The Effect of Adding Waste Tire Rubber on Compressive Strength, Impact Resistance, and Damping Ratio of Fiber-Reinforced Foamed Concrete

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ABSTRACT

Research was conducted to investigate the effects of incorporating optimal proportions of Waste Tire Rubber (WTR) on the compressive strength, impact resistance, and damping of fiber-reinforced Foamed Concrete (FC) modified with a Super-Plasticizer (SP). In this study, four FC types with a density of 1100 kg/m^3 were produced: conventional FC, modified FC with SP, polypropylene (PP) fiber-reinforced FC, and fiber-reinforced rubberized FC (containing SP, PP, and WTR). To evaluate the effect of density on the FC properties, two additional fiber-reinforced rubberized FC mixtures were produced with densities of 800 and 1400 kg/m^3. The sand in the FC was partially replaced with WTR at optimum ratios of 50% for coarse WTR (4.75-10 mm) and 34% for fine WTR (≤ 2.36 mm). Additionally, 53 kg/m^3 of cement was substituted with fly ash. The results indicated that the addition of SP enhanced the properties of the fresh and hardened FC. For a given density of 1100 kg/m^3, adding WTR led to decreased consistency and strength while increased the impact and damping compared to the reference containing only SP and PP. However, the fiber-reinforced rubberized FC mix with SP showed improvements of 79.5%, 3700%, and 21.45% in compressive strength, impact resistance, and damping, respectively compared to conventional FC (without SP and PP). With the exception of the damping ratio, the compressive strength and impact resistance increased when the rubberized FC density was elevated.

Keywords- waste tire rubber; polypropylene fiber; compressive strength; impact resistance; damping ratio

I. INTRODUCTION

Foamed Concrete (FC) is a lightweight material comprised of a mix of cement, water, filler, and foam. It does not contain coarse aggregates and can be produced with or without fine sand. The density of this concrete can be regulated within the range of 400 to 1850 kg/m³ by manipulating the quantity of foam included in the mix [1]. Thus, FC is suitable for semi-structural elements, bridge packing, ground insulation, and insulated wall panels. Compared to conventional concrete, FC offers many benefits, including excellent flowability, reduced weight, and minimal use of aggregates. It has a high strength-to-weight ratio, exceptional thermal insulation characteristics, outstanding fire resistance, and noteworthy sound insulation capabilities [2, 3]. Nevertheless, FC has several drawbacks that limit its use such as reduced strength and modulus of elasticity, significant shrinkage, and a higher risk of cracking. To mitigate these issues, one can minimize the size of the pores, optimize their shape, and incorporate various substances, such as silica fume, furnace slag, fibers, rice husk ash, metakaolin, fly ash, waste marble powder, and other fillers from waste materials, as alternatives to cement or aggregates in the cement mixture [4, 5]. Rubberized FC is a material that possesses the advantageous characteristics of FC and incorporates the properties of rubberized concrete, including exceptional energy dissipation, damping, ductility, toughness, and impact resistance. Several studies have examined the replacement of gravel in concrete with Waste Tire Rubber material (WTR). However, the current literature lacks extensive studies on using WTR in FC. Authors in [6] examined the effect of using WTR as a partial replacement for sand in the FC. The findings indicated that when the WTR ratio increased, the density, compressive and flexural strengths, splitting tensile strength, and impact resistance of concrete decreased. Authors in [7] examined the ultra-lightweight WTR foamed mortar. The specimens with WTR components varying between 0% and 30% showed exceptional acoustic and thermal insulation, minimal water absorption, and reduced porosity despite a 10% decrease in compressive strength. Authors in [8] investigated the effect of varying cement quantities (300, 400, and 500 kg/m^3) combined with 20% partial replacement of silica fume and total replacement of fine aggregate with 100% WTR on the mechanical characteristics and abrasion resistance of FC. Authors in [9] investigated the effect of the absence of sand and WTR on the microstructure and mechanical characteristics of FC with cement paste densities of 400 and 600 kg/m³. The results showed that adding WTR to low-density mixes slows down foam material degradation and greatly improves the mechanical properties, especially the compressive strength and impact utilization, when compared to mixes that only contain sand.

In this study, a modified FC was produced by lowering the required mixing water by adding a superplasticizer. The modified FC mix was then reinforced with polypropylene fibers. In addition, WTR of fine and coarse particles were added at optimum ratios to the fiber-reinforced FC to produce fiber-reinforced rubberized FC at various target densities of 800, 1100, and 1400 kg/m^3. Finally, the effects of adding WTR on the fresh (consistency and density) and hardened (compressive strength, impact resistance, and damping properties) properties were investigated.

II. EXPERIMENTAL DETAILS

A. Materials

The investigated mixes were produced using type I (CEM I 42.5R) Ordinary Portland Cement (OPC) according to the ASTM C150-22 standard [10]. The OPC used had a specific gravity of 3.15 and a specific surface area (Blaine fineness) of 326 m²/kg. Part of the OPC was replaced with class F Fly Ash (FA) following the ASTM C618-19 standard [11]. The FA had a specific surface area (Blaine fineness) of 378 m²/kg and a strength activity index of 89%. Table I presents the chemical compositions of the OPC and FA used in this study. Fine aggregate was used according to the ASTM C33-18 specifications [12], which was first sieved to remove particles larger than 2.36 mm [13]. The fine aggregate used had a specific gravity of 2.65, absorption rate of 1.9%, and fineness modulus of 2.55. Figure 1 shows the fine aggregate grading and limits of the ASTM C33-18 standard [12]. Part of the fine aggregate was volumetrically replaced with recycled tires, which are the by-products of grinding old car tires. The fine WTR particles (smaller than 2.36 mm) classification was assessed according to ASTM C33-18, as indicated in Figure 1. Coarse WTR (4.75–10 mm) was also used. Before adding the WTR to the mixes, they were washed and dried to eliminate any dirt or dust. SikaFiber PPM-12 Poly-Propylene (PP) fibers measuring 32 μm in diameter, 12 mm in length, and 0.91 g/cm^3 in density were added to the mix, which helped to uniformly spread the WTR particles and made the FC more resistant to cracking. The foam bubbles were created using a solution of DCP foaming agent, Cemairin F300, at a ratio of 1 part foaming agent to 40 parts of water [14]. The mixtures were made more workable by adding a high-range water-reducing admixture, which was compliant with ASTM C494-17 Types G and F [15]. Figure 2 shows the solid materials used in this research.

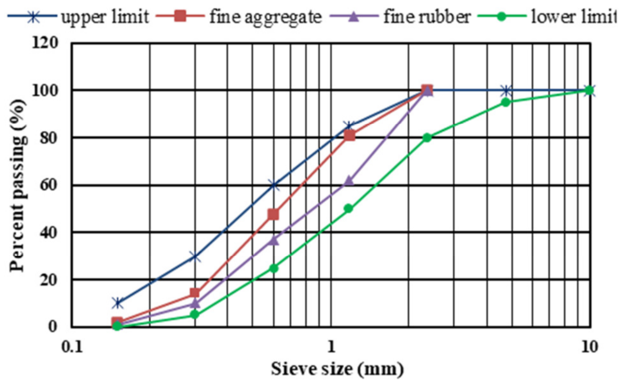

Fig. 1. Particle size distribution curves of fine waste tire rubber and fine aggregates.

Fig. 2. Materials of investigated mixes.

TABLE I. CHEMICAL COMPONENTS OF OPC AND FA

Components (%)	OPC (%)	FA (%)
CaO	63.21	4.74
SiO_2	20.74	55.48
Al_2O_3	5.67	24.66
Fe_2O_3	3.34	7.11
SO_3	2.17	0.43
MgO	1.82	2.26
K_2O	0.63	2.07
Na_2O	0.21	0.53
L.O.I.	1.76	1.92

B. Mix Design

An optimum mix consisting of 450 kg/m³ of OPC, 34% fine WTR, 50% coarse WTR, 0.45% PP fibers, and 53 kg/m³ of FA as a partial replacement of cement was formulated to produce fiber-reinforced rubberized foamed concrete with a density of 1100 kg/m^3. The Water/Cement ratio (W/C) and the superplasticizer (SP) were maintained at 0.32 and 1.4% by weight of the binder, respectively. This mix was selected after evaluating 32 mixes generated using the Central Composite Design (CCD) of Minitab software, based on five variables with a target density of 1100 ±50 kg/m³. Five variables were adopted: cement content between 250 and 450 kg/m³, volumetric replacement of fine aggregate WTR (0-50%) and coarse WTR (0-50%), replacement of cement with FA (0-60 kg/m³), and addition of PP fibers (0-0.5%). The responses were the density, compressive strength, splitting tensile strength, impact resistance, and thermal conductivity, which were evaluated after 28 days. The data obtained from these tests were then entered into Minitab software for optimization using the response surface methodology to obtain the studied fiber-reinforced rubberized FA (FC_{SPR}). Beside FC_{SPR}, five FC mixes were designed: i) a conventional FC mix (FC_O) with a target design density of 1100 kg/m³, ii) a modified FC mix with SP (FC_S), iii) a fiber-reinforced modified FC (FC_{SP}) was fabricated at a target design density of 1100 kg/m³ by adding PP fibers, fiber-reinforced rubberized FC mixes containing WTR, PP, and FA were designed at target densities of iv) 800 kg/m³ (FC_{SPR8}) and v) 1400 kg/m³ (FC_{SPR14}). Table II shows the details on the mixtures. All the mixes were designed using the absolute volume method outlined in ACI 523.3R-14.

TABLE II. MIX PROPORTIONS OF INVESTIGATED FC

	Mixes					
	FC_O	**FC_S**	**FC_{SP}**	**FC_{SPR}**	**FC_{SPR8}**	**FC_{SPR14}**
Target density (kg/m^3)	1100	1100	1100	1100	800	1400
Cement content (kg/m^3)	397	397	397	397	397	397
FA (kg/m^3)	53	53	53	53	53	53
W/C ratio	0.485	0.32	0.32	0.32	0.32	0.32
SP (kg/m^3)	0	6.3	6.3	6.3	6.3	6.3
Water content (kg/m^3)	218	144	144	144	144	144
Sand content (kg/m^3)	439	500	500	80	32	128
Fine WTR (kg/m^3)	0	0	0	73	29	117
Coarse WTR (kg/m^3)	0	0	0	109	44	175
PP fibers (kg/m^3)	0	0	4.1	4.1	4.1	4.1
Foam (L/m^3)	495	495	495	495	615	400

C. Specimens Preparation

The FC was produced using a rotating drum mixer. The dry materials (cement, FA, fine aggregate, and fine and/or coarse WTR) were first combined for three minutes. The slurry was formed by blending the dry components with water and a SP. To avoid balling, the PP fibers were distributed over the slurry and mixed for another two minutes. The last but most important part of making FC was adding a certain amount of foam to the unfoamed mixture and mixing it for two minutes or more until the foam was uniformly distributed in the mixture [16]. Following the guidelines of ASTM C796-19 [17], the densities of the newly collected samples were measured using a container with a known capacity. If the freshly measured density of the FC mix was within ±50 kg/m³ of the target density [18], it was deemed acceptable. To conduct the testing, the specimens were placed into plastic molds of varying sizes and subjected to gentle tapping with a rubber-tipped hammer according to ASTM C796-19 [17]. For curing, the specimens were sealed and cured after 24 h by wrapping them in a plastic film and leaving them at room temperature until testing.

III. EXPERIMENTAL METHODS

A. Consistency

The workability of the FC can be assessed based on its consistency. The widely employed slump workability standard is not appropriate for FC with a lower density. Brewer [19] proposed that the spreadability technique can be used to determine the consistency of lightweight concrete. The specimen was inserted into a cylindrical container with an open end, measuring 150 mm in length and 75 mm in diameter. After lifting the container, the average spread diameter of the FC mixture was determined by calculating the average of these two diameters.

B. Compressive Strength and Impact Test

The compressive strength after curing for 7, 14, and 28 days was determined using 100 mm^3 cubes. For each mix, the average of three measurements was obtained, and the test was conducted according to ASTM C513-11 [20]. Impact resistance was measured by a drop-weight impact test, as shown in Figure 3a, according to the test process suggested by the ACI 544 standard. The experiment was conducted on two discs obtained from each investigated mix at an age of 28 days. Each disc was 150 mm in diameter and 65 mm in thickness. The disc specimens were placed on a horizontal steel base. A steel ball with a diameter of 63.5 mm and weight of 1.178 kg was placed at the center of the top surface of the specimen, as shown in Figure 3b. Next, a steel cylinder weighing 4.57 kg was dropped repeatedly from a vertical height of 455 mm onto the ball at a rate of 25 blows per min. The total number of blows necessary to initiate the first crack was reported, and the experiment was then continued to record the number of blows required to induce the final fracture of the specimen.

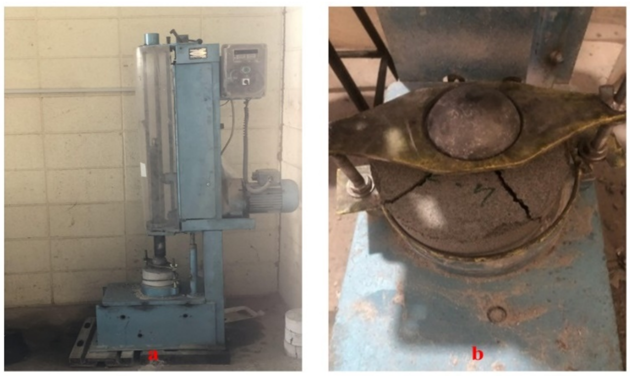

Fig. 3. (a) Impact resistance test device. (b) Specimen during impact test.

C. Damping Ratio

The damping characteristics of FC can be examined by adapting the ASTM E756-05 standard [21] and by following other relevant studies to identify the most suitable approach for concrete, FC, and mortar materials. To study the damping properties of FC, prismatic specimens with dimensions of 100×100×500 mm were used. The specimens were fabricated and mounted according to the experimental arrangement shown in Figure 4a. The beam specimen was secured at one end and unrestricted at the other end. The experiment involved applying a 15 N load to the same beam five times. The weight was hung from the unrestricted end using a string and maintained at a steady state. Upon severing the load string, the sensor detected the oscillation in the beam using an accelerometer with a sensitivity of 26±8 mV/g, which was positioned at the free end of the beam. To convert this vibration into a wave, the accelerometer was connected to a National Instruments PXI-4462 4-Input Dynamic Signal Analyzer, which is a module designed for sound and vibration measurements. This module has a resolution of 24 bits and sampling rate of 204.8 kS/s.

Signal conditioning and analysis were performed using integrated DIAdem software with LabVIEW, developed by National Instruments, installed on a computer. This software was used to convert analog vibration data into digital signals and then transform them into the frequency domain using Fast Fourier transform (FFT).

Fig. 4. (a) Damping test setup. (b) Measurement equipment and the LabVIEW system.

The damping characteristics of the beam were quantified by the damping ratio (ζ), which can be determined by analyzing the wave that occurs when the string is cut using the logarithmic decrement approach described in (1) [22]. Wave analysis was based on the output of the DIAdem tool, as shown in Figure 4b.

$$\zeta = \ln\left[\frac{Y_1}{Y_2}\right] \times \frac{1}{N\times 2\pi} \times 100 \quad (1)$$

where ζ is the damping ratio expressed as a percentage, Y_1 represents the wave peak amplitude, Y_2 is approximately half the magnitude of Y_1 ($Y_2 \approx 0.5\ Y_1$), and N denotes the total number of cycles between Y_1 and Y_2.

IV. ANALYSIS OF TEST RESULTS

A. Consistency

For a given density of 1100 kg/m^3, Figures 5 and 6 illustrate the alteration in the ability of the mixes to spread when SP, PP fibers, and WTR were added before and after the foam was incorporated. When incorporating foam into a base mix, it is important to note that the spread diameter rate decreased due to increased cohesion and lower self-weight (Figure 5). Conversely, the inclusion of SP resulted in a higher level of spreadability compared with the conventional mix (FC_O) [23]. In addition, the spread diameter decreased when the achieved density was reduced, even if the spreadability variance for the unfoamed mixes was small. The decrease in the spread rate was more pronounced when foam was added to mixes that had lower densities (foam volume was high) (Figure 6). One explanation is that when the density is lower, there is a higher proportion of foam than paste. The increased presence of foam improves the adhesion between the bubbles and solid particles in the mixture, resulting in a greater paste stiffness. Figure 6 illustrates that the incorporation of PP into the mixtures that already included WTR, and other additives led to a decrease in the spreadability value for all densities.

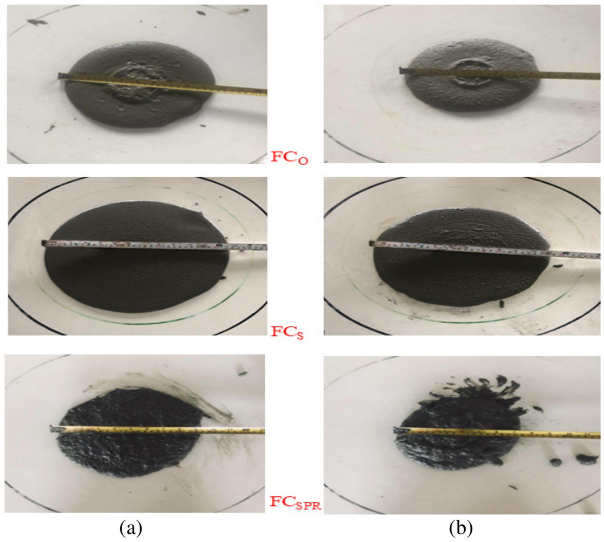

Fig. 5. Spreadability of (a) unfoamd mixtures, (b) foamed mixtures.

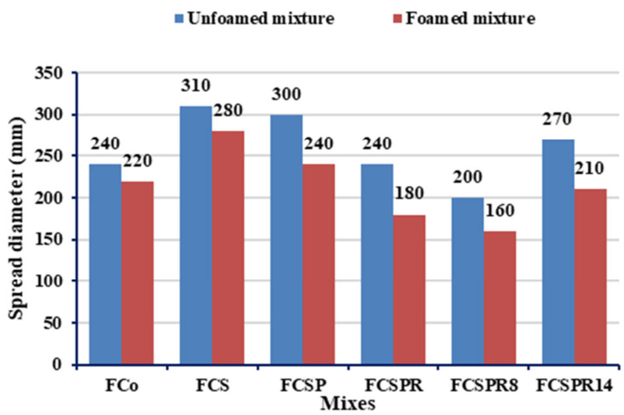

Fig. 6. Effect of SP, PP, WTR, and foam volume on spread diameter of investigated FC mixes.

B. Compressive Strength

Figure 7 illustrates the influence of using SP, adding PP fibers, and partial volumetric substitution of sand with WTR on the compressive strength of the investigated mixes made at various densities. It can be seen from Figure 7 that in terms of modified FC (with SP), there was a significant increase of 128.42% in the compressive strength of the FC_S mix made at 28 days at a density of 1100 kg/m³ compared with the conventional mix (FC_O). Additionally, incorporating PP fibers into the FC mixture (FC_{SP}), resulted in a slight enhancement in compressive strength, by about 1.7% compared to the FC_S mix. In contrast, using 34% fine and 50% coarse WTR in place of sand, while maintaining the same target density of 1100 kg/m^3, resulted in a 22.72% reduction in compressive strength for FC_{SPR} compared to the FC_{SP} mix. The loss in strength is attributed to the incorporation of rubber, which results in inadequate adhesion between the mortar particles and the rubber. Consequently, cracks developed and spread in the interface region [24]. After 28 days, when the density of the rubberized mix was reduced from 1100 to 800 kg/m³, the compressive strength of the FC_{SPR8} mix decreased by 41.26% compared to the FC_{SPR} mix. When the density was increased to 1400 kg/m³, the strength of the FC_{SPR14} mix increased by 22.15% compared with the FC_{SPR} mix of 1100 kg/m^3. This is because the strength of the FC is significantly affected by changes in its density, that is, increasing or decreasing the foam volume. The WTR particles have mostly soft surfaces with irregular protrusions and edges, allowing them to be firmly interlocked into the cement paste. Nevertheless, the adhesion between the rubber particles and cement paste is weak compared with that of conventional stiff aggregates. On the other hand, the presence of cracks and the irregular shape of the rubber particles may facilitate the capture and retention of air [25]. In the FC system, it is difficult to discern these gaps because of the predominant presence of air pores. Notwithstanding this fact, in some regions, a very narrow gap between the rubber and cement binder was observed. Specifically, cracks and gaps were observed surrounding the rubber particles, particularly in the ITZ zone, as shown in Figure 8.

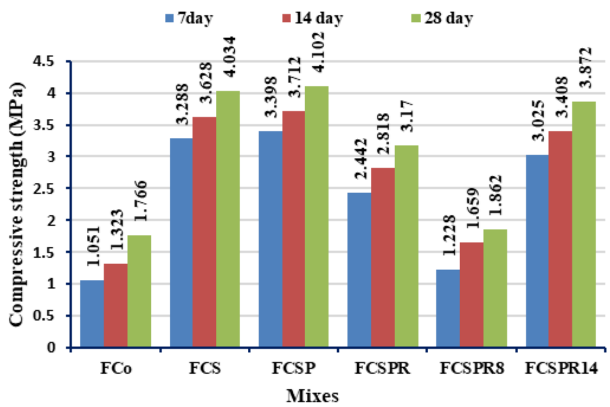

Fig. 7. Compressive strength at 7,14, and 28 days of investigated mixes.

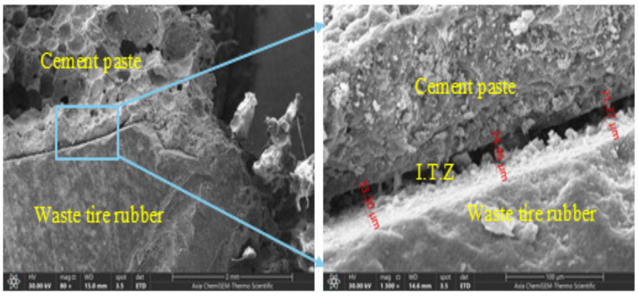

Fig. 8. SEM images of the fiber-reinforced rubberized FC mix.

C. Impact Resistance

Figure 9 shows the effect of SP, PP fibers, and WTR on the number of blows required to cause damage to the samples after 28 days of curing, for mixes made of various densities (800, 1100, and 1400 kg/m³). Adding SP to the conventional foamed concrete mix (FC_O) made the FC_S mix more resistant to impact at pre-failure by 400%. In contrast, the impact resistance of the FC_{SP} mix, which was modified by both SP and PP fibers, exhibited a 140% increase compared to that of the FC_S mix. Moreover, adding WTR at any target density resulted in enhanced impact resistance compared to mixes without WTR (FC_S and FC_{SP}). At the target density of 1100 kg/m^3, the addition of WTR (FC_{SPR} mix) increased the impact strength by 217% at pre-failure compared with FC_{SP}. Furthermore, reducing the density of the rubberized mix to 800 kg/m³ (FC_{SPR8}) resulted in a 40% loss in impact resistance compared to the FC_{SPR} mix. In contrast, when the density was increased to 1400 kg/m³, the impact rate of the FC_{SPR14} mix was 65% higher than that of FC_{SPR}. This enhancement is attributed to the ductile characteristics of the WTR particles. The presence of uneven edges and irregular morphologies of the WTR particles depicted in Figure 8 may improve the impact resistance ratio by creating a pressure-release mechanism. Figure 10 illustrates the various failure modes observed in mixes made with varying additives. The specimens exhibited evident deformation on their top surface upon exposure to the impact force. As shown in the results, increasing the mix density resulted in a proportional increase in both the pre-failure deformation and impact resistance. In contrast to rubberized foamed concrete mixes, conventional (FC_O) and modified (FC_S) mixes exhibited brittle failure.

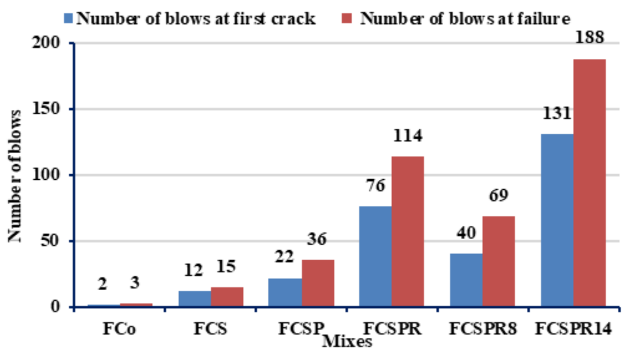

Fig. 9. Impact resistance behavior of the investigated FC mixes.

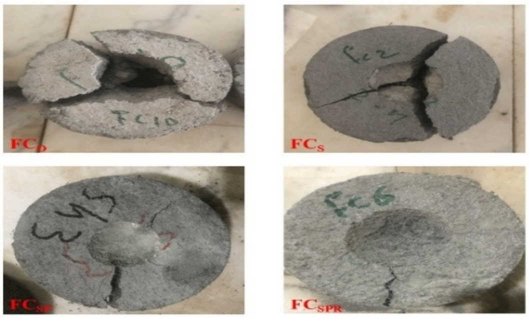

Fig. 10. The failure modes of investigated mixes as conventional, modified, fiber-reinforced, and rubberized FC mixes.

D. Damping

Damping is a measure of a material's capacity to absorb energy. It has been shown that low-strength concrete has a higher damping than high-strength concrete. This means that damping is positively related to ductility, indicating the ability of a material to deform without breaking, rather than being brittle. Table III presents the experimental data, which include the maximum and half-magnitudes of the wave (Y_1 and Y_2) and damping ratios. The decrease in the amplitude of the acceleration, as shown in Figure 11, was used to calculate Y_1 and Y_2 to determine the damping ratio ζ.

TABLE III. RESULTS OF THE DAMPING TEST WITH A LOAD OF 15 N.

Mixture	Y_1	Y_2	N	ζ (%)
FC_0	0.18 (0.016)	0.088 (0.009)	2.2 (0.447)	5.232 (0.559)
FC_S	0.189 (0.024)	0.095 (0.017)	2.4 (0.548)	4.747 (0.785)
FC_{SP}	0.19 (0.013)	0.99 (0.008)	2.0 (0.00)	5.194 (0.186)
FC_{SPR}	0.265 (0.014)	0.112 (0.009)	2.2 (0.447)	6.354 (0.560)
FC_{SPR8}	0.331 (0.017)	0.145 (0.004)	2.0 (0.00)	6.565 (0.471)
FC_{SPR14}	0.221 (0.011)	0.106 (0.01)	2.2 (0.447)	5.515 (0.91)

The value in parentheses is the standard deviation.

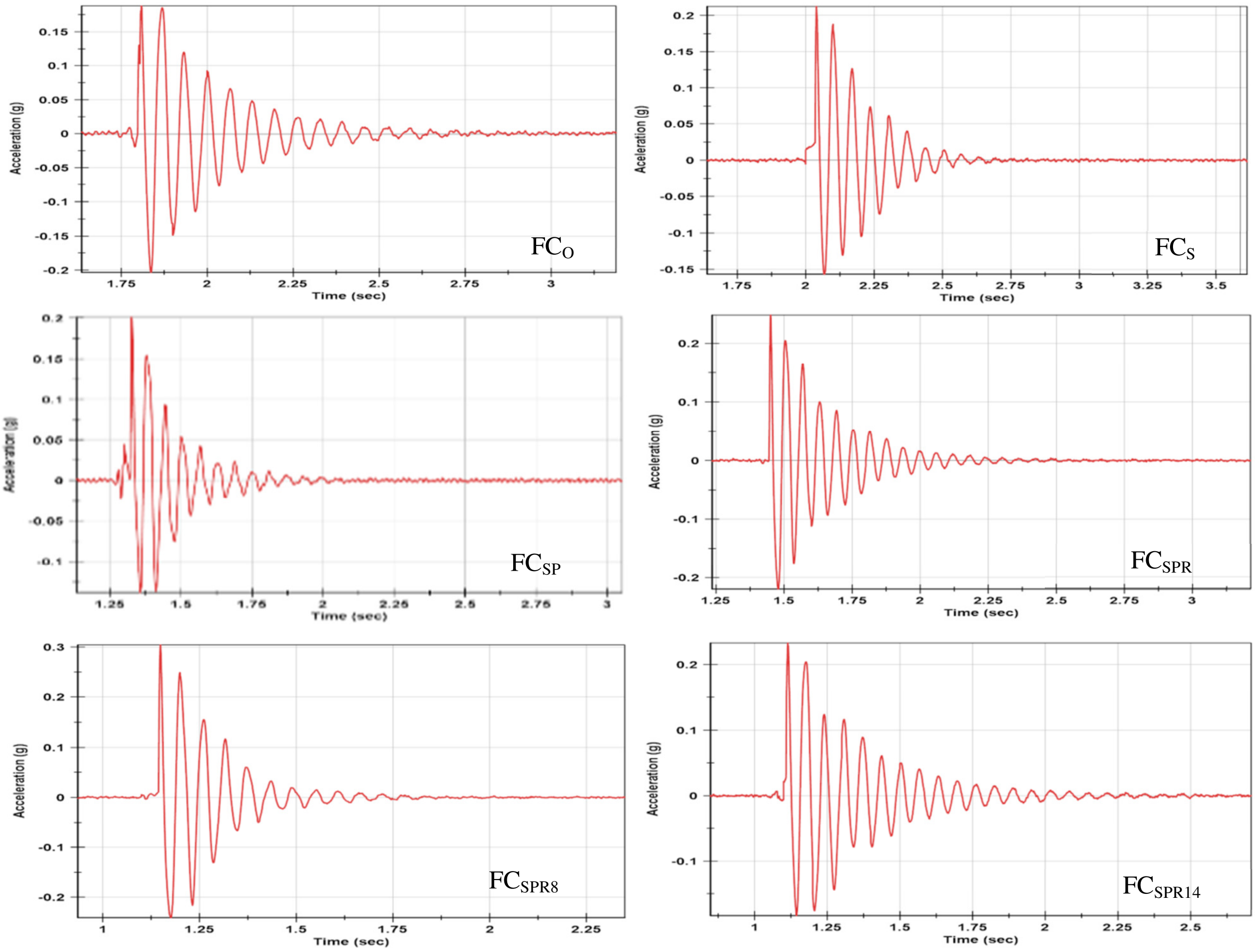

Fig. 11. Typical signal responses in the time domain of foamed concrete under a 15 N load on the free end of the beam for the investigated mixes.

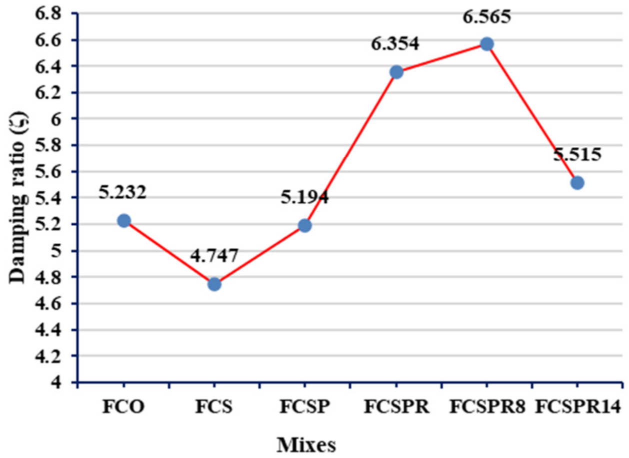

Fig. 12. Damping ratio (ζ) after 15 cycles of the investigated mixtures.

The damping ratio was tested five times for each beam with a weight of 15 N, and the obtained results were averaged for each mix. The data shown in Figure 12 illustrate a 10.2% enhancement in the damping ratios of conventional foamed concrete (FC_O) beams that have a target density of 1100 kg/m³ compared to the mix with superplasticizers (FC_S). Incorporating PP fibers into the modified foamed concrete (FC_{SP}), at the same density improved the damping ratio, by about 9.42% of that of the FC_S mix. Moreover, sand substituted by WTR in rubberized FC beams enhanced the damping ratio at all densities in comparison with FC_O. Meanwhile, the damping ratio with a target density of 1100 kg/m^3 for the FC_{SPR} mix increased by 22.33% compared to that of the FC_{SP}. Furthermore, lowering the density of the FC_{SPR} mixture to 800 kg/m³ (FC_{SPR8}) resulted in a slight increase in the damping ratio (3.32%). Conversely, raising the density to 1400 kg/m^3 (FC_{SPR14}) resulted in a 13.2% reduction in the damping ratio when comparing both mixes with the FC_{SPR} mix.

V. CONCLUSIONS

This study evaluated the potential of Waste Tire Rubber (WTR) to improve sustainable building methods as well as to improve the impact resistance and damping properties of Foamed Concrete (FC). Additionally, the freshness (consistency and density) and compressive strength parameters were examined.

We modified the conventional FC by adding 1.4% Super-Plasticizer (SP) to reduce the amount of water used in the mixing process and incorporated 0.45% Poly-Propylene (PP) fibers to improve the dispersion of rubber particles. Furthermore, 84% of the volumetric sand was replaced with Waste Tire Rubber (WTR), 34% with fine WTR, and 50% with coarse WTR. Additionally, all mixes consisted of 450 kg/m³ of Ordinary Portland Cement (OPC) and 53 kg/m³ of Fly Ash (FA), which was introduced as replacement of cement, producing fiber-reinforced rubberized FC at various target densities of 800, 1100, and 1400 kg/m^3.

Modifying conventional FC with a SP improved its compressive strength and impact resistance. However, adding PP fibers and/or WTR decreased the consistency of the FC, leading to an improvement in the compressive strength. However, replacing a portion of sand with WTR improved the impact resistance and damping ratio by approximately 217% and 22.33%, respectively, compared with FC_{SP}. Furthermore, compared to the FC_{SPR}, impact resistance, and damping ratio decreased by about 40% and 3.32%, respectively, when the density was reduced to 800 kg/m^3, and improved by about 65% and 13.2%, respectively, when the density was increased to 1400 kg/m^3.

In general, making fiber-reinforced rubberized FC modified with SP (FC_{SPR}) increased the compressive strength, impact resistance, and damping ratio by about 79.5%, 3700%, and 21.45%, respectively, for a density of 1100 kg/m^3. This was performed while maintaining the same consistency (spreadability value) of the foamed concrete mix (FC_O).

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