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Investigation of the Feasibility of Using Recycled Fibers to Improve the Mechanical Properties of Shotcrete

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Abstract

Shotcrete is used as a component of the support system in tunnels, and one of the methods to enhance its mechanical properties is by incorporating fibers. Fibers can significantly improve the mechanical properties of shotcrete, including compressive and tensile strength. This leads to savings in time, cost, and post-installation maintenance. In recent years, due to the environmental pollution caused by the production of synthetic fibers, there has been increasing interest in using recycled materials, mainly recycled steel fibers from worn tires. The present study is a laboratory-based research program investigating the feasibility of using recycled fibers to improve the mechanical properties of shotcrete. In this study, recycled steel fibers from worn tires and shaves of basalt stone were used to create laboratory samples. The laboratory samples included cubic (10×10 cm) and cylindrical (15×30 cm) specimens with five different mix designs: ordinary shotcrete, shotcrete containing 0.5%, 1%, 1.5%, and 2% recycled fibers. These fibers were categorized into three length groups: coarse, mixed, and fine. The laboratory tests included compressive and tensile (Brazilian) strength tests at 3-day intervals. The results of the laboratory studies indicated that recycled fibers from worn tires could significantly enhance the mechanical properties of shotcrete, with a two-fold increase in compressive strength observed when the fiber content was increased by 2%. Moreover, the inclusion of basalt stone shaves not only improved the compressive strength of the samples but also had a substantial effect on enhancing the tensile strength.

1. Introduction

Shotcrete is a mixture of cement, water, and aggregates, widely used in the tunneling industry. Shotcrete subjected to tensile loads can experience displacement and cracking [1]. The wear and failure of shotcrete are highly dependent on the formation of cracks and micro-cracks. As the load increases, micro-cracks coalesce to form primary cracks, which propagate into the system and may ultimately lead to unexpected damage to the support system [2, 3, 4]. The inclusion of steel fibers plays a crucial role in preventing the initiation of cracks and inhibiting the progression of damage, thereby significantly enhancing the ductility of the concrete [5]. This means that the damage morphology shifts from brittleness to ductility [17]. Studies show that if the mortar mix is designed correctly, the flexural strength of the first tensile crack increases, however the results for compressive strength vary, with some studies reporting an increase and others a decrease in strength [7, 8]. In recent decades, various types of fibers such as steel fibers (SF), carbon fibers, basalt fibers, polypropylene fibers (PPF), and natural fibers have been used. These fibers are available in different specifications, shapes, and sizes. The length of the fibers should be several times the maximum aggregate size to ensure proper bonding between the fibers in the shotcrete. However, the production of synthetic fibers results in environmental pollution and the release of carbon dioxide [2].

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With the development of the economy and urbanization, solid waste has significantly increased [9]. In recent years, sustainable development has become a key focus for researchers, with studies concentrating on three main categories: environmental aspects (recycling, greenhouse gases, carbon footprint), economic considerations, and improving material properties [10-13]. In the context of sustainable development, the environmental benefits of using recycled tire fibers appear to be the most significant. The steel production industry, which contributes to 25% of CO2 emissions, has seen growing interest in finding new solutions, such as utilizing various recycled fibers, including those from end-of-life vehicle tires, due to the high production costs and negative environmental impacts [12].

It has been reported that over 250,000 tons of waste tires are produced annually in the European Union, mainly processed through burning, landfilling, or shredding [14]. Burning can lead to serious CO2 emissions, while 500 million waste tires are landfilled without treatment, causing even more severe environmental issues [15-16]. Recycled steel fibers from tires have proven effective in improving tensile and flexural strength, ductility, and toughness in concrete, making them a promising alternative to traditional steel fibers [17-18]. The advantages of recycled fibers can be summarized as follows: Environmental Preservation: Using recycled steel fibers helps reduce industrial waste, utilize recycled materials, and decrease the consumption of natural resources, thus preserving the environment. Cost Reduction: Recycled steel fibers, due to their reusability, generally lower the costs of producing industrial steel fibers [12, 19-20]. Recycled tire fibers have properties similar to industrial steel fibers, and studies have shown that recycled steel fibers can be an efficient and effective substitute for industrial steel fibers [21-22]. In recent years, natural and recycled materials, including silica, have been used as cementitious reinforcements to improve the mechanical properties and performance of concrete [23-24]. Silica enhances the dispersion of steel fibers [25]. Furthermore, silica fume contributes to the strength of concrete mixtures by reducing porosity and minimizing capillary reactions. Silica fume has shown positive effects in increasing the density, strength, and performance of concrete [26].

Külekçi el. al investigated shotcrete support systems in the Gümüşhane Mastra gold mine. The study evaluated the performance of shotcrete under challenging mining conditions and identified factors affecting its effectiveness, such as material composition, application methods, and environmental conditions. The findings contributed to optimizing shotcrete mix designs and installation techniques for improved safety and performance in underground mining operations [44]. Zhang et al. investigated the impact of adding silica to concrete and concrete containing steel fibers, finding that silica improves the performance and workability of concrete, reduces voids, and strengthens the bond between concrete and steel fibers, thereby enhancing the mechanical properties of steel fiber-reinforced concrete. The study also highlighted that silica addition enhanced the workability of concrete, making it easier to mix and apply, particularly in fiber-reinforced systems where uniform fiber dispersion is critical. The improved bond between the steel fibers and the concrete matrix translated into better load transfer, resulting in increased tensile strength, flexural toughness, and resistance to cracking under dynamic and static loads [6]. Abhilash et al. explored the effects of nano-silica in fiber-reinforced concrete and found that increasing the fiber percentage from 2% to 3% improves the mechanical properties of the concrete. The study provided insights into the challenges associated with the use of nano-silica, such as dispersion difficulties, potential agglomeration, and cost implications. However, the authors pointed out that advancements in material processing and the development of optimized mix designs could address these limitations. Overall, the review concluded that nano-silica is a transformative material for enhancing the mechanical properties, durability, and sustainability of concrete, making it highly suitable for applications in modern construction and infrastructure projects. In another study, they examined the properties of concrete containing 3% nano-silica and found that it performed better than ordinary concrete [27]. Kanchidurai et al. studied the compressive strength, toughness, and impact resistance of hybrid reinforced concrete. The results revealed that HFRC with nano-silica exhibited superior impact resistance compared to conventional concrete, with significantly higher energy absorption under repeated impact loads. Furthermore, the combined use of hybrid fibers and nano-silica reduced the formation of microcracks, enhancing long-term durability and resistance to environmental degradation [28]. Chen et al. evaluated the effects of recycled polymer fibers from tires with different content levels (1.2, 2.4, 4.8, 9.6 kg) equivalent to 0.1%, 0.2%, 0.4%, and

0.8% in concrete, comparing them with ordinary concrete and concrete containing 0.9 kg of polypropylene fibers. They found that the optimal amount for increasing dynamic and static compressive strength and workability was 2.4 kg of recycled fibers, while for polypropylene fibers, it was approximately 1.8 kg. The research concluded that recycled tire polymer fibers are a viable solution for enhancing the dynamic performance and sustainability of concrete. The findings provide valuable insights for designing high-performance fiber-reinforced concrete for infrastructure subjected to dynamic or impact loads, while also contributing to the reduction of environmental waste [20].

Binglin et al. studied the impact of recycled waste steel fibers on the mechanical properties of concrete, finding that while steel fibers influence compressive strength, they significantly enhance flexural strength. Based on these results, it was concluded that recycled waste steel fibers can be used as a green and sustainable building material. Binglin also discussed the durability benefits of waste steel fiber-reinforced concrete, such as improved resistance to freeze-thaw cycles, abrasion, and chemical attacks. The study emphasized that the fibers' irregular shapes and variable dimensions—typical characteristics of recycled materials—did not negatively affect performance when proper mixing and dosage optimization techniques were applied [29]. Chen et al. examined the effects of recycled steel and polymer fibers from end-of-life tires, finding that including recycled steel fibers significantly compensates for the reduction in compressive and flexural strength caused by the addition of rubber particles. Increasing the recycled steel fibers from 0.5% to 1% led to approximately 29.4% and 76.1% improvements in compressive and flexural strength, respectively. The results showed that although the polymer fibers decomposed at elevated temperatures, the residual compressive strength of RTPFRC was comparable to that of plain concrete, while its resistance to spalling was significantly improved. The micro-channels left by the melted fibers also enhanced vapor dissipation, reducing internal stresses and improving the thermal stability of the concrete [30]. Jahandari et al. found that combining ISF (industrial steel fibers) with silica fume significantly improves the compressive strength and elastic modulus for enhancing RAC. The optimized mix design combining silica fume, steel fibers, and recycled aggregates demonstrated performance comparable to, or even exceeding, conventional concrete in terms of strength and toughness [32]. Qureshi et al. studied the performance of adding ISF (industrial steel fibers) and silica fume to RAC, finding that the combination can improve compressive strength by up to 5%. The study also highlighted the environmental benefits of this approach, emphasizing the reduction of construction waste through the use of recycled aggregates and the replacement of cement with industrial byproducts. This strategy not only improved the mechanical performance of RAC but also contributed to reducing its carbon footprint and promoting sustainable construction practices [33]. Ali et al. examined the mechanical properties and durability of RAC reinforced with glass fibers and silica fume, finding that the combined addition provides better benefits than adding them separately. Ali et al. concluded that the synergistic incorporation of silica fume and fibers provides an effective strategy to overcome the limitations of recycled concrete, transforming it into a high-performance, sustainable construction material. The findings have significant implications for promoting recycled concrete in structural applications while reducing the environmental impact of concrete production [34]. Nath et al. found that the combined addition of silica fume and RSF (recycled steel fibers) improves the compressive strength and splitting resistance of RAC. The results showed that the incorporation of recycled steel fibers significantly enhanced the mechanical performance of RAC. Fibers derived from waste tires, demolition debris, and industrial byproducts improved the compressive strength, tensile strength, and flexural toughness of RAC compared to conventional mixes without fibers. The study revealed that these fibers acted as crack arresters, providing effective stress redistribution and preventing the propagation of cracks under loading. It was observed that the geometry and source of the steel fibers influenced the extent of performance enhancement. Longer fibers and those with hooked or irregular shapes exhibited better mechanical interlocking with the concrete matrix, resulting in higher tensile and flexural strengths. The recycled fibers also contributed to improved energy absorption capacity, enabling the concrete to withstand higher loads and deformations before failure [35].

Zia et al. used industrial steel scrap and discarded steel fibers in concrete and observed improvements in mechanical properties. Chen et al. [3] investigated concrete containing hybrid recycled steel and polymer fibers from tires, finding that the optimal volume fraction was 1%

for steel fibers and 0.2% for recycled polymer fibers. The mechanical properties of the mix containing steel and recycled polymer fibers improved by 13.2% in compressive strength, 19.7% in tensile strength, and 59.9% in flexural strength. However, workability decreased with the addition of fibers [31]. Michalik et al. explored the feasibility of using steel fibers from recycled tires instead of industrial steel fibers, finding that the adhesion of cement slurry to recycled steel fibers was better than with industrial fibers, leading to improved properties of cementitious composites. Additionally, from an environmental and economic perspective, recycled steel fibers are a suitable replacement for industrial steel fibers [12]. Zhang et al., explored the incorporation of silica and steel fibers into concrete to enhance its mechanical properties. The researchers demonstrated that silica fibers improved crack resistance and reduced permeability, while steel fibers contributed significantly to tensile strength and ductility. The combination of both fibers optimized the concrete's performance in terms of durability and load-bearing capacity, making it suitable for infrastructure with high durability requirements [45]. Külekçi et al., examined the mechanical properties of shotcrete made using recycled aggregates derived from construction waste. They found that recycled aggregates could replace natural aggregates without significant compromises in compressive strength or flexural performance. Moreover, the study emphasized the environmental benefits of recycling, showcasing its potential for sustainable construction practices while maintaining the required performance standards in underground mining and tunneling [46]. Chen et al., conducted a comprehensive study on hybrid fibers, combining synthetic and natural fibers in shotcrete. The results revealed that hybrid fiber systems provided a synergistic effect, improving tensile strength, flexural toughness, and energy absorption compared to single-fiber systems. This approach optimized shotcrete performance for high-stress environments, such as tunnels and underground structures, and showcased improved long-term durability under dynamic loads [47].

Previous studies in related fields have shown that the production of industrial steel fibers contributes significantly to carbon emissions, with estimates ranging between 1.5 to 2.0 kg of CO_2 equivalent per kilogram of fiber produced. In contrast, the use of recycled fibers repurposes waste materials, preventing these fibers from being landfilled and reducing the carbon footprint associated with their disposal. For instance, in this study, replacing 40 kg/m^3 of industrial fibers with an equivalent amount of recycled fibers results in avoiding approximately 60 to 80 kg of CO_2 equivalent emissions per cubic meter of shotcrete, based on available literature data. Moreover, basalt stone shaves are extracted as a byproduct from existing processes and do not require additional extraction or manufacturing processes, further minimizing their environmental impact. Their incorporation as a replacement material not only reduces the reliance on industrial fibers but also mitigates the environmental hazards associated with mining and raw material processing.

This study investigates the effects of using recycled steel fibers from worn-out tires and basalt stone shaves on the mechanical properties of shotcrete. All data were collected through experiments in the Rock Mechanics Laboratory at Sahand University of Technology, Tabriz, under controlled conditions. The test samples include cubic samples (10×10 cm) and cylindrical samples (15×30 cm). These samples are categorized as follows: those without fibers, those containing industrial steel fibers at 1%, 2%, and 5%, and those with recycled fibers at concentrations of 0.5%, 1%, 1.5%, and 2%. Additionally, samples containing silica at concentrations of 0.5%, 1%, 1.5%, and 2% were also tested. The recycled fibers from worn-out tires were classified into three types: fine, coarse, and medium. Considering the importance of 3-day compressive strength for shotcrete, all samples were tested at this age.

2. Materials and methods

Today, fiber-reinforced shotcrete for tunnel linings is preferred due to its reduced costs and shorter construction time compared to cast-in-place concrete [36]. Shotcrete reinforced with medium and long fibers shows better flexural and tensile properties than concrete reinforced with short fibers. The optimal fiber length should be 2 to 5 times the maximum aggregate size [37]. The materials used in shotcrete include cement, aggregates, water, and additives. The desirable bonding strength of the cement can fully bind the aggregates, fibers, and other matrix materials together. The cement used in this project is Type 2 Sofian cement, conforming to the ASTM C150/C150M standard [38]. Coarse aggregates typically form the structural components of shotcrete. Fine aggregates must be carefully combined with coarse aggregates to ensure proper mix performance [39]. The aggregates used in shotcrete should conform to the upper and lower passing percentages of the grading curve shown in Figure 1.

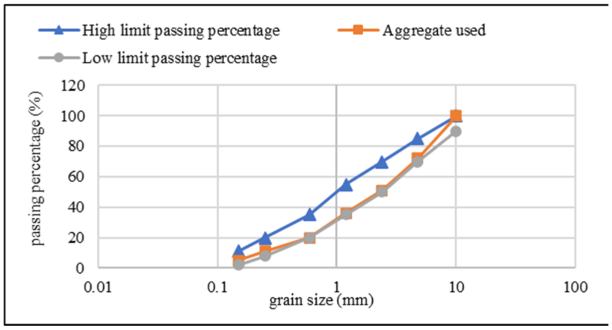

Figure 1. Granulation diagram of the used sand

City or clean water can be used in combination with shotcrete. Due to its corrosive action, seawater or other contaminated waters are not recommended for use [40]. The water used in the mixture is the drinking water from Sahand University of Technology. Some additives, such as accelerators, can be used to improve the compatibility of shotcrete containing steel fibers under certain specific conditions [40]. The additive used in this study is a liquid accelerator under the trade name SA-161, whose properties are presented in Table 1.

In this study, industrial steel fibers (ISF) and recycled steel fibers (RSF) with three different length categories were used. The images of the fibers used are shown in Figure 2, and their mechanical properties are presented in Table 2.

In this study, to examine the effect of basalt stone shaves on the mechanical properties of shotcrete, percentages of 0.5, 1, 1.5, and 2 were used in the mix. The basalt stone shaves powder, or basalt powder (BP), is a byproduct of the stone cutting process and passes through a 200 sieve. The chemical composition of this powder is presented in Table 3, and in Figure 3, the image of basalt powder is shown.

Table 1. Additive properties

Name	Density (kg/m^3)	Amount used (kg/m^3)
Sodium silicate	1500	10

Table 2. Mechanical properties of the fibers used.

Type of fiber	Diameter (mm)	Length (mm)	Length to diameter ratio (l/d)
Industrial steel fibers (ISF)	1.5	37.5	25
Coarse recycled steel fibers $(RSF)_1$	0.2	52	260
Medium recycled steel fibers $(RSF)_2$	0.2	3 to35	15 to175
Fine recycled steel fibers $(RSF)_3$	0.2	0.1 to 10	0.5 to50

Table 3. Chemical composition of BP

parameters	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
Value (%)	50.3	14.9	10.6	0.27	9.95	7.6	2.3	0.8	1.1	0.42	0.7

Figure 2. Types of fibers used in tests: 1- Coarse recycled steel fibers, 2- Medium recycled steel fibers, 3- Fine recycled steel fibers, and 4- Industrial steel fibers

Figure 3. Basalt powder.

In this study, the mix designs considered for evaluating regular shotcrete, shotcrete containing industrial steel fibers, shotcrete containing recycled fibers of type 1, type 2, and type 3, and shotcrete containing basalt stone shaves are presented in the table. As shown in the table 4, the amounts of cement, gravel, sand, accelerator, and water are identical across all designs, and only the fiber content differs. The mix design used for regular shotcrete is based on the mix design from the eastern extension of the Tabriz Metro Line 2 tunneling project and the ACI 544.3R standard (Table 4) [41]. For other mix designs, varying amounts of fibers 20, 40, and 100 kg/m^3 for industrial fibers and recycled fibers of types 1, 2, and 3 in amounts of 10, 20, 30, and 40 kg/m^3 and basalt stone shaves in volumes of 10 (S-10), 20 (S-20), 30 (S-30), and 40 kg/m^3 (S-40) were used.

To prepare the required samples for laboratory tests, the materials were first placed in a mixer and, after mixing, were poured into cubic and cylindrical molds. A vibration table was also used to prevent the formation of voids and to ensure uniform distribution of the samples. After completing these steps, and 24 hours after molding the samples, they were removed from the molds and placed in a water bath at of 23-25°C to conduct the relevant tests at 3 days of age.

Table 4. Mix design of samples

Design	Cement (kg/m^3)	Additive (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Water ($Liter/m^3$)	Fibers (kg/m^3)
Shotcrete (without fibers)	460	10	205	1255	280	-
Shotcrete (ISF-20)	460	10	205	1255	280	20
Shotcrete (ISF-40)	460	10	205	1255	280	40
Shotcrete (ISF-100)	460	10	205	1255	280	100
Shotcrete (RSF-10) (Type 1)	460	10	205	1255	280	10
Shotcrete (RSF-20) (Type 1)	460	10	205	1255	280	20
Shotcrete (RSF-30) (Type 1)	460	10	205	1255	280	30
Shotcrete (RSF-40) (Type 1)	460	10	205	1255	280	40
Shotcrete (RSF-10) (Type 2)	460	10	205	1255	280	10
Shotcrete (RSF-20) (Type 2)	460	10	205	1255	280	20
Shotcrete (RSF-30) (Type 2)	460	10	205	1255	280	30
Shotcrete (RSF-40) (Type 2)	460	10	205	1255	280	40
Shotcrete (RSF-10) (Type 3)	460	10	205	1255	280	10
Shotcrete (RSF-20) (Type 3)	460	10	205	1255	280	20
Shotcrete (RSF-30) (Type 3)	460	10	205	1255	280	30
Shotcrete (RSF-40) (Type 3)	460	10	205	1255	280	40
Shotcrete (S-10)	460	10	205	1255	280	10
Shotcrete (S-20)	460	10	205	1255	280	20
Shotcrete (S-30)	460	10	205	1255	280	30
Shotcrete (S-40)	460	10	205	1255	280	40

3. Laboratory tests

In recent years, recycled fibers from worn tires, as well as natural and recycled materials such as silica, has been used as a cementitious reinforcing material to improve the mechanical properties and workability of concrete. The significant performance improvements in both compressive and tensile strength observed in the fiber-reinforced shotcrete samples can be attributed to several key mechanisms involving the interaction between the fibers and the shotcrete matrix. First, the addition of fibers, whether industrial or recycled, enhances the overall matrix by providing additional reinforcement that helps to distribute stresses more evenly across the shotcrete. This is particularly important in shotcrete applications that are subject to dynamic loads or potential cracking. Fibers play a crucial role in bridging cracks, preventing them from propagating, and improving the overall ductility of the material. The increased fiber content leads to a more effective crack arrest mechanism, especially in the tensile tests, where the fibers prevent the formation and widening of cracks that would otherwise compromise the structural integrity.

For this reason, to evaluate the properties of shotcrete after the addition of these materials, the mechanical properties were examined through compressive strength and indirect tensile strength (Brazilian) tests on cubic (10×10×10 cm) and cylindrical (15×30 cm) samples (Figure 4).

3.1. Compressive strength test

To determine the compressive strength, cubic samples (10×10×10 cm) at 3 days of age, including those without fibers, with industrial fibers, with recycled fibers of types 1, 2, and 3, and those containing basalt stone shaves, were tested according to the BS EN 12390 standard [42].

As shown in Table 5 and Chart 6, in samples reinforced with 20, 40, and 100 $\mathrm{kg/m^3}$ of industrial steel fibers, an increase of 20%, 28%, and 38%, respectively, was observed in the 3-day-old samples. The use of type 1 recycled fibers (coarse) at 10 $\mathrm{kg/m^3}$led to a decrease in strength compared to the fiberless sample, but at amounts of 20, 30, and 40 $\mathrm{kg/m^3}$, there was an increase of 16%, 40%, and 60%, respectively, in the 3-day-old sample.

Figure 4. Cubic (10×10×10 cm) and cylindrical (15×30 cm) samples

Figure 5. Several samples tested for compressive strength and uniaxial compressive testing machine.

Table 5. 3-day compressive strength.

Sample	σ_c (MPa)
Shotcrete (without fibers)	8.9
Shotcrete (ISF-20)	10.7
Shotcrete (ISF-40)	11.4
Shotcrete (ISF-100)	12.3
Shotcrete (RSF-10) (Type 1)	8.7
Shotcrete (RSF-20) (Type 1)	10.4
Shotcrete (RSF-30) (Type 1)	12.53
Shotcrete (RSF-40) (Type 1)	14.3
Shotcrete (RSF-10) (Type 2)	9.1
Shotcrete (RSF-20) (Type 2)	13.6
Shotcrete (RSF-30) (Type 2)	15.8
Shotcrete (RSF-40) (Type 2)	18.1
Shotcrete (RSF-10) (Type 3)	9.15
Shotcrete (RSF-20) (Type 3)	9.7
Shotcrete (RSF-30) (Type 3)	12.4
Shotcrete (RSF-40) (Type 3)	14.3
Shotcrete (S-10)	9
Shotcrete (S-20)	10.7
Shotcrete (S-30)	11.8
Shotcrete (S-40)	12.6

The compressive strength of samples with 10, 20, 30, and 40 $\mathrm{kg/m^3}$ of type 2 recycled fibers (medium) showed an increase of 24.2%, 52.8%, 77.5%, and 103.3%, respectively, compared to the fiberless sample. In samples with 10, 20, 30, and 40 $\mathrm{kg/m^3}$ of type 3 recycled fibers (fine), the increases were 2%, 8%, 39%, and 60%, respectively, compared to the reference sample. Samples containing silica amounts of 10, 20, 30, and 40 $\mathrm{kg/m^3}$showed an increase of 1%, 20%, 32%, and 41%, respectively, compared to the reference sample. Based on the laboratory test results for industrial and recycled fibers and basalt stone shaves at a volume of 40 $\mathrm{kg/m^3}$ it can be concluded that recycled fibers and basalt stone shaves can effectively replace industrial fibers. These results suggest that recycled fibers, particularly Type 2 RSF (recycled steel fibers), can replace industrial fibers in achieving superior compressive strength. Importantly, the increase in strength is substantial and applicable to practical construction scenarios requiring load-bearing capacity, such as in shotcrete applications for tunneling and mining. The data supports the use of RSF (recycled steel fibers) as a cost-effective and environmentally sustainable alternative to industrial fibers.

3.2. Tensile strength

The indirect tensile (Brazilian) test was conducted on cylindrical samples (15×30 cm) at 3 days of age according to ASTM C469 [43]. For this test, the load must be applied along the diameter of the sample, and the loading continues until the sample splits into two parts.

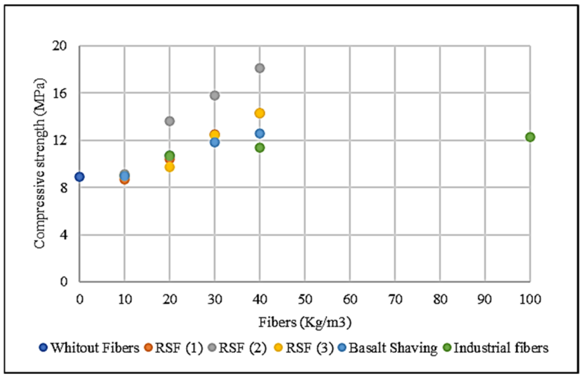

Figure 6. Compressive strength diagram of samples without fibers, with fibers, and containing basalt shavings.

Figure 7. The number of tested samples

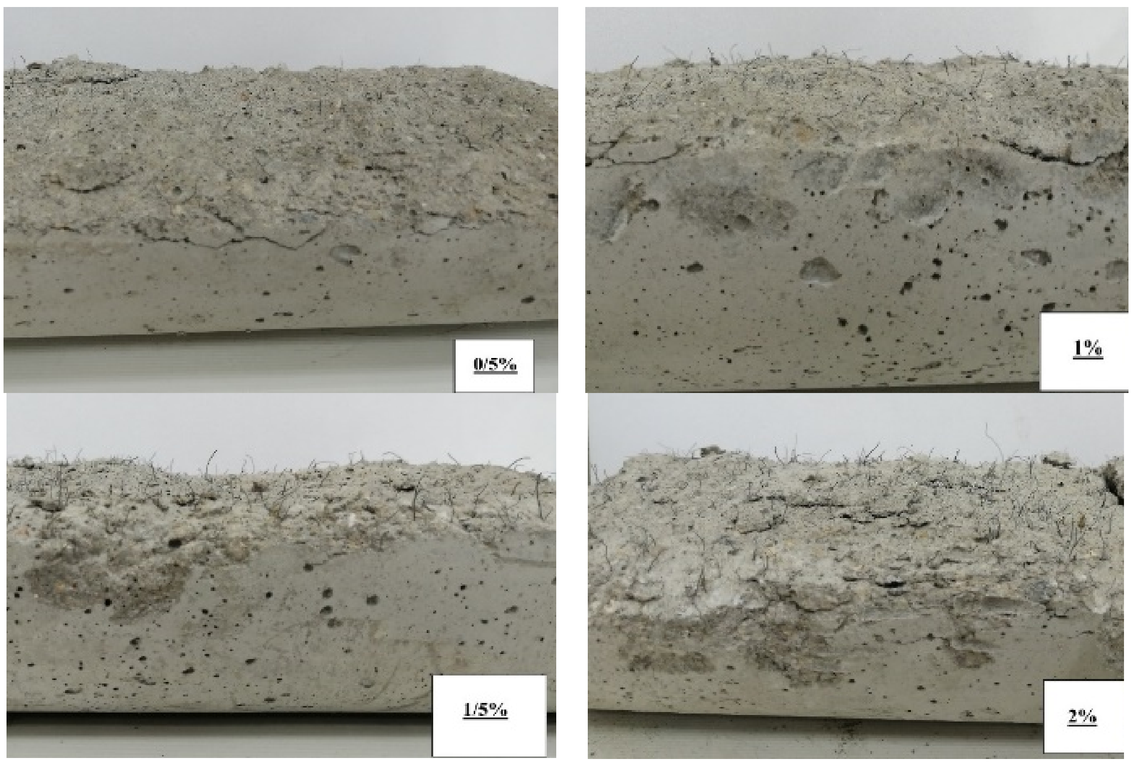

Figure 8. Proper distribution of fibers in cylindrical samples with fibers.

Based on Table 6 and Figure 9, adding industrial fibers at volumes of 20, 40, and 100 kg/m^3, the tensile strength of the 3-day-old samples increased by 1%, 22%, and 59%, respectively. Adding 10, 20, 30, and 40 kg/m^3 of type 1 recycled fibers resulted in a 72%, 84%, 86%, and 81% increase in tensile strength, respectively. For shotcrete samples containing type 2 fibers, adding 10, 20, 30, and 40 kg/m^3 of recycled fibers led to a 50%, 53%, 59%, and 43% increase in tensile strength, respectively. In shotcrete samples with type 3 recycled fibers at volumes of 10, 20, 30, and 40 kg/m^3 , the tensile strength increased by 72%, 89%, 90%, and 93%, respectively. For samples containing basalt stone shaves, adding 10, 20, 30, and 40 kg/m^3 increased by 47%, 73%, 81%, and 93% tensile strength, respectively. Considering the results and analysis, it can be concluded that using recycled fibers and basalt stone shaves as a replacement for industrial fibers is feasible. It is also economically viable and has positive environmental impacts. The data indicates that Type 3 RSF and basalt stone shaves provide high tensile strength enhancements, comparable to industrial fibers. This finding has significant practical value in shotcrete applications subjected to tensile forces, such as structural reinforcement in slopes or walls. Additionally, the economic and environmental benefits of using recycled fibers and basalt shaves further reinforce their practicality.

Table 6. Tensile strength of 3 days samples.

Sample	$\tau\ (MPa)$
Shotcrete (without fibers)	1.1
Shotcrete (ISF-20)	1.2
Shotcrete (ISF-40)	1.35
Shotcrete (ISF-100)	1.75
Shotcrete (RSF-10) (Type 1)	1.9
Shotcrete (RSF-20) (Type 1)	2.05
Shotcrete (RSF-30) (Type 1)	2.03
Shotcrete (RSF-40) (Type 1)	2
Shotcrete (RSF-10) (Type 2)	1.656
Shotcrete (RSF-20) (Type 2)	1.755
Shotcrete (RSF-30) (Type 2)	1.684
Shotcrete (RSF-40) (Type 2)	1.578
Shotcrete (RSF-10) (Type 3)	1.96
Shotcrete (RSF-20) (Type 3)	2.08
Shotcrete (RSF-30) (Type 3)	2.1
Shotcrete (RSF-40) (Type 3)	2.13
Shotcrete (S-10)	1.625
Shotcrete (S-20)	1.91
Shotcrete (S-30)	1.996
Shotcrete (S-40)	2.128

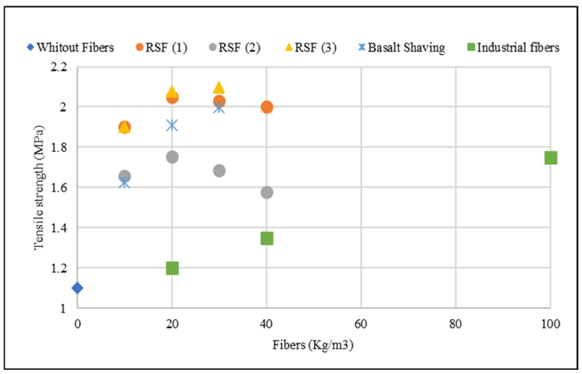

Figure 9. Tensile strength diagram of samples without fibers, with fibers and, containing basalt shavings.

In the compressive strength tests, the fibers provide a reinforcing framework within the shotcrete, allowing it to better withstand the internal stresses caused by applied loads. As fiber content increases, the fibers better anchor within the matrix, thus improving the load transfer between the fibers and the surrounding concrete material. Recycled fibers, particularly those from Type 2 RSF (medium), showed superior interaction with the matrix, contributing to higher compressive and tensile strengths. The rough surface texture and irregular shape of recycled fibers improve mechanical bonding with the matrix, thus enhancing the interfacial bond between the fibers and the shotcrete. The effect of this interfacial bond is particularly pronounced at higher fiber volumes (30 and 40 kg/m³), where a more pronounced reinforcement effect is observed, leading to substantial increases in both tensile and compressive strengths compared to the fibreless control samples. Furthermore, the basalt stone shaves in the mixture contribute to improved mechanical performance by acting as an aggregate reinforcement. The interaction between the basalt particles and the shotcrete matrix provides additional resistance to fracture propagation, which enhances both compressive and tensile strengths. The basalt particles also improve the overall packing density of the shotcrete, thus reducing voids and enhancing the material's resistance to cracking.

In summary, the enhanced mechanical properties of fiber-reinforced shotcrete result from the combined effects of improved crack bridging, better load distribution, and stronger bonding between fibers and the shotcrete matrix. The substitution of industrial fibers with recycled fibers and basalt stone shaves not only offers environmental benefits but also results in a material that performs equally well, if not better, than traditional industrial fiber-reinforced shotcrete.

4. Conclusions

Shotcrete is one of the construction stages in infrastructure maintenance systems, which can be implemented alone or primarily alongside other systems. The mechanical properties of shotcrete can be enhanced by using steel fibers. However, the production of fibers results in air pollution and adverse environmental effects. In recent years, the use of recycled fibers and alternative materials to improve the mechanical properties of shotcrete has become common.

The present laboratory research program includes regular shotcrete, shotcrete containing industrial steel fibers (at volumes of 20, 40, and 100 kg per cubic meter), coarse recycled fibers (at volumes of 10, 20, 30, and 40 kg per cubic meter), medium recycled fibers (at volumes of 10, 20, 30, and 40 kg per cubic meter), fine recycled fibers (at volumes of 10, 20, 30, and 40 kg per cubic meter), and basalt stone shaves (at volumes of 10, 20, 30, and 40 kg per cubic meter) to investigate and compare the mechanical properties of regular shotcrete, shotcrete with industrial fibers, shotcrete with recycled fibers (coarse, medium, and fine), and basalt stone shaves. The results obtained from the laboratory tests are as follows:

1. Shotcrete containing industrial steel fibers at volumes of 20, 40, and 100 kg per cubic meter

(corresponding to 1%, 2%, and 5%) exhibited an increasing trend in compressive strength at the 3-day age compared to the fiber-free samples in cubic (10×10 cm) specimens. This indicates a positive impact of increasing the fiber content on the sample properties. In the tensile test conducted on cylindrical (15×30 cm) specimens, the addition of industrial fibers to the mix led to an increase in the tensile strength of the samples.

2. Shotcrete containing coarse recycled fibers at volumes of 10, 20, 30, and 40 kg/m^3 (corresponding to 1%, 2%, and 5%) showed an initial decrease in compressive strength with the addition of 10 kg/m^3 but subsequently, an increase in fiber content led to an improvement in compressive strength at the 3-day age, compared to the fiber-free samples in cubic specimens. For the tensile test conducted on cylindrical specimens, the increase in fiber content by 0.5% and 1% resulted in higher tensile strength, while further increases of 1.5% and 2% led to a decrease in tensile strength.

3. Shotcrete containing medium recycled fibers at volumes of 10, 20, 30, and 40 kg/m^3 (corresponding to 1%, 2%, and 5%) showed an increase in compressive strength at the 3-day age compared to the fiber-free samples, with the increase in fiber content resulting in higher compressive strength. For the tensile strength test, increasing the fiber content to 10 and 20 kg/m^3 led to a rising trend in tensile strength, while fiber contents of 30 and 40 kg/m^3 resulted in a decreasing trend in tensile strength

4. For shotcrete with fine recycled fibers at volumes of 10, 20, 30, and 40 kg/m^3 (corresponding to 1%, 2%, and 5%), the compressive and tensile strengths of 3-day-old samples increased with the higher fiber percentages.

5. In shotcrete containing basalt stone shaves at volumes of 10, 20, 30, and 40 kg/m^3 (corresponding to 1%, 2%, and 5%), an increase in compressive and tensile strength was observed in the 3-day-old samples as the amount of basalt stone shaves increased.

6. The compressive and tensile strengths in samples containing coarse recycled fibers compared to industrial fibers at volumes of 20 and 40 kg/m^3 are as follows: for compressive strength, there is a decrease of 2% and an increase of 25%, respectively, and for tensile strength, there is an increase of 70% and 48%, respectively, in the samples.

7. The compressive and tensile strengths in samples containing medium recycled fibers compared to industrial fibers at volumes of 20 and 40 $kg/m^3$are as follows: for compressive strength, there is an increase of 27% and 58% in the tested samples, and for tensile strength, there is an increase of 46% and 16%, respectively, in the samples.

8. The compressive and tensile strengths in samples containing fine recycled fibers compared to industrial fibers at volumes of 20 and 40 kg/m^3 are as follows: for compressive strength, there is a decrease of 9% and an increase of 27% in the tested samples, and for tensile strength, there is an increase of 73% and 57%, respectively, in the samples.

9. The compressive and tensile strengths in samples containing basalt compared to industrial fibers at volumes of 20 and 40 kg/m^3 are as follows: For compressive strength, there is no change (same value) and a 10% increase in the 3-day-old samples. For tensile strength, there is an increase of 59% and 77% in the samples, respectively.

In samples containing 30 and 40 $kg/m^3$of recycled fibers and basalt stone shaves, compared to 40 and 100 $kg/m^3$of industrial fibers, the results of compressive and tensile tests suggest that recycled fibers and basalt stone shaves can effectively replace industrial fibers in shotcrete. This substitution not only achieves higher tensile and compressive strength but also helps in reducing pollution and environmental hazards associated with the production of these fibers.

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بررسی امکان‌سنجی استفاده از الیاف بازیافتی برای بهبود خواص مکانیکی شاتکریت

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چکیده

شاتکریت به عنوان یکی از اجزای سیستم پشتیبانی در تونل‌ها مورد استفاده قرار می‌گیرد و یکی از روش‌های بهبود خواص مکانیکی آن، افزودن الیاف است. الیاف می‌توانند خواص مکانیکی شاتکریت، از جمله مقاومت فشاری و کششی آن را به طور قابل توجهی بهبود بخشند که این امر منجر به صرفه‌جویی در زمان، هزینه و کاهش نیاز به نگهداری پس از نصب می‌شود. در سال‌های اخیر، به دلیل آلودگی زیست‌محیطی ناشی از تولید الیاف مصنوعی، تمایل به استفاده از مواد بازیافتی، به ویژه الیاف فولادی بازیافتی از تایرهای فرسوده، افزایش یافته است. مطالعه حاضر یک برنامه تحقیقاتی آزمایشگاهی است که امکان‌سنجی استفاده از الیاف بازیافتی برای بهبود خواص مکانیکی شاتکریت را بررسی می‌کند. در این تحقیق، از الیاف فولادی بازیافتی از تایرهای فرسوده و تراشه‌های سنگ بازالت برای ساخت نمونه‌های آزمایشگاهی استفاده شده است. نمونه‌های آزمایشگاهی شامل نمونه‌های مکعبی (۱۰×۱۰ سانتی‌متر) و استوانه‌ای (۱۵×۳۰ سانتی‌متر) با پنج طرح اختلاط مختلف بودند: شاتکریت معمولی و شاتکریت حاوی ۰.۵٪، ۱٪، ۱.۵٪ و ۲٪ الیاف بازیافتی. این الیاف در سه گروه طولی مختلف شامل درشت، مخلوط و ریز دسته‌بندی شدند. آزمایش‌های آزمایشگاهی شامل آزمون‌های مقاومت فشاری و کششی (برزیلی) در فواصل زمانی ۳ روزه انجام شد. نتایج مطالعات آزمایشگاهی نشان داد که الیاف بازیافتی از تایرهای فرسوده می‌توانند خواص مکانیکی شاتکریت را به طور قابل توجهی بهبود بخشند، به طوری که با افزایش ۲ درصدی محتوای الیاف، مقاومت فشاری تا دو برابر افزایش یافت. علاوه بر این، افزودن تراشه‌های سنگ بازالت نه تنها باعث بهبود مقاومت فشاری نمونه‌ها شد، بلکه تأثیر قابل توجهی بر افزایش مقاومت کششی آنها نیز داشت.

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