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Effect of Aqua Heat Treatment on the Mechanical, Durability and Water Resistance Performance of Rubberized Sand Concrete

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ABSTRACT

The exponential growth in vehicle tire production has resulted in a substantial accumulation of rubber waste, raising serious environmental issues due to its resistance to decomposition. To address this issue, the current investigation sheds light on the use of crumb rubber (CR) as a partial substitute for fine aggregates in sand concrete, applied at varying dosages (0%, 3%, 6%, 9%, and 12%). The primary objective is to enhance the durability of sand concrete, particularly its resistance to water penetration, which is critical for maintaining structural integrity in aggressive environments. The influence of both untreated and aqua heat-treated rubber on the physical and mechanical properties of sand concrete was systematically investigated. Workability, density, compressive and flexural strengths, porosity, and water absorption were evaluated Additionally, Scanning Electron Microscopy (SEM) analysis was conducted to characterize the microstructural modifications induced by aqua heat-treated rubber particles. The results demonstrated that the incorporation of heat-treated rubber improved water penetration resistance by up to 9% compared to concrete containing untreated rubber. Nonetheless, both untreated (UTR) and treated rubber (TR) caused a reduction in density and workability. While the initial inclusion of rubber increased porosity and water absorption, these adverse effects were significantly mitigated over time through aqua heat treatment. Overall, the optimal content of aqua-heat –treated rubber powder was identified as 3%, yielding the most favorable balance between workability, water absorption, porosity and mechanical performance.

1. INTRODUCTION

The increasing progress in transportation infrastructure, coupled with global population growth, has led to an exponential increase in the production and use of vehicle tires. Consequently, the accumulation of end-of-life tires (ELTs) has become a major environmental concern, primarily due to their non-biodegradable nature and limited sustainable disposal options [1]. Traditional disposal methods such as land filling or incineration pose significant environmental risks, including soil contamination, air pollution, and fire hazards. In this context, the valorization of ELTs with growing interest in alternative materials for civil engineering applications. Among the proposed solutions, the partial replacement of natural aggregates in concrete with recycled tire rubber emerges as a promising and sustainable approach. This practice not only contributes to reducing the volume of rubber waste but also promotes the circular use of industrial by-products in construction. Moreover, it has been suggested that the incorporation of rubber particles in concrete may extend the service life of tire-derived materials by several decades, potentially up to a century, thereby offering a long-term pathway for their reuse in durable infrastructure [2]. Research on Rubcrete, a composite material combining rubber particles with concrete has yielded mixed findings. Several studies have reported enhancements in specific performance aspects, including damping capacity, ductility, energy dissipation, impact resistance, and toughness [3, 4].

Anetta et al. [5] in their study examined the performance of self-compacting concrete incorporating crumb rubber at 15% and 20% replacement levels of fine aggregate. They observed that although the compressive strength decreased with increasing rubber content, the concrete maintained satisfactory self-compacting properties and exhibited enhanced impact resistance and ductility, Ji et al. [6] found that replacing fine aggregate with recycled rubber in desert sand concrete reduced compressive strength but significantly improved toughness, ductility, and energy absorption, particularly at higher rubber contents. Aleeyana et al. [7] examined the mechanical characteristics of concrete in which rubber fine aggregate was substituted for natural fine aggregate in varying proportions, usually 0%, 3%, 6%, and 9%. According to their findings, in comparison to regular concrete, concrete containing rubber fine aggregate had a density of below 2400 kg/m³ and a compressive strength of less than 30 MPa. In spite of this,

rubber aggregate increased durability, flexibility, and impact resistance, providing advantages such as improved sound insulation and weight savings.

In the study conducted by Alamri and Khawaji [8], 0.1% edge-oxidized graphene oxide (EOGO) was added to cement mortars containing 5%, 10%, and 15% crumb rubber as a replacement for sand. The findings showed that EOGO enhanced the mortar's mechanical qualities; the mixture of 0.1% EOGO and 5% crumb rubber outperformed the control mix devoid of rubber, demonstrating the efficacy of replacing crumb rubber with EOGO. The effects of partially substituting rubber aggregates for fine and coarse aggregates in self-compacting concrete were examined by El Marzak et al. [9]. They evaluated the mechanical characteristics of hardened concrete as well as the rheological behavior of the modified concrete indicated that the optimal replacement ratios were 20% for fine aggregates, 25% for coarse aggregates, and 20% for a combined (mixed) aggregate replacement. These levels promoted sustainability in the manufacturing of concrete by reaching a balance between workability and strength.

Consequently, the integration of waste tire rubber into concrete has been deemed a promising strategy for developing more resilient and sustainable composites. However, other investigations have raised concerns regarding the deterioration of key mechanical properties, including compressive strength, elastic modulus, and tensile strength, which may limit the structural applicability of rubberized concrete in conventional construction practices [10].

The reduction in the mechanical strength of rubberized concrete is primarily attributed to the surface characteristics of rubber particles and their limited hydraulic reactivity, which collectively result in poor interfacial bonding between the rubber particles and the cement-based matrix [10, 11]. To overcome these drawbacks—particularly when high rubber content is employed—various surface treatment methods have been explored to enhance the compatibility of rubber within concrete. One common strategy involves pre-treating rubber particles prior to their incorporation. Awan et al. [12] evaluated several treatment approaches, including immersion in sodium hydroxide (NaOH), lime, water, and commercial detergent for 24 hours. Among these, detergent treatment was found to be the least effective, resulting in decreased strength despite its anticipated benefits. Conversely, NaOH treatment significantly improved the mechanical performance of crumb rubber concrete. Mohammadi et al. [13] further demonstrated a recovery of up to 25% in strength loss following NaOH treatment of rubber particles for durations of 20 minutes, 24 hours, and 7 days, with the 24-hour treatment yielding the most favorable results.

In research carried out by Si et al. [14], the application of NaOH treatment was shown to effectively mitigate drying shrinkage in rubberized mortar, despite the initial tendency for shrinkage to increase with higher rubber particle content. Their findings also revealed that NaOH-treated rubber particles reduced both air void content and porosity in rubberized concrete (RC), indicating increased material density and improved structural performance. Similarly, Rivas-Va´zquez et al. [15] investigated the effect of solvent-based surface treatments using ethanol, acetone, and methanol (in a 50% solvent-to-water volume ratio). Among the tested treatments, acetone yielded the greatest improvement in mechanical strength.

Tian et al. [16] explored the pre-treatment of rubber using the inorganic salt calcium chloride ($CaCl_2$), which led to notable improvements in the mechanical performance of crumb rubber concrete (CRC). In contrast, treatments involving organic, acidic, and alkaline solutions did not result in significant enhancements. Xiong et al. [17] reported substantial microstructural improvements at the rubber/cement interface following pre-treatment with a silane coupling agent solution, applied at concentrations between 0.5% and 1.0%. This treatment significantly enhanced the quality of the interfacial transition zone.

In another investigation, Swilam et al. [18] examined the effects of thermal treatment on CRC incorporating high rubber contents (40%, 60%, and 80%). Heat treatment at 200°C for 2 hours led to improvements in impact resistance at ultimate failure by 57%, 28%, and 7%, respectively, compared to untreated concrete. Youssf et al. [19] further combined heat pre-treatment of rubber (200°C for 2 hours) with the use of magnetized water. Their results demonstrated a 62% increase in impact resistance at first crack and a 37% increase at ultimate failure. Moreover, employing 100% magnetized water for 24 hours significantly improved the concrete's impact resistance, increasing it by 2.2 times at the first crack and by 92% at ultimate failure relative to the control mixture.

Afshin et al. [20] reported that magnetized water (MW) improves the durability of conventional concrete by reducing porosity and water absorption. Notably, its use may eliminate the need for chemical admixtures, thereby reducing production costs and environmental impacts.

Sanjaya et al. [21] introduced an aqua-thermal treatment method for coarse crumb rubber (1-5 mm), involving water soaking and washing followed by heat treatment. They replaced fine aggregates with rubber at substitution levels ranging from 2.5% to 15% to assess effects on mechanical performance. Their study showed that Aqua-Thermally Treated Rubberized Concrete (ATTRuC) exhibited significantly higher strength and performance than untreated rubber concrete (AR-RuC), particularly at lower replacement levels, highlighting its suitability for structural applications.

Building on previous research, this study explores a hybrid aqua-thermal surface treatment for rubber particles on fine rubber particles in an optimized sand matrix., aiming to enhance their interfacial bond with the cementitious matrix and improve the mechanical, physical, and water resistance properties of sand concrete. Unlike earlier studies focusing on single chemical or thermal treatments, our method combines a aqua-thermal treatment (boiling + drying), this eco-friendly method removes impurities without solvents, hardens the rubber surface while preserving its flexibility, and reduces treatment costs by 50%. A modest rubber content and limestone filler are used to optimize particle packing and promote a denser, more sustainable concrete suitable for circular construction practices.

2. EXPERIMENTAL PROGRAM

2.1 Material composition

2.1.1 Crushed sand

Crushed sand (CS) is characterized by a maximum particle size of 5 mm, making it suitable for use as fine aggregate in concrete mixtures (Figure 1). The particle size distribution of the sand, along with that of the crumb rubber utilized in the experimental investigation, is illustrated in Figure 2. Relevant physical properties, including specific gravity, bulk density,

and fineness modulus, of fine aggregate are summarized are summarized in Table 1.

Figure 1. Fine aggregates (a) Limestone Filler, (b) Rubber aggregate, (c) Crushed sand

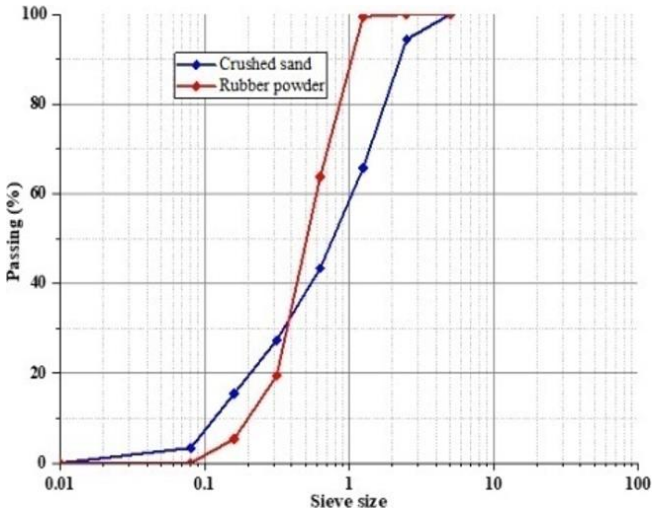


Figure 2. Particle size distribution of fine aggregates

Table 1. Physical characteristics of fine aggregate (CS and CR) and limestone filler

	Crushed Sand	Limestone Filler	Rubber Powder
Apparent Density (kg/m³)	1650	940	380
Specific Density (kg/m³)	2540	2700	1.03
Fineness Modulus	2.54	–	–
Piston sand Equivalent (%)	80.16	–	–

2.1.2 Cement specification

Ordinary Portland Cement (OPC) was used in this study, classified as CEM II/A 42.5 N according to EN 197-1. The cement exhibits an absolute density of 3.1 g/cm³ and a Blaine fineness of 370 m²/kg.

2.1.3 Rubber powder

Crumb rubber powder with a specific gravity of 1.03 and a particle size corresponding to 60 mesh was sourced from the local recycling company. The tire waste was mechanically processed and sieved to achieve a consistent grain size distribution.

2.1.4 Limestone filler

Limestone Filler consists of neritic limestone, with an average particle diameter of 12.5µm. This filler is distinguished by its high chemical purity and brightness.

2.1.5 Superplasticizer

Superplasticizer is a versatile superplasticizer/high-range water reducer of a new generation based on polycarboxylates According to standard NF EN 934-2, with density of 1,060.

2.2 Methods

2.2.1 Treatment of recycled rubber

An aqua heat treatment was applied to the crumb rubber before mixing, with the aim of improving its interaction with the cement matrix. This treatment consisted of immersing rubber particles boiling water. After the water had reached the boiling point, the temperature of the boiling water was measured using a thermometer to ensure it remained at 100 ± 1°C during the 30-minute treatment period using a plate thermostatic heater followed by drying in a ventilated oven at 160 ± 2°C for 2 hours with digital control of the temperature to ensure reproducibility of the process. The objective of this process was to initiate partial thermal degradation or surface modification of the rubber, thereby enhancing its bond with the surrounding paste. Figure 3 provides a schematic representation of the treatment process. Although this approach has shown potential in preliminary trials, further investigation is necessary to fully elucidate its effects on the microstructure and mechanical behavior of rubberized SC. Additionally, Table 2 presents the elemental composition of the UTR and TR rubber waste, offering insights into its intrinsic chemical characteristics. Although this study focuses on a single combination of parameters (100°C for 30 minutes, then drying at 160°C for 2 hours), a parametric study integrating different temperatures and processing times is underway and will further optimize the effectiveness of the method.

Figure 3. Schematic representation of the methodology employed for the aqua heat-treatment of rubber: (a) Rubber boiling; (b) Rubber drying

Table 2. The chemical composition of UTR (A) and TR (B) in%

%	(A)	(B)	%	(A)	(B)
C	73.23	73.45	**Mo**	0.62	1.38
O	11.69	13.24	**Cu**	0.42	0.06
Zn	2.35	2.28	**Fe**	0.45	0.23
S	1.94	2.43	**Na**	0.15	0.63
Si	1.51	0.55	**Al**	0.12	0.19
Ca	0.74	0.98	**Mg**	0.29	0.32

2.2.2 Development of sand concrete formulations

The sand concrete (SC) was formulated based on methodologies established in prior studies, notably those of Gadri and Guettala [22], which emphasize optimizing the granular packing density to enhance mechanical performance.

The cement content was fixed at 350 kg/m³, a dosage commonly adopted in numerous studies for achieving a good balance between strength and workability [23, 24]. The volume of sand was determined using the compactness coefficient (γ), calculated according to the Dreux and Festa method (1976), which relates the absolute volume of solid constituents (per 1000 liters of concrete) to the consistency class and the maximum aggregate size (D_max).

For mixtures with D_max ⩽ 5 mm and designed to reach a plastic consistency under standard vibration, a reference value of γ = 0.775 is recommended. However, due to the use of crushed sand, a correction factor of -0.03 was applied, resulting in an adjusted γ of 0.745. The sand volume (V_s) was then computed using the formula:

$$Vs=1000\times\gamma-V_cV_s = 1000 \times \gamma - V_cV_s=1000\times\gamma-V_{ct}$$

where, V_c is the absolute volume of cement [25].

Crushed limestone sand was specifically chosen for its favorable influence on mechanical behavior of the concrete. To further improve particle packing and reduce voids, a portion of the sand (0–12%) was replaced with finely ground limestone filler. The optimum formulation, referred to as SCR0 was identified at a 12% substitution level. This filler addition is critical for filling inter granular voids, thereby increasing the compactness and density of the mixture. Building upon previous findings, this study also explored using rubber as a partial substitute for sand aggregates in varying volumetric proportions (0% to 12%) to assess their influence on the SC properties. Table 3 defines the mix nomenclature, which is used in Table 4 to summarize the investigated concrete formulations.

Table 3. Nomenclature of sand concretes

Symbol	Description
SCR0	Control mix incorporating 12% limestone filler as a replacement for sand
SCR1	Sand concrete with 3% rubber aggregates by sand volume and 9% limestone filler.
SCR2	Sand concrete with 6% rubber aggregates by sand volume and 6% limestone filler.
SCR3	Sand concrete with 9% rubber aggregates by sand volume and 3% limestone filler.
SCR4	Sand concrete with 12% rubber aggregates by sand volume and 0% limestone filler.
SCRT1	Sand concrete with 3% treated rubber aggregates by sand volume and 9% limestone filler.
SCRT2	Sand concrete with 6% treated rubber aggregates by sand volume and 6% limestone filler.
SCRT3	Sand concrete with 9% treated rubber aggregates by sand volume and 3% limestone filler.
SCRT4	Sand concrete with 12% treated rubber aggregates by sand volume and 0% limestone filler.

Table 4. Composition of sand concrete mixes (per 1 m3)

Mix Type	Aqua Heat Treatment	CR%	W\C Ratio	Net Water (kg/m³)	SP (kg/m³)	Cement (kg/m³)	Limestone Filler (kg/m³)	Fine Aggregate	
								Sand (kg/m³)	Rubber (kg/m³)
SCR0	_	0	0.65	192.5	5.95	350	204.8	1412.84	0
SRC1	No	3	0.65	192.5	5.95	350	153.6	1412.84	19.53
SRC2	No	6	0.65	192.5	5.95	350	102.4	1412.84	39.1
SRC3	No	9	0.65	192.5	5.95	350	51.2	1412.84	58.6
SRC4	No	12	0.65	192.5	5.95	350	0	1412.84	78.13
SRCT1	yes	3	0.65	192.5	5.95	350	153.6	1412.84	19.53
SRCT2	yes	6	0.65	192.5	5.95	350	102.4	1412.84	39.1
SRCT3	yes	9	0.65	192.5	5.95	350	51.2	1412.84	58.6
SRCT4	yes	12	0.65	192.5	5.95	350	0	1412.84	78.13

2.2.3 Preparation and testing of specimens

A methodical experimental campaign was carried out to assess the physical and mechanical properties of SC including recycled rubber aggregates. Three identical specimens (n = 3) were used for each experimental test (resistance, absorption, porosity, and permeability); the results shown are averages with standard deviations. The relevant numbers now display error bars. The main objectives of this study were to assess the impact of rubber incorporation on the performance of sand concrete and to examine the effectiveness of aqua heat treatment in enhancing the properties of rubber-modified mixtures.

Workability was assessed using the mini-cone slump test, following the procedure described in standard NF EN 1015-3. The fresh mixed concrete was placed into a conical mold in two successive layers, each compacted by gentle shaking for 15 seconds. The mean spread diameter was recorded to quantify the flowability of the mix.

Dry density was determined in accordance with NF EN 12390-7 using prismatic specimens measuring 4 × 4 × 16 cm³. After curing, the samples were oven-dried at 70°C until a constant mass was achieved, and the dry density was calculated by dividing the final mass by the corresponding specimen volume.

Ultrasonic pulse velocity (UPV) testing, conducted as per NF EN 12504-4, was employed to assess the internal quality and homogeneity of hardened sand concrete. The test involved transmitting ultrasonic waves through the length of the specimens and measuring the travel time to calculate wave velocity.

Using a universal testing equipment, flexural strength was determined to conform with NF EN 12390-5. The prismatic specimens (4 × 4 × 16 cm³) were subjected to three-point bending, and the maximum load at failure was recorded.

Compressive strength was subsequently evaluated on the two halves obtained after the flexural test, by applying axial compression to the resulting fracture surfaces (16 cm² contact area), in accordance with standard test procedures.

Water-accessible porosity was evaluated following ASTM C642-06 using cubic specimens (10 × 10 × 10 cm³). The procedure involved oven drying, immersion in water, boiling, and hydrostatic weighing to determine the total open pore volume.

Total water absorption was measured on prismatic samples

($4 \times 4 \times 16$ cm³) following the NBN B15-215 standard. Specimens dried in an oven were immersed in water for 48 hours, and the mass of absorbed water was expressed as a percentage of the dry mass.

Capillary water absorption was determined using the method described in NF EN 480-5 and ASTM C1585-11. Prismatic specimens were partially immersed in water, and their mass was noted at specific time intervals to evaluate the absorption kinetics and capillary rise behavior.

3. RESULTS AND DISCUSSIONS

3.1 Initial characteristics of concrete

3.1.1 Assessing workability

Visual observations confirmed that all sand concrete mixtures exhibited good cohesion throughout the mixing and placement processes. No signs of segregation or bleeding were detected, indicating the stability of the mixtures. The workability test results, presented in Figure 4, show that the mixture characteristics were significantly affected by the addition of rubber. The reference sample (OSC) demonstrated the highest workability, recorded at 90%, while workability progressively declined with increasing rubber content. Holmes et al. [26] suggested that increasing both the rubber content and particle size in concrete leads to reduced workability, as larger particles hinder flowability and contribute to a stiffer mixture. Additionally, the decreased interparticle friction caused by the presence of rubber particles resulted in a measurable decline in the fresh mix's unit weight.

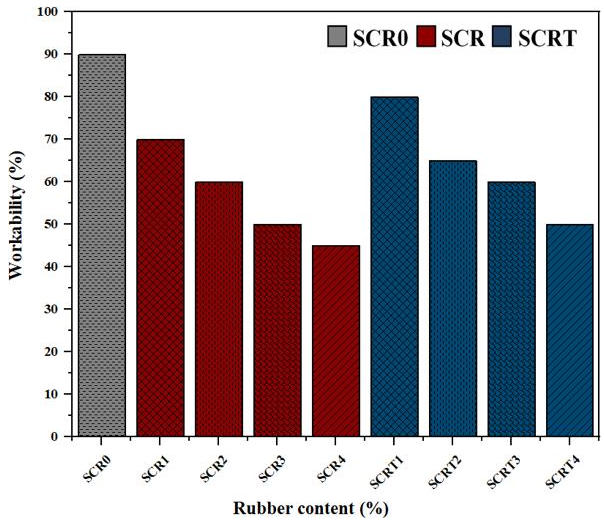


Figure 4. Effect of treated rubber content on the workability of sand concrete mixtures

These findings are consistent with studies [27-29]. For mixtures incorporating TR (SCRT1 to SCRT4), workability decreased from 80% in SCRT1 to 50% in SCRT4. However, slight improvements were observed in comparison to the UTR mixtures at similar rubber content levels. Swilam et al. [18] reported that thermal treatment of rubber slightly improved slump due to the evaporation of volatile compounds during heating, which enhanced water absorption and particle mobility in the mix.

3.1.2 Evaluating fresh density

Figure 5 illustrates the fresh density results, which demonstrate a noticeable reduction in density with the incorporation of both untreated (SCR) and treated (SCRT) rubber, compared to the reference sample (SCR0). The reference sample (SCR0) exhibited the highest fresh density, with a value of 2289.5 kg/m³, representing the typical density of a mixture without rubber. In contrast, the addition of UTR in the SCR1 to SCR4 samples led to a progressive reduction in density, ranging from 2111.9 kg/m³ in SCR1 to 1941.6 kg/m³ in SCR4. This decrease in fresh density primarily results in the reduced density of rubber in contrast to the other constituents of the mixture, a finding also reported by Su et al. [30].

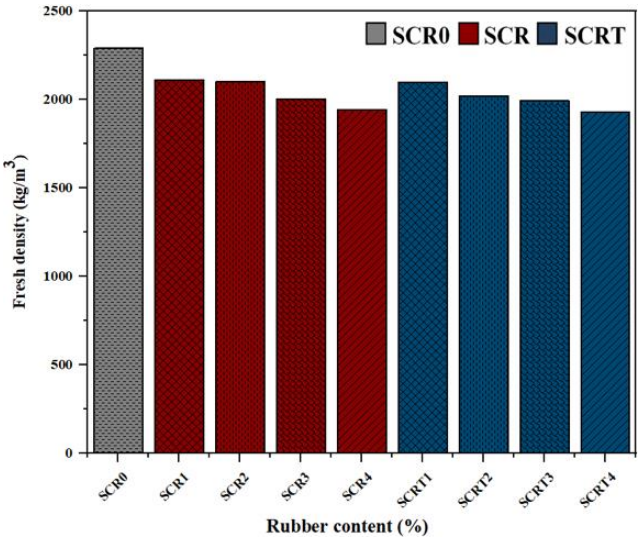


Figure 5. Impact of rubber content on the weight of fresh sand concrete

Similarly, the TR samples (SCRT1 to SCRT4) exhibited a decrease in fresh density, with values ranging from 2098.7 kg/m³ in SCRT1 to 1930.2 kg/m³ in SCRT4. Moustafa and ElGawady [31] noted that partial replacement of sand with rubber resulted in a slight reduction in concrete density, with a 30% sand replacement leading to an approximate 6% decrease in density. Notably, the fresh density of sand concrete incorporating TR was slightly lower than that of the corresponding UTR mixtures at the same rubber replacement levels. For example, the SCRT1 mixture exhibited a density of 2098.7 kg/m³, while the SCR1 mixture recorded a density of 2111.9 kg/m³.

3.2 Mechanical behavior

3.2.1 Determining dry density

The dry density results, shown in Figure 6, reveal a consistent reduction in density with both added UTR (SCR) and TR (SCRT), compared to the reference sample (SCR0). The reference sample (SCR0) exhibited the highest dry density, with a value of 2454.91 kg/m³, which is typical for a mixture without rubber. In the samples containing UTR to SCR4), a gradual decrease in dry density was observed, with values ranging from 2390.35 kg/m³ in SCR1 to 2293.85 kg/m³ in SCR4. This trend is consistent with findings [32-34] which indicated hat as the rubber content in SC increases, its density decreases. The main reason for these decreases can be attributed to rubber having a lower density by nature than the other components in the mixture, resulting in a lighter overall mixture [12].

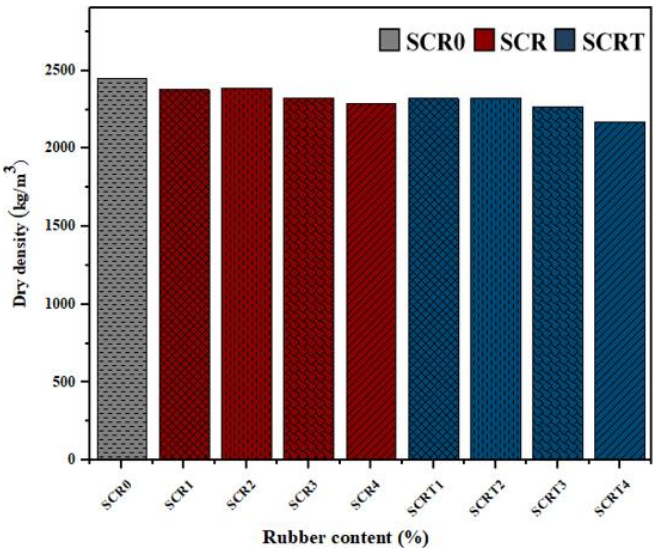


Figure 6. Hardened density of sand concrete

3.2.2 Measuring compressive strength

As shown in Figure 7, the incorporation of both untreated and heat-treated rubber led to a decrease in 28-day compressive strength compared to the reference sample (SCR0), which exhibited a compressive strength of 50.33 MPa. The strength decline was more pronounced in samples containing UTR (SCR1–SCR4), where values decreased from 37.96 MPa to 24.36 MPa. As the amount of rubber increased from 3% to 12%, the compressive strength decreased by approximately 24%, 29%, 43%, and 51%, respectively compared with the conventional concrete (SCR0). This reduction can be attributed to the disruption of the cementitious matrix and diminished load-bearing capacity, which aligns with the findings [35, 36] which reported a decline in concrete strength when the amount of rubber increases because air gaps are created.

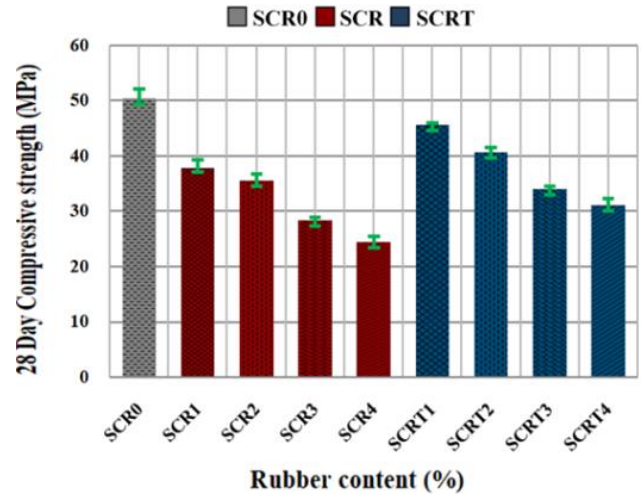


Figure 7. Compressive strength variation of aqua heat-treated and untreated rubber concrete

Zrar and Younis [37] attributed the reduction in compressive strength primarily to the weak interfacial bond between the rubber particles and the cement paste, as it impairs stress transfer inside the matrix of concrete. Furthermore, the flexibility of rubber particles can induce microcracking in the surrounding cement matrix, leading to premature failure under compression [38].

Similarly, the heat-treated rubber samples (SCRT1–SCRT4) displayed a reduction in compressive strength, from 45.58 MPa to 31 MPa, although they outperformed the untreated samples. Despite the improvements achieved through thermal treatment, the presence of rubber continued to negatively affect compressive strength, underscoring its impact on the material's structural integrity. These findings are in line with those reported by Swilam et al. [18]. Furthermore, Dou et al. [39] demonstrated that heat treatment enhances the bonding strength and interfacial compatibility between rubber and cement, thereby reducing pore gaps at the rubber–cement interface. Likewise, Sanjaya et al. [21] Showed an enhancement in compressive strength with aqua-thermal treatment, attributing the improvement to the removal of surface impurities, which led to a cleaner rubber surface and enhanced adhesion with the cement matrix. Additionally, thermal treatment altered the rubber's contact angle, further improving its compatibility with the surrounding cementitious material.

3.2.3 Analyzing flexural tensile strength

As the proportion of rubber-based aggregates increased, the flexural tensile strength decreased (Figure 8). However, this reduction was less pronounced compared to the decline observed in compressive strength. In contrast to the reference sample (SCR0), the flexural strength showed a notable decrease. This decreasing trend in flexural strength has been documented in previous studies [40, 41].

The reference sample (SCR0) achieved a flexural tensile strength of 8.77 MPa, demonstrating strong mechanical performance. However, the incorporation of UNT in samples SCR1, SCR2, SCR3, and SCR4 resulted in a progressive decrease in strength, with values of 7.85 MPa, 6.40 MPa, 5.85 MPa, and 5.75 MPa, respectively. Compared to the conventional mix. These declines, which translate into decreases of 10.49%, 27.02%, 33.29%, and 34.42%, respectively, show that flexural strength is negatively impacted by UTR.

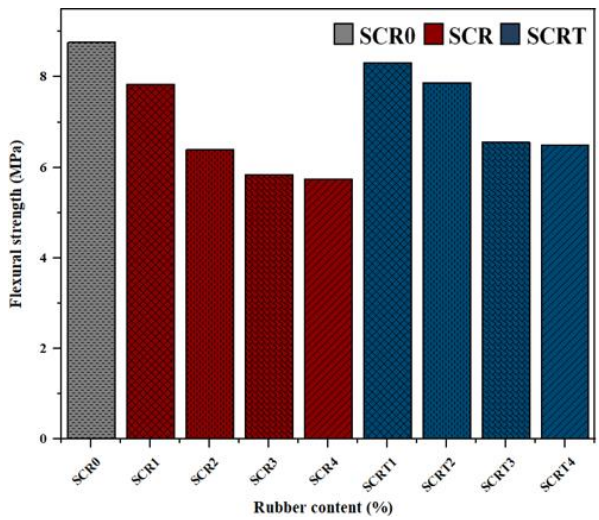


Figure 8. Flexural strength test with heat-treated and untreated rubber content

The same results have been published by Záleská et al. [42], where rubber particles were used as a 20% replacement for fine aggregates, which lead to in a 12.8% decrease in flexural strength Rubber particles were utilized as a 20% replacement for fine aggregate in the study conducted [30].

This trend emphasizes the weakening effect of UTR on the material's structural cohesion. The insufficient bond between cement paste and rubber facilitates separation under low stress, creating interfacial defects. Additionally, the significant stiffness contrast between RA and the cement matrix induces differential deformations, promoting early cracking and reducing overall strength [43].

Although the aqua heat-treated rubber samples exhibited slightly improved performance compared to their untreated counterparts, such as SCRT1 with a strength of 8.32 MPa compared to 7.85 MPa in SCR1, the overall trend of decreasing strength with increasing rubber content remained consistent.

3.2.4 Examining ultrasonic pulse velocity

The ultrasonic pulse velocity (UPV) results, presented in Figure 9, demonstrate the significant impact of rubber incorporation on sound wave transmission, reflecting the material's integrity. The reference sample (SCR0) exhibited the highest UPV, with a value of 4290 m/s, indicating superior compactness. In contrast, the UTR samples (SCR1–SCR4) showed a progressive decline in UPV, ranging from 4010 m/s (SCR1) to 3770 m/s (SCR4). A similar trend was identified by Jalal et al. [44], who observed structural discontinuities as a result of rubber incorporation. This finding is further corroborated by Djebien et al. [45], which reported a reduction in UPV due to the introduction of rubber waste into concrete. The presence of rubber particles in concrete can create discontinuous interfaces and low-density regions, leading to a reduction in ultrasonic pulse velocity [46].

The heat-treated rubber samples (SCRT1–SCRT4) also exhibited a decrease in UPV, with values ranging from 4200 m/s (SCRT1) to 3879 m/s (SCRT4). Although aqua heat treatment improved wave transmission compared to UTR samples, the overall trend showed a decline in UPV as the rubber content increased. A comparable decrease was noted in the compressive strength, as both properties are closely linked to the internal cohesion and structural integrity of the material.

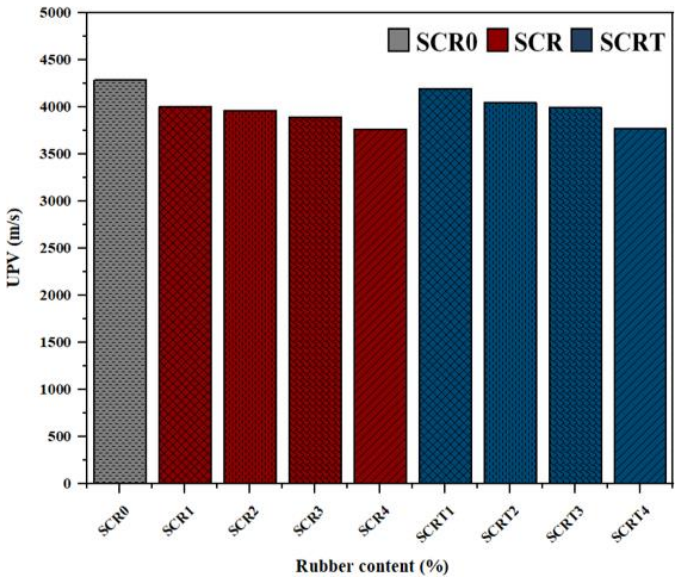


Figure 9. UPV of sand concretes mixes

3.3 Durability analysis

3.3.1 Analysis of water absorption by capillarity

The capillary water absorption ratio is a key parameter in evaluating the durability of concrete materials. Figure 10(a) presents the results of the capillary absorption test for water absorption which demonstrated that capillary water absorption increased in proportion to an increase in rubber content. At 24 hours, the sample with 12% untreated rubber (SCR4) exhibited a notably higher capillary water absorption rate. The rise is the consequence of weak cement-rubber interface bonding, resulting in the SC mix developing voids. These additional voids facilitate water penetration, thereby enhancing water absorption via capillary action. Similar results were reported by Belmouhoub and Abdelouahed [47].

Despite the aqua heat-treatment, the incorporation of crumb rubber replacing fine aggregates in concrete has been shown to reduce capillary water absorption. This is supported by microstructural investigation using Scanning Electron Microscopy (SEM), as shown in Figure 10(b). The findings suggest that the decrease in water absorption is due to the decreased pore spaces in the sand concrete, which result from enhanced adhesion at the rubber-cement interface.

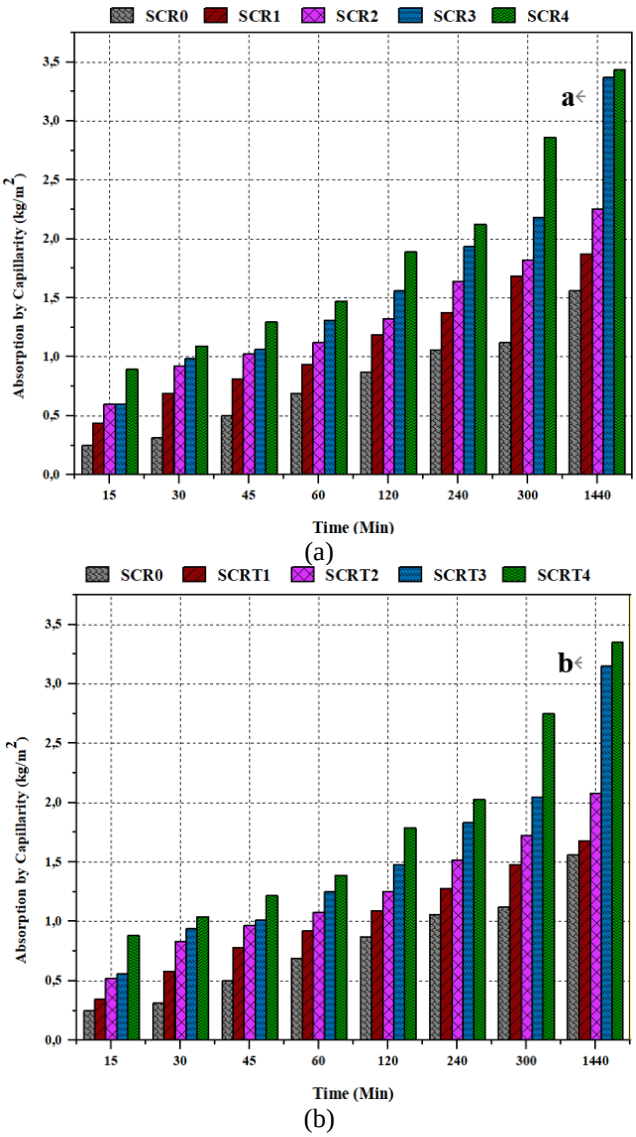


Figure 10. The water absorption via capillarity of sand concrete mixtures over time for (a) treated rubber and (b) untreated rubber

3.3.2 Total water uptake

Water absorption (W) is a critical parameter reflecting the porosity and pore connectivity within concrete. In this study,

the inclusion of both UTR and TR was found to substantially influence absorption characteristics. As shown in Figure 11, UTR-modified concretes exhibited greater total water absorption by immersion compared to the reference SC mix. The reference sample (SCR0) exhibited a total absorption of 2.18%, indicating a low tendency for moisture uptake. In contrast, the addition of rubber resulted in an initial increase in water absorption. The highest absorption value was recorded at 4.01% for SCR4, while SCR1 had a lower absorption of 2.49%. These results align with findings reported by other researchers [47, 48].

The air trapped in sand concrete containing rubber aggregates increases its porosity, rendering it more permeable and consequently facilitating greater water absorption [49]. A similar trend was observed in TR samples (SCRT1 to SCRT4), where total absorption values started at 2.36% in SCRT1 and gradually increased to 3.13% in SCRT4. This aligns with the findings of Yajie Liu et al., who reported that the water absorption rate of rubber mortar treated at 100℃ and 200℃ was lower than that at room temperature [50]. This reduction suggests that treatment may enhance the material's resistance to moisture uptake over time, which agrees with results reported by Awan et al. [12].

These results demonstrate the complex relationship between water absorption and rubber composition, with significant implications for material's durability over time. The reduced water absorption in TR samples is likely due to enhanced adherence of the rubber particles to the cement paste, reducing void formation and limiting water infiltration. A similar trend was noted by Chiraz et al. [51].

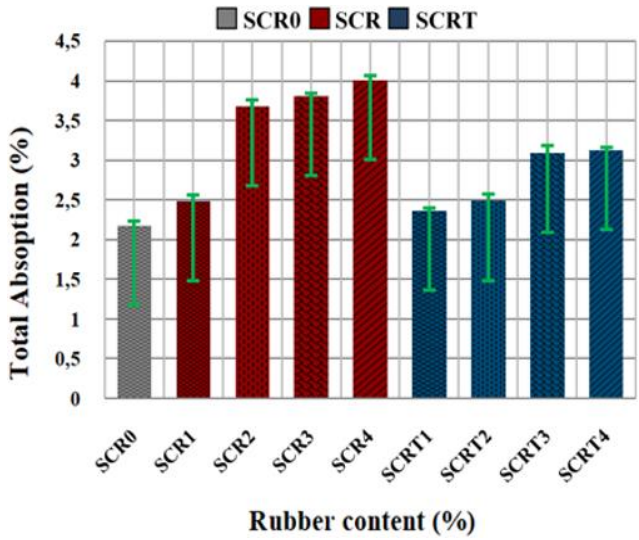


Figure 11. Water absorption (W) at 28 days

3.3.3 Porosity evaluation

Figure 12 illustrates the porosity curve of rubberized sand concrete at varying rubber contents. A gradual increase in porosity is observed with the increase in rubber content. This phenomenon can primarily be attributed to the concrete matrix's expanded pore spaces resulting from the inclusion of rubber particles [21]. The maximum average total porosity recorded was 6.41%.

Concrete containing aqua heat-treated rubber demonstrated a significant reduction in porosity compared to both the reference sample (SCR0) and the UTR mixtures. This reduction in porosity is likely attributed to the aqua heat treatment, which enhances the interfacial bond between rubber particles and the cement paste, thereby minimizing the voids that facilitate water penetration [51].

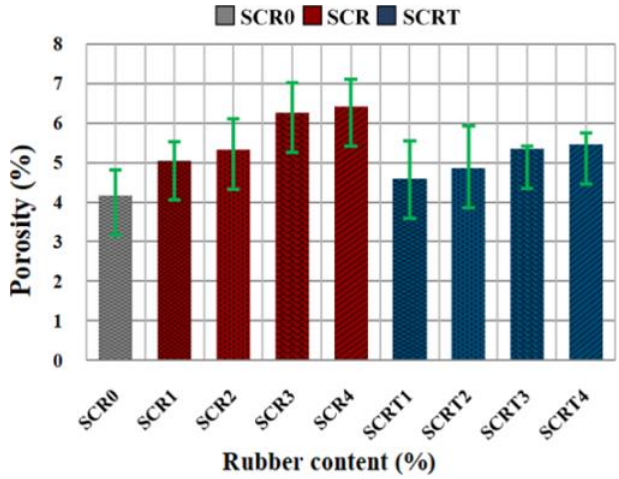


Figure 12. Porosity of different types of sand concrete mixtures

3.4 Microstructural analysis

3.4.1 Transformation of rubber aggregate microstructure post-aqua heat treatment

Figure 13 presents the surface morphology of rubber particles observed through (SEM), comparing (a) untreated and (b) treated particles. The SEM image of untreated crumb rubber (Figure 13(a)) reveals a rough and uneven surface, covered with fiber remnants and organic residues. These impurities contribute to a weaker interfacial transition zone (ITZ), which hinders the formation of a strong interfacial bond between the rubber particles and the cement matrix. However, significant microstructural changes were observed after the thermal treatment procedure, which involved boiling the rubber particles in water for 30 minutes followed by drying at 160℃ for two hours (Figure 13(b)). The treatment effectively removed fibers and surface contaminants, resulting in a cleaner and more uniform surface. Additionally, this process causes the rubber particles to develop a harder outer shell [19], enhancing their integration into the concrete matrix and reducing their deformability. This densification of the rubber surface enhances overall adhesion between the rubber particles and the cementitious matrix, while also promoting mechanical interlocking at the interfacial transition zone. Moreover, the aqua heat treatment led to a slight reduction in the rubber's zinc content, from 2.35% to 2.28%, which may contribute marginally to enhanced cement hydration and interfacial bonding. Collectively, these improvements result in enhanced performance and longevity of rubberized concrete.

Although this study is limited to morphological (SEM) and elemental (EDS) analysis, more in-depth surface chemistry analyses (such as FTIR, XPS or TGA) could provide a better understanding of the modification mechanisms induced by aqueous treatment. These investigations are proposed as research perspectives.

3.4.2 Enhancement of rubber/cement interface bonding through aqua heat treatment

The adhesion between rubber particles and the cement matrix provides a crucial part in establishing concrete's durability and mechanical qualities. To investigate this at the microstructural level, (SEM) was used to investigate the

interfacial transition zone (ITZ). In sand concrete incorporating UTR, a distinct space was observed between the rubber particles and the cement paste. Figure 14(a) indicates this weak interfacial bonding. This poor adhesion is caused by the presence of surface impurities and the inherently hydrophobic nature of UTR, which impedes effective integration with the cementitious matrix.

In contrast, sand concrete containing aqua heat-treated rubber (Figure 14(b)) displays a significantly improved bond, with no visible separation at the rubber/cement interface. This enhancement can be attributed to the removal of impurities, the formation of a rougher and stiffer surface, and a possible increase in surface energy, which promotes wetting and cement bonding. This results in a denser and more cohesive interfacial transition zone (ITZ). Moreover, the development of a rigid surface layer on the rubber particles reduces their inherent elastic deformability, thereby facilitating more effective stress transfer throughout the concrete matrix.

The aqua heat-treatment contributes to a visible reduction of the interface voids observed at the SEM and to better compaction of the interfacial transition zone (ITZ). These microstructural changes largely explain the improvements observed in compressive strength and capillary absorption, as discussed in section 3.2.

As a result, the rubber particles treated in this way contribute to a more cohesive and durable composite material. These findings align with those of previous studies [18, 19, 21], which also highlight the beneficial impact of surface treatment on the cement-rubber bond.

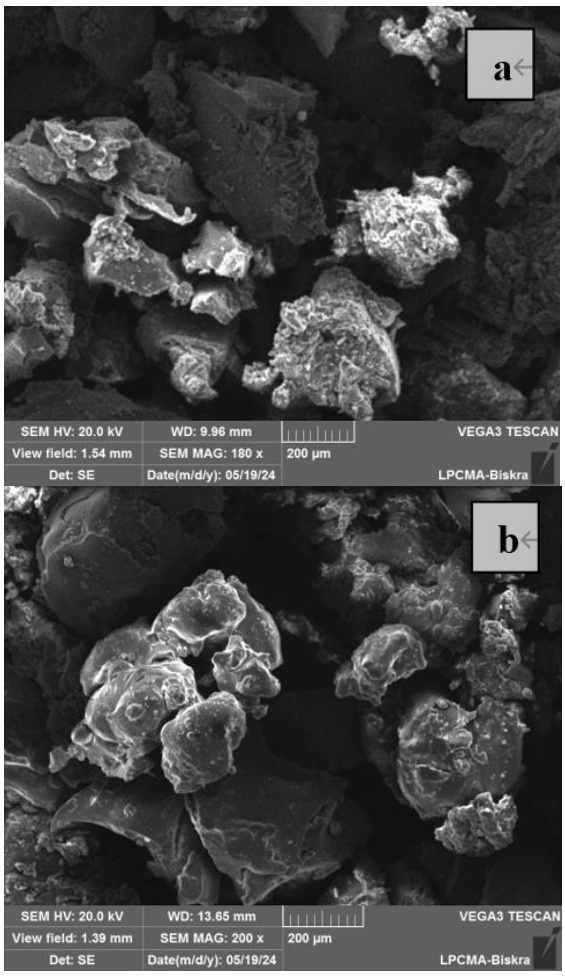


Figure 13. SEM micrographs of rubber samples: (a) untreated rubber, (b) aqua heat-treated rubber

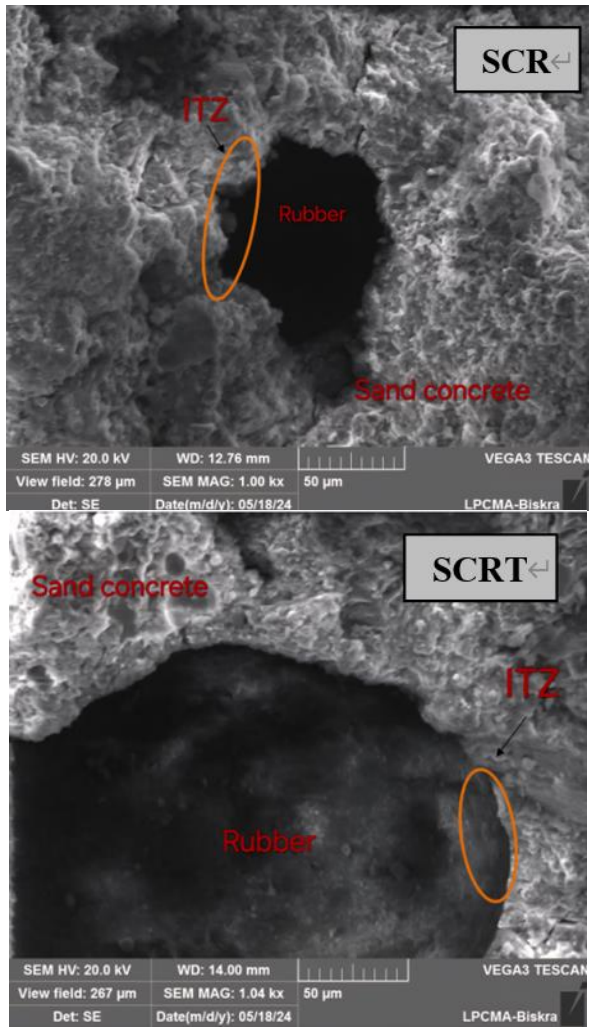


Figure 14. Microstructure evolution of the rubber/cement interface due to aqua heat treatment

3.5 Statistical correlations

3.5.1 Porosity and compressive strength correlation

Figure 15 presents two plots that illustrate the correlation between porosity and compressive strength in rubber-modified SC, differentiating between untreated and aqua heat-treated rubber. For untreated rubber, a substantial inverse relationship between porosity and compressive strength is observed, as indicated by the regression equation $Y = -10.73x + 93.64$ and the high coefficient of determination $R^2 = 0.97$. This inverse relationship can be attributed to the poor adhesion of UTR to the cement matrix, which promotes the formation of voids and weakens the overall structure.

In the case of aqua heat-treated rubber, a similar negative trend is observed, but with a more pronounced decrease in compressive strength as porosity increases. The regression equation for this data is $Y = -14.72x + 112.19$ with an even greater $R^2 = 0$. Although aqua heat treatment enhances bonding between rubber particles and the cement matrix and tends to lower porosity, its impact remains dependent on factors like mix composition, treatment efficiency, and curing regime, the remaining voids have a more significant impact on mechanical performance. This is likely due to the increased cohesion of the treated mix, which amplifies the effect of any residual voids on the material's strength.

The strong negative linear correlation between porosity and compressive strength in both cases highlights the critical

importance of microstructural integrity in determining the overall mechanical properties of rubberized concrete composites.

3.5.2 Water absorption and porosity link

A direct relationship was observed between the water absorption (W) of sand concrete with the largest continuous pore dimension [52]. As the porosity increased, the total water absorption coefficient showed a notable rise. Strong relationships between water absorption and porosity were observed for sand concrete reinforced with surface-treated and untreated crumb rubber (SCR), as well as for the unmodified control mix (SCR0). A strong correlation coefficient of 0.94 for the SCRT and 0.82 for the SCR, as shown in Figure 16, indicates a strong relationship between porosity and water absorption, especially in the case of surface-modified rubber.

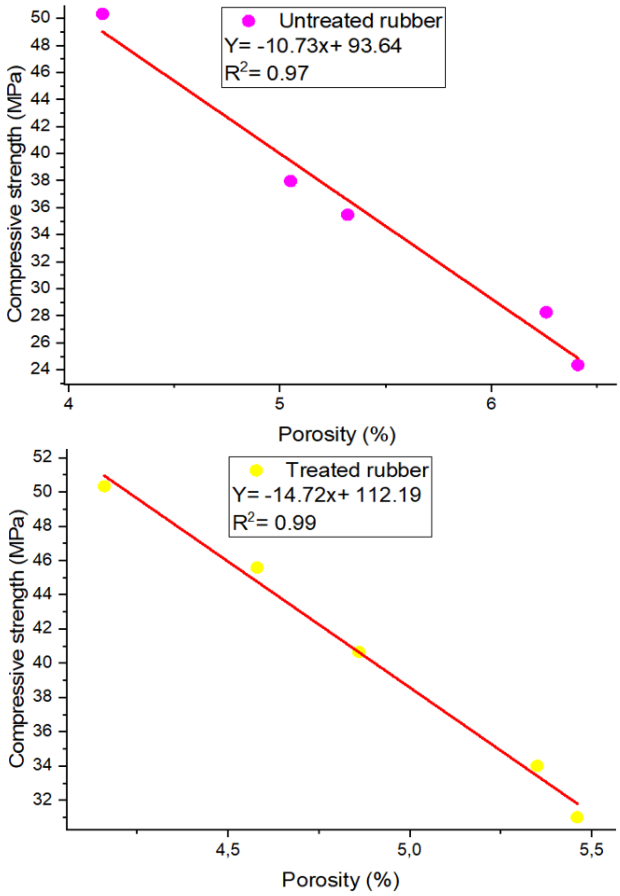
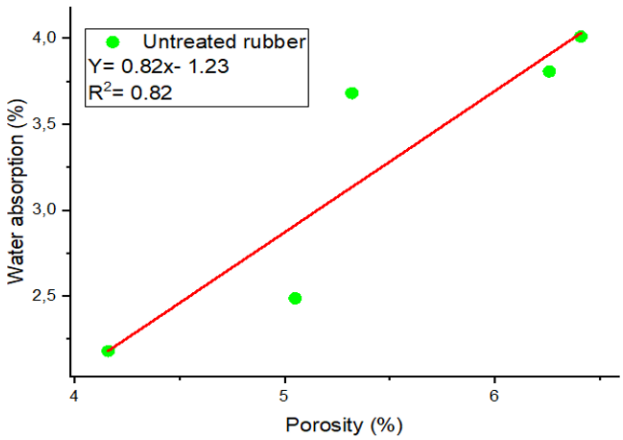


Figure 15. Relationship between compressive strength and porosity of sand concrete (SC) mixtures



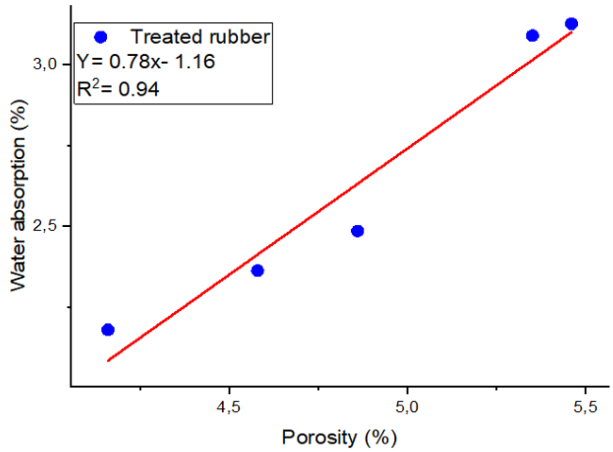


Figure 16. Influence of porosity on water absorption in rubberized concrete

4. ENVIRONMENTAL IMPACT ASSESSMENT OF THE RUBBER TREATMENT PROCESS

The use of waste rubber in construction materials raises important environmental concerns, especially in relation to processing impacts and long-term sustainability. A life cycle assessment (LCA) of crumb rubber in road pavements showed that the wet process may offer health and environmental benefits. However, these findings are based on estimates and remain preliminary. Thus, comprehensive LCA studies are strongly recommended for broader applications [53]. The aqua-thermal treatment offers an environmentally friendly alternative to chemical methods like NaOH or acetone, which, although effective, raise toxicity and sustainability concerns. This water- and heat-based approach avoids toxic byproducts while achieving comparable performance, such as a 12% reduction in porosity versus 15% with silane. Though slightly less effective than hybrid methods (e.g., magnetized water combined with heat), this approach remains promising due to its chemical-free nature and ease of implementation, making it attractive for large-scale industrial applications. This makes it a viable option and sustainable solution for large-scale applications, with life cycle assessment (LCA) suggested for further evaluation.

Table 5. A cost comparison between different treatment methods

Treatment	Advantages	Drawbacks	Cost (€/kg)	Ref
NaOH	Improves adhesion +25% strength	Corrosive effluents	0,25	[8, 9]
Silane	Reinforced interface	Prohibitive cost	0,30	[16]
Dry thermal	Void reduction	High energy consumption	0,18	[17]
Aqua-thermal	No chemicals required, moderate cost	Longer treatment time	0,12	This study

Economically, it is 52% cheaper than NaOH treatment (0.12 €/kg vs. 0.25 €/kg) and presents a lower environmental impact, with a carbon footprint of 0.45 kg CO_2 eq/kg of rubber significantly less than incineration or landfilling. Table 5 presents a cost comparison between different treatment

methods, highlighting the economic advantage of the proposed method over other techniques reported in the literature.

5. CONCLUSION

The incorporation of crumb rubber (CR) as a partial aggregate replacement in sand concrete helps reduce rubber waste, contributing to environmental sustainability. Based on the experimental findings, several key insights emerge regarding the influence of aqua heat-treated rubber on the properties of sand concrete, particularly in comparison to untreated rubber.

- Aqua heat-treated rubber improves certain properties such as workability, durability, and water resistance compared to untreated rubber.
- Both untreated and treated rubber lead to reductions in fresh and dry density, as well as permeability, negatively affecting the overall mechanical properties of sand concrete.
- Aqua heat-treated rubber demonstrates slight improvements in workability and water absorption compared to untreated rubber.
- Aqua heat-treated rubber recovers 61%, 36%, 27%, and 25% of the compressive strength losses relative to conventional untreated rubber for rubber contents of 3%, 6%,9%, and 12%, respectively, after 28 days.
- The reduction in mechanical strength caused by crumb rubber can be minimized or even prevented through appropriate pretreatment with modifying agents.
- The improvement observed can be attributed to the aqua-thermal treatment, which effectively removes surface impurities and enhances the material's performance.
- The decrease in water absorption observed in SCRT compared to SCR at all replacement levels suggests a reduction in porosity, which could lead to improved durability properties.
- Scanning Electron Microscopy (SEM) observations reveal that aqua heat treatment enhances the bond at the rubber–cement interface, contributing to improved microstructural integration.

DECLARATION

This study examines the short-term mechanical and durability properties of the material. It is part of a broader research project, with ongoing investigations aimed at evaluating the aging behavior and long-term performance of treated rubber particles in concrete under various environmental conditions, including chemical attacks, freeze-thaw cycles, shrinkage, and crack resistance, to ensure a comprehensive understanding of the material's behavior over time. In addition, a parametric study involving water temperatures (ranging from 80 to 120°C) and drying durations (1 to 4 hours) is necessary to identify optimal, energy-efficient treatment conditions.

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