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The Effect of Fire Flame Exposure on Some Properties of Structural Lightweight Self-Compacting Sustainable Concrete

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ABSTRACT

This study investigates the mechanical, physical, and microstructural performance of structural lightweight self-compacting concrete (SLWSCC) using waste glass as a partial substitute for natural sand and micro-steel fibers as reinforcement under high-temperature conditions. The research will focus on optimizing the sustainability, fire resistance, and structural performance of lightweight concrete and reducing the effects of waste disposal. Four mixes were made, a control mix (REF) and three mixes, which included 20%, 30%, and 40% of waste glass, which weighed 30%of sand, reinforced by 1% of micro-steel fibers. Slump flow, V-funnel, and L-box tests were used to determine fresh properties based on EFNARC guidelines to verify self-compacting behavior. Measurement of hardened properties, before and after exposure to 200°C, 400°C, 600°C, and 800°C, was done to assess compressive strength, splitting tensile strength, density, and water absorption. The specimens were heated in a gas furnace, followed by foam cooling. Scanning Electron Microscopy (SEM) analysis of the microstructure revealed information on the integrity of the matrix and the development of pores and fiber-matrix bonding at high temperatures. The resultant of waste glass enhanced the strength and density of values dramatically in ambient conditions because of the micro-filling effect. The G30+MS mix was the most effective one, with a higher compressive strength of 9.2% (52.2 MPa) than the control mix; it retained 35% of its strength at 800°C, which was higher than that of the reference mix. Micro-steel fibers limited the propagation of cracks and avoided spalling, retaining the structural integrity of the composite after exposure to fire.

Keywords: Self-compacting lightweight concrete, Waste glass, Micro-steel fibers, Thermal resistance, Compressive strength.

1. INTRODUCTION

The increased need was to find sustainable and high-performance construction materials, that have finally led to extensive studies on self-compacting lightweight concrete (SCLWC), characterized by high workability, low density, and complexity in structures **(Akbulut et al.,**

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2024; Karamloo et al., 2017). In more recent undertakings, available endeavors have done away with conventional aggregates and binders in favor of industrial waste products and materials that significantly reduce the effects on the environment. Among them, silica fume and waste glass have become potentially promising additives, which, in addition to improving the mechanical strength of concrete, also lessen its carbon footprint **(Qaidi et al., 2022)**. Such environmentally friendly materials will be integrated in line with the world sustainability targets, where the aim is to produce durable and yet energy-efficient concretes without undermining their performance.

In its specific case, waste glass (WG) has gained more and more interest because of the high level of silica and pozzolanic reactivity, which may make concrete improve its microstructure and strength heavily when replacing fine aggregates or cement in some proportion **(Abalouch et al., 2021)**. Also, glass is one of the most widely used materials in daily life, and large quantities of waste glass are disposed of in landfills. Its disposal represents a significant environmental challenge because it is non-biodegradable. Glass powder, being an inorganic material, has been investigated as a potential partial replacement for sand and cement in concrete applications. Studies have shown that the use of glass powder as a substitute for part of the cement or fine aggregate can yield positive effects on workability, impermeability, and chloride resistance, with performance comparable to conventional concrete. This improvement is attributed to the hydrophobic nature of glass and its low porosity **(Liu et al., 2022)**.

Furthermore, research indicates that incorporating glass powder into concrete can enhance long-term compressive strength and reduce hydration heat, thereby contributing to improved durability. However, it has also been concluded that the replacement level of glass powder in concrete should generally not exceed 20% to maintain optimal performance **(Majeeda et al., 2022)**. Being finely ground, waste glass has binding properties, which result in refining and densification of the pore structure of the concrete as well as raising its resistance to aggressive environments and durability. It has been demonstrated that compressive strength can be boosted by 8.12% and thermal conductivity can be decreased by up to 15, thereby making WG the best material to be used as thermal insulation and thermal fire-resistant structures when 20-30 percent of the concrete is replaced with WG **(Khan and Sarker, 2020; Yang et al., 2019).** Additionally, the recycling of the glass waste after consumption will contribute to the principles of a circular economy as well as decrease the landfills, which is one of the significant environmental issues in cities.

In an attempt to enhance even more the thermal and mechanical characteristics of lightweight concretes, scientists have considered hybrid reinforcement techniques of mixing WG with fiber materials like steel, polypropylene, or glass fibers. Fibers are a crack-bridging component that increases toughness, ductility, and resistance to fire in concrete **(Rawaa et al., 2024; Li et al., 2024; Akhtar and Bezerra, 2019).** concluded that 15 % glass powder, coupled with 1% fiber reinforcement, enhanced up to 25 % the residual compressive strength even after thermal treatment at 800 ^{o}C because the fibers and matrix interact and prevent crack movement and structural glue. On the same note, **(Jani et al., 2020)** noted that self-compacting concrete mixes comprising hybrid fibers had better post-fire mechanical retention than fiber-free mixes.

Pumice, which is a lightweight aggregate, has also been used in SCLC so as to increase insulation and fire resistance. **(Jamal et al.,2024; Celik et al., 2024)** said that geopolymer concretes with pumice exhibited a (20-30) % decrease in thermal conductivity and preserved over 60% of their initial compressive strength at 700 ^{o}C. These results emphasize that the lightweight aggregates and the use of the pozzolanic materials with glass foundations may be combined to resist high temperatures and maintain mechanical stability. Also, **(Wang et al., 2024)** have established that modulating pumice aggregates using sodium silicate enhanced the woodenness of the lightweight concrete as it diminished the porosity and advanced the connection between the aggregate and cementitious body**.**

Although the use of waste glass, micro-steel fibers, and pumice lightweight aggregates as a combination entity has made remarkable progress, there is a lack of research regarding the combination of these elements in self-compacting concrete under high temperatures. The current research addresses this research gap by attempting in an organized manner to examine how these sustainable materials affect the workability, mechanical strength, and thermal performance of SLWSCC. The study will be made to determine the suitability of the concrete in building a structure in a place prone to fire by assessing the residual strength, microstructure, and physical stability of the material in the case of exposure to temperatures up to 800 ^{o}C.

This study aims to develop environmentally friendly and thermally efficient construction materials that contribute to sustainable and durable infrastructure development. The research specifically investigates the effect of incorporating waste glass, pumice lightweight aggregates, and micro-steel fibers on the fresh, mechanical, and thermal properties of self-compacting lightweight concrete under elevated temperature conditions.

2. MATERIAL, CHARACTERIZATION AND MIX PROPORTION

The resources of the undertaken study were thoroughly chosen and described so that the uniformity and repeatability of the manufacturing process of structural lightweight self-compacting concrete (SLWSCC) using waste glass and micro-steel fibers could be achieved. Ordinary Portland Cement (OPC) meeting **(ASTM C150, 2022)** Type I with a fineness of about 320 m^2/kg and specific gravity of 3.15 was the main binder. Silica fume was incorporated at the level of 12 kg/m^3 in order to improve the mechanical performance and strength of the concrete, which serves as an additional cementitious component since it enhances the particle packing and minimizes the porosity.

Natural sand was used (gradation zone 2) according to the Iraqi specification **(IQS NO. 45, 1984)**, and waste glass bottles were used (with a slope degree similar and close to that of the sand). The crushed glass was volumetrically replaced with sand with a specific density of 2.64, a fineness modulus of 2.8, and 4.75 mm as the maximum particle size, with a particle size range similar to natural sand (0.15-4.75 mm). Three mixtures (G20+MS, G30+MS, and G40+MS) were prepared by adding glass at 20%, 30%, and 40% (volumetric replacement). It was dried with coarse aggregate, 100% pumice, chosen for its low density and thermal stability, with a specific density between 1.3 and 1.4, an apparent density of about 850 kg/m^3, and the largest aggregate size being 10 mm.

The cementitious material weight included 1.6 % of a polycarboxylate-based superplasticizer to provide the necessary flowability without segregation, and 144 kg/m^2 of water was added to the cementitious material with a water-to-binder ratio of 0.27-0.28. 1% volume fraction was adopted as a balanced proportion to improve the mechanical and thermal performance of the concrete without adversely affecting its fresh properties. The micro-steel fibers used in this study had a length of 13 mm, a diameter of 0.2 mm, and an aspect ratio of 65, which are suitable dimensions for enhancing crack resistance and controlling microcrack propagation, especially under elevated temperature conditions

All mixes contained cement 508, silica fume 12, water 144, and pumice 412 in their final mix proportions (in kg/m^3). The content of the sand and glass was different: REF (sand 882, glass

0), G20+MS (sand 705.6, glass 148.8), G30+MS (sand 617.4, glass 223.2), and G40+MS (sand 529.2, glass 297.4). This was a composition that guaranteed structural lightweight characteristics with target densities as low as 1800 kg/m^3 and retention of enough self-compaction capability and fire resistance.

3. MIXING, CASTING, CURING, AND FRESH PROPERTIES

The mixing, casting, and curing operations were well-adjusted so that all mixes of structural lightweight self-compacting concrete (SLWSCC) would be uniform and reproducible. This process involved weighing and batching of all the materials based on the intended mix proportions as shown in **Table 1**. A concrete mixer of 0.1 m^3 was used to carry out the mixing process in a pan-type mixer. To ensure uniformity and homogeneity, the entire mix time was kept at 5-7 minutes. The dry material of cement, silica fume, sand, pumice and waste glass was first dry-mixed and blended for 2 minutes to obtain an even distribution of the particles. The mixing water, which was about 80 %, with the super plasticizer (1.6% by weight of binder) was then added gradually during 2 minutes before the micro-steel fibers (1 % by volume) were slowly added. The remaining 20 % of water was added at the last stage, to bring workability in it and to have a smooth and coherent mix with self-compacting properties.
After the mixing was complete, we hurriedly poured the concrete into normal cube molds (100*100*100 mm) and cylinder molds (100*200 mm) and did not vibrate, as we would do with self-compacting concrete. The combos were identified as REF (0% glass), G20 +MS (20% glass), G30 +MS (30% glass), and G40 +MS (40% glass). A cast of each mix was done in three copies in order to have statistical validity. The molds were compared in the layer and covered with plastic sheets to avoid the loss of moisture. All the specimens were then demolded after 24 hours and then transferred to a curing tank at 23 ^{o}C and a relative humidity greater than 95 % in the curing period of 28 days before testing.
The new aspects were evaluated to ascertain self-compacting ability as per EFNARC (2005) guidelines. There was the slump flow test, T_{500} time, V-funnel test, and L-box test. The average slump flow diameter was 650 to 740 mm, which was of excellent filling ability. The T_{500} flow time was 2.9-5.2 seconds, and this proved moderate viscosity. Flow times of the v-funnel were between 6.5 and 9.1 seconds, and ratios between L-box (H2/H1) were 0.83 and 0.91, showing good passing quality. These findings confirmed that any combination passed the test of the desired self-compacted lightweight concrete having the best fresh properties.

Table 1. Materials and Mix Proportions Used in the Experimental Program

Material	Type / Description	Properties / Specifications	Quantity (kg/m^3)	Remarks
Cement	Ordinary Portland Cement (OPC, Type I)	Specific gravity: 3.15; Fineness: 320 m^2/kg	508	Main binder
Silica Fume	Mineral admixture (pozzolanic)	Specific gravity: 2.20	12	Improves strength and durability
Water	Potable water	pH = 7; W/B ratio ≈ 0.27	144	Mixing water
Superplasticizer (SP)	Polycarboxylate-based	Dosage: 1.6% by wt. of binder	–	Enhances flowability
Fine Aggregate (Sand)	Natural river sand	Fineness modulus: 2.8; Max size: 4.75 mm; Specific gravity: 2.64	Variable (see below)	Replaced partly by glass waste

Waste Glass	Crushed recycled glass	Particle size: 0.15–4.75 mm; Specific gravity: 2.50	Variable (see below)	Partial sand replacement (20–40%)
Coarse Aggregate	Pumice (lightweight aggregate)	Max size: 10 mm; Specific gravity: 1.35; Bulk density: 850 kg/m^3	412	Provides lightweight structure
Micro-Steel Fibers	Straight steel fibers	Length: 13 mm; Diameter: 0.2 mm; Aspect ratio: 65	1% by volume	Improves toughness and crack resistance

4. COOLING REGIMES AND FIRE EXPOSURE (FURNACE)

A closely controlled fire exposure and cooling regime was applied to measure the high-temperature performance and post-fire behavior of the high -strength structural lightweight self-compacting concrete (SLWSCC), which is a composite with waste glass and micro-steel fiber. All the specimens (cubes and cylinders) were dried in the oven at 105 ± 5 ^oC to eliminate all the free moisture and store the explosive spalling at room temperature to inhibit explosive spalling during exposure to the furnace.
The samples were subjected to burning at high combustion temperatures according to **(ASTM E119-00a, 2017)** standard at a slow rate of temperature increase of 5 ^oC per minute to prevent any thermal shock and/or internal stress concentration. Specimens were subjected to four target temperatures, namely, 200 ^oC, 400 ^oC, 600 ^oC, and 800 ^oC, which represented varying degrees of structural and fire conditions. Three cube specimens (100 *100 *100 mm) and three cylinder specimens (100 * 200 mm) were positioned at the center of the furnace chamber in order to get uniform heating. When the target temperature is reached, the samples are burnt for a full hour, and then the fire is extinguished. The samples are cooled after being removed from the gas furnace using fire-extinguishing foam to cool them completely. Foam cooling regimes were followed to look into the influence of temperature drop on the remaining mechanical and physical properties of the SLWSCC that were developed after fire exposure. Cooling system using foam, where the samples were directly covered with fire foam after being taken out of the oven and kept underwater for an hour. This approach simulated rapid cooling conditions that occur during fire extinguishing or other emergency cooling conditions, as illustrated in **Fig. 1**.

Figure 1. Foam-cooling method

To guarantee the accuracy of temperature distribution inside the furnace, a digital data logger was used to continuously monitor temperature distribution using K-type thermocouples, as shown in **Fig. 2**. After every exposure, visual observation demonstrated that the colors changed to light red at 400 ^oC, pale pink at 600 ^oC, and dark brown at 800 ^oC, which indicated an increase in the extent of oxidation and dehydration **(Hassen and Awad,**

2023). Such systematic thermal exposure and controlled cooling were a sure bedrock in estimating the remaining strength, density and stability against microstructural disintegration of SLWSCC following fire exposure **(Karem and Awad, 2025)**.

Figure 2. a) Gas burning furnace, b) Thermocouple device at 500 °C

5. HARDENED TESTS, PHYSICAL TESTS, AND MICROSTRUCTURE

On completion of the curing and fire exposure steps, the high-strength structural lightweight self compacting concrete (SLWSCC) specimen will be subjected to an extensive test regime of hardened state testing to determine the mechanical strength, physical properties and microstructural performance of the specimen under high temperature exposure. Hardened properties analyzed were compressive strength, splitting tensile strength, density and water absorption and microstructural evaluation was done to know the integrity of the matrix, porosity and interfacial transition zone (ITZ) between the binder and lightweight aggregate.

5.1 Hardened Mechanical Tests

The compressive strength was ascertained based on **(BS EN 12390-3, 2019)** test performed at 100 × 100 × 100 mm cube based on compressive strength at room temperature and in exposure to 200, 400, 600 and 800 oC. The tests had been done on a 2000 kN capacity hydraulic testing machine with a loading rate of 0.5 MPa/s. The unsettled compressive strengths of the reference (REF) and glass-modified mixes prior to heating were 47.8 MPa (REF), 49.5 MPa (G20+MS), 52.2Mpa (G30+MS), and 51.0 MPa (G40+MS). Ratios of retained strengths decreased to 28-35 % after exposure to 800 ^oC, and this was influenced by the glass content and cooling regime. According to **(ASTM C496, 2017)** splitting tensile strength tests were conducted on 100*200 mm cylinders, and the results indicated that the tensile strength decreased to 1.2-1.5 MPa after being exposed to 800 ^oC proving the positive effect of micro-steel fibers in preventing thermal cracking

5.2 Physical Measurements

(ASTM C642, 2022) was followed by bulk density and water absorption tests. Dry densities were found to be 1720-1810 kg/m^3, which again confirmed their lightweight nature. Densities dropped by some 8–12 % in response to post-exposure at 800 ^oC, and this drop was primarily attributed to dehydration and loss of matrix. The water absorption increased by 6.3% in REF to 9.5% in G40+MS, showing a higher capillary porosity at higher glass contents and heat.

5.3 Microstructural Analysis

The scanning electron microscope (SEM) was used to conduct microscopic analysis of concrete samples. Where small samples representing the tested samples were taken after exposure to high temperatures and cooling processes. The samples were dried in the oven to remove moisture and then coated with a layer using a spray coating device to improve electrical conductivity before inspection. SEM analysis was conducted under appropriate acceleration voltage and different magnifications to investigate microstructural changes, including pores, microcracks, hydration products, and the interfacial transition zone (ITZ) between cement paste and aggregate.

A microstructure assay was done; the unheated samples had a tight-knit mat with firmly bonded interfaces between the cement paste and glass particles as well as the pumice aggregate. But when temperature increased to 600 °C and 800 °C, micrographs showed enormity of microcracking, pore development, and partial melting of glass and initiated microstructural discontinuities. The existence of micro-steel fibers was able to seal the cracks as well as hold the matrix together, which proved their vitality in determining post-fire integrity and toughness of the SLWSCC.

6. RESULTS AND DISCUSSION

An extensive dataset of the study of the interaction between waste glass inclusion and micro-steel fiber addition on the mechanical, physical, and microstructural behavior of lightweight concrete with self-compaction (SCLWC) at ambient and high temperatures was obtained, and the study results are published. The findings in terms of compressive strength, splitting tensile strength, density, absorption behavior and microstructural evolution are elaborated on. The analysis would combine both numerical and performance percentages and visual observations to form obvious connections between the material make-up and its post-fire behavior.

6.1 Results of Compressive Strength.

The compressive strength of the control mix (REF) at room temperature was determined to be 47.8 MPa, and the modified mixes recorded higher values: 49.5, 52.2 and 51.0 MPa respectively (G20+MS, G30+MS and G40+MS). The 20-40 per cent incorporation of the waste glass led to an overall increase of 3.592 per cent in the strengthening of the mixture supported by the G30+MS mixture, which clearly exhibited its balanced filler density and the pozzolanic activity of the fine glass particles. All mixes showed gradual weakening of compressive strength when subjected to high temperatures, though the rate of such decrease differed markedly according to the composition of a particular mix.

The strength loss at 200 ºC was not very significant, with an average of 8-10 % across all mixes, because of evaporation of free water. The thermal stability of REF mix reduced the initial strength to 62% at 400 ºC, compared to 68 percent in G30+MS. The decline was even stronger at 600 ºC, where the retention of strength in the G30+MS mixture and REF decreased by 52 to 44 %, respectively. Treatment of 800°C G30+MS mix retained 35 % of the original compressive strength (which is about 18.2 MPa) of the control mix, only 27 and (12.9 MPa). This high performance is due to the interaction of micro-steel fibers with microcracks and partial vitrification of glass that formed a more advanced matrix to slow down thermal decomposition.

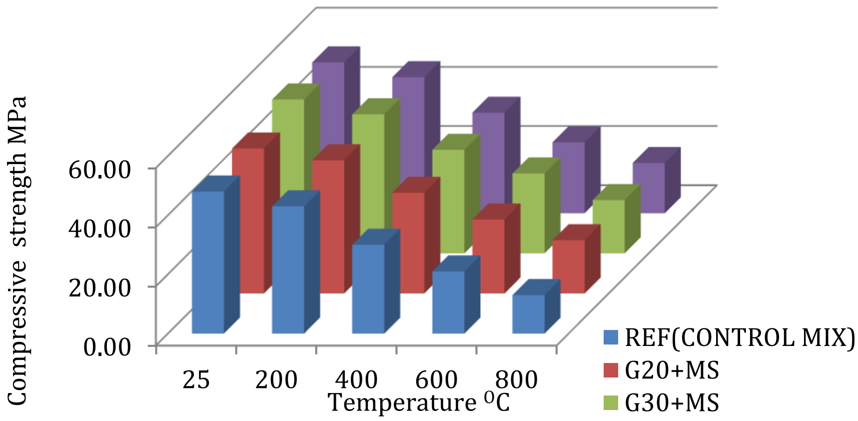

Figure 3. Compressive Strength vs. Temperature for Waste Glass–Modified Concrete Mixes

6.2 Splitting Tensile Strength and Physical Properties

Repeated values of the tensile strength of the splitting material had a similar degradation trend but with a higher temperature sensitivity. The tensile strengths of the measured ambient conditions (REF, G20+MS, G30+MS, and G40+MS) were 4.1 MPa, 4.3 MPa, 4.6 MPa, and 4.4 MPa, respectively, which indicated a significant 12% improvement in the tensile strength with the addition of glass and steel fibers. The G30+MS mix was found to have 70 % of its tensile capacity after heating to 400 C and at 800 °C, the tensile capacity was 1.4 MPa, 69.6 % lower. But the fiber-reinforced mixes had better residual strength and ductile post-crack behavior that did not cause instant failure during loading.

Physically, the initial dry density was 1720-1810 kg/m^3, which is in the range between lightweight structural concrete (<1850 kg/m^3) and heavyweight structural concrete (>2000 kg/m^3). The waste glass involved a little bit of lowered density due to the reduced specific gravity (2.50) as compared to natural sand (2.64). Due to the release of bound water and the expansion of internal pores, densities decreased by 812 %, based on the type of mix exposed to a heat of 800 °C. On the other hand, water uptake was higher in G40+MS as compared to REF of 6.3, representing the fact that the greater the amount of glass and the temperature exposure, the more porosity was developed. A moderate growth of 8.2 % was observed in the G30+MS mix which indicated favorable pore structure between permeability and durability.

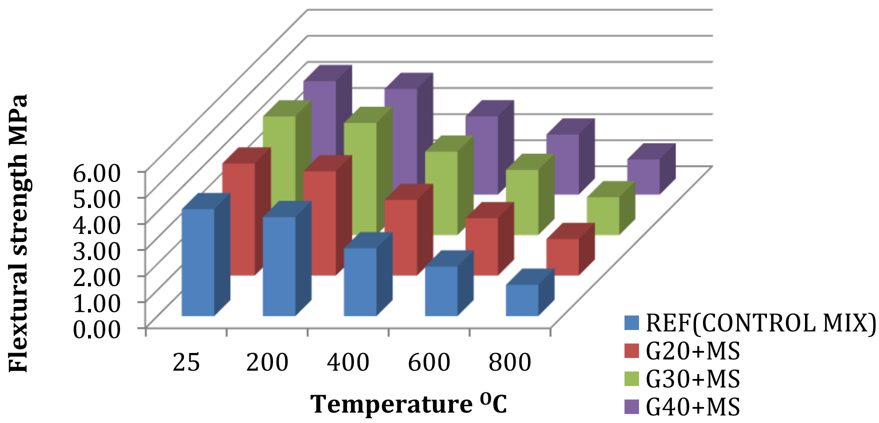

Figure 4. Tensile Strength vs. Temperature for Waste Glass–Modified Concrete Mixes

6.3 Microstructural Analysis

Fig. 5 shows that the SEM analysis confirmed a dense and homogeneous microstructure at room temperature, with good bonding between cement paste, volcanic materials, and recycled glass particles. The glass particles improved particle packing and reduced voids. At 400°C, minor cracks appeared without significant separation. At 600 °C, crack propagation increased with localized softening of glass particles, while at 800 °C, severe deterioration occurred, including pore coalescence and partial melting of glass. Despite this damage, steel fibers continued to bridge cracks and reduce spalling. The reduction in mechanical performance at high temperatures was mainly due to the decomposition of hydration products such as C–S–H and CH above 600 °C.

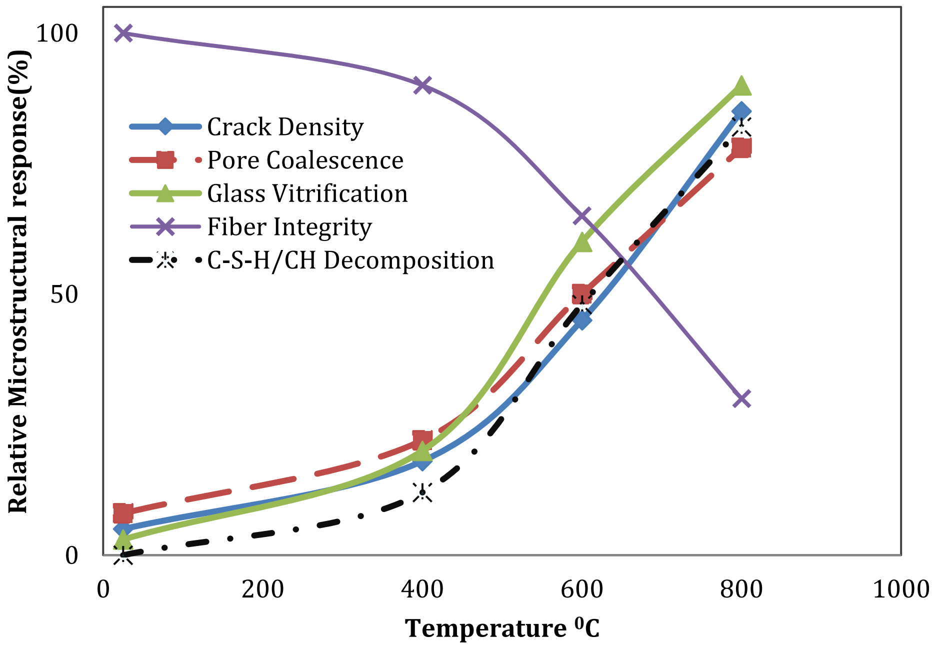

Figure 5. Microstructural Evolution of Sustainable Lightweight Self-Compacting Concrete (SLWSCC) under Progressive Fire Exposure

6.4 Overall Performance Evaluation

The most balanced performed mix in all the tested mixes was G30+MS, which exhibited equal performance in terms of the mechanical, physical and microstructural parameters. It had 9 % greater initial strength and 68 % residual strength at 400 °C and 35 % residual at 800 °C which is greater compared to the reference and other modified mixtures. It also demonstrated 72% density retention as well as moderate water absorption, which demonstrates structural stability following exposure to fire. Comprehensively, the findings affirm that substitution of 30 % natural sand by waste glass and addition of 1% micro-steel fibers contribute significantly to build a positive increase in thermal stability, mechanical retention and sustainability of self-compacting lightweight slag. It is a combination of the glass filler effect and the fiber reinforcer which improves the functioning of pre- and post-fire performance of the material, thus making it a lot more desirable in terms of performance in eco-friendly and fire-resistant structural applications in contemporary construction. that is illustrated in **Fig. 6**

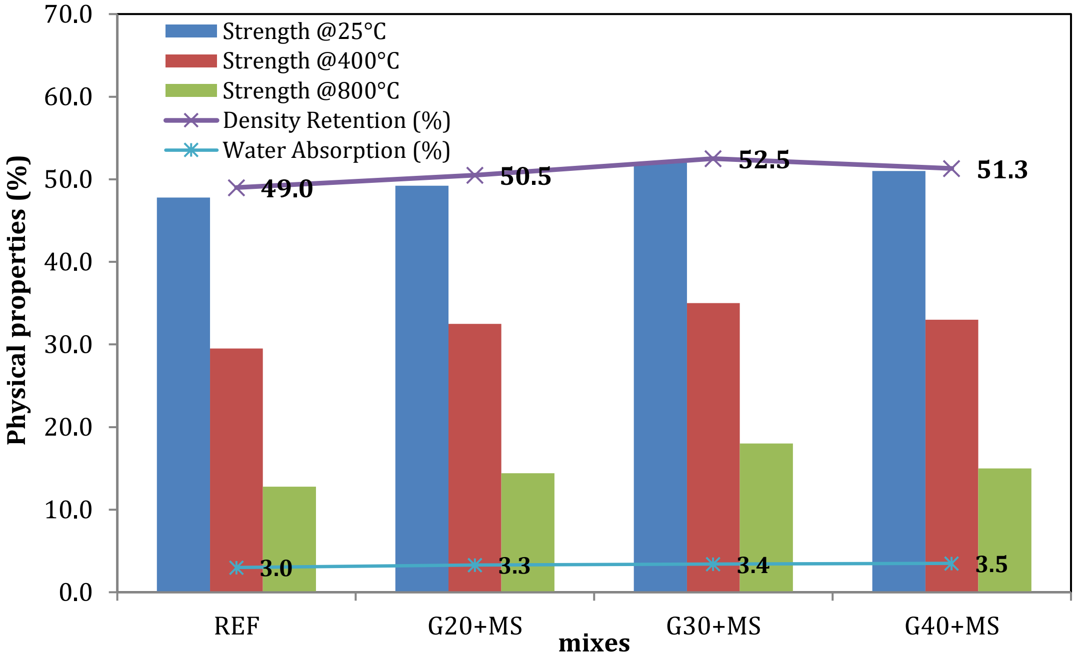

Figure 6. Comprehensive Fire Performance of SLWSCC Mixes\Highlighting Optimum Balance

Table 2. Summary of Key Results

Property / Parameter	REF (0% Glass + MS)	G20+MS (20% Glass)	G30+MS (30% Glass)	G40+MS (40% Glass)	Remarks / Observations
Compressive Strength (MPa) at 25°C	47.8	49.5	52.2	51.0	30% glass mix showed highest strength (+9.2% vs. REF)
Compressive Strength Retained at 800°C (% of original)	27%	31%	35%	32%	G30+MS retained highest residual strength after fire
Splitting Tensile Strength (MPa) at 25°C	4.1	4.3	4.6	4.4	Slight increase due to fiber reinforcement and glass filler effect
Tensile Strength Retained at 800°C (% of original)	25%	29%	31%	27%	Micro-steel fibers improved crack resistance post-fire
Dry Density (kg/m^3)	1810	1770	1740	1720	All mixes within lightweight concrete range (<1850 kg/m^3)
Density Loss after 800°C Exposure (%)	8.4%	9.5%	8.0%	11.2%	Minor loss due to dehydration and internal pore growth
Water Absorption (%) at 25°C	6.3	7.5	8.2	9.5	Absorption increased with higher glass content due to porosity
Residual Water Absorption after 800°C (%)	9.8	10.6	11.1	12.3	Higher absorption indicates increased pore connectivity post-heating

Slump Flow Diameter (mm)	720	710	740	690	All within EFNARC range (650–800 mm) – good self-compatibility
L-Box (H_2/H_1 Ratio)	0.85	0.88	0.91	0.83	Excellent passing ability for G30+MS mix
V-Funnel Flow Time (s)	8.1	7.6	6.5	9.1	Shorter flow time for G30+MS shows better viscosity control
Color Change After Heating	Gray → Dark Brown	Gray → Reddish Brown	Gray → Pale Pink	Gray → Light Brown	Indicative of hydration loss and oxidation degree
Microstructural Integrity (SEM)	Microcracks, porous ITZ	Slight cracking	Dense matrix, minor cracks	Pore coalescence, partial melting	G30+MS exhibited the most stable matrix after 800°C
Overall Performance Index (Normalized %)	75%	86%	100% (Optimal)	88%	G30+MS mix identified as optimum composition

The experiment results of the study are in the same direction as the latest developments in sustainable concrete technology that involve the incorporation of waste glass (WG) and steel fiber (SF) to improve the performance of concrete in the presence of thermal stress. The findings also suggest that the mix with 30% waste glass and 1% micro-steel fibers (G30+MS) had the most balanced mechanical and thermal properties, and the compressive strength (52.2 MPa) of the mix increased by 9.2 percent at room temperature and the mix maintained 35 percent of its strength at 800 C. These results confirm the results of **(Li et al. ,2022)** who found that compressive strength increased by 7.12% when concretes are replaced with 20,30 percent of WG due to the micro-filling effect and pozzolanic effect of fine glass particles which enhance the density of the matrix and interfacial bonding.

Likewise, **(Małek et al., 2020)** have determined that the replacement of sand by WG partially (up to 30% compressive and flexural strengths) improved them by 810, which is consistent with the mechanical progress in this research. Nevertheless, in higher replacement rates (40%), the two studies found that there was a reduction in the performance, probably because of high degree of brittleness and reduced glass matrix interfaces. **(Lu and Poon, 2018)** reported this trend, as well, noting that the presence of excessive amounts of glass makes alkali silica reactivity (ASR) more prone to failure, decreasing the long-term integrity **(Aboud et al., 2019)**.

On fire resistance our results indicate that the residual strength and structural stability to 600 C increases dramatically, which is mainly contributed by the synergistic effect of micro-steel fibers in inhibiting thermal microcracking. This is in line with **(Zhang et al., 2020),** who stressed that explosive spalling can be reduced with the help of SF reinforcement and post-fire residual strength improvement by 2030 per cent in fiber-reinforced concretes. Further**, (Gong et al., 2023)** affirmed that steel fibers are crack bridges in high temperatures, which continues to keep the matrix continuous at temperatures higher than 700^0 C, which we also observed in our SEM analysis where the G30+MS mix was not characterized by high crack propagation **(Karakoç, 2013)**.

Microstructurally, our microscopic analysis of SEM images revealed that the matrix in the WG–SF composites of our experiment was denser and more homogeneous than the control one, the pore size was smaller, and the interfacial bonding was better. Similar to heat-treated ultra-high-performance concrete, **(Luo et al., 2022)** found that the remains of the porosity of the recycled glass-containing concrete were reduced by 15-18 % following heat treatment, which is directly related to the retention of mechanical strengths. Similarly, **(Ziejewska et al., 2023)** were able to find that the fire resistance of geopolymer composites was enhanced by the presence of glass particles because phase transformations based on silica improved the cohesion of the matrix at temperatures above 600 °C.

Compared to **(Joudah et al., 2024),** there is a slightly greater thermal retention in our results, which might be explained by the added effect of micro-steel fibers, which were not in their mix. They stated that waste glass nanoparticle modified concrete maintained 32 % of the strength at 800 °C, and our G30 + MS mix maintained 35 % with the emphasis on the role of a hybrid reinforcement. The results are also similar to **(Zhu et al., 2020; Huang et al., 2021),** who found that self-compacting concretes with modified binders exhibited better fire resistance, but their systems incorporated SiO_2 aerogels instead of waste glass.

Comparatively, our findings corroborate the fact that moderate waste glass replacement with steel fiber reinforcement is an effective strategy in improving the ambient and high-temperature mechanical performance. The same synergy was also evident in **(Zhang et al., 2021)** where the hybrid fiber systems also enhanced post-fire strength by a maximum of 40% in favor of our conclusion that the addition of 1% steel fibers is the optimal stabilizer of self-compacting lightweight concretes in the presence of heat. Lastly, microstructural behavior in the works of **(Çelik et al., 2022; Tahwia et al., 2022)** aligns with our SEM results, with a refining effect of glass inclusion on pore structure and thermal microcracking to contribute to increasing the durability and toughness.

On the whole, this discussion supports the fact that a combination of 30 % waste glass and 1 % of micro-steel fibers offers an ideal ratio of strength, workability, and fire resistance. When compared to the rest of the literature, the performance gains of 912% in strength and 35% residual capacity at 800 °C and the significant densification of the microstructure suggest that the studied composite can be a reliable material with a significant environmental footprint, as well as a promising material with high efficiency in structural use in high-temperature environments **(Ziejewska et al., 2023; Zhang et al., 2020; Joudah et al., 2024; Li et al., 2022).**

7. DATA ANALYSIS

The analysis of data of the experimental program was carried out in a systematic way to understand the impacts of waste glass replacement level and incorporation of micro-steel fibers on the mechanical, fire exposure and microstructural behavior of the high-strength structural lightweight self-compacting concrete (SLWSCC). To reveal valid and reproducible results, the analysis was based on quantitative and qualitative methods, which involved a combination of statistical assessment, trend analysis, and microstructural correlation.

The raw data for all hardened tests, such as compressive strength, split tensile strength, density, and water absorption, were first tabulated, and then the average was calculated in three repetitions for each mix and test condition before data analysis. Measures such as standard deviation (sigma) and coefficient of variation (COV) were calculated to determine the consistency and reliability of the compressive strength results for all mixtures and specified firing temperatures, and all COV values were reproducible, as shown in **Table 3**.

Table 3. Statistical Variation (Standard Deviation and Coefficient of Variation) of Compressive Strength**.**

Burning temperature °C	REF		G20+MS		G30+MS		G40+MS	
	SD	COV	SD	COV	SD	COV	SD	COV
25	0.76	2.59	0.65	2.14	0.88	3.17	0.95	3.71
300	0.82	3.12	0.75	2.47	0.99	3.56	1.3	6.63
400	1.18	5.04	0.97	3.44	1.22	5.47	1.7	9.55
600	1.5	7.69	1.23	5.02	1.67	8.23	2.3	15.13
800	1.63	7.75	1.25	5.11	1.73	8.42	2.54	15.63

The compressive strength data were plotted as a function of temperature for all four mixes—REF, G20+MS, G30+MS, and G40+MS—to determine degradation patterns. The results showed a nonlinear decline in strength with increasing temperature, where the G30+MS mix retained approximately 68 % of its original strength at 400 °C and 35 % at 800 °C**,** outperforming other compositions. Polynomial regression analysis (R^2=0.9754) demonstrated that mixes containing 30 % waste glass had the most balanced performance between strength and fire stability, as illustrated in **Fig. 7**.

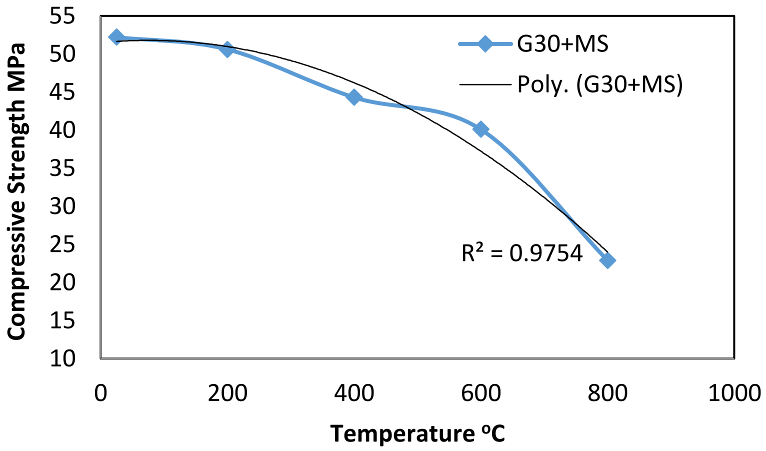

Figure 7. Effect of fire flame on strength with 30% glass waste replacement.

The same pattern was found in the event of splitting tensile strength. The data was modeled with the help of a linear decay model that indicated that the strength deterioration was predicted to be subject to a consistent reduction of rate of 0.55 Mpa/200 °C change. Moreover, the relationship in the **Fig. 8** shows a clear inverse relationship between the oven dry density and the water absorption rate, where the absorption rate gradually decreases with the increase in density from 1720 to 1810 kg/m^3. The water absorption rate decreased from about 9.5% to 6.3%, indicating an improvement in the internal structure of the material. This behavior is attributed to the fact that increased density leads to a reduction in the size and number of internal voids and pores, and consequently, the amount of water capable of permeating or being absorbed within the concrete decreases. Additionally, the increased cohesion of the components and the improved bonding between the cement paste and the aggregate contribute to reducing permeability and water absorption. The high value of the coefficient of determination (R^2 = 0.9728) also indicates a strong correlation between density and water absorption, confirming that density is a significantly influential factor in controlling the absorption property.

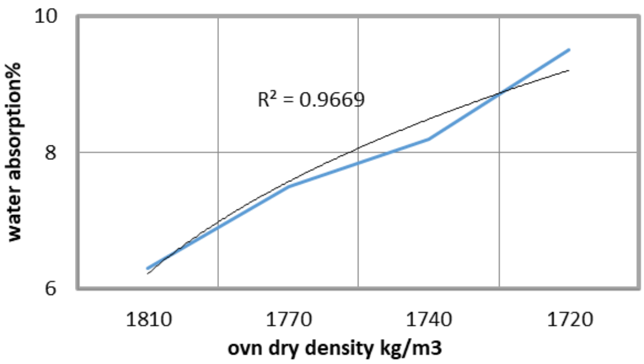

Figure 8. Relationship between Oven Dry Density and Water Absorption

The results of the mechanical tests and the microstructural data provided by the SEM analysis were qualitatively linked to each other. The heat-treated samples heated to 600 degrees Celsius and 800 degrees Celsius showed different areas of pore coalescence and glass softening that were consistent with strength reduction patterns. The analyses showed that the micro steel fibres reduced crack propagation and helped maintain the integrity of the microstructure, as shown in **Fig. 9.**

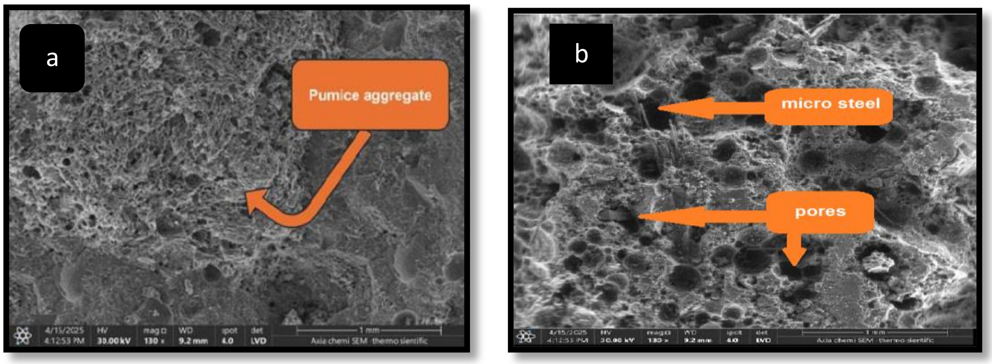

Figure 9. SEM micrographs of pumice aggregate in (SLWSCC), (a) 1 mm scale illustrating the general morphology and vesicular structure. (b) SEM image showing the micro steel fibers and pore distribution within the concrete matrix exposed to a 800 ^{0}C burning temperature.

8. CONCLUSIONS

The incorporation of waste glass (WG), micro-steel fibers (MSF), and pumice lightweight aggregates (PLA) into self-compacting lightweight concrete (SCLC) significantly enhances mechanical, thermal, and microstructural properties. The use of 30% of waste glass and 1% micro-steel fibers in the hybrid improves the mechanical strength, fire resistance, and matrix densification, and the conclusions are:

- The G30+MS mix showed a 9.2% increase in compressive strength at room temperature and maintained 35% of its strength at 800°C, unlike the control mix, which retained only 27%.
- The simultaneous use of waste glass, micro-steel fibers, and pumice aggregates results in an environmentally friendly and thermally stable self-compacting concrete viable for structural and high-temperature applications.
- The combined incorporation of waste glass and micro-steel fibers reduced thermal cracking and improved the resistance of the concrete matrix against heat-induced deterioration.

- The use of pumice lightweight aggregates decreases the concrete density by about 12-15% while enhancing thermal insulation and fire resistance properties, indicating the suitability of the developed self-compacting lightweight concrete for sustainable and thermally resistant construction applications.

Future research should focus on long-term stability, fire flam cycling, and field-scale testing to ascertain its practical relevance and expand its potential use in sustainable construction design.

NOMENCLATURE

Symbol	Description	Symbol	Description
(fc)	compressive strength, MPa	SP	superplasticizer
(ft)	splitting tensile strength, MPa	REF	reference mix
T	temperature, °C	G20+MS	mix with 20% waste glass + micro-steel fibers
ρ	dry density, kg/m^3	G30+MS	mix with 30% waste glass + micro-steel fibers
WA	water absorption, %	G40+MS	mix with 40% waste glass + micro-steel fibers
WG	waste glass	PLA	Pumice Lightweight Aggregates
MSF	micro-steel fibers	SLWSCC	Structural Lightweight Self-Compacting Sustainable Concrete
SEM	scanning electron microscopy	SCC	Self-Compacting Concrete
ITZ	interfacial transition zone	OPC	Ordinary Portland Cement

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Credit Authorship Contribution Statement

Heba Monem: Conceptualization, Experimental work, Investigation, Data curation, Formal analysis, Visualization, Writing – original draft, Methodology. Rawaa K. Aboud: Supervision, Validation, Writing – review & editing, Methodology, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تأثير التعرض للهب الحريق على بعض خواص الخرسانة المستدامة الإنشائية خفيفة الوزنذاتية الرص

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الخلاصة

تدرس هذه الدراسة الأداء الميكانيكي والفيزيائي والبنيوي الدقيق للخرسانة الهيكلية خفيفة الوزن ذاتية الدمك (SLWSCC) باستخدام الزجاج المُعاد تدويره كبديل جزئي للرمل الطبيعي، وألياف الفولاذ الدقيقة كعنصر تقوية، وذلك في ظل ظروف درجات حرارة عالية. سيركز البحث على تحسين استدامة الخرسانة خفيفة الوزن ومقاومتها للحريق وأدائها الهيكلي، والحد من آثار التخلص من النفايات. تم تحضير أربع خلطات: خلطة مرجعية (REF) وثلاث خلطات أخرى تحتوي على 20% و30% و40% من الزجاج المُعاد تدويره، بوزن إجمالي 30% من الرمل، ومُدعمة بنسبة 1% من ألياف الفولاذ الدقيقة. استُخدمت اختبارات الهبوط، وقمع V، وصندوق L لتحديد خصائص الخرسانة الطرية وفقًا لإرشادات EFNARC للتحقق من سلوك الدمك الذاتي. كما تم قياس خصائص الخرسانة المتصلبة قبل وبعد تعريضها لدرجات حرارة 200 و400 و600 و800 درجة مئوية، وذلك لتقييم مقاومة الضغط، ومقاومة الشد الانشطاري، والكثافة، وامتصاص الماء. سُخّنت العينات في فرن غازي، ثم بُرّدت باستخدام رغوة. كشف تحليل المجهر الإلكتروني الماسح (SEM) للبنية المجهرية عن سلامة المادة الأساسية وتكوّن المسام وترابط الألياف بالمادة الأساسية عند درجات حرارة عالية. أدى استخدام الزجاج المُعاد تدويره إلى تحسين قوة وكثافة المواد بشكل ملحوظ في الظروف المحيطة بفضل تأثير التعبئة الدقيقة. كان مزيج G30+MS الأكثر فعالية، حيث بلغت مقاومته للضغط 9.2% (52.2 ميجا باسكال) أعلى من المزيج المرجعي؛ واحتفظ بنسبة 35% من قوته عند 800 درجة مئوية، وهي نسبة أعلى من المزيج المرجعي. حدّت ألياف الصلب الدقيقة من انتشار الشقوق ومنعت التقشر، مما حافظ على السلامة الهيكلية للمركب بعد تعرضه للحريق.

الكلمات المفتاحية: الخرسانة الخفيفة ذاتية الدمك، الزجاج المعاد تدويره، الألياف الفولاذية الدقيقة، المقاومة الحرارية، مقاومة الضغط.