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Research Article

Investigation of usability of recycled aggregate in SIFCON production

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ABSTRACT

Using recycled aggregates is crucial for a more sustainable environment and economy. In this study, the properties of recycled aggregate-based SIFCONs were examined. In the scope of the study, compressive strength, high-temperature resistance, sorptivity, and fracture energy of SIFCONs produced with recycled aggregate were investigated. The results were compared with those of the limestone-bearing SIFCONs. It was determined that the compressive strength and fracture energy of SIFCONs produced with recycled aggregate were 61.2 MPa and 14.9 N/mm, respectively. Although these values are lower than those of SIFCONs produced with limestone, it has been determined that recycled aggregates are advantageous in high-temperature resistance. The results demonstrated that the recycled aggregate could be used to produce SIFCON.

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1. INTRODUCTION

Conventional concrete is a brittle building material and performs poorly under tensile stresses [1]. It is known that with the addition of fiber, some concrete properties like flexural and tensile strength [2], post-cracking behavior [3], first cracking strength, and impact resistance [4] improve. Steel fibers are widely used to reduce the brittleness of concrete and increase tensile strength and toughness. The amount of fiber is crucial in this regard [5]. However, fibers decrease the workability of concrete, and this reduction can also negatively affect mechanical and durability properties [6]. Thus, the amount of fiber used in producing fiber-reinforced and high-performance fiber-reinforced concrete is generally limited to around 1–3% by volume [7]. The limitation of fiber content in traditional fiber-reinforced concrete has led to a focus on new alternative composite materials with high fiber dosage [8]. Slurry infiltrated fiber concrete (SIFCON) is a type of high-volume fiber-bearing concrete produced with a special production method different from conventional concrete [9]. In SIFCON production, the fibers are first placed in the mold, then the phase prepared with cement, water, fine aggregate, and chemical and mineral additives (defined as slurry) is poured into the mold. In this way, the volume of fiber used in SIFCON increases by up to 30% [10]. SIFCON composites have superior properties like very high toughness and compressive and tensile strength [11]. The properties of the matrix phase and the fiber properties, like type, volume, and alignment, are critical for the mechanical properties of SIFCONs [12]. The highest fiber dosage that can be used in production depends on the length and diameter of the fiber, the fiber orientation, the dimensions of the mold, and the vibration [13]. SIFCON composites can be used in different application fields, such as strengthening, industrial floors [9], pavements [14], military complexes, and underground shelters [15] due to their advantages.

Today, sustainable constructions have significant importance on the concept of sustainability. Civil engineers also have essential duties and responsibilities in achieving sustainability goals [16]. For this reason, researchers have started investigating the recycling of different materials, the use of alternative materials to cement, and the use of

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recycled materials in the production of building materials. Similar studies are carried out in SIFCON production. Al-Hadithi and Al-Hadithi [17] examined the usability of waste plastic fibers in SIFCON production. Celikten and Canbaz [18] and Drdlova et al. [19] investigated the properties of SIFCON composites produced using waste steel fibers obtained from waste automobile tires. Canbaz and Celikten [20] explored the effect of crumbed waste automobile tire rubbers on the properties of SIFCON composites. Tiwari et al. [21] examined the impact of replacing cement with waste glass powder on SIFCON properties. Khan and Selvaraju [22] investigated the effect of substituting various pozzolans with cement and replacing steel fibers with waste high-density polyethylene and waste plastic fibers on SIFCON properties. Altunci and Ocal [23] investigated the properties of SIFCON composites produced by using peanut shell ash partial replacement with cement.

The increase in the demand for construction causes an increase in the need for cement and aggregate. Recycling the construction and demolition wastes and using these recycled aggregates is essential for sustainability and reducing the demand for natural aggregates [24]. Also, most of the waste concrete obtained from the construction and demolition process is landfilled in open fields in nature, and this waste is one of the reasons for environmental pollution. Therefore, it is essential to obtain recycled aggregates from these wastes and use them as raw materials to produce new concrete [25]. However, recycled aggregates' properties differ from natural aggregates due to the mortar adhered to the aggregate of the old concrete. The transition zone between this mortar and aggregate significantly impacts recycled aggregate properties such as porosity and water absorption capacity [26]. Numerous studies have been conducted on concrete produced with only recycled aggregate or partially replacing recycled aggregate with traditional aggregate. It is mentioned that, in general, recycled aggregate negatively affects the concrete's strength and some of its durability properties [27]. The extent of the adverse effects of recycled aggregate on concrete properties depends on different factors like water/cement ratio, replacement ratio, and the quality of recycled aggregate [28]. The porosity and homogeneity determine the quality of recycled aggregate [29]. As recycled aggregate substitution increases, concrete properties such as workability, density, and strength decrease; meanwhile, the risk of bleeding and drying shrinkage increases [30]. Although studies show that utilization of 20–30% recycled aggregate can produce concrete of similar grade to conventional concrete, such low amounts cannot ensure the disposal of waste concrete [28].

Due to negative properties arising from the nature of recycled aggregate, early studies on recycled aggregate generally focused on non-structural concrete production. As the number of studies on recycled aggregate increases, different techniques like carbonation, exposure to different solutions, and coating with different materials have been examined to improve the properties of recycled aggregate. However, these improvements require an additional process before using [31]. Various factors, such as undesirable materials such as brick, wood, and plastic, inadequate standards, and quality control, raise concerns about using recycled aggregate [32]. Research continues for the characterization and more efficient use of recycled aggregate [33]. Countries like Belgium, Denmark, and Germany have developed different standards and acceptance criteria for recycled aggregates. It is possible to use these aggregates as fine or coarse aggregates in concrete [34].

Table 1. Chemical composition and some properties of cement

Compound	% (by weight)	Mechanical properties	
CaO	63.06	Compressive strength	
SiO_2	18.53	7 days	38.4 MPa
Al_2O_3	5.21	28 days	47.2 MPa
Fe_2O_3	3.65		
MgO	1.01	Physical properties	
Na_2O	0.48	Specific gravity	3.11
K_2O	0.64	Initial setting time	210 minutes
SO_3	3.20	Final setting time	315 minutes
Free CaO	0.91	Blaine's specific surface area	3420 cm^2/g
Loss on ignition	2.94		

Table 2. Chemical composition and some physical properties of kaolin and recycled aggregate

Compound	Kaolin % (by weight)	Recycled aggregate (<0.125 mm) % (by weight)
CaO	0.38	34.46
SiO_2	73.15	29.17
Al_2O_3	16.55	4.25
Fe_2O_3	0.69	1.97
MgO	0.31	2.06
Na_2O	0.10	4.81
K_2O	0.24	<0.10
Loss on ignition	6.90	21.08
Specific gravity	2.60	2.15

There are many studies on recycled aggregate utilization in building materials production. Most of these studies used recycled aggregate as fine and coarse aggregate. However, the recycled aggregate has the potential to be used in the production of SIFCON slurry, and there is a lack of literature on this topic. This study investigated the usability of recycled aggregate powder produced from recycled aggregate in SIFCON production. This way, the usability of recycled aggregate powder generated in the facility during recycled aggregate production will also be examined. It was aimed to determine

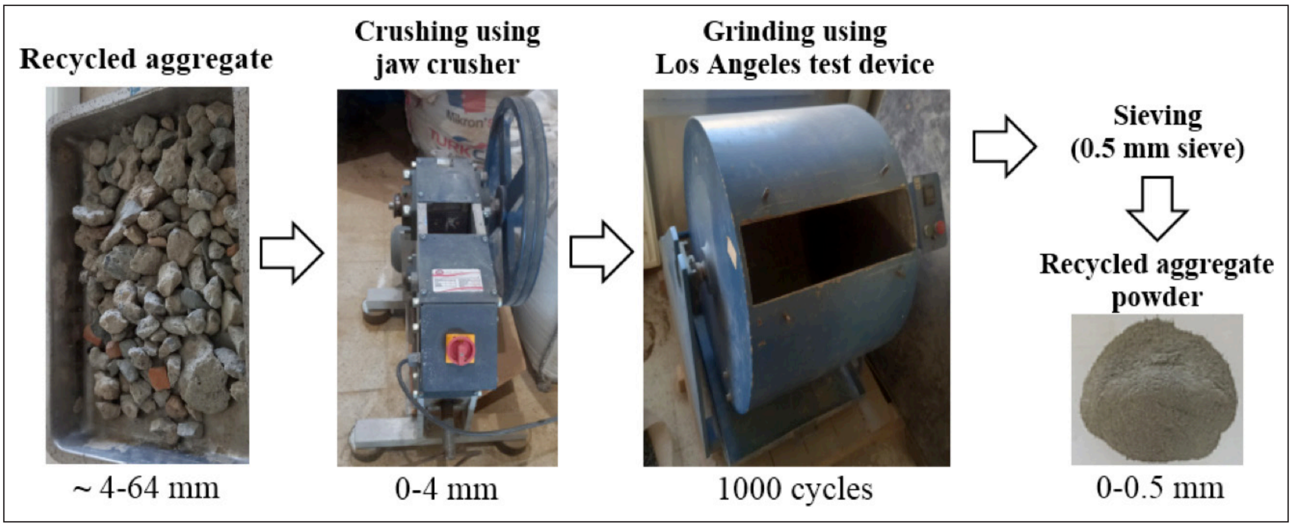

Figure 1. Preparation of RA powder.

whether reducing the particle size would enable both old concrete aggregate and old mortar to be used more effectively. The results were compared with the SIFCON composite produced using natural limestone powder. In the scope of the study, fracture energy, compressive strength, sorptivity, and high-temperature resistance tests were carried out.

2. MATERIALS AND METHODS

2.1. Materials

Hooked-end steel fiber 30 mm in length, 0.75 mm in diameter, and 1160 MPa in tensile strength, CEM I 42.5 R type Portland cement, crushed limestone aggregate (LA), and recycled aggregate (RA) were used to produce the specimens. The water absorption capacity of LA and RA were 1.1% and 10.4%, and the specific gravity of aggregates were 2.60 and 2.15, respectively. The water absorption of the RA was considerably higher than that of LA due to the adhered cement mortar.

Kaolin clay was utilized to adjust the viscosity of the slurry. Tables 1 and 2 show the chemical composition and some physical properties of cement and kaolin/recycled aggregate, respectively. In the production of the mixtures, tap water and polycarboxylate ether-based superplasticizer were also used.

2.2. Preparation of Recycled Aggregate Powder

The preparation of RA powder and the situation of aggregates at every step are summarized in Figure 1 and Figure 2, respectively. The RA was provided with a 4–64 mm size range (Fig. 2a). The aggregate also contained brick/roof tile, glazed wall tile, and many flat and elongated particles (Fig. 2b). This aggregate was crushed with a jaw crusher to 0–4 mm (Fig. 2d) and then ground with a Los Angeles test device for 1000 cycles. Afterward, the fine aggregate was sieved through a 0.5 mm sieve, and the fraction passing the sieve (Fig. 2e) was used to produce SIFCON.

The gradation of the aggregates used in the preparation of the slurries is given in Figure 3. LA and RA were screened through different sieves and remixed in definite proportions to obtain the specified gradation.

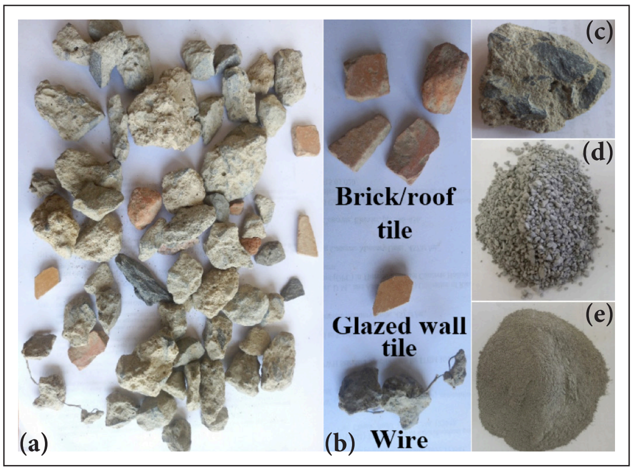

Figure 2. Obtaining RA powder **(a)** recycled aggregate as received; **(b)** different particles; **(c)** adhered mortar to the old concrete aggregate; **(d)** aggregate after crushing to 0–4 mm; **(e)** sieved RA powder after Los Angeles degradation.

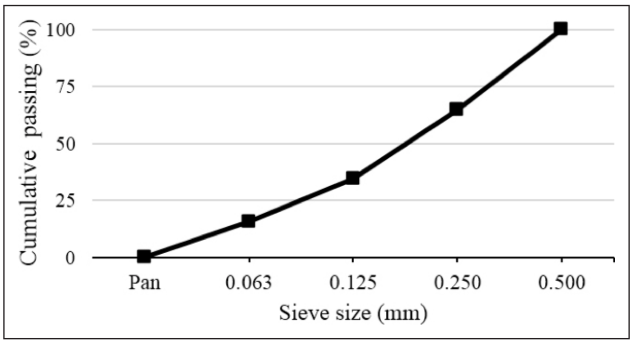

Figure 3. Gradation of aggregates.

2.3. Mixtures and Method

2.3.1. Sample Preparation

The ingredients and some properties of SIFCON mixtures are presented in Table 3. After the molds were lubricated, the fibers were put into the molds with the sprinkling

Table 3. Ingredients and some properties of SIFCONs

Ingredient (kg/m³)	LAS*	RAS**
Cement	640	605
Water	372	365
Limestone aggregate	780	–
Recycled aggregate	–	685
Kaolin	73	63
Steel fiber	620	620
Superplasticizer	7	12
Property		
Flow diameter of slurry (cm)	32.0	32.8
Fresh unit weight (kg/m³)	2441	2294

*: Limestone aggregate SIFCON; **: Recycled aggregate SIFCON.

method without any routing or vibration. At this stage, the fibers were only randomly distributed horizontally, and the position of the fibers in a vertical direction was prevented manually. Sand, kaolin, cement, water, and superplasticizer admixture were put into the mixer bowl during the slurry preparation. With the help of a spoon, the ingredients were mixed for approximately 15 seconds, and then the mixer was operated for 180 seconds at 62.5 rpm. The materials adhering to the wall of the container were removed in 15 seconds with a spoon, and the mixer was operated for another 180 seconds at 125 rpm.

For the sake of comparison, it was aimed to produce slurries with similar flow diameters. To determine the flow diameters of the slurry, a truncated cone with 7 cm top diameter, 10 cm bottom diameter, and 6 cm height was filled with slurry without any compaction. The cone was pulled vertically, and the flow diameter was measured in two perpendicular directions after 30 seconds. The average of these two values was recorded as the flow diameter (Fig. 4). The SIFCONs prepared with limestone and recycled aggregate were coded as LAS (limestone aggregate SIFCON) and RAS (recycled aggregate SIFCON), respectively.

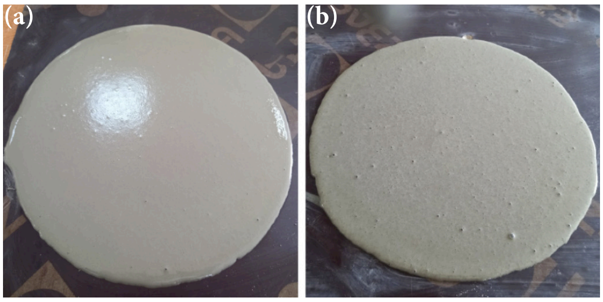

Figure 4. Photographs of slurries at the end of flow diameter tests **(a)** LAS; **(b)** RAS.

The slurry was poured into the molds with preplaced fibers, and a vibration table was used for 10 seconds to compact the specimens. The molds were kept in laboratory conditions for 24 hours before demoulding, and standard water curing was applied for 27 days (Fig. 5). 71 mm cube, 40×40×160 mm prism, and 50×50×240 mm notched prism specimens with 10 mm notch height and 3 mm notch width were used to determine the compressive strength, sorptivity, and fracture energy, respectively.

Figure 5. Sample preparation and curing.

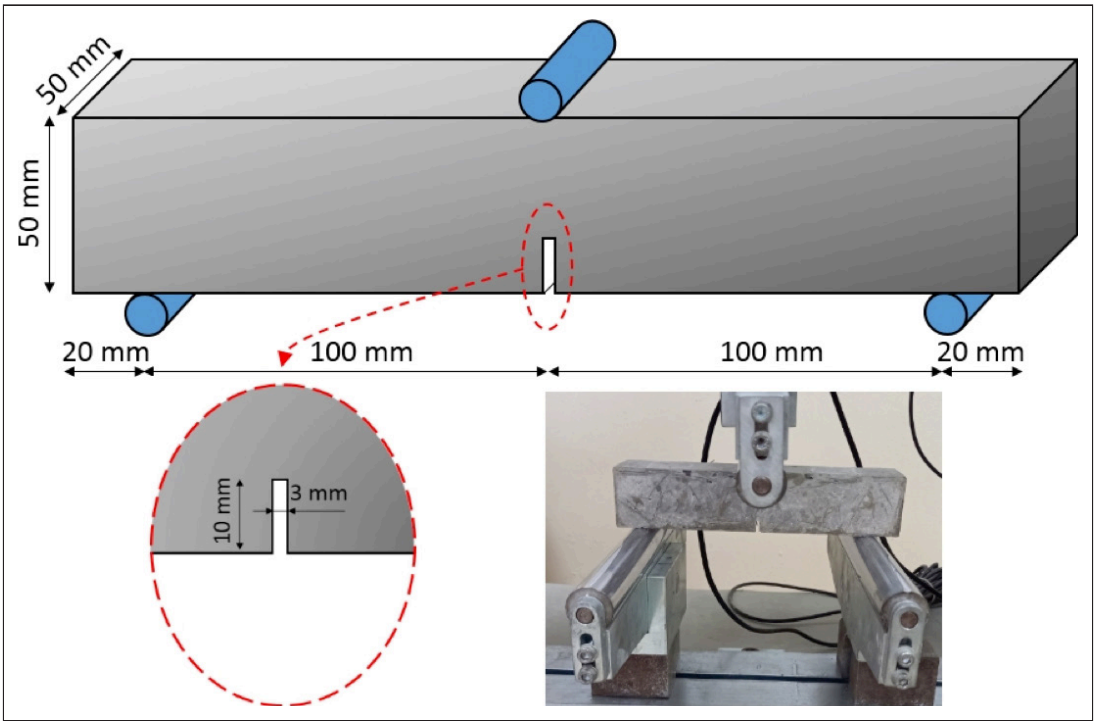

Figure 6. Details of specimen and test setup.

2.3.2. Tests

All hardened state tests were applied to the 28-day age samples. The compressive strengths were determined with 71 mm cube specimens using a mortar compression testing machine at a loading rate of 2.4 kN/s.

A muffle furnace was used to investigate the high-temperature resistance of SIFCONs. Samples were dried in an oven at 60 °C for 72 hours before the test. The temperature rise rate of the muffle furnace was 10 °C/minute. The samples were heated at 900 °C for 3 hours. Then, the specimens were allowed to cool gradually in the furnace. When the sample temperatures reached room temperature, the flexural test was applied, and the fracture energy losses were recorded.

ASTM C1585 Standard [35] was used to determine the rate of capillary water absorption. During the test, samples of 40×40×160 mm prism specimens were used. All parts of the samples, except the bottom surfaces (40×40 mm) that will come into contact with water, were covered with a waterproof insulation material, and experiments were carried out according to the relevant standard.

RILEM [36] defined fracture energy as the required energy for creating one unit area of a crack and stated that notched beam specimens can be used to calculate fracture energy. In this study, a fracture energy test was carried out using a 3-point flexural test setup with a displacement-controlled universal test machine at a 0.01 mm/minute rate. The test was ended when the peak load dropped by 95%. The fracture energy was calculated using Equation 1. considering the RILEM (50-FMC) [36]. The W_0, mg, δ_0 are the area under the load-displacement curve, the weight of the specimen between supports, and maximum displacement, respectively. The displacements were taken from the universal test device's measurement at the specimen's midspan. A is the midspan cross-sectional area without the notch. The details of the specimens used and the application of the test are shown in Figure 6.

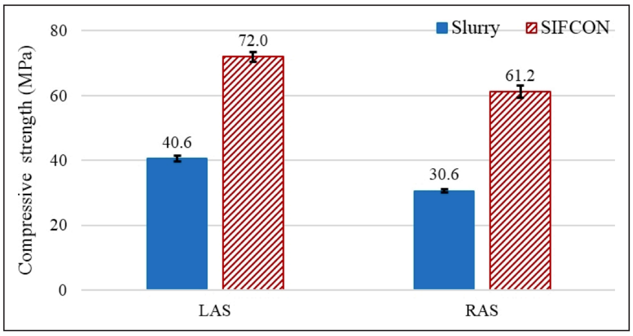

Figure 7. Compressive strengths of slurries and SIFCONs.

$$G_F=(W_0+ mg\delta_0)/A \tag{1}$$

3. RESULTS AND DISCUSSION

3.1. Compressive Strength

The compressive strength of slurry and SIFCON specimens are shown in Figure 7. The compressive strengths of SIFCON samples produced with LA and RA are higher than those of fiber-free slurries by 77% and 100%, respectively. The compressive strength of slurry and SIFCON samples containing limestone aggregate was higher than those of specimens prepared with RA by 33% and 18%, respectively. Fan et al. [37] investigated the effect of fine recycled aggregate produced by two methods on the concrete properties produced with 0.35 and 0.55 w/c ratios. The researchers stated that the compressive strengths of the concretes produced with 100% recycled fine aggregate were up to 33% and 48%

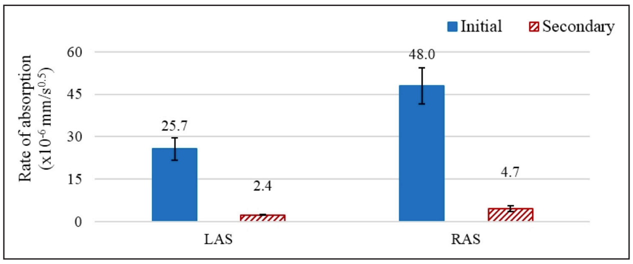

Figure 8. Rates of capillary absorption of LAS and RAS samples.

lower in the 0.35 and 0.55 w/c ratio concretes than those of the control samples (having the same water/cement ratios). In a similar study, Ju et al. [38] used fine recycled aggregate as a partial replacement for natural fine aggregate in normal- and high-strength concrete. It was determined that the compressive strengths in normal- and high-strength concrete mixtures decreased by 29% and 8%, respectively, using 100% recycled aggregate. The fact was attributed to the high porosity of the recycled aggregate arising from its adhered mortar, which was also the cause of the low density and high-water absorption capacity of recycled aggregate [39, 40].

3.2. Rate of Capillary Absorptions

The rate of capillary absorption values of the samples is shown in Figure 8. Initial and secondary rates of absorptions of SIFCON prepared with RA were 87% and 96% higher than those of the limestone aggregate SIFCON. It is thought that both the mortar still stuck to the aggregate particles after grinding in the Los Angeles testing device and the separated old mortar particles, which have a porous structure, are responsible for the high rate of sorptivity values. Ayub et al. [41] reported that the sorptivity of recycled aggregate concrete was higher than that of the reference mixture. In addition, it was stated that sorptivity gradually increases with the increase of the recycles aggregate substitution rate. Civioglu [42] also obtained similar results in his study. Algin [43] investigated the effects of recycled aggregates on self-compacting concrete. The researcher reported that using recycled aggregates increased the sorptivity. This situation was attributed to the high-water absorption capacity of the recycled aggregate [44].

3.3. Fracture Energy and the Effect of High Temperature on Fracture Energy

Load-midspan displacement graphs of the samples before and after exposure to high temperatures are given in Figure 9 and Figure 10, respectively. The peak load and maximum displacement values of the samples produced with limestone were higher than those containing RA before and after the high-temperature effect. Peak loads were reached quickly in the samples produced with both aggregate types. After the peak, the composite continued carrying the load until the maximum displacement values (end of test), but the load gradually decreased. After the effect of high temperature, both the peak loads and the maximum displacement values decreased compared to the samples not exposed to high temperature.

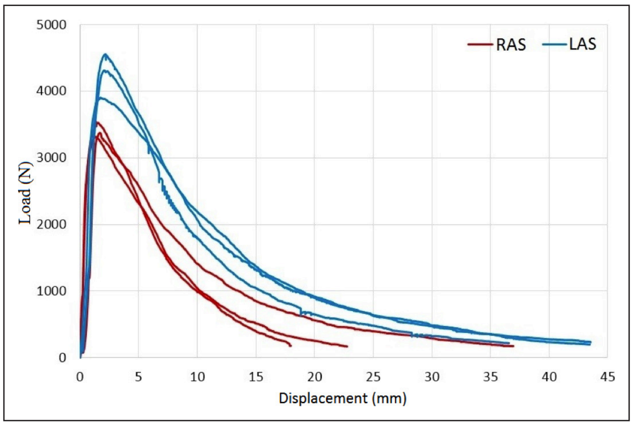

Figure 9. Load-displacement curves of samples before high-temperature effect.

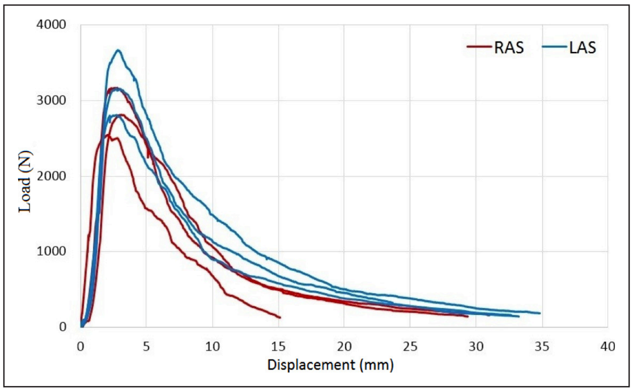

Figure 10. Load-displacement curves of samples after exposure to 900 °C.

The average peak load, fracture energy values, and displacement corresponding to the peak load of SIFCONs are shown in Figure 11. It was seen that the peak loads of LA SIFCONs either before or after the effect of 900 °C were higher than those of the SIFCONs produced with RA. The fact seems to be caused by the porous structure of the old mortar adhering to the recycled aggregate particles and the weak structure of the old mortar particles separated from the aggregate particles. In addition, new interfacial transition zones formed between the new and the old mortar and between aggregate and new paste are likely to impact this behavior of the mixtures significantly. While the peak loads of LASs were 25% higher than those of the RASs before the high temperature, this value decreased to 13% after the high-temperature effect.

Similarly, the displacement values corresponding to the peak loads of the LASs were 35% and 3% higher than those of the RASs before and after the high temperature, respectively. The higher displacement values corresponding to the peak loads of LASs indicated that these SIFCONs were more resistant to the initial crack formation than RAS and prevented the crack formation for a more extended period than RAS. Here, as in the peak loads, the difference between the displacement of two series decreased after exposure to high-temperature and even reached almost the same point.

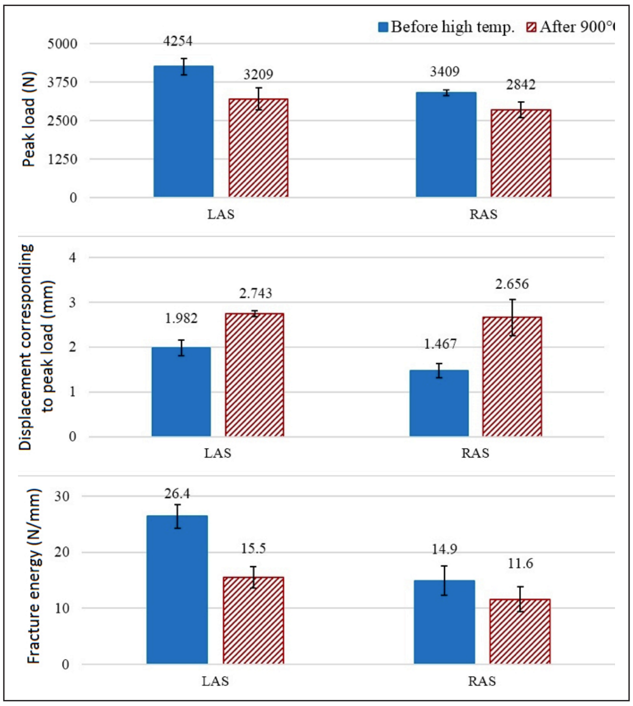

Figure 11. Peak loads, displacement corresponding to peak loads, and fracture energy of mixtures.

There are similar trends in fracture energies to peak load and displacement values corresponding to peak load. As expected, both before and after the high temperature, the fracture energies of LASs are higher than those of RASs. The fracture energies of LASs were 77% and 34% higher than RASs before and after the high-temperature effect. Like the other results, the fracture energy values became close after high temperature.

The losses in peak load and fracture energy with high temperature are shown in Figure 12. Samples produced using limestone suffered more than those produced with recycled aggregate. Although the peak loads and fracture energy values before the high-temperature effect are not the same, it is possible to say that SIFCONs produced with recycled aggregate are more resistant to high temperatures. The number of factors affecting this situation is relatively high. Kou et al. [45] investigated the effect of recycled aggregate substitution on the high-temperature resistance of concrete. They stated that with recycled aggregate, the compressive strength losses of concretes exposed to 800 °C were reduced compared to that of the control sample.

Similarly, in this study, with high temperatures, the SIFCON samples produced with recycled aggregate lost strength at lower rates than the LAS mixture. It has been stated that the thermal expansion coefficient of the old adhered mortar in the recycled aggregate is more compatible with the thermal expansion coefficient of the new mortar layer than that of the natural aggregate [46]. In addition, it is thought that the porous structure of the recycled aggregate facilitates the evacuation of the evaporated water. In this way, the internal stresses caused by the vapor pressure are reduced.

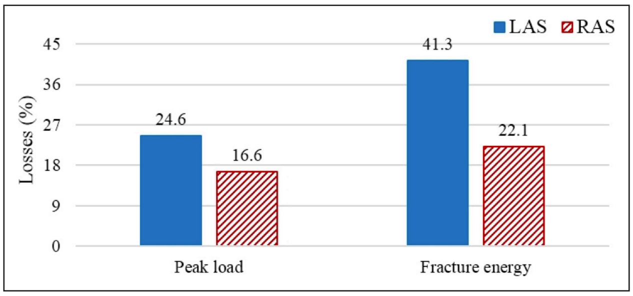

Figure 12. Peak load and fracture energy losses after high-temperature effect.

4. CONCLUSIONS

This study investigated the effects of recycled aggregate on compressive strength, sorptivity, fracture energy, and high-temperature resistance of SIFCONs. For this purpose, limestone and recycled aggregate under 0.5 mm were used. For the materials used and tests applied, the following conclusions may be drawn:

- The compressive strength of slurry and SIFCON prepared with recycled aggregate were 30.6 MPa and 61.2 MPa, respectively. The strength of limestone aggregate-bearing slurry and SIFCON were 33% and 18% higher than those of the recycled aggregate-bearing counterparts.
- The initial and secondary absorption rates of limestone aggregate SIFCON were 25.7×10^{-6} "mm/√s" and 2.4×10^{-6} "mm/√s", respectively. These values increased by 87% and 96% with using recycled aggregate.
- The fracture energy of recycled aggregate SIFCON was 14.9 N/mm, 44% lower than that of the SIFCON prepared with limestone aggregate. Additionally, the peak load and displacement corresponding to the peak load of limestone aggregate SIFCON were higher than those of the recycled aggregate SIFCON.
- After exposure to 900 °C temperature, the fracture energy of limestone and recycled aggregate SIFCON reduced to 15.5 N/mm and 11.6 N/mm, respectively. The relative reduction in fracture energy of the recycled aggregate SIFCON upon exposure to 900 °C (22%) was roughly half that of the SIFCON containing limestone aggregate (41%).

This study is a preliminary study examining the usability of recycled aggregate in SIFCON production. Increasing the number of studies on these materials' strength and durability properties will increase the cumulative knowledge on this subject.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declare that he have no conflict of interest.

FINANCIAL DISCLOSURE

The author declared that this study has received no financial support.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

PEER-REVIEW

Externally peer-reviewed.

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