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Reactive Powder Concrete Reinforced with Manufactured Fibers or Recycled from Waste Tire

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Abstract: Reactive powder concrete is an improved type of concrete with high durability and strength compared to regular concrete. Its characteristics include that it does not contain coarse aggregate and all its components are smooth, so it has a homogeneous fine structure with few pores and high durability. It is also characterized by a low water-to-cement content, but it is brittle, so it is reinforced with fibers to make it more flexible. Manufactured steel fibers are expensive, and their manufacture also harms the environment and reduces non-renewable raw materials so that they can be replaced with steel fibers recycled from discarded tires. This study will compare the manufactured steel fibers and the recycled steel fibers from discarded tires in different proportions (0.25%, 0.5%, 0.75%, 1%, 1.25%, and 1.5%) for each of them. Their effect on the properties of reactive powder concrete will be known by conducting compressive strength, splitting tensile strength, flexural strength tests, thermal conductivity, and absorption. The results showed that recycled steel fibers from tires give higher compressive strength and flexural strength than manufactured steel fibers. The optimum dosage of recycled steel fiber is 1% and 0.75%.

Keywords: Reactive powder concrete, Recycled steel fiber, Silica fume, Thermal conductivity, Absorption of concrete

Introduction

Reactive powder concrete is a high-strength concrete characterized by durability and toughness. It contains a high silica fume content and a low percentage of water to cement (Cheyrezy et al., 1995). Enjoy high freezing, thawing, corrosion, sulfate resistance, and low permeability to water. Due to its unique advantages, it can be used in many engineering structures and applications, including bridges, tunnels, military buildings, marine buildings, and high-rise residential buildings. Its advantages include reducing the thickness and dimensions of the structural element, which reduces costs and increases space. It contains steel fibers to give ductility to the concrete. Hedages & Company conducted a statistical study estimating the number of vehicles worldwide in 2024. The study revealed 1.475 billion vehicles worldwide, including small and large cars, trucks, and vehicles with four wheels or more, except motorcycles. This means that there is one vehicle for every seven people in the world, given that the approximate number of the world's population is 7.951 billion people in 2024 (GoDaddy Security - Access Denied, n.d.).

According to Statista and Eurostat, there are about 600 million motorcycles worldwide (Volume in the Motorcycles Market Worldwide 2016-2029 | Statista, n.d.), which means that the total number of vehicles and motorcycles is estimated at 2.075 billion. The default age for replacing car tires is 6 to 10 years, and it is

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possible to dispose of them before this age if they were used in rough places, because of accidents, or were exposed to corrosion for various reasons (How Long Do Tires Last? Explore Tire Lifespan / Nokian Tyres, n.d.). One of the environmental hazards caused by discarded car tires is the pollution of the environment and soil because tires contain chemicals such as heavy metals and volatile organic materials that can seep into groundwater and soil. The decomposition of tires is also dangerous because they contain toxic materials that negatively affect plants and animals. Burning tires is considered air pollution because of the release of toxic gases such as sulfur dioxide and carbon monoxide, which cause human diseases, including cancer, asthma, pneumonia, and shortness of breath (The Environmental Impact of Waste Tires and How Pyrolysis Solves It – Green Tech Solutions, n.d.).

In recent years, the world's interest has been directed towards preserving the environment due to the large number of pollutants and the large use of non-renewable raw materials. Our environment is a trust that we must preserve for a better future for future generations. Solutions must be found to recycle and reuse this waste to reduce environmental risks. In the past years, research and studies have appeared on using granular rubber and steel fiber found in tires to improve the properties and/or replace manufactured materials for concrete production. In 2009, the effect of using recycled steel fibers from tires with regular concrete was studied in different proportions, lengths, and diameters. The fibers were not straight but rather had curves. It was found that steel fibers slightly improve their compressive strength compared to synthetic fibers. The bending test found that the behavior after cracking was identical to that of synthetic fibers and showed good energy absorption (Aiello et al., 2009). Recycled fibers from post-consumer tires suppress micro-crack propagation into meso and macro-cracks and therefore improve fatigue behavior. In contrast, synthetic fibers do a better job of stopping macro-cracks. In addition, it reduces the thickness of the pavement by 26%. It can withstand higher levels of stress than plain concrete (Graeff et al., 2012). Using silica fume and recycled steel fibers improves mechanical properties and impact resistance (Mastali & Dalvand, 2016). Recycled steel fibers from discarded tires are a promising material in structural applications and can completely or partially replace synthetic fibers in reactive powder concrete (Al-Tikrite & Hadi, 2017a). The results indicate that recycled steel fibers can be used as a reinforcing material and an alternative to synthetic fibers in high-performance concrete, especially if the recycled fibers are rubber-free (Yang et al., 2019). Using recycled steel fibers from waste tires improves the mechanical properties of high-strength concrete. The higher the fiber content, the better the mechanical properties. It also delays the crack width in concrete and increases ductility (Fauzan et al., 2019). Using recycled steel fibers from tires in ultra-high-performance concrete provides lower costs and environmental benefits, contributing to developing new and more sustainable applications for the construction industry (Awolusi et al., 2021), (Isa et al., 2020). Using recycled steel fibers from car tires improves the mechanical properties of concrete and can replace synthetic fibers in some engineering applications. Their use is considered a response to green environmental requirements (Zhang et al., 2022).

Recycled steel fibers from car tires are environmentally friendly, less costly, and improve the mechanical properties of concrete, in addition to increasing the volume fraction of the fibers (Zeybek et al., 2022). Recycled steel fibers from tires perform 90% of the potential equivalent to synthetic fibers for all the mechanical properties of reactive powder concrete with the same fiber size, and are environmentally friendly (Raza et al., 2022). Recycled fibers from car tires are a positive aspect when considering the impermeability and flexural performance of the mixture (Esmailzade et al., 2022). Recycled steel fiber reinforced concrete from tires has the toughness and energy absorption capacity (Zia et al., 2023). Recycled fibers from car tires are recommended for manufacturing ultra-high-performance precast concrete for earthquake and blast-resistant structures (Abdolpour et al., 2023). Using recycled steel fibers from car tires with mortar positively affects compressive strength, splitting tensile strength, and flexural strength (Markpiban & Sahamitmongkol, 2023). When using recycled steel fibers from tires for reactive powder concrete, we will get the same properties as synthetic fibers, and increasing the amount of fibers will give better results (Hasan, 2024).

Recycled fibers from tires improve the ductility of concrete (Manan et al., 2024). Using recycled steel fibers from tires in ultra-high-performance concrete not only improved concrete's compressive and tensile strength but also contributed to waste management by reusing discarded products and thus providing a sustainable alternative to infrastructure construction (Althoey et al., 2024; Manan et al., 2024; Tuleun & Adedeji, 2024). Using recycled textile fibers from tires in shotcrete improves the mechanical properties, especially its energy absorption capacity and deformability (Khosh & Atapour, 2024). Reactive powder concrete with high mechanical properties, sustainable, economical, and environmentally friendly, can be obtained when using waste materials such as recycled fibers from tires (Atlı & Ipek, 2024). The mechanical properties of concrete depend mainly on the properties of the materials that make it up, which are the fibers, the matrix, and the binding material between them.

This work is based on studying the effect of steel fiber recycled from the tires on the mechanical properties of concrete. The mechanical properties of concrete were evaluated with ordinary steel fibers to determine the difference between them. Six different proportions of each type of fiber will be used to determine their effect on the mechanical properties of reactive powder concrete.

Materials and Methods

Components of Reactive Powder Concrete

Reactive powder concrete consists of high-sulphate resistance Portland cement, SRC. This type was used because it is considered finer than ordinary Portland cement to increase the homogeneity of the concrete. Fine sand with a maximum size of 600 µm. Silica fume was produced according to the specifications C 1240 – 03a (ASTM, 2003). A substitute for cement by 25% because it is a pozzolanic material that improves the resistance of concrete and is considered an environmentally friendly material. A superplasticizer of the type MasterGlenium® 54 was used according to the specification: C 494/C 494M – 04 (C 494/C 494M – 04, 2004). Because it is not possible to obtain suitable workability for concrete without the superplasticizer due to the low water-to-cement ratio. Two types of steel fibers were used according to the specification: A 820/A 820M – 04 (A 820/A 820M – 04, 2004). The first type is manufactured fibers with a diameter of 0.5 mm and a length of 35 mm with hooked ends, as shown in (Figure 1). Hooked steel fibers give better mechanical performance than zigzag or straight steel fibers for high-performance concrete (Wu et al., 2016). The other type is straight and recycled from tires, with a diameter of 0.28 mm and a length of 35 ±5 mm, as shown in (Figure 1). Tire-recycled steel fibers have excellent ductility and tensile strength comparable to manufactured steel fibers (Domski et al., 2017). The direct tensile strength of individual recycled steel fibers is greater than 2000 MPa (Caggiano et al., 2015). Figure 2 shows how steel fibers are extracted from old tires.

(a) (b)

Figure 1. Steel fiber (a) manufactured steel fiber, (b) recycled steel fiber from a tire.

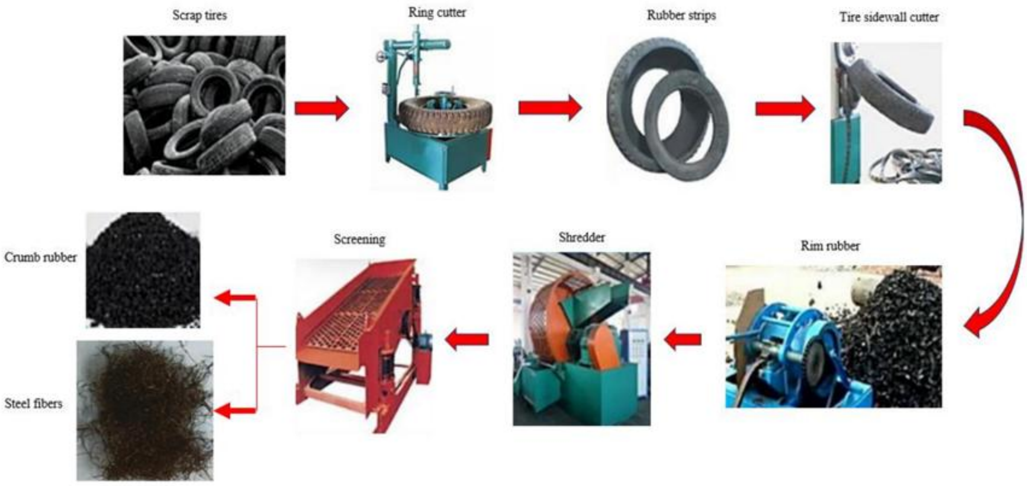

Figure 2. Tire recycling and steel fiber extraction process

Design and Preparation of RPC Batches

Twelve mixtures were studied in this research, and the following proportions were adopted based on the experimental mixtures. As shown in (Table 1), the proportions of cement, sand, silica fume, and water were fixed, and the proportions of superplasticizer were changed with increasing proportions of steel fibers to give the mixture suitable workability. The proportions of steel fibers were changed to six different proportions (0.25, 0.5, 0.75, 1.0, 1.25, and 1.5) for each of the manufactured and recycled steel fibers from car tires. In the first six mixtures in which manufactured steel fibers were used, the dry materials (cement, sand, silica fume, and steel fibers) were placed together and mixed with a horizontal mixer for 3 minutes. Then, the water and superplasticizer were mixed together and added gradually to the mixture, continuing to mix for 2.5-3.0 minutes.

For the other six mixtures of recycled steel fibers from tires, the dry materials (cement, sand, and silica fume) were placed in the mixer for 2.0 minutes. Then, water and superplasticizer were gradually added to the mixture and mixed for 3.0 minutes. After that, the recycled steel fibers were added manually and gradually to obtain a homogeneous mixture and good distribution of the fibers because this type of fibers is highly entangled during mixing. Mixing continued for 2.5-3.0 minutes.

Table 1. Mixing ratios

Type	Name	Cement (kg/m³)	Silica fume (kg/m³)	Sand (kg/m³)	Water/binder	Superplasticizers (L/kg) (by weight of binder)	Steel fiber (by volume)
Manufactured steel fibers	1MSF	980	245	1050	0.21	1.75	0.25%
	2MSF	980	245	1050	0.21	2	0.5%
	3MSF	980	245	1050	0.21	2.25	0.75%
	4MSF	980	245	1050	0.21	2.5	1%
	5MSF	980	245	1050	0.21	2.75	1.25%
	6MSF	980	245	1050	0.21	3	1.5%
Recycled steel fiber	1RSF	980	245	1050	0.21	1.75	0.25%
	2RSF	980	245	1050	0.21	2	0.5%
	3RSF	980	245	1050	0.21	2.25	0.75%
	4RSF	980	245	1050	0.21	2.5	1%
	5RSF	980	245	1050	0.21	2.75	1.25%
	6RSF	980	245	1050	0.21	3	1.5%

Casting and Curing of Samples

After completing the mixing process, each mixture was poured into molds of six cubes measuring (10×10 cm), three cylinders measuring (10×20 cm), and three prisms measuring (10×10×50 cm). The vibrating table was used for the compaction process for 5 minutes. After that, the sides of the mold were struck with five blows on each side, and the surface was leveled with a trowel, placed in the appropriate place, and covered with polyethylene sheets for 24 hours. After that, it was removed from the molds and put in a water basin containing a thermal heater to obtain water suitable for the treatment process. The mixing and pouring process was completed in December, and the treatment was completed for 28 days. (Figure 3) shows the samples after the curing process is completed and they are lifted from the curing tanks.

Figure 3. Samples

Testing Methods

A number of tests were conducted to determine the effect of recycled and industrial steel fibers on the mechanical properties of reactive powder concrete.

A- The compressive strength test was conducted according to the standard specification BS 1881-116: 1983 (Testing Concrete, 1983) It was conducted on six cubes measuring (10×10 cm) as shown in (Figure 4-a).
B- The splitting tensile strength test was conducted according to the specification ASTM C 496/C 496M – 04e1 (C 496/C 496M – 04, 2004) On three cylinders measuring (10×20 cm) as shown in (Figure 4-b).
C- The flexural strength test was conducted according to the specification ASTM C 78 – 02 (Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) 1, n.d.) On 3 prisms (10×10×10 cm) as shown in (Figure 4-c).
D-thermal conductivity test on three cylinders (2.5×12 cm).
E-absorption test was conducted according to the specification. (ASTM C642, 2013) On three cylinders, (10×20 cm).

(a) (b) (c)

Figure 4. (a) Compressive strength device, (b) Splitting tensile strength device, (c) Flexural strength device.

Results and Discussion

Density

Concrete density is an essential factor in determining the quality of concrete and its strength because when its density increases, this means the homogeneity of the concrete and the use of correct proportions of water, cement, sand, and silica fume, resulting in a small number of cracks and voids inside the concrete. It also plays a significant role in the self-loading process of structures, so high-density materials have high self-loading and more durability. Density test results for all mixes ranged between 2415 and 2474 kg/m³, as shown in Figure 5.

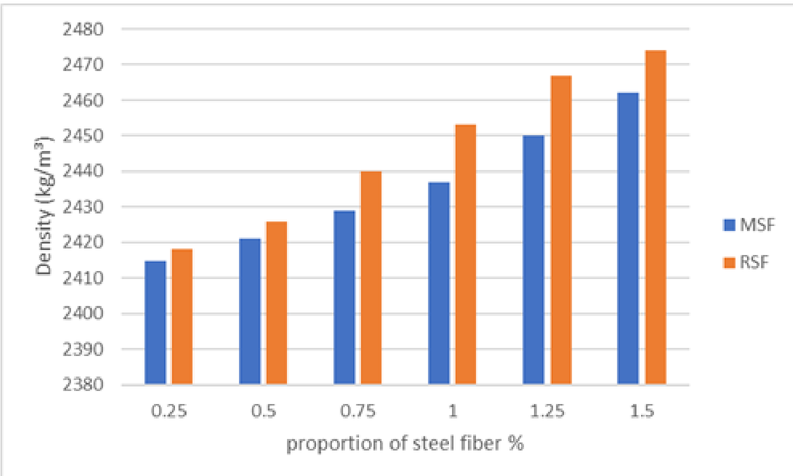

Figure 5. Density test result

According to the results, the mixes containing recycled steel fibers gave slightly higher densities than the mixes containing manufactured steel fibers. When using a fiber volume of about 0.25%, the density difference between recycled and manufactured steel fiber is 0.124%, which is considered a small percentage. However, increasing the volume of fiber used will result in a greater difference in densities. For example, using a fiber volume of about 1.5%, the difference between recycled and manufactured steel fiber will be 0.487%. Nevertheless, the difference between the two is minimal. It is also known that when the fiber content is increased, the density of the mixture will increase. Increasing the density of reactive powder concrete using manufactured or recycled steel fibers increases the self-loading of the structure, due to steel fibers having a higher density than manufactured steel fibers.

Compressive Strength

Compressive strength testing is one of the most critical tests performed on concrete because it relates to the safety and durability of concrete, as it determines the concrete's tolerance to the compressive loads it is exposed to, helps verify the quality of concrete, and reveals any defects or problems in the concrete mixture, such as a lack of cement or an excess of water. The compressive strength test results for all mixes ranged between 71.2 and 93.6 MPa, as shown in (Figure 6). Looking at the results, it is clear that recycled steel fibers from tires give a higher compressive strength of reactive powder concrete than manufactured steel fibers. This difference is due to the different shape, aspect ratio and orientation, and surface properties of the steel fiber ('Tejchman & 'Kozicki, 2010). At 1.5% fiber volume, the compressive strength is almost the same for both manufactured and recycled steel fibers from tires, and at 0.25% fiber volume, the compressive strength is also very close to the value. The 1% fiber size of the manufactured steel fiber gave the highest value of compressive strength, and is considered the optimal value. When increasing the volume of the steel fiber, the compressive strength will decrease. For steel fibers recycled from tires, the optimal value is 0.75%, and the value of 1% is very close to the optimal value, after which the compressive strength begins to decrease as the volume of the fiber continues to increase. Although the recycled steel fibers are old and rusty, and their lengths are not equal, they increase the capacity of the cracked load (Banthia & Sappakittipakorn, 2007). Therefore, it is preferable not to use high percentages of manufactured or recycled steel fibers, as their increase leads to disorganization in their distribution and tangling, which is counterproductive. According to the results of Raza at. el. (Al-Tikrite & Hadi, 2017b; Raza et al., 2022) and Al-Tikrite and Hadi (Al-Tikrite & Hadi, 2017b; Raza et al., 2022), the using a fiber size of 4% of recycled steel fibers from tires results in lower compressive strength compared to a lower fiber volume due to increased dispersion that reduces the efficiency of steel fiber bonding to the concrete matrix and leads to additional interstitial zones. The aspect ratio of manufactured steel fibers is precisely controlled, while the aspect ratio of recycled steel fibers is uneven, which can improve performance in terms of compressive strength (Alshammari et al., 2023).

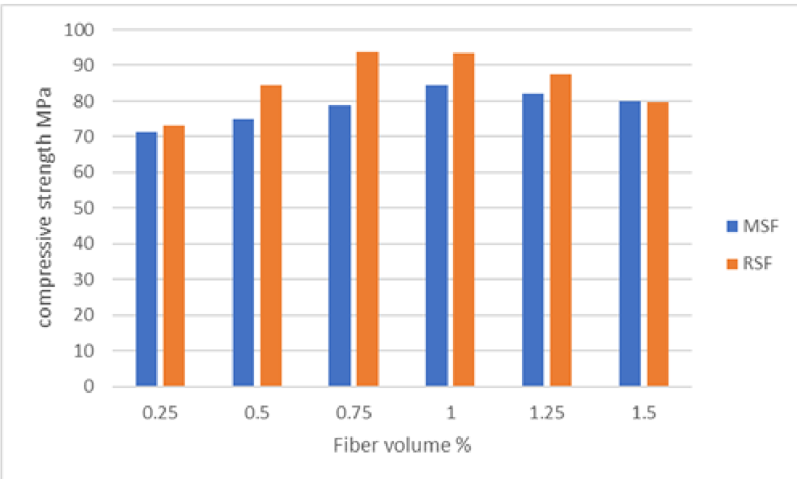

Figure 6. Compressive strength test results.

Splitting-Tensile Strength

This test is used instead of the direct tensile strength test because it is difficult to apply a uniform axial tensile force to the axis of the concrete. The splitting tensile strength test is used as an indirect tensile test by applying a compressive force along the lateral diameter of the cylinder, thus generating internal stresses that lead to the splitting of the concrete. This test gives an estimate of the tensile strength. This test is conducted to evaluate the effect of adding fibers on the tensile strength of concrete and to determine the extent of improvement in its performance in resisting fracture and cracking. The splitting tensile strength test results for all mixes ranged between 7.16 and 10.933 MPa, as shown in (Figure 7). According to the results, the recycled steel fibers from tires gave higher splitting tensile strength than the manufactured steel fibers at fiber size from 0.25% to 0.75%, but at 1% fiber volume, the manufactured steel fibers had a higher value. After this value, the splitting tensile strength decreased, but the manufactured steel fibers still gave higher values compared to the recycled steel fibers from tires. For steel fibers recycled from tires, the highest value was obtained at a fiber volume of 1%, after which the splitting tensile strength began to decrease, which means that increasing the size of the steel fibers leads to the opposite result.

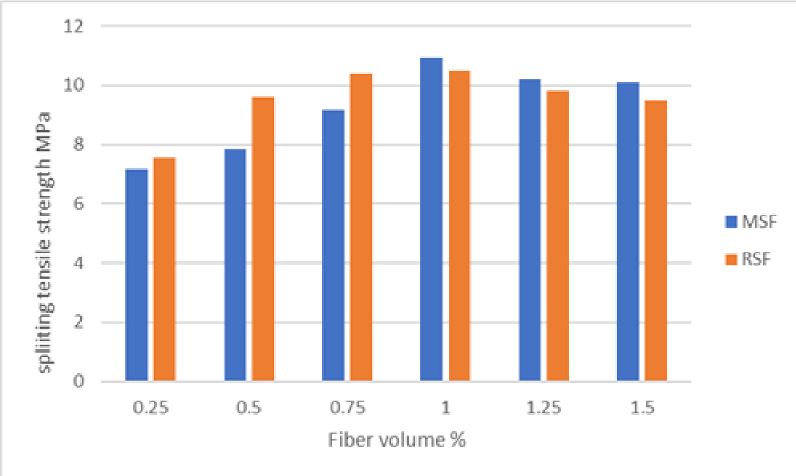

Figure 7. Splitting tensile strength test result.

Flexural Strength

This test measures the resistance of concrete to bending loads, which is very important in structural elements and contributes to understanding the behavior of concrete when exposed to tensile and compressive forces resulting from bending, as well as to assess the quality of concrete and the extent of the effect of the fibers used on the flexural strength. The flexural strength increases with the steel fibers added to the concrete mixture. The flexural strength test results for all mixes ranged between 8.6 and 14.2 MPa, as shown in (Figure 8). According to the results, reactive powder concrete containing recycled steel fibers from tires gives a higher flexural strength than reactive powder concrete containing manufactured steel fibers. The manufactured steel fibers give the highest flexural strength at a fiber volume of 1% and then show a decrease due to increased interlocking and interference between the fibers and the formation of gaps. For recycled steel fibers, the highest flexural strength is achieved at a fiber volume of 0.75%. And then it starts to decrease gradually. The quality of the steel used in recycled steel fibers is higher because they are specially manufactured for tires and resist repeated friction and deformation. In contrast, the quality of steel fibers explicitly manufactured for concrete differs, affecting their mechanical performance.

Thermal Conductivity

This test is done to know the ability of concrete to pass heat through it and also to understand the behavior of concrete when exposed to different temperatures, and concrete with low thermal conductivity is considered better because it will maintain a constant temperature inside and is good for thermal insulation. The thermal conductivity test results for all mixtures range from 1.006 to 1.56 (w/m.k), as shown in Figure 9. As shown in the results, when increasing the steel fibers of reactive powder concrete, an increase in thermal conductivity will occur because steel is a metal with good thermal conductivity, and when added to concrete, it will act as a bridge or path with less thermal resistance. These paths or bridges will make the heat transfer through the concrete better or easier, and with the observation that the thermal conductivity of steel is 50 times that of the thermal conductivity of concrete (Hassanzadeh-Aghdam et al., 2019; Lie & Kodur, 1995; Liu et al., 2017). Adding recycled steel fibers from tires increases the thermal conductivity of concrete (Kadela et al., 2023). Using recycled steel fibers from tires will slightly reduce thermal conductivity compared to manufactured steel fibers. Plain concrete without fiber gives less thermal conductivity, which means it is more thermally insulating. Plain concrete without fiber gives less thermal conductivity, which means it is more thermally insulating.

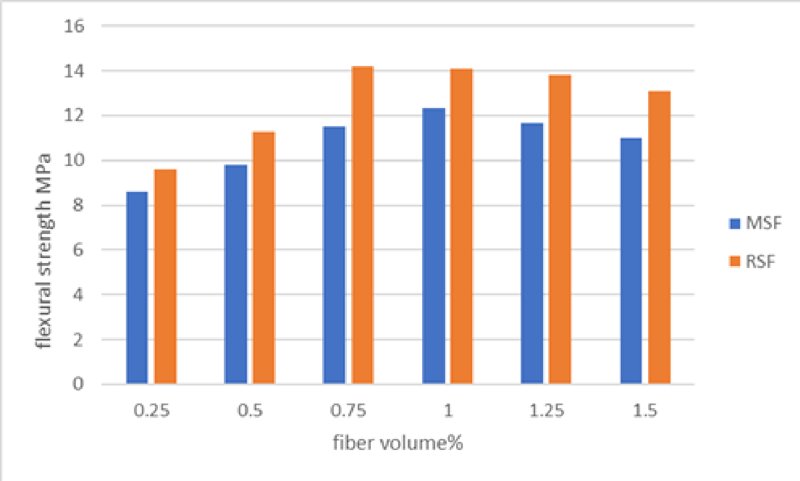

Figure 8. Flexural strength test result

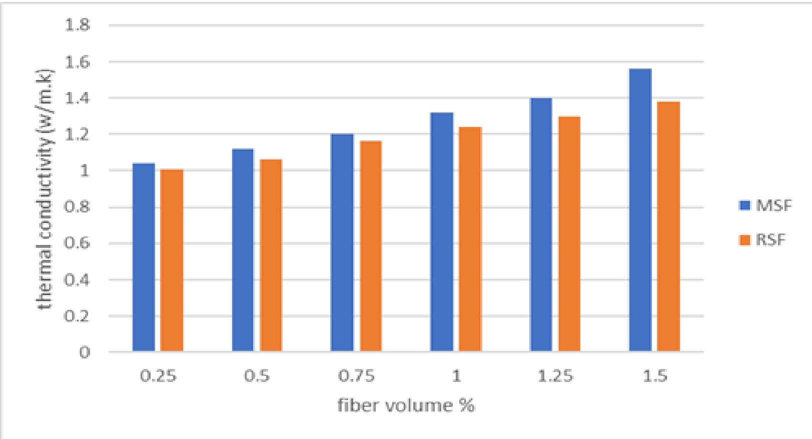

Figure 9. Thermal conductivity test result

Absorption

It is a way of knowing how much water concrete can absorb and store within its pores and voids when it is in contact with water. It is an indicator of the durability, quality, and permeability of the concrete. Concrete that absorbs the most water has higher porosity and lower strength. The absorption test results for all mixtures range from 1.9 to 3 % as shown in Figure 10.

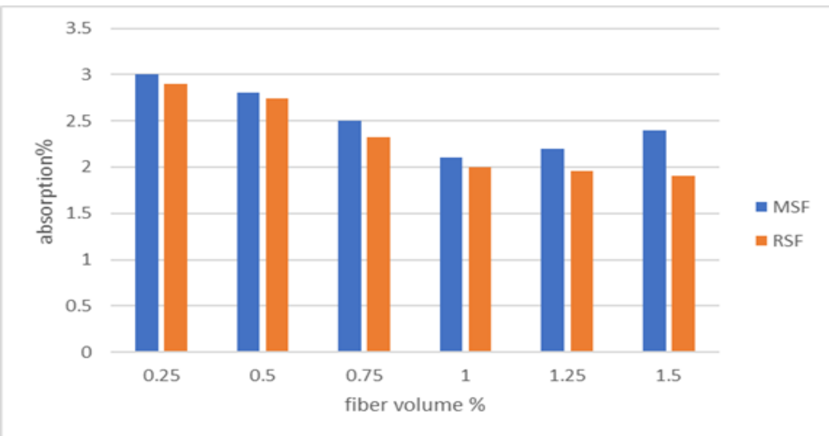

Figure 10. Absorption test result

Adding manufactured or recycled steel fibers to reactive powder concrete will reduce absorption because it reduces the plastic shrinkage cracks that occur after casting as a result of rapid water evaporation, and thus reduces porosity, meaning it reduces the pathways that allow water to penetrate the concrete. The porosity decreases when the content of manufactured steel fibers increases up to 1%, and after increasing this percentage, the absorption will start to increase because the steel fibers, when increasing their content, will cause agglomeration, and these agglomerations allow more air to be trapped, thus increasing the porosity. As for recycled steel fibers, when the content of recycled steel fibers increases, the absorption will decrease. This is because increasing its content reduces the porosity of the reactive powder concrete.

Conclusion

This research studies the difference between manufacturing and recycled steel fibers from tires and their effect on reactive powder concrete. Six different ratios (0.25%, 0.5%, 0.75%, 1%, 1.25%, 1.5%) of both types of fibers were used. Below are the main findings of this study:

- The density of mixtures containing recycled steel fibers is slightly higher than that of mixtures containing manufactured steel fibers because steel fibers have a higher density than manufactured steel fibers.
- The compressive strength of mixtures containing recycled steel fibers is higher than that of mixtures containing manufactured steel fibers, and the percentage of increase is not constant, but somewhat varies with the change in the rate of fibers used in the mix.
- 1% fiber volume gave the highest compressive strength to the manufactured steel fibers. 0.75% fiber volume gave the highest compressive strength to the steel fibers recycled from car tires.
- Recycled steel fibers from tires have less tensile strength than manufactured steel fibers.
- A steel fiber volume of 1% gave the highest splitting tensile strength for the manufactured steel fibers. A fiber volume of 1% gave the highest splitting tensile strength for steel fibers recycled from tires.
- Steel fiber reinforced composites give higher flexural strength than steel fiber composites, and increases by adding fibers to the composite.
- Steel fiber volume of 1% gave the highest flexural strength for the manufactured steel fibers. A fiber volume of 0.75% gave the highest flexural strength of steel fibers recycled from tires.
- Using recycled steel fibers from tires is better for the environment, improves the mechanical properties of reactive powder concrete, and is economically cheaper.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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