Effects of Rubber Particle Size and Substitution Rate on the Behavior of Eco-Friendly Rubberized Concrete

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ABSTRACT

One of the world's largest tire graveyards is located in the Al-Salmi area of Kuwait, where over 42 million discarded waste rubber tires have been accumulated over a time period of 17 years. This study aims to develop sustainable, cost-effective building materials for the construction industry, utilizing waste rubber as a partial substitute for fine and coarse aggregates in concrete mixtures. Three types of untreated rubber particles were used: powder rubber (P) with a diameter between 0.4 and 0.6 mm, crumb rubber (CR) with a diameter between 0.6 and 2 mm, and 2.6 and 3.5 mm respectively, and rubber chips (CH) with a diameter ranging between 2 and 18 mm. Fine aggregates were replaced by P and CR, while coarse aggregates were replaced by CH, at a substitution rate of 10 and 20% by volume. The impact of rubber particles on workability was assessed on fresh rubberized concrete, while the compressive strength was evaluated at 7, 14, and 28 days. Microstructural analysis using Scanning Electron Microscopy (SEM) was also conducted to collate the macroscopic behavior with internal structural changes. The results showed that increasing the rubber content and particle size led to reductions in workability and compressive strength. Large rubber particles, particularly chips, caused gaps and microcracks in the matrix, exhibiting poor adhesion at the Interfacial Transition Zone (ITZ). These findings demonstrate the potential of rubberized concrete as an eco-friendly alternative, with optimization needed for practical applications.

Keywords-rubber; concrete; workability; compressive strength; microstructure

I. INTRODUCTION

The improper disposal of waste tires has raised significant environmental and health concerns, particularly in the Al-Salmi area of Kuwait, where millions of tires are discarded. This accumulation has resulted in environmental pollution, habitat destruction, and the creation of breeding grounds for disease-carrying pests, posing severe risks to public health [1]. Addressing this issue requires innovative waste management strategies, especially recycling techniques that repurpose waste tire rubber into useful products. One promising solution is the incorporation of recycled tire rubber into concrete mixtures, which not only mitigates environmental harm, but also enhances certain mechanical properties of concrete [1, 2]. By partially replacing conversional fine and coarse aggregates with rubber particles, rubberized concrete conserves natural resources, reduces landfill waste [2, 3], and lowers the carbon footprint of concrete production by decreasing the need for virgin materials [1, 4]. Sustainable methods, such as shredding and pyrolysis, effectively convert waste rubber into a construction material, while simultaneously addressing the environmental concerns related to tire disposal [4, 5].

Beyond its environmental benefits, rubberized concrete enhances concrete performance, particularly in terms of durability and ductility [6, 7]. The addition of rubber, improves impact resistance, sound absorption, thermal insulation, water absorption, and abrasion resistance of concrete, making it suitable for applications, such as in pavements, roads, hydraulic structures, and geotechnical works [4, 8]. Additionally, the increased flexibility and ability to return to its original shape after deformation make rubberized concrete ideal in areas exposed to dynamic loads, such as highways, playgrounds, and structural lightweight concrete [9]. It also dominates in freeze-thaw conditions, as the rubber particles dissipate energy, preventing cracking and increasing toughness [1, 10-12]. This alteration in the mechanical properties can be attributed to rubber's ability to modify the pore structure of concrete, thereby influencing durability factors, such as permeability and resistance to environmental stress [13]. Scanning Electron Microscopy (SEM) has been extensively used to study the interaction between rubber particles and the cement matrix, revealing critical insights into the bond characteristics at the ITZ. SEM investigations have shown that while untreated rubber often exhibits poor adhesion to the cement paste resulting in microcracks and voids, surface treatments like alkali treatment (NaOH), can improve bonding at the ITZ, enhancing the strength and durability of rubberized concrete [13-15].

Despite its advantages, rubberized concrete has specific limitations, primarily related to strength reduction. The inclusion of rubber generally decreases the compressive and tensile strength of concrete due to the lower density and stiffness of rubber compared to traditional aggregates [7, 9]. Studies have suggested that substituting more than 20% of aggregate volume with rubber results in significant strength reduction, making it essential to optimize the mix design [2, 16]. Authors in [17], found that substituting fine aggregates with crumb rubber led to a decrease in compressive strength but enhanced ductility and crack resistance. Similarly in [18], it was observed that rubberized concrete developed lower compressive and splitting tensile strengths but higher toughness and energy absorption capacity.

The size and shape of rubber particles also play a critical role in determining the concrete's mechanical properties. CR, (typically 0.5-4 mm), improves the ductility and strength-to-weight ratio, whereas larger rubber particles, such as chips, reduce the specific weight and compressive strength [19]. In [20], it was demonstrated that smaller particles (0.15-0.6 mm) led to higher compressive strength compared to larger particles (1-4 mm). However, authors in [21] reported that larger rubber particles were more effective in improving concrete resistance to chloride ion penetration. Certain studies have also examined the relationship between rubber content and particle size. Authors in [22] found that the best mechanical performance was achieved with a specific combination of rubber content and particle size. Additionally, workability varies depending on the type and size of rubber. Even though CR can reduce the possibility of segregation and bleeding in concrete mixes, larger particles increase water absorption and adversely affect the concrete's performance [7].

This paper proposes an experimental program to investigate the use of waste rubber in concrete, aiming to evaluate its feasibility and benefits as a sustainable solution to Kuwait's waste management challenges. Locally sourced materials are utilized to ensure the findings are directly applicable to the Gulf region's unique climate and construction.

II. METHODOLOGY

A. Materials

The materials used in this study were chosen based on their availability in Kuwait for sustainability reasons and compliance with the standards to enhance the rubberized concrete mechanical properties.

1) Rubber Particles

Rubber particles were obtained from EPSCO Kuwaiti company, which has one of the largest factories in the region with a productive capacity of recycling 2,500,000 tires per year. Rubber particles were provided in different forms:

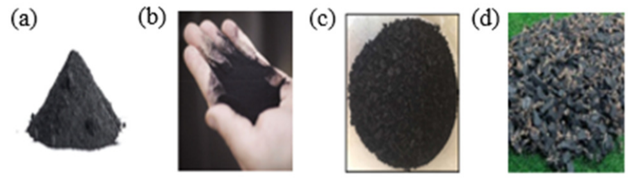

Fig. 1. Types and shapes of rubber particles: (a) Powder (0.4-0.6 mm), (b) Crumb (0.6-2 mm), (c) Crumb (2-3.5 mm), and (d) Chips (2-18 mm).

P is produced through a crunching process, transforming waste rubber into a finely ground powder with particles smaller than one millimeter in size [32]. In this study, the fine powder used has a particle size ranging between 0.4-0.6 mm. CR is a flexible addition that can replace fine aggregates in concrete mixtures up to a certain percentage. Different sizes between 0.6 to 2 mm and 2 to 3.5 mm were used, respectively. Additionally, CH, with sizes ranging from 2 to 18 mm was deployed to partially replace traditional coarse aggregate in concrete mixtures. The rubber particles utilized in the experiment had a density of approximately 1.2 g/cm^3. Figure 2 illustrates the particles size distribution of the different rubber particles used following the American Society for Testing and Material (ASTM) standard for sieving [24]. It should be noted that rubber particles with different sizes absorb varying amounts of water. Thus, superplasticizer admixture was added to control workability.

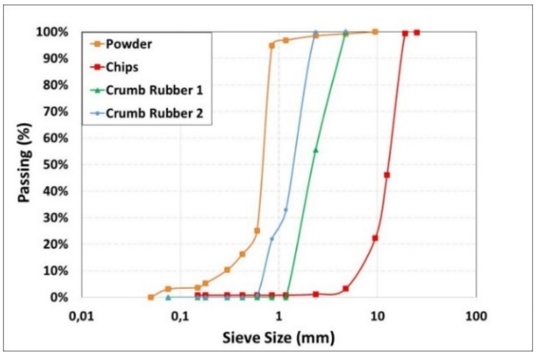

Fig. 2. Grading curves of rubber particles of different sizes.

2) *Fine and Coarse Aggregates*

The type and volume of coarse aggregates play a crucial role in determining the strength and workability of concrete. Fine Aggregates (FA) and Coarse Aggregates (CA) were processed into appropriate sizes following the ASTM standard [24] (Figure 3):

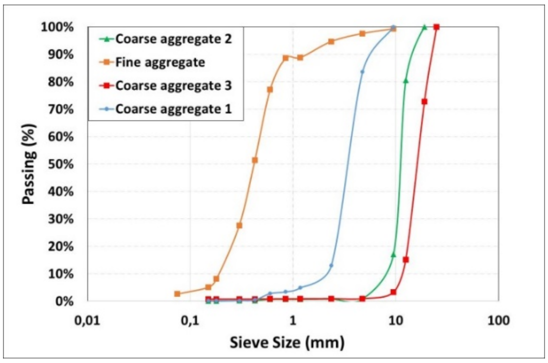

Fig. 3. Grading curves of FA and CA.

FA or washed sand, has a fineness modulus of 3 and a specific gravity of 2.54 [25]. Coarse limestone aggregates with different sizes were used, including CA1 (0.425-9.5 mm), CA2 (4.75-19 mm), and CA3 (4.75-25 mm). The uniformity coefficient, defined as the ratio from D60 to D10, was calculated for CA, with a value less than 4, indicating that it was poorly or uniformly graded. The specific gravity of CA was 2.62 [28]. Water absorption values, measured in accordance with the ASTM C127 standards [26], were 1.5% for CA and 2.5% for FA.

3) *Cement*

Cement type I, obtained from the Kuwaiti company ACICO, was used as the binding agent. This cement meets the requirements of BS EN 197 [27], ASTM C150/C150M [28], and KWS GOS 1914/2010, with an ultimate concrete strength similar to cement's classified as 42.5 N.

4) *Superplasticizer*

The superplasticizer CAPLAST SF 500, meeting the requirements of ASTM C494/C494M [29], was also used to reach an optimum workability and uniformity for concrete mixtures. It was obtained from Alahlia Chemicals in Kuwait.

B. *Concrete Mixtures*

Seven concrete mixes were prepared with different proportions of rubber particles replacing FA or CA at substitution rates of 10% and 20% by volume. These included a Control Mix (CM), two mixtures where sand was replaced by 10% and 20% of powder (P10 and P20, respectively), two mixtures where FA were replaced by 10% and 20% of a combination of P and CR (PCR10 and PCR20 respectively), and two mixtures where CA2 and CA3 were replaced by 10% and 20% of CH (CH10 and CH20) in accordance with their grading curves. Table I presents the mixture proportions of concrete in kg/m^3, as prepared in the Construction Materials Laboratory of the American University of the Middle East.

The water-to-cement ratio was kept constant across all mixtures at 0.5. The aggregates were first mechanically mixed with rubber particles for 1 minute to ensure homogeneity. Cement was then added and mixed for 1 more minute, followed by the gradual addition of water over 2 minutes. Superplasticizer was added at the end. Each mix underwent at least two replications to ensure statistical reliability and robust results. For each batch, 12 cubic specimens of 150x150x150 cm^3 were prepared. After pouring, the specimens were covered with plastic sheet. removed from their molds after 24h, and cured in water at 20 ± 5 ºC according to ASTM C192/C192M [30].

TABLE I. MIXTURE PROPORTIONS PER UNIT VOLUME

Mix Code	FA (kg/m^3)	CA1 (kg/m^3)	CA2 (kg/m^3)	CA3 (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	P (kg/m^3)	CR1 (kg/m^3)	CR2 (kg/m^3)	Chips (kg/m^3)	Superplasticizer (ml)
CM	647	248.3	354.9	509	400	200	0	0	0	0	30
PCR10	538.9	223.3	314.8	509	400	200	19.4	7.76	11.6	0	30
PCR20	477.8	226.4	314.8	509	400	200	38.4	15.36	23.1	0	30
P10	587	248.3	314.8	509	400	200	24.3	0	0	0	30
P20	480	248.3	314.8	509	400	200	54.9	0	0	0	30
CH10	647	248.3	354.9	457.9	400	200	0	0	0	37.5	30
CH20	600	248	252.3	406.8	400	200	0	0	0	75.4	30

C. Methods

1) Slump Test

During the process of mixing and molding, concrete gains workability, allowing it to be poured into various shapes. The slump test was conducted to assess the workability of fresh concrete following ASTM C143/C143M standards [31] (Figure 4 (a)).

2) Mechanical Test

The compressive strength test was carried out according to the ASTM C39/C39M standard [32], using an electromechanical machine at the ages of 7, 14, and 28 days (Figure 4 (b)).

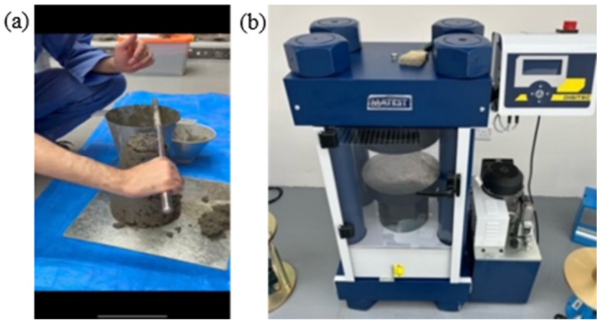

Fig. 4. Methods: (a) Slump test, (b) Mechanical Test.

3) Microstructural Test

SEM was employed to analyze the microstructural changes in concrete resulting from the incorporation of rubber [33]. This technique provided valuable information about the dispersion and impact of rubber particles within the concrete matrix. The SEM test was conducted in collaboration with Kuwait Institute for Scientific Research (KISR). To prepare the sample, a small specimen was collected, dried and polished to a smooth finish. Then, it was coated with a thin layer of gold to ensure compatibility with the high vacuum environment of the SEM. The sample was inserted into the SEM chamber, and key parameters, such as accelerating voltage, and working distance, were adjusted according to the sample's characteristics. Imaging involved selecting an appropriate magnification, optimizing the focus and stigmatism, and capturing images by moving the electron beam across the sample. Various detectors collect specific electrons for the desired contrast.

III. RESULTS AND DISCUSSION

A. Fresh Concrete Properties

Workability is a crucial factor in determining the ease of mixing, transporting, placing, and finishing rubberized concrete. The addition of rubber particles affects the workability due to their surface characteristics and interaction with the cement matrix [15]. The impact of varying sizes and proportions on workability was evaluated using the slump test, and the results are shown in Figure 5. The findings indicate that smaller rubber particles, P and CR, enhance workability at lower substitution rates, while larger particles, CH, notably reduce it.

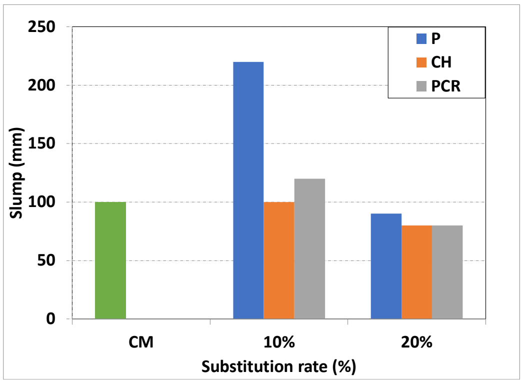

Fig. 5. Slump values in fuction of rubber particles size and substitution rate.

Mixtures with P and CR showed better stability and consistency, with a reduced possibility of segregation and bleeding, compared to mixtures with CH. Medium workability was observed in the CM. At a 10% substitution rate, P resulted in higher slump and improved fluidity compared to CM, possibly due to its smoother texture and larger surface area, allowing for better distribution in the cement matrix. In addition, the finer particle size of P absorbs less water, contributing to improved fluidity [34]. However, at a 20% substitution rate (P20), the slump decreased slightly compared to P10 but remained higher than CM. This suggests that while small amounts of P improve fluidity, higher replacement levels may lead to increased air entrapment and water absorption, negatively affecting workability [15].

A similar pattern was observed for mixtures containing CR. At a 10% replacement, workability was comparable to CM. Increasing the CR content to 20% resulted in a significant reduction in workability. This can be attributed to the rougher texture and larger surface area of CR, which increases the friction between particles and the cement paste. Furthermore, the irregular shapes of CR particles hinder the mixture's flow, while its porous structure absorbs more water, reducing fluidity [34].

The most significant reduction in workability was observed in the mixes containing CH. At both 10% and 20% replacement levels, the slump values were lower than those of CM. Their large size and irregular shape increased the friction coefficient, leading to a dramatic slump loss and poor workability [13]. This effect was further deteriorated by the hydrophobic nature of CH, which hinders bonding with the cement paste and causes segregation. Consequently, heavier cement particles settle while CH rise, leading to an uneven mix [35].

B. Mechanical Properties

1) Compressive Strength Analysis

The compressive strength of all concrete mixes is tested at 7, 14, and 28 days (Figure 6). Concrete gains strength over time due to the hydration process. At 7 days, the concrete is still in the early hydration period and achieves about 60 to 80% of its ultimate compressive strength. At 14 days, this rate increases, while at 28 days, most of the concrete achieves 90 to 100% of its potential strength. Specifically, P10 achieved a 12%

reduction in compressive strength compared to CM, while P20 showed a 25% reduction even though it is easily integrated into the cement matrix. This trend is consistent with previous studies [35, 36]. The mixes incorporating CR (PCR10 and PCR 20) exhibited a notable difference in compressive strength. PCR10 achieved a compressive strength of 34.7 MPa (28 days) slightly lower than CM [2], while the strength of PCR20 decreased to 23.2 MPa, indicating a 36% reduction from the CM. This suggests a threshold beyond which the increase in rubber content leads to excessive voids and a loss of strength [15]. In contrast, the rubber chips mixes presented the most observed reduction in compressive strength. CH10 reached 27.1 MPa (25% reduction), while CH20 reached only 24.8 MPa (31% reduction). This reduction can be attributed to the larger size and irregular shape of the CH, which create weak points in the cement matrix [19].

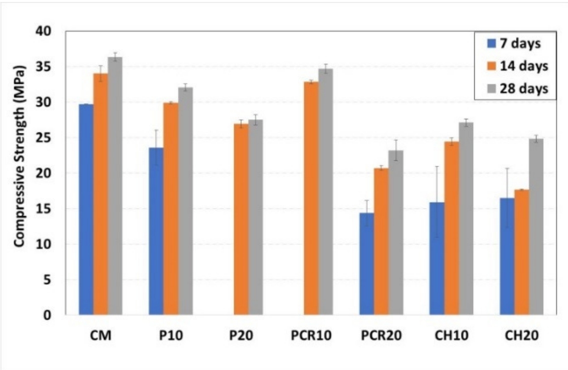

Fig. 6. Compressive strength values for all the mixtures.

These findings indicate that increased rubber content leads to reduced comprehensive strength, primarily due to decreased density and increased porosity. Furthermore, the significant difference in the modulus of elasticity between rubber and the cement matrix aggregates stress concentrations, contributing to crack propagation. The hydrophobic nature of rubber also weakens the bond with the cement paste, leading to inhomogeneities [36].

2) Failure Mode Analysis

Despite reductions in compressive strength, the incorporation of rubber had a positive impact on the failure mode of concrete. The CM exhibited brittle failure with vertical cracks and complete rupture, while rubberized concrete demonstrated a soft failure behavior. After reaching the ultimate load, the specimens showed multi-cracking and continued to carry less load with more strains avoiding complete break. The higher the rubber content was, the greater was the ductility after the first crack. Additionally, an increase in particle size led to a significant improvement in toughness, demonstrating higher fracture energy and the ability of rubberized concrete to absorb energy.

Figure. 7 presents the failure modes after the compression strength test for rubberized concrete cubes with 20% fine powder, and concrete with 10% chips. P20 displayed restricted disintegration compared to CH10. Chips introduced strain gradients due to their lower modulus of elasticity, promoting crack initiation at weak points. However, chip offered a bridging action, enhancing crack resistance and ductility [15].

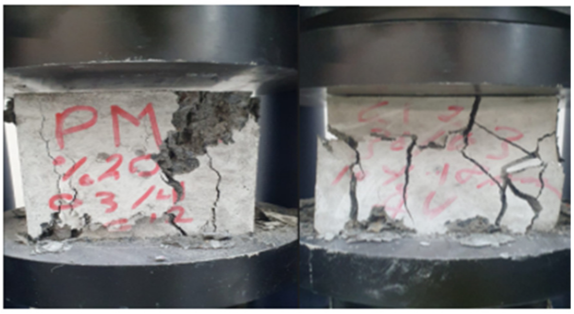

Fig. 7. Failure mode of concrete cubes under compressive test with 20 % powder susbtitution and 10% CH substitution at the age of 28 days.

C. Microstructural Analysis of Rubberized Concrete

Microstructural analysis was performed on two samples: a CM and rubberized concrete (Figure 8).

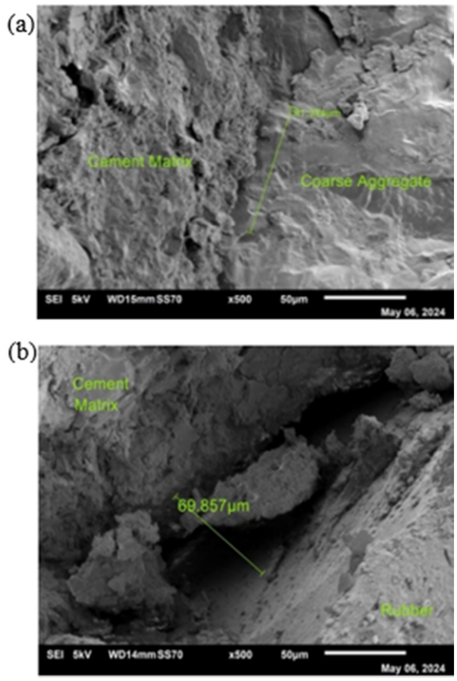

Fig. 8. SEM images at a x500 magnification level: (a) CM and (b) CH10.

1) CM

The SEM imaging of the CM at a magnification of x500 revealed a dense matrix with strong bonding between the cement paste and aggregates (Figure 8(a)). The microstructure seemed stable, with no unfavorable pores, visible cracks or spacing at the ITZ. This finding aligns with the observations of [37], where it was reported that the microstructure of the CM exhibits greater compaction and hydration, resulting in minimal microstructural defects. The dense microstructure of CM contributes to its high compressive strength (36.4 MPa).

2) Rubberized Concrete

The SEM images of rubberized concrete displayed significant microstructural differences compared to CM, particularly at the ITZ, where rubber particles interact with the surrounding cement matrix (Figure 8(b)). Large gaps were obtained between rubber particles and cement paste, indicating poor adhesion at the ITZ, reducing the material's density and strength. These voids act as stress concentrators, facilitating crack initiation and propagation [15, 35, 38]. These microstructural flaws align with the notable decrease in compressive strength seen in these mixtures. Additionally, the contrast in stiffness between rubber and cement results in stress concentrations at the ITZ, ultimately causing premature failure under load [38].

IV. CONCLUSIONS

This study addresses the environmental and health concerns associated with waste tires in Kuwait's Al-Salmy area and waste management challenges by incorporating shredded tires into concrete mixtures. Sustainable concrete was developed by valorizing waste rubber in various forms -powder, crumb rubber, and chips- at substitution rates of 10% and 20%. The findings provide important insights into optimizing rubberized concrete for both practical and structural applications.

- The workability of rubberized concrete is significantly influenced by the size, shape, and content of rubber particles. While smaller particles improve or maintain workability at lower replacement levels, larger rubbers result in a substantial loss of workability due to increased internal friction, water absorption, and segregation.
- The compressive strength test in rubberized concrete indicates that the increase in the rubber content and particle size, generally leads to its further reduction, especially at higher replacement levels due to the extreme inherent difference between the elasticity modulus of rubber and cement matrix.
- The SEM analysis of rubberized concrete reveals that larger sizes lead to significant microstructural defects at the Interfacial Transition Zone (ITZ), including gaps, pores, and microcracks.
- Despite these challenges, rubberized concrete demonstrates improved flexibility, toughness, and energy absorption making it a viable, eco-friendly alternative in construction, contributing to waste reduction and sustainability.

Future research will focus on optimizing mix designs and investigating alternative treatment methods for rubber particles, long-term durability of rubberized concrete, and evaluating other characteristics, such as energy absorption and thermal conductivity with a complete life cycle assessment. Artificial intelligence will be also employed to develop predictive models for optimizing rubber particle size distributions, and forecasting mechanical properties based on mix design parameters.

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