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Enhancing Mechanical Properties of Alkali-Activated Slag SIFCON for Sustainable Construction Using Recycled Glass and Tire-Derived Waste Steel Fibers

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Abstract

This paper presents the outcomes of a study in which continuous steel fibers, recovered from scrap tires of vehicles, were used to prepare alkali-activated slag-based slurry infiltrated fibrous concrete (SIFCON). In this experimental study, the steel fibers used were 250 mm long, with varying fiber contents of 0%, 1%, 2%, 3%, 4%, and 5%. The alkali-activated SIFCONs were produced by activating ground granulated blast furnace slag (GGBS) with a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. Mixtures with ordinary Portland cement (OPC) were also cast for comparison purposes. The feasibility of utilizing finely ground waste glass as a silicate source for chemical activator solution in alkali-activated SIFCONs was also investigated. In this context, two different molar concentrations of NaOH, namely 8 M and 14 M, were employed during production. As activators, one series of mixtures utilized sodium hydroxide and sodium silicate solutions, while the other series replaced sodium silicate with finely ground waste glass. As a result, three different waste materials were utilized in concrete. 30 different mixtures were cast and examined in the experimental study. Load–deflection curves were obtained in three-point bending test and mechanical properties of the mixtures such as compressive, splitting and flexural strengths, fracture energy, and toughness were determined. The flexural strength and toughness increased with the use of waste steel fibers. The continuous waste fibers derived from discarded tires yielded results comparable to commercially available fibers, demonstrating their effectiveness in enhancing mechanical properties. Depending on mix design, the alkali-activated SIFCON attained flexural strength exceeding 75 MPa and compressive strength surpassing 100 MPa. These results suggest that concretes incorporating a variety of waste materials can be effectively combined. This innovative approach bridges an existing gap in the literature by combining alkali activation, waste glass, and waste steel fibers, ultimately yielding a sustainable composite that outperforms normal concretes in terms of mechanical properties while promoting environmental sustainability. Test results demonstrate that it is possible to obtain concrete with comparable mechanical properties while primarily composed of by-products and waste materials. This approach marks a substantial step in achieving high-performance concrete that relies solely on waste or by-products.

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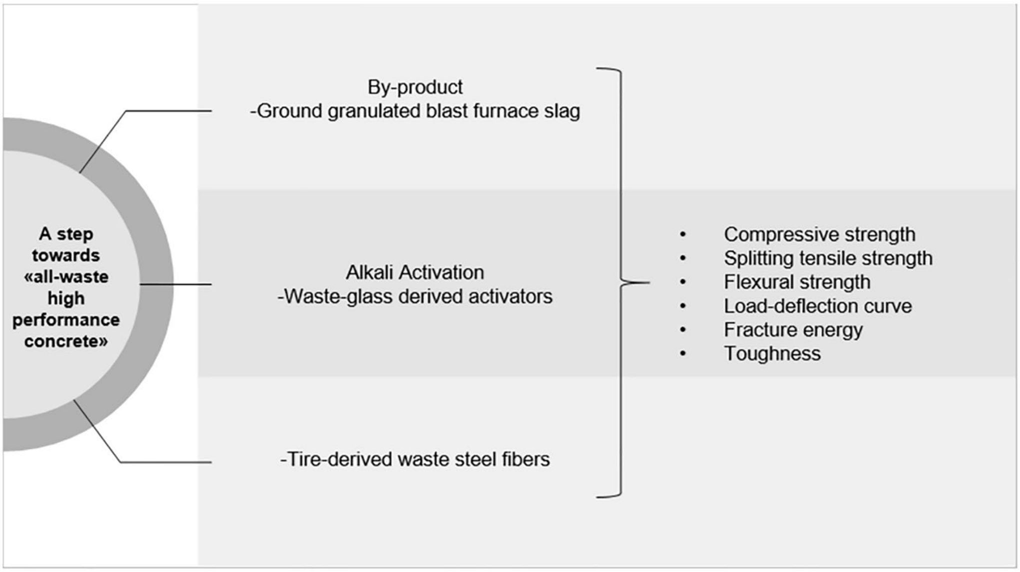
Highlights

- For sustainable production, continuous steel fibers that were obtained from worn out tires were used in various amounts in order to prepare alkali-activated ground granulated blast furnace slag based SIFCON.
- The usability and feasibility of ground waste glass as a potential silicate source in chemical activator solution were also investigated.
- Higher amounts of waste fibers recovered from scrap tires increased both flexural strength and fracture energy.
- The alkali-activated SIFCON attained flexural strength surpassing 75 MPa and compressive strength exceeding 100 MPa.
- Results confirmed that continuous waste steel fibers obtained from end-of-life scrap tires can effectively be used in high-strength SIFCONs and can be successfully utilized in alkali-activated SIFCONs.

Keywords SIFCON, Alkali activation, Waste fibers, Scrap tires, Mechanical properties

Graphical Abstract



1 Introduction

Concrete is unsustainable due to its significant consumption of natural materials during production. The energy requirement for the cement production is also very high (Afkhami et al., 2015). Annual concrete consumption worldwide is estimated at 14 billion m^3, making it the second-largest contributor to global carbon dioxide emissions (Global Cement & Concrete Association, 2021; Marey et al., 2022). While reducing concrete usage may be challenging due to high demand, enhancing the performance and durability of concrete can extend the service life of structures, potentially reducing future demand. This will not only lower costs and damages associated with repair, demolition, and rebuilding but also reduce the carbon footprint and ecological impact of concrete through the recycling and utilization of waste materials in concrete technology.

In the effort to reduce cement consumption in concrete, pozzolanic materials can be employed. Pozzolans not only reduce the cement requirement but also enhance concrete durability, particularly in later stages (Becerra-Duitama & Rojas-Avellaneda, 2022). To reduce the use of cement, the search for alternative binders has emerged (Tan et al., 2021). Utilizing alkali-activated pozzolanic materials in concrete is an innovative approach to reduce cement requirements. Pozzolans can be activated with alkaline materials and mechanical properties similar to those of normal concretes can be achieved

(Alonso et al., 2018; Robayo-Salazar et al., 2017; Thomas & Peethamparan, 2015; Toniolo et al., 2018). As a result, both cement consumption is reduced and waste materials are utilized simultaneously. In the production of alkali-activated materials, chemicals with basic character, such as potassium hydroxide, sodium hydroxide, and sodium silicate, are used (Gok & Kilinc, 2017; Shi et al., 2003). In alkali activation, using waste materials as activators may also provide a solution for cleaner production. Given the significant space waste glass occupies in landfills, research is being conducted to explore its recycling in the construction sector (Mohajerani et al., 2017). Previous studies indicated that waste glass can be a potential source of sodium silicate for the alkali-activated materials (Gok & Sengul, 2021; Puertas & Torres-Carrasco, 2014; Torres-Carrasco & Puertas, 2015; Torres-Carrasco et al., 2015). Concrete properties similar to those of normal concretes or improved properties can be achieved by pozzolans and reusing various wastes in concrete (Gok, 2020; Gok et al., 2021; Kilic & Gok, 2021a; Saxena et al., 2021; Sengul, 2016, 2018), and environmentally friendly and innovative building materials can be developed in the future that are entirely made of waste materials or by-products.

Various fibers made from different materials are used in concrete (Kilic & Gok, 2021b; Plizzari et al., 2019; Su et al., 2023). Car tires are designed to endure substantial levels of impact and stress, thanks to the inclusion of various types of high-strength steel cords. The steel cords obtained from the scrap tires is regarded as waste and are solely utilized as raw materials in steel production. The steel cords from the tires can be reclaimed in sizes comparable to commercial steel fibers. Prior studies have shown their effective use in concrete to produce steel fiber-reinforced concretes (Caggiano et al., 2017; Liew & Akbar, 2020; Sengul, 2016, 2018). These waste fibers are notably more cost-effective than commercial steel fibers since they are obtained through the recycling of scrap tires (Amin et al., 2023). Recycling this material can reduce energy, time, and economic losses associated with the transport, storage and disposal of end-of-life tires, and the production of new steel fibers.

Slurry infiltrated fiber concrete (SIFCON), which is a special kind of fiber-reinforced concrete, incorporates a substantial quantity of prepacked fibers. Typically, SIFCON contains a higher cement content than regular concrete. As a result of its elevated fiber content, SIFCON exhibits remarkable tensile strength, ductility, impact resistance, and toughness (Yazici et al., 2010). These characteristics make SIFCON well suitable for applications in which conventional concrete may be insufficient, such as structural elements demanding increased crack resistance or enhanced load-bearing capacity. However, the cost of SIFCON is relatively high due to its substantial cement and fiber content, which serves as a limiting factor for its widespread use. Previous studies have shown that SIFCON production costs were reduced when utilizing waste steel fibers. It was demonstrated through multi-objective optimization that waste fibers can be a more favorable reinforcement option in slurry infiltrated fiber concrete production (Sengul, 2018).

The principal aim of this experimental study was to assess how waste fibers influence the properties of alkali-activated SIFCON. Waste steel fibers recovered from scrap tires were used in the mixtures. The length of the waste fibers in this study was 250 mm, which were actually cords. Hence, the use of the term "continuous fiber" helps in distinguishing this material from the short fibers typically employed in concrete. Long fibers like these are not suitable for use in traditional steel fiber-reinforced concrete; however, they can be effectively employed in the production of SIFCON. Comparison of mechanical properties of Portland cement mixtures with those of the alkali-activated mixtures formed a part of the study. The ground granulated blast furnace slag (GGBS) used in this study was activated by sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). The viability and the potential of the usage of finely ground waste glass as an alternative source of silicate were also investigated. Consequently, waste steel fibers and waste glass were used together in alkali-activated slag mixtures.

This study presented herein stands out from existing studies in the literature, as it presents an innovative approach to high-performance concrete production. This approach leverages the synergy of alkali activation, ground waste glass, and continuous waste steel fibers derived from tires. Through this experimental study using the SIFCON production technique, which resulted in a composite distinct from traditional fiber-reinforced concrete or traditional SIFCON, a novel approach has been demonstrated for the development of eco-friendly building materials. In this study, within the alkali-activated mixtures, the aggregates and sodium hydroxide (as part of the activator) were the non-waste materials, while all other components were derived from waste sources. Notably, prior studies have validated the successful utilization of waste aggregates in concrete (Elibol & Sengul, 2016; Salihpasaoglu & Sengul, 2020). While a recent study (Gok & Sengul, 2023a) has explored a similar path using waste steel fibers, our objective here is to attain greater bending strength and toughness through the utilization of high-strength continuous recycled tire-derived fibers, thus unlocking the full potential of the high-strength long steel cords. This study may play a role in part of the global effort to reduce the impact of building materials and energy usage, and it is a step

Table 1 Chemical Composition of GGBS (Gok, 2020)

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl^-	LOI
(%)	43.5	1.2	11.3	29.2	10.3	1.3	1.1	0.35	0.011	1.9

Table 2 Properties of sodium silicate solution (Pozitif Kimya, 2024)

Product name:	Sodium silicate solution
Other names:	Sodium silicate, water glass
Quality class:	Technical grade
Chemical formula:	$Na_2O.nSiO_2 + H_2O$
Density (20ºC):	Density (20ºC): 1.38–1.42 gr/cm^3
pH (in 1% solution):	11–12.5
Physical appearance:	Clear, colorless or slightly gray colored liquid
Purity degree:	2 Module, 40° Baumé
UN code:	3266

toward more sustainable concrete production. The high strengths achieved in the experimental program could represent an advancement toward the development of concrete composed solely of waste materials.

2 Materials and Methods

2.1 Materials

2.1.1 Cement, Slag, Aggregates, and Activators

Alkali-activated mixtures did not contain any cement, but an ordinary Portland cement (OPC) (CEM I 42.5 R) was used in production of the reference specimens. In the experimental studies, Portland cement CEM I 42.5 R, supplied from Akçansa Cement Industry and Trade Inc. (Türkiye), and compatible with TS EN 197–1 (2012) standard, was used.

In alkali-activated SIFCON production, GGBS having a Blaine fineness of 550 m^2/kg was used as the only binder. Ground granulated blast furnace slag was supplied from Kardemir Karabük Iron and Steel Industry and Trade Inc. (Türkiye). The specific weight of the GGBS is 2.97 g/cm^3. The chemical composition of the GGBS is shown in Table 1.

The same siliceous sand was used in all mixtures and the maximum particle size of the aggregate was 0.5 mm. NaOH and Na_2SiO_3 were used for the activation of GGBS. The NaOH pellets with 99% purity were used and these pellets were dissolved by stirring in water to prepare 8 M and 14 M sodium hydroxide solutions. Sodium silicate (40°Baumé, and silica modulus Ms: $SiO_2/Na_2O = 2$) used was in liquid form, and the solid amount in the sodium silicate solution was 33%. Sodium silicate solution was supplied from Pozitif Kimya (Türkiye). Its properties are given in Table 2.

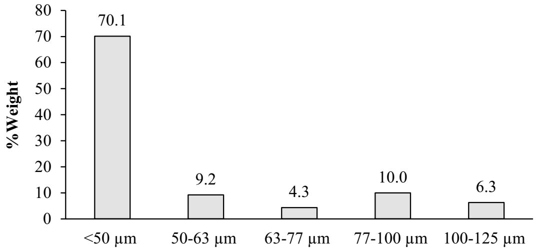


Fig. 1 Particle size distribution of ground glass

2.1.2 Waste Glass

Rather than employing commercial Na_2SiO_3, ground waste glass was utilized for an alternative silicate source. For this purpose, 150 g of waste glass powder was added to one liter of NaOH solution, and during 6 h it was stirred at 80 °C. The glass powder's grain size is below 0.125 mm and it has an average particle size of 30 µm. The particle size distribution of the ground glass is given in Fig. 1. The specific weight and bulk density of the glass powder is 2.58 g/cm^3 and 1.56 g/cm^3, respectively. The concentrations of the NaOH solutions used were 8 M and 14 M. The activators, prepared by heating and mixing the ground waste glass in NaOH solution, were used in SIFCON production after appropriate filtering. Before using the prepared activator solutions in production, waiting for a minimum of 24 h is necessary to enable the chemical activator to reach room temperature, ensuring sufficient cooling.

2.1.3 Waste Fibers

As a reinforcement element, waste steel fibers recovered from steel bead wires of the scrap tires were used in the experimental study. Continuous cords recovered from scrap tires can be cut into any desired length. Unlike the traditional fibers used in concrete technology that are usually a few cm in length, the fibers used in this study were 250 mm long. Therefore, these fibers used in this study are in fact continuous cords that span along the length of the specimens. Due to their lengths, these fibers may be accepted as continuous fibers or cords. That is why this waste material was named as continuous fibers by the authors. The diameters of the fibers were between 1.59 and 1.80 mm. The length of the fibers was 250 mm. As a result, the average fiber aspect ratio (length/

diameter ratio) of the fibers was 153. There is a curvature in these cords due to the shape of the vehicle tire. The fibers were cut to the desired length to fit the mold. Even if the curvature of the fiber was tried to be corrected by hand, some curvature still remained and the fibers could not be brought into a completely flat straight shape. The fibers used in this study are shown in Fig. 2. Tensile test was performed on ten fiber samples and the average tensile strength was 2147 MPa with a standard deviation of 37 MPa. These results indicate that the fibers can be classified as high strength. The waste fibers used in this study had clean surfaces and were free from contaminants commonly found in waste steel fibers that were recovered from scrap tires, such as rubber and textile residues.

2.2 Mixtures

Five different series of mixtures were produced in the study. The initial stage of the study included determining the highest waste fiber volume that could fit within the mold, which was obtained as approximately 5% by trial productions. Starting from a baseline of 0%, the fiber contents were incrementally increased to 5% in steps of 1%, based on the maximum fiber content established. Thus, for each series, six different mixtures were cast.

Each mixture series was prepared with a different matrix phase. One of the series were produced with Portland cement as reference, while the other four series were containing alkali-activated blast furnace slag as binder. The alkali-activated mixtures were produced with 8 M NaOH or 14 M NaOH. Commercially available liquid sodium silicate was used in two of these mixture series. For comparison, the same mixtures were also prepared using the sodium silicate obtained from waste glass. As a result, 30 different mixtures were produced which are summarized in Table 3. The composition of the mixtures was established using the insights and results obtained from a prior study (Gok & Sengul, 2021). Composition of mortars are shown in Table 4.

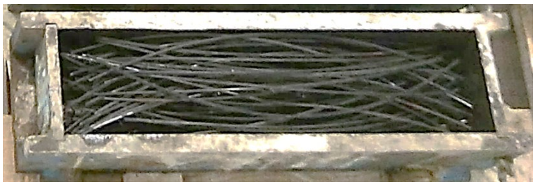


Fig. 2 Continuous waste fibers which were preplaced into mold randomly

In Table 3, the code PC represents Portland cement, 8 M and 14 M represent the molarities of NaOH, and WG shows waste glass, which is used in activator solutions instead of commercial sodium silicate.

The steel fibers were preplaced into the greased molds, so that the fibers did not move or change their direction during the casting of the flowable mortar. After the fibers placed in the mold, the flowable cement slurry was poured in. The workability of the slurries used exhibited similarities. At this stage, thanks to their consistent viscosity, ease of handling and placement were assured, while segregation was effectively prevented.

2.3 Specimens and Testing

Since the lengths of the fibers were substantially long, they cannot be fitted into cubic or cylindrical samples. Therefore, it was possible to prepare only prism specimens. 70 × 70 × 280 mm-sized samples were used. These smaller-sized prisms may be criticized since they do not confirm the sizes recommended in the related standards. However, using larger specimens would mean higher failure loads in flexural testing and the capacity of the test

Table 4 Composition of mortars

Ingredients (kg/m^3)	Mixtures				
	PC	**8 M**	**8MWG**	**14 M**	**14MWG**
OPC	795	0	0	0	0
Blast furnace slag	0	771	771	771	771
NaOH solution	0	181	0	195	0
Na_2SiO_3 in liquid form (commercial)	0	470	0	507	0
Waste Glass + NaOH solution	0	0	763	0	864
Water	431	0	0	0	0
Fine aggregate	994	963	963	963	963

Table 3 Mixture series prepared

Series designation	Binder type	Activator type	Fiber content (%)
PC	Portland cement	–	0, 1, 2, 3, 4, 5
8 M	Alkali-activated GGBS	8 M NaOH + Commercial sodium silicate	
8MWG		8 M NaOH + Waste glass	
14 M		14 M NaOH + Commercial sodium silicate	
14MWG		14 M NaOH + Waste glass	

equipment, which was 100 kN, would be exceeded. To avoid this issue, smaller-sized prisms were prepared. It should be also noted that even if the specimen size given in related standards was selected, the size effect would still be expected since the continuous fibers used have sizes larger than the commercial fibers. The waste fibers were preplaced along the longitudinal axis of the prisms as shown in Fig. 2. The distribution of the fibers in the mold was uniform as they were placed by hand.

The placement of the fiber on the longitudinal direction of the tested specimens may be criticized. While fibers oriented in a single direction may be considered a drawback due to their directional impact on material properties, this material can be readily employed in bending elements functioning in a single direction.

Since SIFCON mixtures usually contain high amounts of fibers, it may be criticized that the fiber contents used (for example 1% or 2%) in some mixtures of this study are not typical SIFCON mixtures. However, all the specimens in this study were obtained by preplacing the fibers into the greased molds and then filling up by the flowable slurry, which is the preparation technique for casting SIFCON. As a result, all the specimens prepared in the study were identified as SIFCON mixtures. For the low fiber contents ($v_f = 1$, 2, and 3%), the molds were cast in two layers to ensure homogeneous fiber distribution in the cross section. Half of the fibers were preplaced, followed by pouring the slurry. Remaining fibers were then placed and slurry was poured in. With this method, distributions of the fibers were uniform for all fiber contents. Cross sections of the specimens inspected after the tests confirmed that the fiber distributions were homogeneous for the samples.

Flexural testing was performed on the prism-shaped specimens based on EN 14651 (2007). To force the crack to propagate in a given section, notches were formed on the prisms. The prisms were rotated over 90° around their long axes and notches at mid-span with a depth of 1/6th of the specimen height were obtained using a diamond saw. Closed-loop testing device was used for loading, the deflections were recorded, and load–deflection curves were obtained. The fracture energies were determined according to the recommendations of RILEM 50-FMC Technical Committee (1985). Since the samples were notched before bending, the cracks followed this path and other sections of the sample (i.e., the ends of the prisms) were not affected from this test. After the flexural testing, cubes cut out from the undamaged ends of the prisms underwent compression testing based on EN 12390–3 standard (EN 12390–3, 2019). Rate of compressive loading was selected as 0.6 MPa/s and kept constant in all tests. Tensile splitting strength of the mixtures were determined according to EN 12390–6 (2009). Loading rate was also 0.6 MPa/s for this testing. Five prisms were prepared for each mixture. For each prism, two cubes were cut out, and as a result, ten cubes were obtained for each mixture. Of these cubes, half of them were used in compression test while the remaining in splitting test. The tests were carried out at 90 days. The concretes were kept in 20 °C lime-saturated water for curing until testing.

3 Results and Discussion

3.1 Compressive Strength

Compressive strengths of the SIFCON mixtures are shown in Table 5 and Fig. 3. The plain mixtures produced with ordinary Portland cement (mixture coded as PC0 in Table 5) and 8 M commercial activators (8M0) had almost the same compressive strength (Fig. 3 and Table 5). For these mixture series (PC and 8 M) increases in strength were observed with the fiber content. For instance, the compressive strength of SIFCON containing OPC as the binder and 5% fiber (PC5) was approximately 37% higher than the same mixture without fibers (PC0). For the same fiber content, strength increase was slightly more (approximately 9%) for the mixtures with 8 M commercial activators.

The compressive strengths of the SIFCON mixtures prepared with waste glass as the source of silica (8MWG and 14MWG) were similar for various fiber contents. As shown in Fig. 3, depending on the fiber content, there were some slight changes in the compressive strength of these mixtures. For the 8MWG mixture series, small decreases in strength were obtained with fiber content. Compressive strength of the 14MWG mixture series, however, increased slightly. Despite such changes, compressive strength of these mixtures (8MWG and 14MWG) containing waste glass were still the lowest among the mixtures cast.

In comparison to the reference concretes incorporating CEM I 42.5R Portland cement, the strength of the ones produced with waste glass were approximately 40 to 70% lower (Fig. 3). For 3% fiber content, compressive strength of reference mixture (PC3) was 47.6 MPa. However, the strength of the 8MWG3 and 14MWG3 was 18.3 MPa and 17.8 MPa, respectively. For the mixtures prepared with waste glass, except the plain concretes, the compressive strengths were similar and differ from each other only by a few MPa. Based on these test results and within the confines of the experimental investigation, it seems that the molarity of the NaOH did not have a significant effect on the compressive strength and both of the mixtures activated by waste glass (8MWG and 14MWG) have very low strengths compared to other mixture series.

Mixtures activated by 14 M NaOH + commercial sodium silicate, reached the highest strengths.

Table 5 Mechanical properties (av. ± st. dev.)

Series	Compressive strength (MPa)	Splitting strength (MPa)	Flexural strength (MPa)	Fracture energy (J/m^2)	Toughness (J)
PC0	39.5 ± 1.0	7.1 ± 0.6	4.6 ± 0.8	131 ± 27	0.6 ± 0.1
PC1	45.2 ± 2.0	9.6 ± 0.7	12.8 ± 4.1	8765 ± 247	36.7 ± 14.7
PC2	46.4 ± 2.2	10.4 ± 0.9	32.2 ± 3.8	23752 ± 4157	99.6 ± 17.5
PC3	47.6 ± 2.1	11.8 ± 1.2	35.4 ± 1.5	27757 ± 4710	116.5 ± 19.8
PC4	52.2 ± 4.3	13.1 ± 1.4	40.3 ± 4.5	31468 ± 1863	132.0 ± 7.8
PC5	54.3 ± 3.7	13.2 ± 1.9	59.0 ± 3.9	49478 ± 4886	187.1 ± 20.5
8M0	39.2 ± 0.8	3.0 ± 0.4	3.7 ± 0.4	203 ± 6	0.8 ± 0.1
8M1	37.5 ± 7.6	6.7 ± 1.6	13.2 ± 0.6	9928 ± 624	41.6 ± 2.1
8M2	42.0 ± 8.2	6.9 ± 0.8	35.2 ± 6.3	27433 ± 5367	115.1 ± 13.5
8M3	49.4 ± 8.7	10.4 ± 0.3	38.1 ± 0.6	29856 ± 5217	125.3 ± 21.9
8M4	51.6 ± 8.4	13.1 ± 2.2	50.5 ± 10.7	44529 ± 6557	186.9 ± 27.5
8M5	59.0 ± 8.6	15.3 ± 2.8	55.2 ± 9.2	47943 ± 6908	201.2 ± 29.0
8MWG0	24.6 ± 0.6	3.4 ± 0.3	3.1 ± 0.2	103 ± 19	0.4 ± 0.1
8MWG1	18.7 ± 2.0	4.3 ± 0.1	6.5 ± 2.0	7477 ± 1320	31.2 ± 5.5
8MWG2	17.3 ± 3.1	4.4 ± 0.2	10.1 ± 2.0	8595 ± 1392	36.0 ± 5.8
8MWG3	18.3 ± 2.2	4.6 ± 0.4	14.3 ± 1.5	11843 ± 869	49.6 ± 3.7
8MWG4	18.6 ± 2.1	8.7 ± 2.2	18.4 ± 3.1	17513 ± 2770	73.4 ± 11.6
8MWG5	14.6 ± 4.2	10.0 ± 1.7	21.2 ± 2.1	25435 ± 2377	106.7 ± 10.0
14M0	68.0 ± 0.7	5.9 ± 0.2	1.8 ± 0.4	80 ± 16	0.3 ± 0.1
14M1	83.7 ± 8.6	8.2 ± 2.1	23.3 ± 4.3	16384 ± 2933	68.7 ± 12.3
14M2	87.2 ± 7.4	13.5 ± 2.7	27.0 ± 8.0	20278 ± 197	85.0 ± 14.2
14M3	95.5 ± 6.5	16.3 ± 2.9	44.1 ± 8.4	33989 ± 5211	142.6 ± 19.8
14M4	100.9 ± 9.8	18.8 ± 3.2	62.9 ± 11.8	47582 ± 877	199.7 ± 17.2
14M5	102.5 ± 8.7	19.4 ± 3.1	75.7 ± 9.5	53761 ± 7296	225.7 ± 30.6
14MWG0	14.4 ± 1.7	2.8 ± 0.7	1.4 ± 0.1	56 ± 8	0.2 ± 0.0
14MWG1	14.8 ± 1.0	4.2 ± 0.2	7.1 ± 2.0	4882 ± 1664	20.4 ± 7.7
14MWG2	15.6 ± 1.4	4.4 ± 0.6	15.8 ± 0.1	10014 ± 459	42.0 ± 1.9
14MWG3	17.8 ± 2.1	6.2 ± 1.8	23.0 ± 0.2	12292 ± 139	51.5 ± 0.8
14MWG4	18.4 ± 2.0	7.2 ± 1.2	24.9 ± 0.9	16367 ± 248	68.6 ± 1.0
14MWG5	19.5 ± 2.7	7.3 ± 2.0	26.8 ± 0.4	45350 ± 1138	70.2 ± 4.8

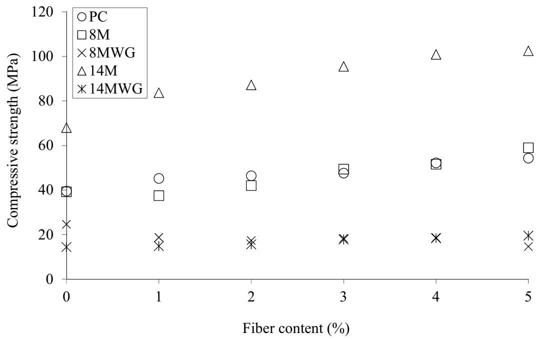


Fig. 3 Compressive strength test results

Compressive strength of the plain mixture (14M0) in this mixture series was 68.0 MPa. The effect of fibers is significant for this binder type and higher strengths were obtained by increasing fiber content. For example, 102.5 MPa was achieved with 5% fiber (Mixture 14M5), which corresponds to 51% increase compared to plain mixture without fibers (14M0).

In fiber-reinforced concretes or SIFCON, compressive strength does not differ significantly with the use of fibers (Sengul, 2016, 2018). However, as presented above, the compressive strengths obtained in this study increased with fibers. The compressive strengths of the mixtures were obtained based on EN 12390–3 (2019). When concrete is subjected to uniaxial compression, axial strain occurs and height of the specimen is reduced. At the same time, lateral strains take place and increase in the diameter of the specimen is recorded. This is a very well-known behavior of materials and it is reflected with the Poisson's ratio. Since the fibers used in this study were long continuous fibers and preplaced in a single direction into the prism mold before casting, they span through the whole width of the specimen. As mentioned above, concrete cubes extracted from prism samples were used in the compressive testing. As a result of the prearranged placement of the fibers, they were uniformly distributed and oriented perpendicular to the loading direction. During the loading, these fibers might have a contribution in limiting the lateral strains, thus increasing the strength obtained. These mechanisms may have a role behind the increase in compressive strength with fiber content.

The steel fiber used is a high-strength material. In a composite material, although the components that make up the composite retain their properties, the properties of the composite depend on the desired interfacial bond between the matrix and the reinforcement element. The composites' properties are affected by the properties of the components. Here, due to the formation of a strong bond between the alkali silicates and the steel, the increase in bonding may improve the mechanical properties. Generally, the increase in surface energy with increasing alkali concentration improves adhesion and bonding, and the active groups on the surface of the steel provide bonding locations to the active groups of alkali silicates; however, since too much alkali concentration will cause crystallization of silicates, this concentration has to be limited structurally (Marks, 2014). Furthermore, with the inclusion of continuous and long fibers, the surface area of the fiber has increased, also the anchorage and adhesion between the fiber and the matrix have increased, which is expected to enhance the mechanical properties.

On the other hand, as mentioned above, substantial strength reductions occurred when commercial silicate was replaced by waste glass. There reductions were much more significant for the mixtures activated by 14 M NaOH and reductions up to 82% were recorded (Fig. 3). These low strengths indicate that the silicate obtained from waste glass was not effective enough for the activation.

3.2 Splitting Tensile Strength

Fig. 4 shows the splitting tensile strengths of the concretes. When the mixtures without fibers (i.e., 0% fiber) are compared, it may be seen that the reference concrete containing ordinary Portland cement as the binder had the highest splitting tensile strength. Among the plain concretes, the alkali-activated mixture containing 14 M NaOH had the second highest strength, which was approximately 17% lower. The splitting strengths of the other plain mixtures were less than half of the reference mixture.

In general, splitting strength increased with fiber content. Strength of the SIFCON containing OPC and 5% fiber (mixture PC5 in Table 5) was 85% higher than the plain one (PC0). For the same fiber content, these increases were more than five-fold and three-fold for the activated mixtures with 8 M and 14 M of commercial activators, respectively.

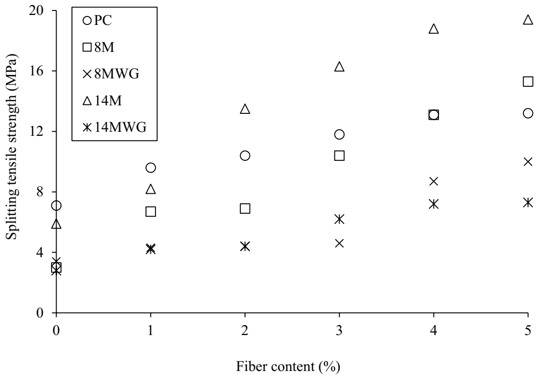


Fig. 4 Splitting strengths

The effect of fibers on splitting tensile strength was more significant for the alkali-activated mixture containing 14 M NaOH. As shown in Fig. 4, these mixtures achieved the highest splitting tensile strengths for the fiber contents of 2% and higher. However, the mixtures activated by 14 M NaOH and waste glass resulted in the lowest strengths. Except for the plain mixture and the one with 1% fiber, the splitting strength of these mixtures (14MWG) were approximately 35% of the corresponding mixtures prepared with commercial sodium silicate. The reductions were less for the mixtures prepared with 8 M NaOH. Therefore, these results indicate that the use of waste glass as a silicate source was not that effective as the commercial silicate used in this study.

Fig. 4 illustrates that the splitting tensile strengths increased with the activator concentration. As shown in Fig. 4, the splitting tensile strengths increased with the activator concentration. The mixtures prepared with 14 M of commercial activators had higher strength compared to those prepared with 8 M. The splitting strength of these mixtures prepared by alkali activation was higher than the references in all fiber contents.

3.3 Flexural Strength

Flexural strengths of the specimens are shown in Table 5 and Fig. 5. The numbers (0 to 5) at the end of each mixture series indicate the fiber content as percentage. Flexural strength of the normal mixture containing ordinary Portland cement but without any fibers (Mixture PC0) was 4.6 MPa. When comparing plain specimens (fiber volume 0%), the mixtures prepared by OPC exhibited the highest flexural strengths.

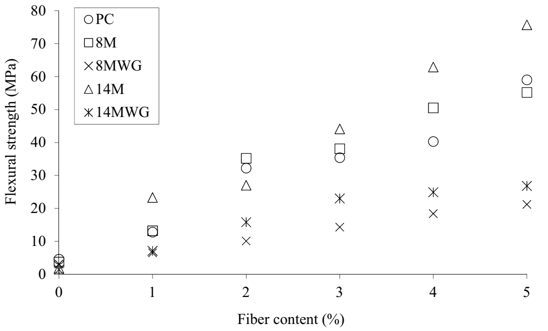


Fig. 5 Flexural strengths

However, the increase in flexural strength with fiber inclusion was more pronounced in alkali-activated mixtures. As shown in Table 5, higher strengths were obtained with increasing fiber content. As the fiber volume ratio increased from 1 to 5%, the flexural strength increase was almost five-fold and compared to reference mixture without fibers, this increase is more than ten-fold.

Fibers act as crack arresters or limiters of the crack propagation and as the fiber content increases, higher strengths may be attained. The fibers, which were actually continuous steel cords, had lengths of 250 mm and span through the long axis of the prism specimens. As a result, the bonding lengths of these fibers are higher compared to conventional fibers used in concrete. Alignment of the fibers perpendicular to the crack propagation path may also play a positive role in the results obtained. It may be criticized that the fiber alignment is only one direction and the high flexural strengths may not be obtained in other directions. The long fibers can be extended also in the transverse direction in slab types of specimens (for example, such as the specimen defined in EN 14488–5 (2006) standard) to enhance the mechanical properties in the transverse direction.

When flexural strengths of the mixtures containing commercial sodium silicate (alkali-activated slag mixtures coded as 8 M or 14 M) are compared to those of the reference mixtures, it can be seen that for a same fiber content, the strengths of the alkali-activated SIFCON were either comparable or superior. At a fiber content of 3%, the flexural strength of the reference mixture (PC3) was 35.4 MPa. The strengths of the activated mixtures with commercial sodium silicate were 38.1 MPa and 44.1 MPa for the mixtures containing 8 M sodium hydroxide and 14 M sodium hydroxide (mixtures 8M3 and 14M3), respectively. Among the mixtures tested, the alkali-activated series prepared with commercial sodium silicate and 14 M NaOH achieved the highest flexural strengths, except for the fiber content of 2%. The alkali-activated mixture produced with 5% fiber and 14 M NaOH had flexural strength higher than 75 MPa (Table 5). It should be noted that the size effect might have contributed to the flexural strengths obtained (Sengul, 2018). As the specimen size gets smaller, higher strengths may be expected. However, when the obtained results were compared with mixtures produced using commercial steel fibers and samples having the same sizes as in this study (Bulutlar, 2006), it can be mentioned that the strengths with continuous waste fibers were higher for same fiber contents (Bulutlar, 2006). According to these results, it can be stated that the continuous fibers utilized in this study can be successfully used in alkali-activated mixtures to obtain similar or higher strengths compared those of reference concretes.

Flexural strengths of concretes that contain finely ground waste glass as the silica source, however, were substantially lower than those produced using commercial sodium silicate. The reductions were more than 50% depending on the mixture series and fiber content. In reference mixtures and activated SIFCON with commercial activators, the flexural strengths increased with fiber content. However, these increases with fiber content were limited for the ones containing waste glass as the activator and this trend (i.e., a more gradual increase) is easily recognizable in Fig. 5. When the fibrous specimens were compared, it has been concluded that the use of ground waste glass has a negative effect on the tensile strengths. In their study, Torres et al. (2009) indicated that as the waste glass content increases, both compressive and flexural strengths decrease, also waste glass resists chemical activation. Excessive amounts of glass cause the pH of the system to decrease, which can negatively affect alkali activation and strength values (Gok & Sengul, 2023b; Torres-Carrasco & Puertas, 2015). The result is consistent with these results obtained in this study. One potential factor contributing to a reduction in flexural strength could be the insufficient activation of the chemical activator containing finely ground waste glass. In order to prevent this situation during the preparation of the chemical activator, an alternative option is to increase the surface area of the waste glass by finely grinding the material. Additionally, processing at higher temperatures for longer durations can enhance activation. However, it must be noted that these methods will raise the production costs of the SIFCONs, and the associated time and energy consumption will also increase.

While producing alkali-activated slag SIFCONs, although the chemical activator, containing finely ground waste glass, underwent appropriate filtering, it is possible that inefficiencies in filtering led to the presence of waste glass particles remaining uninvolved in the chemical reaction. This could contribute to a reduction in strengths due to the amorphous nature of glass. Moreover, these remained glass particles may cause a reduction of the adherence between the matrix and the fiber, and this may also decrease strengths of the specimens which contain waste glass. Alternatively, the strongly formed chemical bonds between the steel and alkali silicates in the specimens that were activated by commercial sodium silicate solution provide stronger adhesion and lead to a stronger bond between the matrix and steel; this phenomenon increased with alkali concentration, thereby strengthening the fiber–matrix interface of the material (Gok & Sengul, 2023a). In other terms, the fiber–matrix adherence enhanced, improving the contribution of reinforcement (i.e., fibers), thus enhancing the mechanical properties.

3.4 Load–Deflection Curves

Fig. 6 shows load–deflection curves of the mixtures prepared with commercial sodium silicate and 14 M sodium hydroxide solution.

The curves of different mixtures with same amount of fiber are shown in Fig. 7. The descending branch of the graph is shown up to a deflection of 5 mm. In Fig. 6, it can be seen that the increase in fiber content resulted in higher peak loads. The long continuous fibers were aligned through the length of the prism (Fig. 2) and under flexural loading these fibers limit the propagation of the cracks. Since the length of the fibers were very long compared to traditional fibers, fibers are involved more effectively in the failure mechanism. When the fiber content increases, more fibers resist the crack opening which increases the force needed for deflection, and as seen in this figure, deflection hardening type of response occurs. Such behavior is a typical for fiber-reinforced concretes. The fibers were aligned perpendicular to the loading direction (i.e., parallel to crack opening direction). This fiber orientation probably helped improve the mechanical behavior.

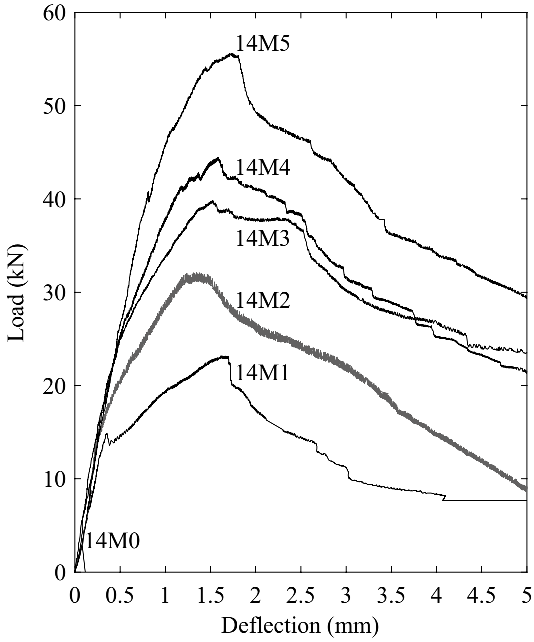


Fig. 6 Load–deflection curves of the SIFCON specimens for different fiber volume ratios

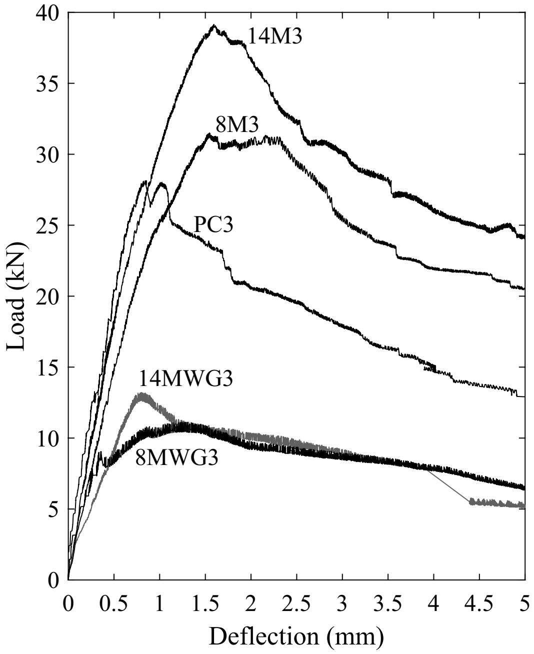


Fig. 7 Load–deflection curves of different mixtures for fiber volume ratio of 3%

As shown in Figs. 6 and 7, the descending part of the load–deflection curves demonstrate a deflection hardening response. The specimens were examined visually after the testing and no fiber rupture was seen. As a result, it was concluded that only fiber pull-out response took place due to loading. The diameter of the waste fibers was larger than commercial steel fibers and although they were waste, they had high strength, both of which might have contributed to the results. The fibers used in this study were very long compared to conventional fibers and the bonding between mortar matrix and fibers was high due to the high anchorage length. This behavior resulted in a less steep descending branch. Although the load–deflection curves in Figs. 6 and 7 were shown for the deflection of 5 mm, the curves actually continued for much higher deflections. When the post-crack residual strength at large strains is compared, it can be

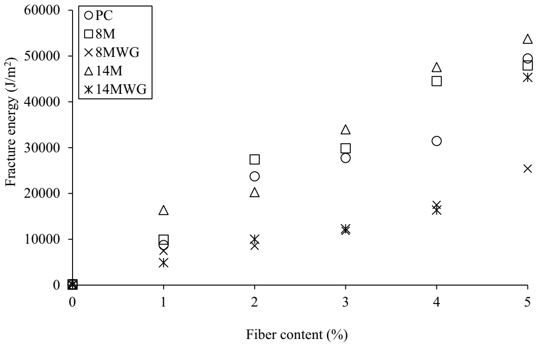


Fig. 8 Fracture energies of the mixtures

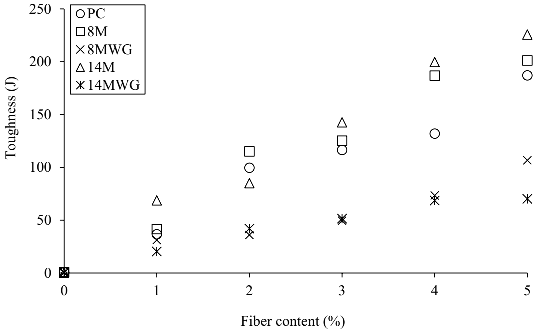


Fig. 9 Toughness values of the mixtures

seen that the alkali-activated mixtures had higher values which is an indication of the better mechanical response. The results are similar or even better than those that may be expected from SIFCON prepared with commercially available fibers. Based on results obtained from the experimental study, it may be concluded that the concretes containing waste steel fibers behave like conventional fiber concretes.

3.5 Fracture Energy and Toughness

The toughness and fracture energy of the specimens were calculated using the load–deflection graphs. The toughness value was obtained by calculating the area under the load–deflection graph. Fig. 8 shows the fracture energy depending on the fiber amount for different SIFCON specimens. When the amount of fiber used increases, the fracture energy and therefore the ductility of the material increase. The highest fracture energy was obtained in the specimens activated with 14 M NaOH and commercial Na_2SiO_3, using 5% of fiber. The lowest value belongs to the plain specimen coded as 14MWG0. While the mixtures activated by ground waste glass achieved the lowest strengths in this experimental program, their fracture energy values remain higher than those of comparable mixtures produced with Portland cement and commercial steel fibers (Bulutlar, 2006).

Toughness values of the SIFCON specimens are displayed in Table 5 and Fig. 9. The specimens activated by using a mixture of NaOH and Na_2SiO_3 provided superior toughness compared to the specimens prepared by OPC, where the previously mentioned adhesion forces were effective and better adhesion was achieved with steel fibers. In the specimens produced by using 14 M sodium hydroxide solution and finely ground waste glass as chemical activator, at the fiber volume ratio of 5%, the toughness value increased by 350-fold compared to the specimen without fiber.

A significant increase in toughness values has been achieved with the inclusion of scrap fibers. Higher toughness values were obtained as the amount of fiber increased. The highest toughness value was obtained in the specimens activated with 14 M sodium hydroxide and commercial sodium silicate and produced with 5% fibers. Toughness is the ability of the material to absorb energy within the limits of plastic deformation and it is calculated by using the area under the load–deflection graph. It is expected that the use of fiber will increase the ductility of the material. The use of fibers restrains the crack propagation and increases toughness. The main role of these mechanisms is to provide a decrement on the stress intensity factor at the crack tip with "crack tip shielding" (Swain, 1989). Crack deflection is one of these toughening mechanisms. As a crack meets different reinforcing elements that have higher toughness and strength than the matrix, the path and direction of the crack change, and by this way crack propagation is limited. When the crack path lengthens, and the propagation of the crack becomes more difficult, the absorbed energy and the toughness of the material increase. Also, fibers act as crack bridging mechanism that increase toughness (Swain, 1989). In cement-based fiber-reinforced composites, fiber–matrix adhesion is one of the main factors that affect the performance of the composite, and various parameters like matrix strength, fiber type, fiber geometry, fiber–matrix interface properties, and curing conditions affect bonding of fiber and matrix (Bentur & Mindess, 2007). The test results demonstrate that the effect of the continuous waste steel fibers used in this study is similar to those of commercial fibers. Thus, it can be concluded that the waste steel fibers used in the form of continuous fibers can be successfully utilized to obtain both normal and alkali-activated SIFCON.

4 Conclusions

Incorporating three distinct waste materials or by-products—waste fibers, finely ground waste glass, and ground granulated blast furnace slag—into slurry infiltrated fibrous concrete (SIFCON) was the focus of this experimental study. Combination of various wastes is a unique approach to obtain high-performance concrete. Consequently, the following conclusions can be drawn from the findings:

- Steel cords, sourced from scrap tires, were precisely cut into 250 mm lengths. These fibers, significantly longer than conventional ones and spanning the entire specimen, were classified as "continuous fibers." While such long fibers are unsuitable for traditional steel fiber-reinforced concrete, they prove to be highly effective in SIFCON production. The anchorage length of these fibers was significantly longer compared to conventional fibers, leading to an enhanced bond between the mortar matrix and the fibers.
- While the fiber contents in this study were lower than those in typical SIFCON mixtures, the use of a specific preparation method, involving pre-packing of fibers before pouring the mortar into the molds, still allows these mixtures to be classified as slurry infiltrated fibrous concrete.
- The inclusion of continuous waste steel fibers enhanced mechanical properties, including flexural strengths, splitting tensile strengths, fracture energies, and toughness values. These outcomes align with the improvements typically seen in commercial fibers.
- The mechanical properties of the alkali-activated specimens either matched or outperformed those of the reference mixtures, depending on the specific activator properties. Notably, within the confines of this experimental program, it was observed that the inclusion of ground waste glass had a negative effect on the mechanical properties of the alkali-activated mixtures.
- The compressive strength of reference mixtures and those prepared with commercial activators demonstrated an increase with the fiber content. This enhancement is likely attributed to the length and alignment of the fibers utilized. However, the compressive strengths of the mixtures prepared with waste glass as the source of silica were notably low, consistently below 20 MPa, and remained similar across various fiber contents when compared to the other mixtures.
- The alkali-activated mixtures, which incorporated continuous waste fibers, demonstrated exceptional properties, achieving flexural strengths surpassing 75 MPa and compressive strengths exceeding 100 MPa. Such mixtures can be classified as high-performance concretes. Furthermore, the incorporation of fibers led to a substantial increase in fracture energies. In light of these enhanced properties, it can be concluded that waste fibers and alkali activation can yield high-performance concretes.
- From the findings of this experimental study, it can be inferred that continuous waste steel fibers prove to be a viable choice for producing both conventional and alkali-activated SIFCONs.
- The obtained results are encouraging and support the concept that concrete with sufficient mechanical properties, composed solely of waste materials, can be achieved.

Abbreviations

av.	Average
GCCA	Global Cement and Concrete Association
GGBS	Ground granulated blast furnace slag
M	Molar (mol/L)
Ms	Silica modulus
Na_2O	Sodium oxide
NaOH	Sodium hydroxide
Na_2SiO_3	Sodium silicate
OPC	Ordinary Portland cement
PC	Portland cement
RILEM	The International Union of Laboratories and Experts in Construction Materials, Systems and Structures
SIFCON	Slurry infiltrated fibrous concrete
SiO_2	Silicon dioxide
st. dev.	Standard deviation
v_f	Fiber volume ratio
WG	Waste glass

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Author contributions
Saadet Gokce Gok contributed to investigation, testing, visualization, software, and writing—original draft. Ozkan Sengul was involved in writing—review and editing, supervision, and conceptualization.

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