits of IOS.45/1984**
Specific gravity	0.65	----

Absorption, %	21	----
Bulk density (loose), kg/m^3	320	----
SO_3	0.07	≤ 0.1

2.1.4. Silica Fume (SF)

In this study, Sika SF with an activity index of 122 % was used. The chemical and physical properties, as well as the activity index, all meet the requirements of ASTM C1240-14 standard [19].

2.1.5. Limestone Powder (LP)

LP was used as an inert mineral filler to enhance the workability and resistance to segregation.

2.1.6. Superplasticizer

In this research, BETONAC®1030, a very effective polycarboxylate-based plasticizer, was used. It was designed to enhance workability and improve slump flow. As a result, the concrete has superior workability without segregation. The superplasticizer used in this study meets the requirements of ASTM C494 standard [20].

2.1.7. Water

The mixing and curing water used in this study was clean and free of impurities, in accordance with IOS.1703 specifications [21].

2.1.8. Steel Fiber

Hook-end steel fibers 35 mm in length and 0.55 mm in diameter with an aspect ratio of 64 were used in this research. This fiber was produced by Bundrex (South Korea). The properties of steel fiber are shown in Table 4.

Table 4. Properties of steel fiber.

Appearance	Hook
Length	35 mm
Diameter	0.55 mm
Aspect ratio “L/D”	64
Density	7800 kg/m^3
Tensile strength	2200 MPa

2.1.9. Polypropylene Fiber

Sika PP fiber used in this research was 12 mm in length, 18 μm in diameter and had density 910 kg/m^3. Table 5 shows the properties of PP fiber.

Table 5. Properties of PP fiber.

Shape	Straight
Color	White
Length	12mm
Diameter	18 μm
Modulus of elasticity	4000 N/mm^2
Specific gravity	0.91 g/cm^2

2.2. Mixture Proportion

In this research, LWSCC mixtures were designed to produce structural lightweight concrete that would meet the requirements of the European guidelines for self-compacting concrete [22] and ACI 213R-03 guide [5]. Therefore, several experimental mixtures were conducted to produce this type of concrete. In this study, four LWSCC mixtures were made with different fiber volume fractions (0 fibers, 1 % steel, 0.75 % steel + 0.25 % PP, and 0.5 % steel + 0.5 % PP). The properties of all four mixtures are shown in Table 6.

Table 6. The concrete mixes.

Mixtures	Binder content

	Cement, kg/m³	SF, kg/m³	LP, kg/m³	Water, kg/m³	w/b ratio	Sand, kg/m³	LECA, kg/m³	High range water reducing admixtures (HRWRA), % by wt. of binder content	Steel fiber, kg/m³	PP fiber, kg/m³
MR	480	80	30	195	0.34	800	150	1.6	0	0
M S	480	80	30	195	0.34	800	150	1.65	78	0
M SP1	480	80	30	195	0.34	800	150	1.71	58.5	2.275
M SP2	480	80	30	195	0.34	800	150	1.77	39	4.55

Where MR is the reference mix, MS is the mix containing steel fiber only, MSP1 is the mix containing hybrid fiber (0.75% steel + 0.25% PP), and MSP2 is the mix containing hybrid fiber (0.5% steel + 0.5% PP).

2.3. Mixing Procedure

Since LECA has a high capacity for water absorption, it was soaked in water for 24 h before being added to the mixture, and then spread out in the laboratory for an adequate period of time to obtain a state of dry saturated surface. LECA was treated in this way to keep it from absorbing excess mixing water. The process for mixing was as follows:

4) sand and LECA were mixed in the mixer for 1 min;
5) dry ingredients (SF, cement, and LP) were added;
6) water with superplasticizer was added to dry ingredients, and the mixture was mixed for another 5 min;
7) finally, steel and PP fibers were gradually mixed into the mixture until a consistent distribution was achieved.

2.4. Burning and Cooling

The day after making, the concrete samples were removed from the molds and stored in water for up to 28 days. They were then stored in the laboratory at about 23 °C for up to 56 days (28 day in water and 28 day in air). The LWSCC samples were subjected to fire exposure at 300, 400, and 600 °C according to ASTM E119-00a [31] in a furnace specifically designed for this purpose. The temperatures in this study were chosen based on the results of some previous studies [2, 14]. A digital thermometer, as shown in Fig. 3, was used to record the temperature. After reaching the desired temperature, the samples were kept in the furnace for another hour. After that, the samples were taken out and gradually cooled down to room temperature.

Figure 2. Burning furnace.

Figure 3. Digital thermometer.

3. Results and Discussion

3.1. Fresh Properties Results

3.1.1. Slump Flow Tests and T_{500mm} Value

The flow ability of fresh concrete can be evaluated by slump flow tests with Abrams cone. Table 7 and Fig. 4a show the results of slump flow tests. All of the mixtures showed a diameter of slump flow between 650 and 760 mm. All mixture were in accordance with the European guidelines for self-compacting concrete [22] requirements. The slump flow diameter of LWSCC reduced significantly with added fibers in comparison to the mixture without it. The addition of fibers increased flow resistance and decreased flow ability as a result of increased adhesion and friction between the fibers and aggregate.

T_{500mm} values represent the time necessary for the concrete to reach a diameter of 500 mm during slump flow test (i.e. viscosity). The values varied between 2.1 and 3.7 sec. The addition of fibers to LWSCC mixtures increased T_{500mm} values. This was attributed to the increase in flow resistance and the decrease in flow ability as a result of increased adhesion and friction between the fibers and the aggregate [29]. As has been demonstrated in similar studies [27].

3.1.2. V-Funnel Time

The V-Funnel test was used to determine the viscosity and filling ability of SCC [22]. The findings of the V-Funnel test are shown in Table 7 and Fig. 4b. The values ranged between 7 and 10.5 sec. This indicated an increase in the V-Funnel flow time when fibers were included in the LWSCC mixture. This was due to an increase in the viscosity factor of the mixtures, which resulted in concrete with greater cohesion and adhesion. As a result, the exit velocity of fresh concrete through the tab door of the V-Funnel device was slowed down. As has been shown in similar studies [26].

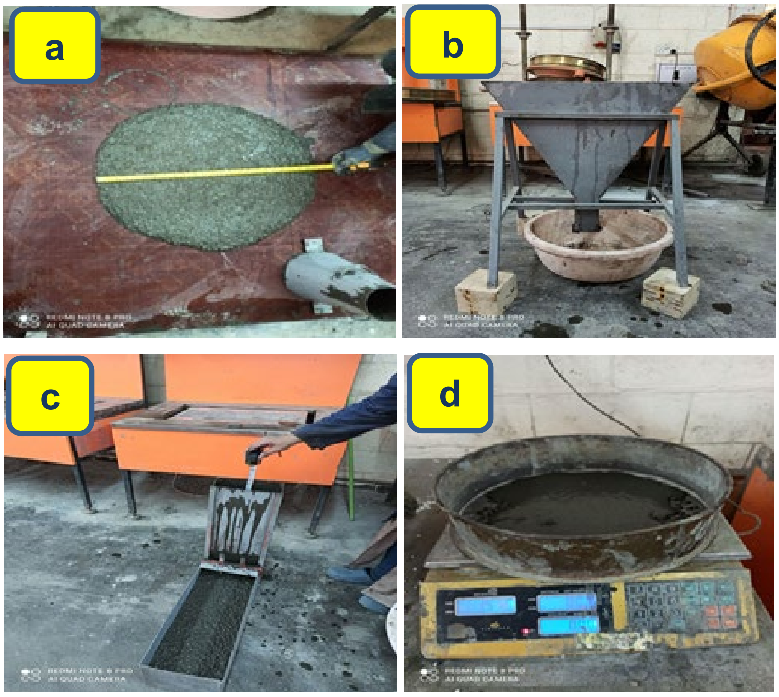

Figure 4. Testing of fresh properties.

Table 7. Fresh properties tests results.

Mixtures	Slump flow, mm	T_{500mm}	V-Funnel, sec	L-Box	Segregation resistance (SR), %
MR	760	2.1	7.0	0.98	18.3
M S	690	2.7	8.5	0.90	12.5
M SP1	675	3.2	9.7	0.85	9.2
M SP2	650	3.7	10.5	0.80	7.7

3.1.3. L-Box Test

In this study, the L-Box with two bars was used to evaluate the passing ability of LWSCC. The findings of the blocking ratio (BR = H2/H1) tests are shown in Table 7 and Fig. 4c. The results ranged between 0.8 and 0.98. This indicated that the addition of fibers into the LWSCC mixture lead to a decrease in blocking ratio (BR). The addition of fiber had a negative effect on passing ability because it increased flow resistance and decreased flow ability as a result of increased adhesion and friction between fibers and aggregate, as has been demonstrated in similar studies [26].

3.1.4. Sieve Segregation Tests

Sieve segregation was used to measure segregation resistance, as shown in Fig. 4d. Table 7 shows the segregation values for all LWSCC mixtures. According to the results, mixes with added fibers showed lower values when compared to mixtures without fibers. This is due to the distribution of fibers in concrete, which resulted in formation of a network that could effectively prevent aggregate particles from becoming separated from one another. This is why LWSCC with fibers had a higher resistance to segregation. The segregation values for all LWSCC mixtures were within the limits set by the European guidelines for self-compacting concrete [22].

3.2. Hardened Properties Results

3.2.1. Compressive Strength

Compressive strength test for LWSCC was conducted using 100 × 100 × 100 mm cube in accordance with BS EN 12390-3 standard [23]. Table 8 shows the compressive strength values at 28 and 56 days. Compressive strength of LWSCC with fibers specimens (MS, MSP1, and MSP2) increased by approximately 19, 14, and 7 % compared with the reference mixture (without fiber). The fibers enhanced mechanical bonding, which slowed the formation of micro-cracks, limited their further spread, and thus increased compressive strength. Fig. 5 shows the compressive strength of LWSCC mixture after exposure to burning at different temperature. The results showed that compressive strength decreased with increasing temperature in both the specimen with and without fibers. The compressive strength of specimen without fibers decreased by approximately 22, 35, and 55 % at 300, 400, and 600 °C, respectively, due to incompatible changes in the volume of cement paste and aggregate during heating and cooling, leading to dissolution of the interfacial bond [28]. Compressive strength of LWSCC specimen containing steel fibers decreased by approximately 14, 22, and 41 %. Compressive strength of specimen containing hybrid fibers (0.75 % steel + 0.25 % PP) decreased by approximately 16, 30, and 46 %. Compressive strength of specimen containing hybrid fibers (0.5 % St + 0.5 % PP) decreased by approximately 19, 32, and 48 % at 300, 400, and 600 °C, respectively. Heating negatively affected all mechanical properties of LWSCC. However, steel fibers prevented cracking and mitigated damage caused by increased temperatures. The melting of PP fibers resulted in the formation of a large number of small holes between concrete materials, which contributed to the decrease in compressive strength in specimens containing PP fiber. This agrees with other research findings [2].

Table 8. Hardened properties tests results.

Mixtures	Compressive strength, MPa		Splitting strength, MPa		Flexural strength, MPa		Density, kg/m^3
	28 days	56 days	28 days	56 days	28 days	56 days	
MR	25.6	27.2	2.5	2.8	3.9	4.1	1710
MS	30.5	33.1	3.6	4.1	6.2	6.5	1850
MSP1	29.2	31.8	3.4	3.8	5.8	6.1	1800
MSP2	27.6	29.2	3.1	3.5	5.3	5.6	1740

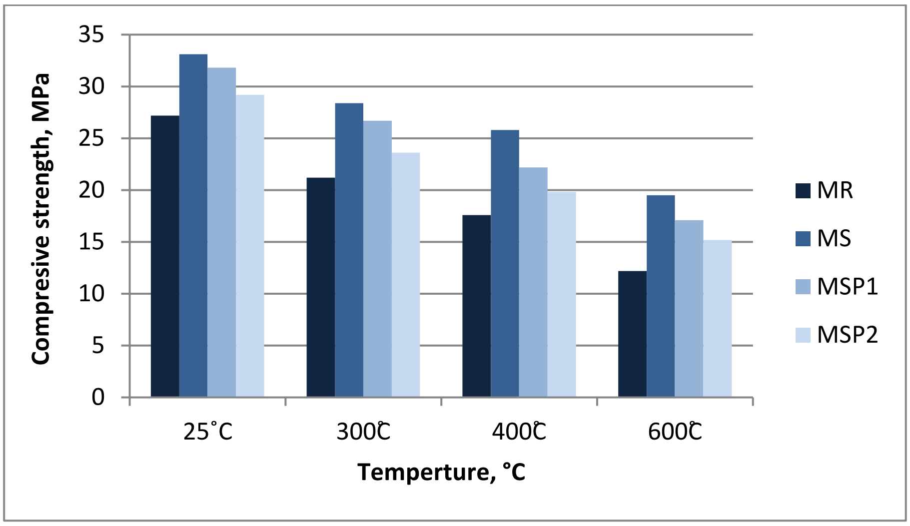

Figure 5. The compressive strength of LWSCC after exposure to different burning temperature.

3.2.2. Splitting Strength

Splitting strength test was conducted using 100 × 200 mm cylinder in accordance with ASTM C496 standard [24]. Table 8 shows the splitting strength values at 28 and 56 days. LWSCC mixtures with fibers (MS, MSP1, and MSP2) had a higher splitting strength than those without fibers by approximately 45, 38, and 25 %, respectively. This was because fibers prevented the formation of micro-cracks in the concrete, thus the tensile strength increased [29]. Fig. 6 shows the splitting strength of LWSCC mixture after exposure to burning at different temperature. The results showed that the splitting strength decreased with increasing temperature in both the specimen with and without fibers. Splitting strength of LWSCC specimen without fibers decreased by approximately 30, 48, and 73 % at 300, 400, and 600 °C, respectively. Splitting strength of specimens with steel fibers decreased by approximately 14, 31, and 51 %. Splitting strength of specimens with hybrid fiber (0.75 % steel + 0.25 % PP) decreased by approximately 18, 34, and 57 %. Splitting strength of specimens with hybrid fiber (0.5 % steel + 0.5 % PP) decreased by approximately 20, 42, and 64 %, respectively. Loss of strength could be caused by a number of factors, including the difference in thermal expansion between the aggregates and cement paste, the degree of drying of the cement paste, and the disintegration of the aggregates.

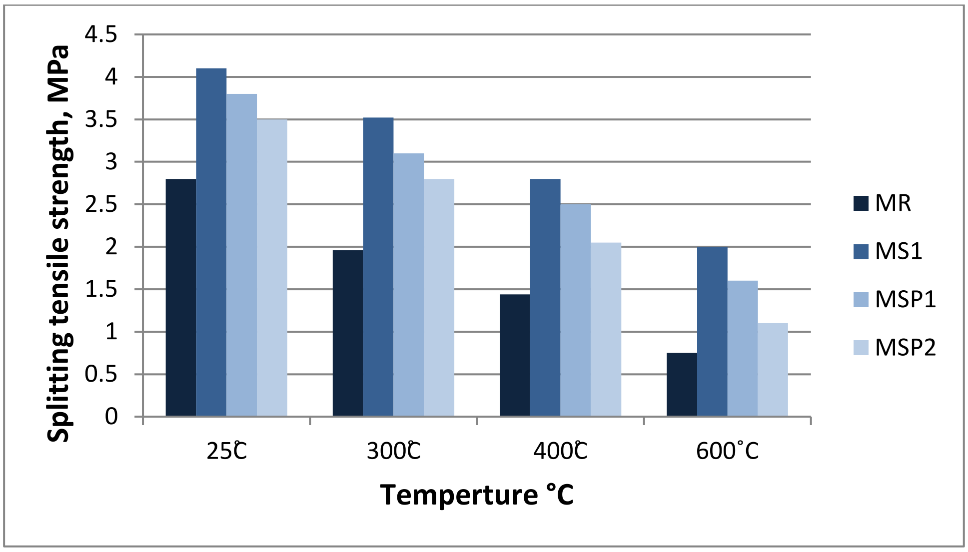

Figure 6. The splitting strength of LWSCC after exposure to different burning temperature.

3.2.3. Flexural Strength

Flexural strength test was conducted using 80 × 80 × 380 mm prism in accordance with ASTM C293-08 standard [25].Table 8 shows the flexural strengths values at 28 and 56 days. In comparison to reference mixtures without fibers, the flexural strength of LWSCC mixtures containing fibers (MS, MSP1, and MSP2) increased by approximately 58 %, 48 %, and 36 %, respectively. This was due to the presence of fibers that prevented the appearance of micro-cracks in the concrete. These results were similar with those obtained by other researchers [2, 30]. Fig. 7 shows the result of flexural strength of LWSCC mixture after exposure to burning at different temperature. The results showed that the flexural strength of LWSCC with and without fibers decreased with increasing temperature. At temperatures 300, 400, and 600 °C, the flexural strength of LWSCC specimen without fibers decreased by approximately 25, 40, and 73 %. Flexural strength of specimens with steel fibers decreased by approximately 14, 25, and 55 %. Flexural strength of specimens with hybrid fiber (0.75 % steel + 0.25 % PP) decreased by approximately 19, 32, and 65 %. Flexural strength of specimens with hybrid fiber (0.5 % steel + 0.5 % PP) decreased by approximately 22, 37, and 69 %, respectively. The reason is that the high temperature had altered the properties of the concrete. Since calcium hydroxide dehydrates at high temperatures, the cement paste contracted. When flexural strength decreased, many micro- and macro-cracks appeared in the specimens due to the thermal incompatibility of the cement used in the paste and the aggregates.

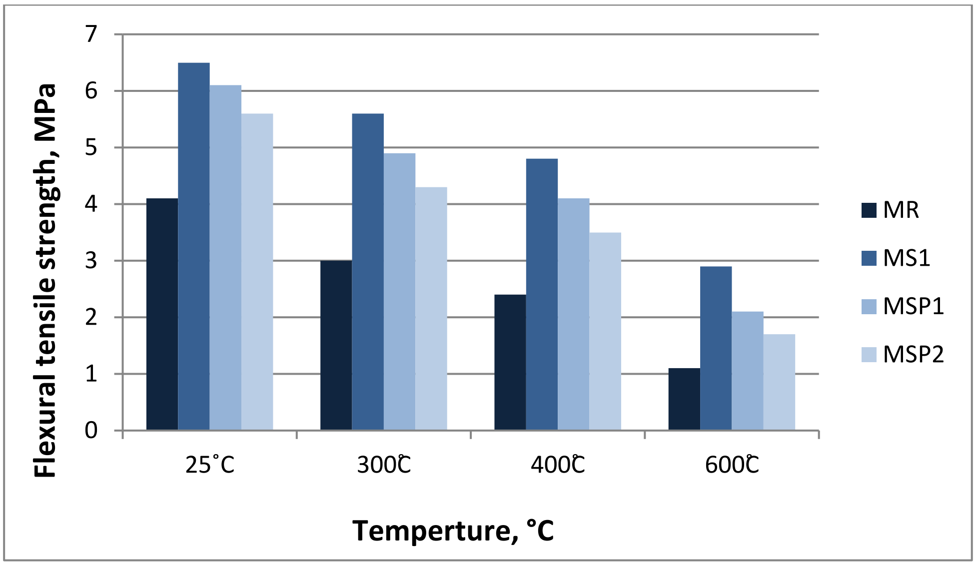

Figure 7. The flexural strength of LWSCC after exposure to different burning temperature.

4. Conclusion

In this study, we conducted a set of experiments to determine the impact of fire exposure on the mechanical properties of LWSCC specimens at different temperatures, as well as to study the effect of using steel and hybrid fibers on same parameters. Based on the discussed results, the following can be concluded:

- All mixtures met the SCC limitations recommended by the European guidelines for self-compacting concrete [22]. Thus, all mixtures had high filling capacity and segregation resistance. The addition of fiber to the mixtures decreased the workability of LWSCC, but the mixtures still met the requirements of the European guidelines for self-compacting concrete [22].
- When compared mixtures without fibers (MR) to mixtures with steel fiber (MS) and hybrid fibers (MSP1, MSP2), slump flow diameter decreased by approximately 9, 11, and 14 %. T_{500mm} increased by approximately 28, 52, and 76 %. V-Funnel increased by approximately 21, 38, and 50 %. L-Box decreased by approximately 8, 13, and 18 %. Sieve segregation resistance decreased by approximately 25, 31, and 40 %. For this reason, large amount of superplasticizer was added to these mixtures in order to preserve their workability.
- The incorporation of steel fibers increased the mechanical properties significantly.
- When specimens were subjected to fire, the compressive strength, tensile strength, and flexural strength decreased.
- When compared to the reference mixture, mixtures with steel and hybrid fibers improved the concrete's residual mechanical qualities at temperatures between 300 and 600 °C.

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Received 07.01.2023. Approved after reviewing 28.05.2024. Accepted 29.05.2024.