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Preliminary trial on the potential of fiber-reinforced rubberized foamed concrete as sustainable roof tiles

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HIGHLIGHTS

- Foamed concrete tiles with SP, PP fibers, and waste tire rubber were produced per IQS 1107 standards.
- Sustainability was achieved by replacing up to 84% of sand with waste tire rubber.
- Fiber-reinforced rubberized foamed concrete tiles were studied at densities of 800, 1100, and 1400 kg/m³.
- Including PP and WTR improved rupture load, weight, and water absorption in FC tiles compared to FCTO.

Keywords:
Foamed concrete tiles; Polypropylene fiber; Waste tire rubber; Rupture force; Water absorption.

ABSTRACT

The growing negative effects of nonbiodegradable trash, including waste tires, underscore the necessity for sustainable alternatives in construction materials. This study examines the feasibility of manufacturing foamed concrete tiles reinforced with fibers, utilizing a superplasticizer (SP) with suitable quantities of waste tire rubber (WTR) from nonbiodegradable tires to reduce environmental pollution. Initially, standard concrete tiles with a density of 2400 kg/m³ and dimensions of 500 × 500 × 50 mm³ (Class A, IQS 1107) were manufactured for comparison. Subsequently, four types of foamed concrete tiles with a density of 1100 kg/m³ were produced: conventional foamed concrete tiles, foamed concrete tiles enhanced with SP, fiber-reinforced foamed concrete tiles utilizing polypropylene (PP), and fiber-reinforced rubberized foamed concrete tiles containing SP, PP, and WTR. To assess the effect of density, fiber-reinforced rubberized foamed concrete tiles were produced with densities of 800 and 1400 kg/m³. In examined foamed concrete tile preparations, a fraction of sand (≤ 2.36 mm) was substituted with WTR at optimal proportions of 50% for coarse WTR (4.75–10 mm) and 34% for fine WTR (≤ 2.36 mm). The comparison of foamed concrete tiles, with and without PP and WTR, against ordinary concrete tiles revealed a reduction in the rupture force while achieving a weight reduction of more than half. The failure modes transformed from brittle to ductile upon adding these wastes. Additionally, when the density of the rubberized samples increased to 1400 kg/m³, water absorption decreased by 3.9 and 9.43 after 0.5 and 24 hours, respectively, which aligns with IQS requirements.

1. Introduction

Foamed concrete (FC), which is a lightweight substance, combines cement, water, filler, and foam. It may be manufactured with or without fine sand. However, it must not include coarse aggregate in all instances. The density of this concrete may be adjusted between 400 and 1850 kg/m³ by varying the amount of foam used in the mix [1], which makes it suitable for semi-structural components, bridge packing, ground insulation, and insulated wall panels. Compared to traditional concrete, FC provides several advantages, such as superior flowability, reduced weight, and less aggregate utilization. In particular, it has a high strength-to-weight ratio, remarkable thermal insulation properties, excellent fire resistance, and significant sound insulation qualities [2-4]. Nonetheless, it has certain disadvantages that limit its usage, such as diminished strength and modulus of elasticity, considerable shrinkage, and an increased susceptibility to cracking. To address these issues, one can reduce pore size, optimize pore shape, and include different substances such as silica fume, furnace slag, fibers, rice husk ash, metakaolin, fly ash, waste marble powder, and other fillers derived from waste as substitutes for cement or fine aggregates in the cement paste [5,6].

In this context, researchers are now investigating the possibility of using ground tire rubber as a component in concrete production. Particularly, concrete is a prevalent construction material that requires substantial quantities of natural resources [7]. Rubberized concrete (rubbercrete) is a sustainable material produced by substituting certain mineral aggregates with recycled tire rubber particles. For almost three decades, specialists have shown interest in rubbercrete due to the environmental consequences of the substantial annual waste tire accumulation and the declining availability of appropriate natural resources

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[8]. Meanwhile, rubberized foamed concrete (RFC) is a material that combines the good qualities of foamed concrete with those of rubberized concrete. In particular, the foamed concrete has great fire resistance, low weight, self-compaction, and good thermal and acoustic insulation. Furthermore, rubberized concrete has great energy dissipation, damping, ductility, toughness, and impact resistance. In this regard, some studies have explored the feasibility of substituting aggregate in concrete with waste tire rubber material (WTR).

For instance, Hilal [9], investigated the effects of substituting sand with crumb tire rubber in foamed concrete. The results showed that an increase in the rubber ratio resulted in a reduction in concrete density, compressive strength, flexural strength, splitting tensile strength, and impact resistance. In addition, Eiras et al. [10], studied the foamed cement composites, substituting sand with waste tire rubber particles in amounts of 40%, 50%, and 60%. The utilization of waste tire rubber and air-entraining agents resulted in lowered compressive and flexural strength values. Moreover, the study by Bayraktar et al. [11], investigated the influence of different cement quantities of (300, 400, and 500 kg/m^3), along with 20% partial substitution of silica fume and complete replacement of fine aggregate with 100% waste rubber tires, on the mechanical properties of foamed concrete. Additionally, Damiani et al. [12], examined the effect of omitting sand and using waste tire rubber on the microstructure and mechanical properties of foamed concrete with cement paste densities of 400 and 600 kg/m^3. Kumar et al. [13], proposed the use of foamed concrete tiles with a unit weight ranging from 900 kg/m^3 to 1100 kg/m^3, which may lower the dead load by about 50%, while the thermal conductivity of foamed concrete drops to 0.021 W/mK. Pati and Sahu [14], examined the utilization of fly ash in concrete tiles and discovered that replacing fine aggregate with fly ash significantly improves strength and durability. Al-Obeidy and Wasan [15], attempted to mitigate the brittleness of geopolymer concrete tiles by including waste tire rubber and recycled steel fibers from damaged tires, resulting in an enhancement of the total flexural energy by 390% and 271%, respectively, compared to tiles devoid of waste materials.

From the discussion above, it is evident that while rubberized foamed concrete has been explored in various applications, limited research has focused on its potential in manufacturing foamed concrete tiles. To bridge this gap, the present study investigates the feasibility of incorporating waste tire rubber (WTR) as both fine and coarse aggregates in optimal proportions to develop fiber-reinforced rubberized foamed concrete tiles at target densities of 800, 1100, and 1400 kg/m^3. These tiles are envisioned for roofing applications in residential and commercial buildings, offering improved thermal and acoustic insulation. Additionally, they hold promise as sound barriers along roads and railways, contributing to enhanced energy efficiency and noise reduction in construction.

2. Experimental details

2.1 Materials

This investigation used Portland cement type I (CEM I 42.5R) according to Iraqi Specification IQS 5/2019 [16]. Particularly, the cement has a specific gravity of 3.15 and a specific surface area (Blaine fineness) of 326 m^2/kg. Ordinary Portland Cement (OPC) was partially substituted with class F fly ash (FA) following the standard of ASTM C618-19 [17]. The fly ash has a specific surface area (Blaine fineness) of 378 m^2/kg and a strength activity index (S.A.I.) of 89%. Table 1 delineates the chemical compositions of the cement and the class F fly ash used in this study. The fine aggregate was used according to Iraqi Specification IQS 45/2016 [18], after searching to exclude particles above 2.36 mm [19]. Specifically, the fine aggregate has a specific gravity of 2.65, an absorption rate of 1.9%, and a fineness modulus of 2.55. Figure 1 illustrates the grading and specifications of the fine aggregate.

A portion of the volumetric fine aggregate was substituted with waste tires obtained from the State Company for Rubber and Tires Industry, Diwaniaya facility, in Iraq. These waste tires are by-products of the grinding of used vehicles' tires. The categorization of the fine waste tire rubber particles of (0–2.36 mm) was evaluated under the Iraqi Specification IQS 45/2016 [18], as can be seen in Figure 1. Moreover, coarse waste tire rubber of (4.75–10 mm) was used. In particular, the waste tire rubber particles were incorporated into the foamed concrete mixes without any preliminary treatment. The incorporation of SikaFiber PPM-12 polypropylene fibers, with a diameter of 32 µm, a length of 12 mm, and a density of 0.91 g/cm^3, facilitated the uniform distribution of crumb rubber particles and enhanced the fracture resistance of the foamed concrete. In particular, the foam bubbles were produced using a solution of DCP foaming agent, Cemairin F300, at a ratio of 1 part foaming agent to 40 parts water [20, 21]. The mixes were enhanced for workability using Sika ViscoCrete-5930 High Range Water Reducing Admixture (HRWRA), which adheres to ASTM C494-17 Types G and F [22]. Moreover, drinking water was used in the mixing procedure. Figure 2 illustrates the solid materials used in this study.

Table 1: Chemical components of the Portland cement and the fly ash

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

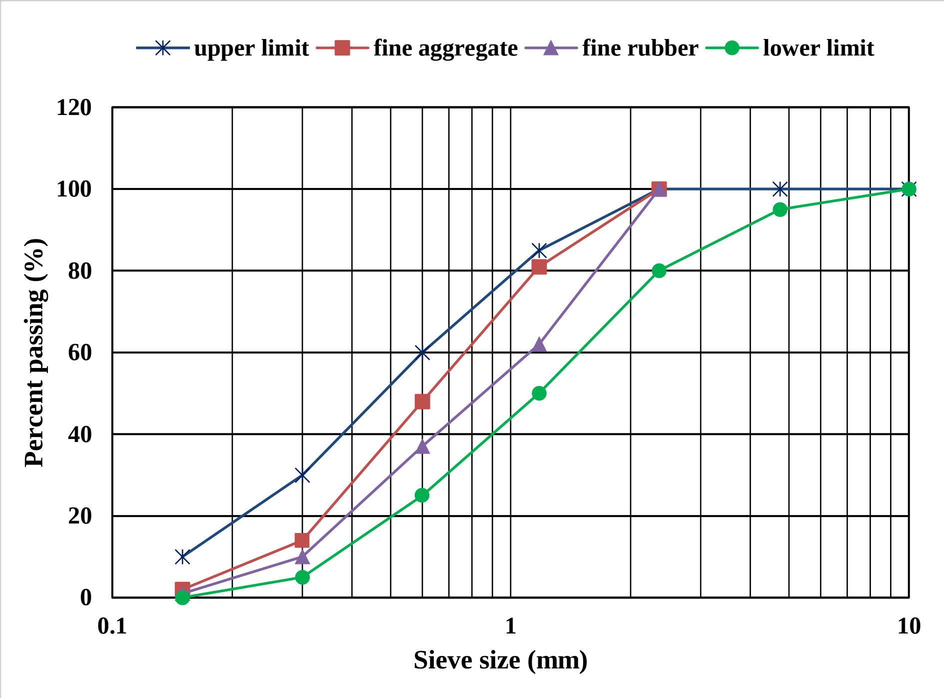

Figure 1: Particle size distribution curves of fine waste tire rubber and fine aggregates

Figure 2: Materials of the investigated mixes

2.2 Mix design

An optimal mixture, which is derived from previous investigations, includes 450 kg/m³ of ordinary Portland cement (OPC), 34% fine waste tire rubber (WTR_f), 50% coarse waste tire rubber (WTR_C) as a replacement for fine aggregate, 0.45% polypropylene fiber (PP) of total mix volumes, and 53 kg/m³ of fly ash (FA) as a partial cement substitute, resulting in fiber-reinforced rubberized foamed concrete with a density of 1100 kg/m³. The water-cement ratio (W/C) was set at 0.32, and the superplasticizer (SP) was kept at 1.4% by the weight of the binder. This mixture was selected from 32 compounds developed using the central composite design (CCD) of the Minitab software, based on five variables with a target density of 1100 ± 50 kg/m³. More precisely, five variables were utilized, including cement content ranging from 250 to 450 kg/m³, substitution of fine aggregate with WTR_f (0-50%) and WTR_C (0-50%), replacement of cement with FA (0-60 kg/m³), and incorporation of PP (0-0.5%). After 28 days, the measured responses included density, compressive strength, splitting tensile strength, impact resistance, and thermal conductivity. Subsequently, the data collected from these experiments was entered into the Minitab software for optimization using the response surface methodology (RSM) to obtain the fiber-reinforced rubberized foamed concrete (FCT_{SPR}). Specifically, this research involved the design of five foamed concrete mixes in addition to the mix of (FCT_{SPR}), including:

1) A conventional foamed concrete mix (FCT_O) with a target density of 1100 kg/m³.
2) A modified foamed concrete mix incorporating the superplasticizer (FC_S) with a target density of 1100 kg/m³.
3) A fiber-reinforced modified foamed concrete (FCT_{SP}) also targeting a density of 1100 kg/m³ enhanced with polypropylene (PP).

Moreover, two further fiber-reinforced rubberized foamed concrete (RFC) mixtures, including WTR, PP, and FA, were formulated with target densities of 800 kg/m³ (FCT_{SPR8}) and 1400 kg/m³ (FCT_{SPR14}), as shown in Table 2. In particular, each foamed concrete mix was formulated using the absolute volume approach specified in ACI 523.3R-14 [23]. Then, a foaming agent was diluted in water at a weight ratio of 1:40 to produce the necessary foam volume. Next, the resultant solution was injected into foam-generating equipment linked to an air compressor. Accordingly, the procedure produced pre-formed homogeneous foam with a density of around 40 kg/m³. In this regard, ASTM C796-19 [24], recommends a stable foam density range of 40 to 70 kg/m^3. Subsequently, the foam was mixed with the base without foam material to generate foamed concrete blends. To this end, the same common mix used by concrete tile production plants was adopted without modification for comparison purposes. The concrete tile (NTC) was made in these plants using volumetric proportions, and it was transformed into a laboratory with a weight ratio of roughly 1:1.5:3.2 and a w/c ratio of 0.6. The cement content used in this mixture was about 380 kg/m^3. In addition, the predominant coarse aggregate used was uncrushed, with a maximum size of 19 mm.

Table 2: Mix proportions of the investigated foamed concrete tiles

	Mixes						
	FCT_O	FCT_S	FCT_{SP}	FCT_{SPR}	FCT_{SPR8}	FCT_{SPR14}	NCT
Target density (kg/m^3)	1100	1100	1100	1100	800	1400	2400
Cement content (kg/m^3)	397	397	397	397	397	397	380
Fly ash (kg/m^3)	53	53	53	53	53	53	0
W/c ratio	0.485	0.32	0.32	0.32	0.32	0.32	0.6
Superplasticizer (kg/m^3)	0	6.3	6.3	6.3	6.3	6.3	0
Water content (kg/m^3)	218	144	144	144	144	144	228
Sand content (kg/m^3)	439	500	500	80	32	128	570
Coarse aggregate content (kg/m^3)	0	0	0	0	0	0	1216
Fine waste tire rubber (kg/m^3)	0	0	0	73	29	117	0
Coarse waste tire rubber (kg/m^3)	0	0	0	109	44	175	0
Polypropylene fibers (kg/m^3)	0	0	4.1	4.1	4.1	4.1	0
Foam (l/m^3)	495	495	495	495	615	400	0

2.3 Specimens preparation

In this study, the production of foamed concrete was achieved using a rotating drum mixer. The dry components, including cement, fly ash, fine aggregate, and fine and/or coarse rubber from waste tires, were first mixed for three minutes. The slurry was created by mixing the dry components with water and a superplasticizer. Next, to prevent the formation of clumps, polypropylene (PP) fibers were evenly spread throughout the slurry and thoroughly blended for an additional two minutes. The last and crucial step in producing the foamed concrete involves incorporating a certain quantity of foam into the mixture with no foam and thoroughly blending it for a minimum of two minutes, ensuring that the foam is evenly dispersed throughout the mixture [25]. Following the guidelines of ASTM C796-19 [24], the densities of the newly collected samples were measured using a container with a known capacity. When the fresh measured density of the foamed concrete mix is within ±50 kg/m^3 of the target density [26], it is deemed acceptable. The concrete tiles in Iraq were classified according to their size from A to F, as specified in the Iraqi Specification IQS 1107/1988 [27]. The chosen measurements were 500× 500×50 mm^3, categorized as class A according to the Iraqi Specification. To carry out the testing, samples were inserted into plastic molds of specified dimensions and exposed to light tapping using a hammer with a rubber tip, as shown in Figure 3 (a), following the guidelines outlined in ASTM C796-19 [24]. After being leveled with a trowel, the specimens were protected from moisture loss by being coated with a thick layer of nylon. To facilitate the curing process, the specimens were hermetically sealed and cured for 28 days. This process was achieved by enveloping them in plastic film and allowing them to remain at ambient temperature until they were ready for testing [28], as shown in Figure 3 (b). In particular, the mixing and casting operations were performed at an ambient temperature ranging from 25 to 30 °C.

Figure 3: a-Samples of foamed concrete tiles into plastic molds. b- Curing foamed concrete tiles by wrapping them in plastic film

2.4 Tests

2.4.1 The dry density and weight test

The dry density of the specimens was determined after 28 days by dividing their weight by the measured volume of a 100 mm^3 specimen. Furthermore, the 28-day weight was measured using a weighing machine. For this purpose, 500 × 500 × 50 mm tiles were utilized. More precisely, three measurements were taken for each combination, and the test was completed according to the Iraqi Specification IQS 1107/1988 [27].

2.4.2 The rupture force

The tiles' rupture force was assessed according to the Iraqi Specification IQS 1107/1988 [27]. Specifically, the rupture force test was conducted using the BESMAK testing equipment with a digital capacity of 200 KN/s. Particularly, the device measures a tile's rupture force by applying a three-point load. The tiles were arranged horizontally on two parallel steel rods, with the worn face facing upwards. Additionally, a third rod was precisely positioned in the middle. The test was conducted by applying the force to the tile until it reached its maximum rupture force, at which point the tile broke. After that, the value of this maximum rupture force was recorded.

2.4.3 The microscopic analysis

An examination of the scanning electron microscopy (SEM) was conducted using the Thermo Scientific Axia Chemi Scanning Electron Microscope apparatus. Particularly, the specimen samples were obtained by extracting a core with dimensions of 1 × 1 × 1cm cubes. This step was executed to specifically focus on the intersecting areas between the waste tire rubber particles or fibers and the cement paste. Subsequently, these samples underwent a 24 hour desiccation procedure at a temperature of 105 ± 3 °C to eliminate any potential moisture evaporation. Afterward, the dried sections were placed onto metal alloy pieces and covered with a thin coating of spray before being exposed to the electron beams generated by the SEM. The experiment was conducted at the designated magnification level to attain the required data and observations.

2.4.4 The absorption test

The absorption test was conducted according to the Iraqi Specification of IQS 1107/1988 [27]. Particularly, two square pieces were prepared, which were cut from two opposite corners on the diagonal of each of the three tile samples, using a saw. These pieces are approximately 100 × 100 cm in size, cut from the whole thickness of the tile, with two edges in contact with the mold. Next, the six specimens were placed in a drying oven at 105 ± 3 °C for 24 hours. Subsequently, they were removed and allowed to cool for 24 hours in a dryer or a tightly sealed container. After that, the mass of each sample (WD) was measured, and the sample was immediately immersed in water at a temperature of 20 ± 2 °C for 30 min± 30 sec. The specimens were extracted at the end of the immersion time and promptly cleaned with a cloth for thirty seconds to ensure that no residual droplets remained on the surfaces of the samples. Then, the mass of each sample (Ww) was promptly measured and documented. Subsequently, the samples were immersed in the water tub once again to determine the absorption of water after 24 ± 1/2 hours, after which they were removed, dried with a cloth, and weighed again (WW). In this regard, the overall absorption percentage can be determined using the following Equation 1:

$$\text{Absorption} = \frac{W_W - W_D}{W_D} \quad (1)$$

where W_W is the weight of the wet sample (g), and W_D is the weight of the dry sample (g).

3. Results and discussion

3.1 Density

Table 3 and Figure 4 show that the dry density of the conventional foamed concrete tiles (FCT_O) was reduced by about 53% compared to that of the ordinary concrete tiles (NCT). Additionally, the foamed concrete tile mixes made without WTR particles (FCT_O, FCT_S, and FCT_{SP}) achieved similar densities, which are close to the target density of (1100 kg/m^3). The results also showed that including 34% fine waste tire (WTR_f) and 50% coarse waste tire rubber (WTR_C) particles in the foamed concrete instead of sand in terms of volume led to a drop in the dry densities of all the combinations that were tested by 16.7%, 6.12%, and 25.3% for FCT_{SPR}, $RFTC_{SPR8}$, and FCT_{SPR14}, respectively, compared to its target density, because the WTR particles have lower density and specific gravity compared to those of cement and sand, which are the primary components of the traditional foamed concrete.

Table 3: Results of the investigated foamed concrete tile mixes

Mixes	Target density	Dry density kg/m^3	Weights (Kg)	Rupture force (KN)	Water Absorb (½hr)%	Water Absorb (24hr)%	Dimensions (mm)
NCT	2400	2365	28.9	8.11	3.8	9.32	499×499×49
FCT_O	1100	1113	13.64	1.87	8.47	13.57	500×500×49
FCT_S	1100	1131	13.70	2.91	6.25	11.48	498×499×49
FCT_{SP}	1100	1132	13.86	3.64	5.78	10.88	499×499×49
FCT_{SPR}	1100	916	11.23	2.96	4.81	10.31	500×499×49
FCT_{SPR8}	800	751	8.82	2.14	8.22	13.48	498×499×48
FCT_{SPR14}	1400	1046	12.80	3.23	3.9	9.43	499×498×49
Limits of IQS 1107/1988 Type A				≤ 8.3	≤ 4	≤ 10	500±2×500±2×50±3

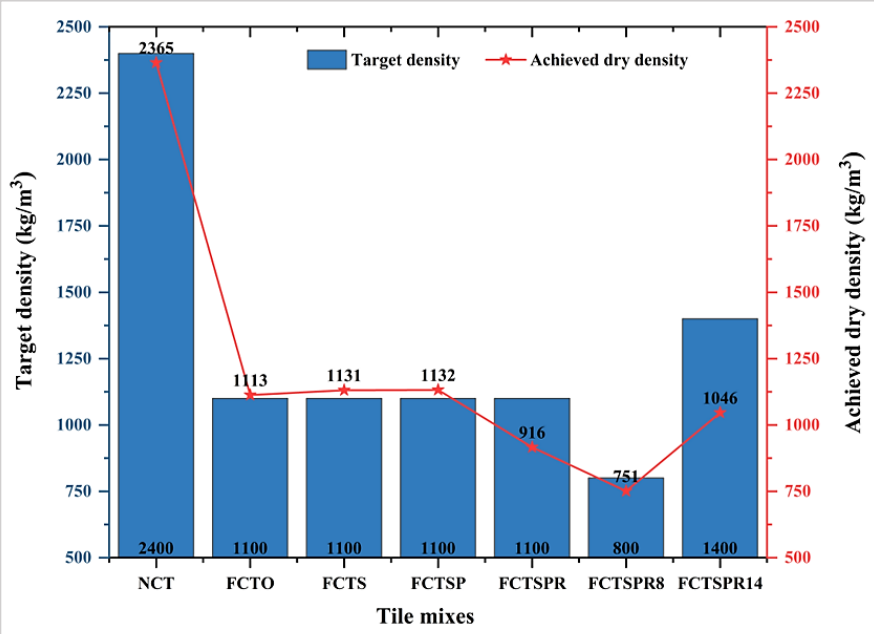

Figure 4: Dry density of the investigated foamed concrete tile mixes

3.2 Weight

The difference between the weights of the foamed concrete tiles and the normal concrete tiles, as well as the effects of including WTR and PP fibers on the weight, is shown in Table 3 and Figure 5. Furthermore, it has been shown that the weight of the foamed concrete tiles is reduced as the densities of the rubberized foamed concrete drop. Generally, making conventional foamed concrete tiles (FCT_O) with a density of 1100 kg/m^3 results in a tile weight reduction of approximately 52.8% when compared to ordinary concrete tiles (NCT). Nevertheless, modifying the conventional foamed concrete tiles with SP or using polypropylene without WTR particles achieved a similar weight, which is close to that of the FCT_O mix at the target density of 1100 kg/m^3. In this regard, the findings indicated that including the WTR in the foamed concrete resulted in a weight reduction of approximately 19% compared to FCT_{SP} at a target density of 1100 kg/m^3. This outcome is primarily due to the fact that the WTR particles have a lower density than that of sand. In addition, the WTR's specific gravity was lower than those of cement and sand, which are the main constituents of conventional foamed concrete. In general, the inclusion of waste tire rubber (WTR) in the foamed concrete tile resulted in a reduction in weight for all the investigated combinations. Compared to FCT_{SPR}, the reduction of the rubberized foamed concrete density from 1100 to 800 kg/m^3 has a significant benefit in reducing the total tile weight by 21.5%. In contrast, there was a marginal alteration when the target density was raised to 1400 kg/m^3 for FCT_{SPR14} compared to FCT_{SPR}. On the other hand, it was determined that the use of the WTR decreased the weight of the -reinforced rubberized foamed concrete tiles by 61%, 69.5%, and 55.7% for densities of 1100, 800, and 1400 kg/m^3, respectively, compared to the normal concrete tiles (NCT).

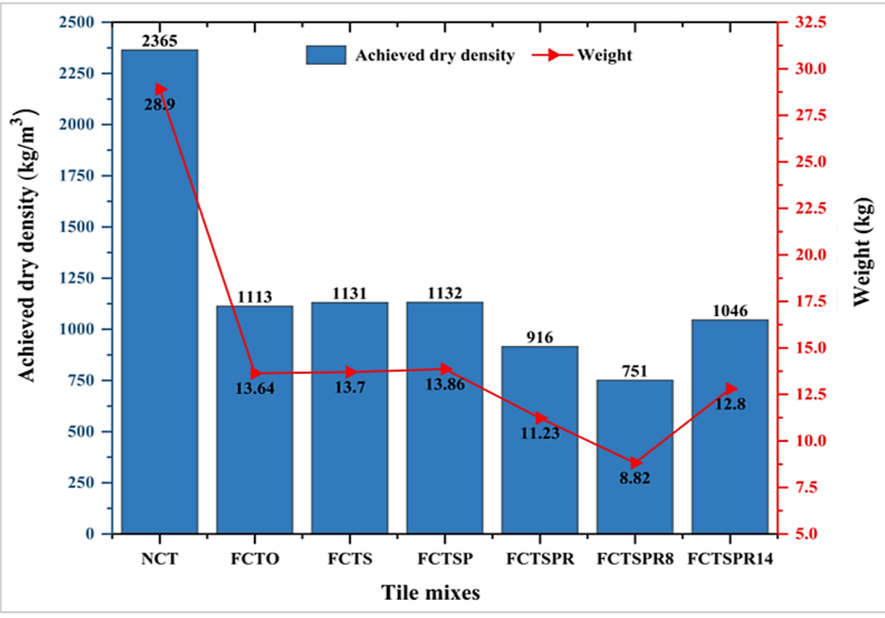

Figure 5: Difference in weight and density between normal concrete and rubberized foamed concrete tile specimens

3.3 The rupture force

Table 3 and Figure 6 illustrate the rupture force of the normal concrete tiles and several foamed concrete tiles created during this investigation. According to the data, the normal concrete tile has a rupture force of 8.11 KN after 28 days, which met the Iraqi Specification of IQS 1107/1988 [27]. For traditional foamed concrete tiles with a density of 1100 kg/m^3, the rupture load was reduced to 1.87 KN, which is below the required limit set by IQS 1107/1988. Furthermore, adding the superplasticizer (SP) to the conventional foamed concrete tile mix (FCT_O) resulted in a 55.6% increase in the failure load of the FCT_S mix after 28 days. On the other hand, the FCT_{SP} mix, modified by both SP and PP, demonstrated a 25% increase in the rupture load compared to the FCT_S mix. This result may be attributed to the fibers' ability to resist failure and transmit forces, increasing the force required for failure. The SEM image in Figure 7 shows that the polypropylene (PP) fibers in the fiber-reinforced foamed concrete still have foamed concrete matrix residue that appears on them, as shown by the red circle. This outcome suggests a strong connection between the foamed concrete and the PP fibers at the interface, which indicates that the PP fibers in the foamed concrete act as a bridging force that crosses cracks in the matrix and decreases the incidence of microcracks. Specifically, the SEM image shows that the foamed concrete around the fibers often has a high density because of the fibrillation process and the adhesion between the fibers. This outcome is consistent with that of previous studies [29]. In this context, the PP fiber enhances the uniform distribution of air gaps. As a result, this step will prevent the merging of bubbles and guarantee that a uniform coating is given to each bubble. Particularly, the three-dimensional arrangement of fibers in the foamed concrete can effectively lead to improved load transmission, resulting in enhanced strength in the foamed concrete [30].

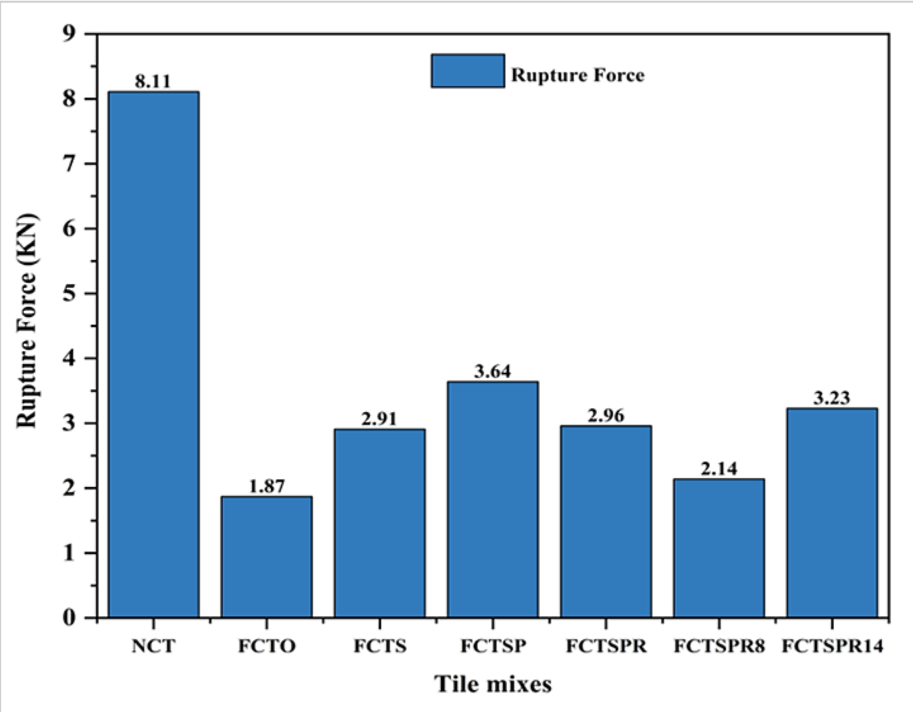

Figure 6: The rupture force of the investigated foamed concrete mixes

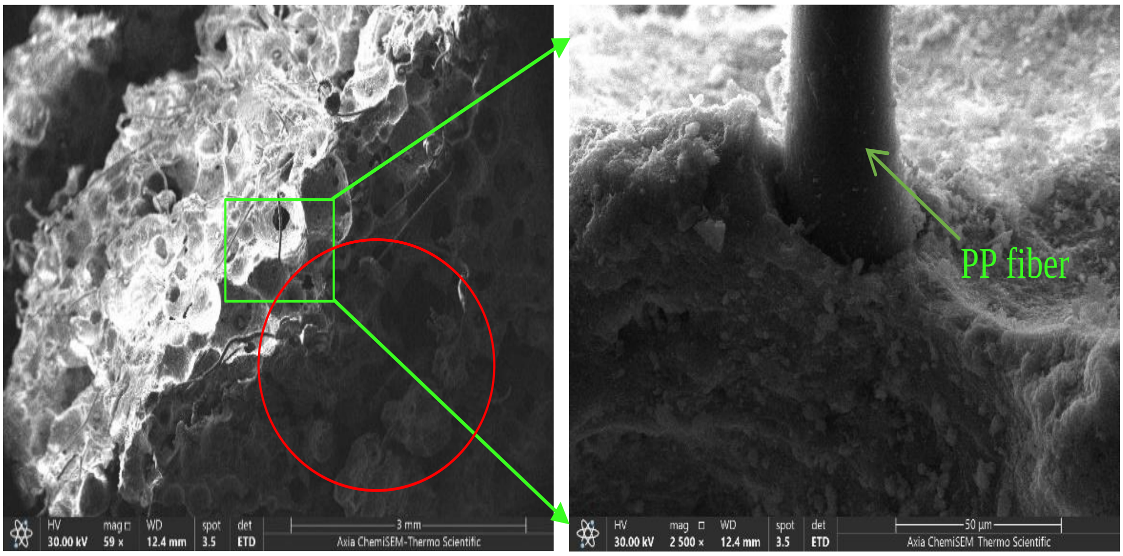

Figure 7: The SEM images for fiber-reinforced foamed concrete mix

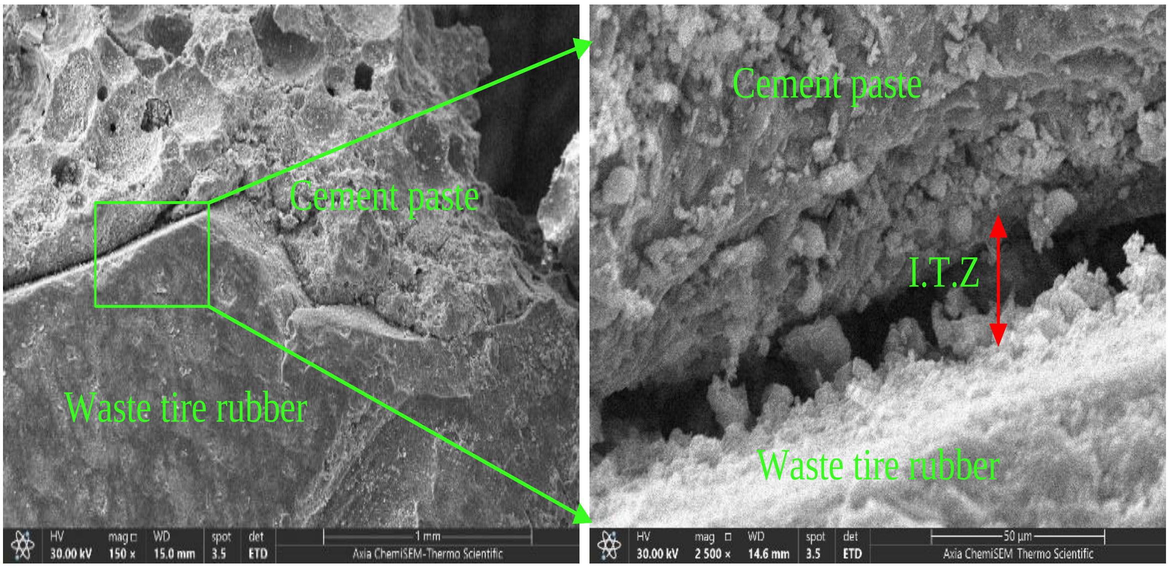

Figure 8: The SEM images for the fiber-reinforced rubberized foamed concrete mix

Furthermore, replacing 84% of sand with the WTR in the rubberized foamed concrete tiles increases the rupture load for all densities compared to the conventional tile foamed concrete. However, it did not meet the minimum criteria set by the Iraqi Specification of IQS 1107/1988, which required a minimum of 8.3 KN. At 28 days, the rupture load of the FCT_{SPR} mix with a target density of 1100 kg/m^3 was 18.7% lower compared to that of the FCT_{SP}. In addition, when the density of the rubberized combination was reduced to 800 kg/m³ (FCT_{SPR8}), there was a 28% drop in the rupture load compared to that of the FCT_{SPR} mix. In contrast, when the density was increased to 1400 kg/m^3 (FCT_{SPR14}), there was a 9.2% increase in the rupture load compared to that of the FCT_{SPR} mix. The main reason for this result was mostly due to the insufficient adhesion between the WTR and the cement paste at the interface. In particular, the WTR particles possess mostly smooth surfaces with irregular protrusions and edges, enabling them to interlock securely inside the cement paste. However, the bond between the WTR particles and the cement paste was weaker than that of the traditional rigid aggregates. Nevertheless, the fissures and uneven forms of the WTR particles may make it easier for air to be captured and held [4, 31]. Moreover, the predominant presence of air pores in the foamed concrete system makes it challenging to distinguish these gaps. Nonetheless, it was observed that in some areas, there was very little space between the WTR and the cement binder. More precisely, these cracks and openings were seen around the WTR particles, particularly in the interfacial transition zone (ITZ), as shown in Figure 8.

3.4 The failure mode

Figure 9 (a-h) depicts the failure behavior of both the ordinary concrete tiles and the foamed concrete tiles. The normal concrete specimen (NCT), the conventional foamed concrete (FCT_O), and the modified foamed concrete with a superplasticizer (FCT_S) exhibit brittle failure. Specifically, the foamed concrete tiles specimen fractures into two distinct parts, which is a characteristic of concrete, as it cannot withstand internal tensile forces, resulting in minimal strain after exceeding the maximum load of failure. The fiber-reinforced foamed concrete tile containing (PP), and the fiber-reinforced rubberized foamed concrete tiles containing SP, PP, and WTR exhibited a ductile failure mode, as they did not fracture into two distinct portions. Furthermore, the tile examples exhibit the stress they endure following failure, highlighting the PP fibers' and the WTR particles' ability to convert the failure from brittle to ductile.

Table 3 and Figure 10 depict the water absorption results for the normal and the foamed concrete tile mixes. In addition, the normal concrete tile sample and the foamed concrete samples, with and without additives, were compared to the Iraqi Specification of IQS 1107/1988. These standards state that the absorption must not exceed 4% after 30 minutes and 10% after 24 hours. In this context, the findings indicate that for the normal concrete tile samples, the water absorption did not exceed 3.8% and 9.32%, respectively, conforming with IQS 1107/1988. On the other hand, after 24 hours, the absorption of the conventional foamed concrete samples without additives (FCT_O) with a given density of 1100 kg/m^3 increased by 35.7% compared to the limits set by IQS 1107/1988. When the superplasticizer (SP) was added to the conventional foamed concrete tile mix (FCT_O), the FCT_S mix absorbed 15.4% less water after 24 hours compared to the FCT_O mix at a target density of 1100 kg/m³, which can be attributed to the distribution and connection of pores enhanced by the SP resulting in reduced volume water absorption since the interconnectivity of the foamed concrete components influences the absorbable pores affecting the water absorption ratio [32,33]. However, it still exceeds the Iraqi Specification limitations by 14.8%. On the other hand, the FCT_{SP} mix, which was modified by the PP in addition to the SP, absorbed about 3% less water compared to the FCT_S mix despite their similar density. This result could be attributed to a decrease in cracking following the incorporation of the fibers. In this regard, the fibers diminish the interconnected pores in the foam concrete, improving the pore structure and reducing water absorption to some extent [30]. Nonetheless, the absorption exceeds the IQS 1107/1988 limitations by 11.4%.

The results demonstrated that using the WTR instead of 84% of volumetric sand in the foamed concrete tile mix, modified by both the SP and the PP, leads to reduced water absorption at a density of 1100 kg/m^3 compared to those of all different types of foamed concrete tiles without the WTR. More specifically, this substitution resulted in a 9.2% decrease in water absorption for the fiber-reinforced rubberized foamed concrete tiles (FCT_{SPR}) compared to the fiber-reinforced foamed concrete tiles

(FCT_{SP}). However, it exceeded the criteria set by the Iraqi specification of IQS 1107/1988 by a marginal 1.1% within 24 hours. Moreover, when the density of the rubberized composite was diminished to 800 kg/m³ (FCT_{SPR8}), there was a 33.3% increase in water absorption compared to the FCT_{SPR} mix. Conversely, when the density was increased to 1400 kg/m^3 (FCT_{SPR14}), there was a 6.7% reduction in the water absorption relative to the FC_{SPR} mix. The increase in density made the rubberized foamed concrete tiles (FCT_{SPR14}) satisfy the IQS 1107/1988 for concrete tile water absorption. Specifically, the maximal water absorption after 0.5 and 24 hours was 3.9% and 9.43%, respectively. The lower water absorption of the rubberized foamed concrete occurred because sand absorbs more water than the WTR and because the WTR aggregates are hydrophobic, which means that they do not allow water to enter even though the composite has a lot of pores. In addition, the fine waste tire rubber fills tiny pores in the foamed concrete, diminishing the seepage pathways [34-36]. Notably, the decrease in the foamed concrete density was achieved by pumping more foam into the mixture, which increased the void diameters, leading to higher water absorption levels.

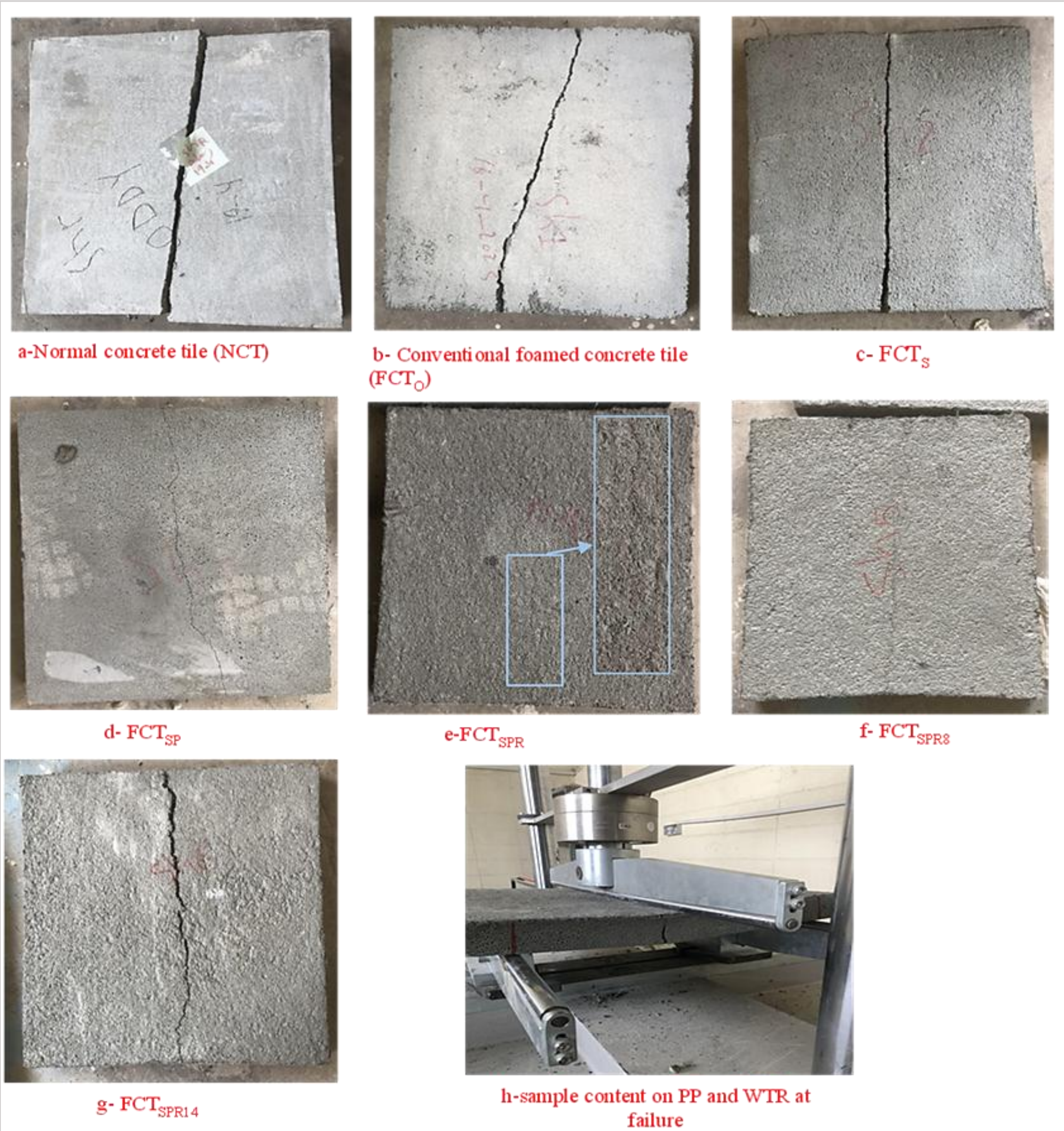

Figure 9: The failure mode in the rupture force tests of the investigated mixes: a) normal concrete tiles (NCT), b) conventional foamed concrete tile (FCT_O), c) conventional foamed concrete tiles modified by SP (FCT_S), d) fiber-reinforced modified foamed concrete (FCT_{SP}), e) fiber-reinforced rubberized foamed concrete tiles with a target density of 1100 kg/m³ (FCT_{SPR}). f) fiber-reinforced rubberized foamed concrete tiles with a target density of 800 kg/m³ (FCT_{SPR8}), g) fiber-reinforced rubberized foamed concrete tiles with a target density of 1400 kg/m³ (FCT_{SPR14}), h) sample content on PP and WTR at the failure point in the rupture force test

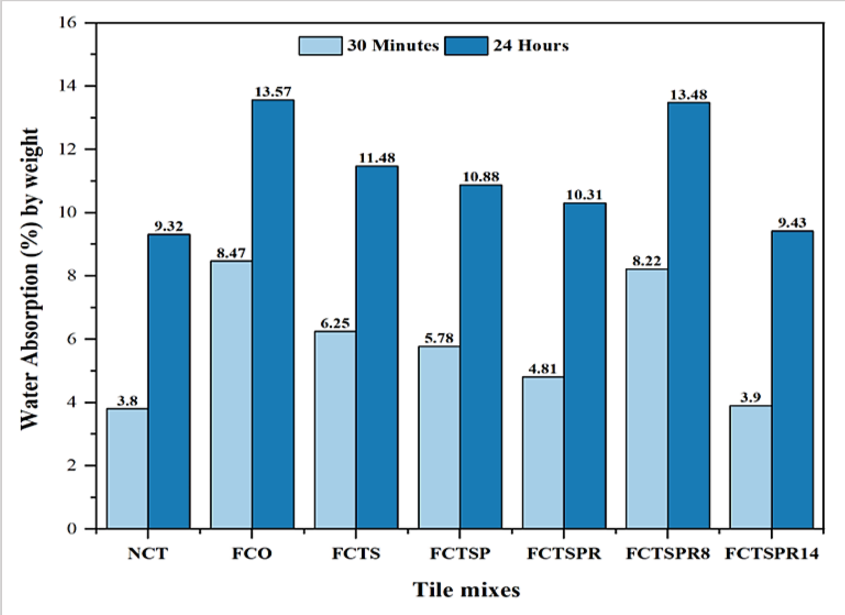

Figure 10: Water absorption (%) by weight for the investigated tile mixes at 28 days

4. Conclusion

From the experimental findings, the following inferences can be derived:

1) The conventional foamed concrete tiles have a rupture force of approximately 77% lower and a water absorption rate of 45.6% higher than those of the normal concrete tiles. Despite these differences, they are lighter.
2) Modifying the conventional foamed concrete tile by reducing the mixing water and including a superplasticizer enhanced its rupture force by about 55.6% and decreased the water absorption by 15.4% after 24 hours.
3) Including the PP in the modified foamed concrete tile mix enhanced the rupture force by 25%. Furthermore, the water absorption reduced by 3%.
4) When substituting a portion of sand with the WTR in the rubberized foamed concrete tiles at a given density of 1100 kg/m^3, the rupture force of the examined tile mixtures diminished by 18.7%.
5) The rubberized foamed concrete tile mixtures demonstrated greater ductility during the rupture force test, in contrast to the foamed concrete mixtures that did not include the fibers and the WTR, which broke abruptly and in a brittle manner.
6) Substituting a part of volumetric sand with the WTR led to a 9.2% reduction in water absorption. Moreover, decreasing the density of 800 kg/m^3 resulted in a 33.3% increase in water absorption compared to that of the FCT_{SPR} mix. Conversely, as the density increased to 1400 kg/m^3, the water absorption diminished by around 6.7%. In general, the elevated density made the fiber-reinforced rubberized foamed concrete tiles (FCT_{SPR14}) meet the IQS 1107/1988 for water absorption in the concrete tiles. Particularly, the maximum water absorption values after 0.5 and 24 hours were 3.9% and 9.43%, respectively.

In general, for a given density of 1100 kg/m^3, producing the fiber-reinforced rubberized foamed concrete modified with the superplasticizer (FC_{SPR}) helped to enhance the rupture force and the water absorption by about 58.3% and 24%, respectively, with lighter-weight tiles by 17.7% of the conventional foamed concrete tile mix (FCT_O). Whereas, compared to the normal concrete tiles with a density of 2400 kg/m^3, the rubberized foamed concrete tile exhibits a 63.5% decrease in the rupture force and a 10.6% increase in the water absorption while also demonstrating a favorable reduction of 61.2% in weight.

Author contributions

Conceptualization, **O. Abd**, **A. Hilal**, and **T. Khaleel**; methodology, **O. Abd**, **A. Hilal**, and **T. Khaleel**; validation, **O. Abd**, **A. Hilal**, and **T. Khaleel**; resources, **O. Abd**, **A. Hilal**, and **T. Khaleel**; data curation, **O. Abd**, **A. Hilal**, and **T. Khaleel**; writing - original draft, **O. Abd**; visualization, **O. Abd**, **A. Hilal**, and **T. Khaleel**; project administration, **O. Abd**; supervision, **A. Hilal**, and **T. Khaleel**. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data supporting this study's findings are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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