Research Article

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Assessment of cement replacement with fine recycled rubber particles in sustainable cementitious composites

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Abstract: Egypt plays an important role in the consuming markets for tires all over the world. There is an urgent need to get rid of them in an economic and environmental way since it is considered as a harmful waste if burnt. The World trend is directed towards the improvement of new techniques to insert the rubber into useful products to maximize the benefit of recycling. This research deals with the expansion of novel techniques for rubber powder recycling for various purposes in a robust construction. Recycled rubber particles (RRP) are mixed with ordinary Portland cement (OPC) using various water to binder ratio (W/B) at 0.3 and 0.4. The Fourier transform – infrared (FT-IR) spectra is measured for RRP. The compressive strength (C.S) is investigated for the rubberized cement pastes at 1, 3, 7, 14 and 28 days. The results aimed to enhance the compressive strength of rubberized cement pastes through improving the bonding strength between RRP and OPC by using fine particles of RRP. Maintaining the compressive strength in the highest levels with different RRP percentages in addition to the vibrational damping property of RRP gives rubberized cement pastes the advantage to replace ordinary concrete in most construction applications.

Keywords: rubber particles, waste management, cement paste, mechanical properties, cement composites

1 Introduction

Sustainable development and environmental conservation became essential priorities of modern society at the end of the twentieth century. Civil engineering, especially the construction materials industry, plays a critical role in building sustainability, pollution reduction, natural resource conservation, and energy conservation. In this context, the primary issues confronting the construction materials industry are primarily linked to high OPC usage and associated high carbon dioxide emissions [1]. Regarding the first point, concrete has been for decades the commonly used material for construction in the world, and the global production of concrete has reached a value of more than 1 ton of concrete per person on the planet. Overall, the cement companies are producing nearly 3 billion tons/year [2]. This led to the emission of almost 2 billion tons of CO₂ (6–7% of global emissions from CO₂) in the process [3, 4, 5, 6, 7]. Several studies have described the enhancement of process efficiency and the increase in usage of different waste materials as a cement substitute as ways to mitigate the greenhouse effect of cement production. According to a recently announced TechSci report, the tire marketplace in Egypt is anticipated to cross USD 1 billion through 2020. Egypt's automotive marketplace is one of the conspicuous markets in the African mainland because of its huge marketplace size and its geological area which spans Asia. Arab Republic of Egypt was the 3rd biggest vehicle creating the marketplace in Africa, after Morocco and South Africa in 2013. Arab Republic of Egypt produces 20 million waste tires/year and barely 10% of those are recycled [8]. Because of their three-dimensional crosslinked structure, which makes them non-biodegradable, used tyres pose a significant challenge for developed countries around the world in terms of use and disposal [9].

The most noticeable hazard accompanying with the abandoned disposal and buildup of a bulky number of tires is the motivator for huge fires, a fact tremendously harmful to the environment [10, 11, 12, 13]. Because of the environmental concerns associated with the global disposal of

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these tyres, there is a growing interest in tyre rubber recycling for economic reasons [14, 15, 16]. The rubber in tires is vulcanized and cannot be melted or dissolved, which makes recycling challenging [17, 18]. As a result, a huge number of used, worn-out tires are ground for the benefits of expanding their applications [19, 20]. Outdoor flooring and pavements, sports tracks, road building, and other applications including ground or powdered tire rubber fell into the sectors with minimal demand and added value. Rubber components have been used as a basic part of the structure in a variety of building industries. This material has been used as an acoustic absorber in concert hall buildings, bridges (buffer), waterproofing, and road filling, among other applications [21]. Research to date on the replacement of aggregates by discarded tire rubber is known as “Rubcrete”. Rubcrete has provided contradictory findings. Some properties are boosted in Rubcrete in comparison to concrete, including ductility, damping ratio, energy dissipation, toughness, and impact resistance [22, 23]. The modulus of elasticity, compressive and tensile strength, on the other hand, are limited. [24, 25].

Owing to the differences in chemical composition and physical properties of admixtures such as silica fume, fly ash, marble dust and rubber particles, they have diverse effects on the durability, mechanical, physico-chemical and rheological properties on concrete matrix [26]. Although there are many ways to recycle tyres, recent research in the structural materials field has concentrated on using crumb rubber from recycled tyres as a partial substitute for coarse aggregates [27, 28]. It is determined that a waste material like worn-out tires may enhance the basic properties of concrete. The data presented in this research showed that there is great potential for the utilization of tires as aggregates. Used tyres were thought to provide much more potential for value-adding and cost recovery because they could be used to substitute more costly materials like rock aggregates [29].

Rubber has the potential to become a permanent member of the concrete family due to a wide range of desirable properties such as flexibility, light weight, and ease of availability. Using rubber aggregates decreased the workability of the resultant mix, but this problematic issue can be dealt with the usage of certain plasticizers [30]. The impact of partial replacement of coarse aggregates in concrete is studied by untreated tire rubber aggregates. Rubber aggregates have a lower specific gravity and bulk density than natural coarse aggregates, according to research. When the use of rubber granules in concrete is increased, the density of the concrete decreases. Correspondingly, lightweight concrete was acquired which assists to decrease the weight of the structure.

Using rubber aggregates in concrete, resulting in decreasing the compressive strength but increasing toughness of concrete. It was discovered that the optimal percentage of rubber aggregate replacement can be up to 15%. It was discovered that this form of concrete could not be used in structural elements requiring high strength. However, it is possible using it in further construction essentials like pavements, road barriers, partition walls, sidewalks, etc. which have huge demand in construction industries [31]. As fine aggregates are replaced with crumb rubber, the properties of concrete are tested. With a marginal increase in concrete workability, up to 15% of fine aggregates can be covered with an equivalent amount of crumb rubber, according to the findings. The compressive strength of the rubcrete contained 15% crumb rubber was increased by over 5%. The splitting tensile strength reduced as the amount of crumbed rubber increased, and the modulus of rupture dropped by an average of 12%. Rubberized concrete, conversely, showed increased strain at failure, strong energy absorption, better modulus of hardness, and ductility in the absence of any typical concrete brittle failure [32].

The partial effect of crumb tyre particle size as a fine aggregate substitute on compressive strength and time-dependent deformations of structural concrete is investigated. Rubcrete had lower compressive strength than the control concrete mix for all crumb rubber sizes, according to preliminary time-dependent and compressive performance. Concrete strength is affected by crumb rubber size; as crumb rubber gets smaller, compressive strength decreases [33]. As mentioned before most of the research papers used rubber particles in form of fine or coarse aggregates in some cases it was used as an additive in concrete application but was limited to be used as a replacement of cement percentage in a mix design. The novelty of this work is studying the impact of partial replacement of cement by fine recycled rubber particles (RRP) on compressive strength of different hardened cement pastes at different water to binder ratios (W/B ratio = 0.3 and 0.4). This was coupled with an extensive ESEM micrographs study.

2 Experimental work

2.1 Raw materials and characterization

The materials used in sample preparation were: (i) Ordinary Portland Cement (OPC) (Type 42.5N) was provided by Torah Co., Helwan, Egypt and (ii) the as-received recycled rubber particles (RRP) was delivered from Egypt local market

which extracted from car tires by grinding then sieving. The chemical composition of OPC was determined by elemental analysis using wavelength dispersive X-Ray Spectrometry (standardless) as shown in Table 1.

FTIR test was performed for RRP to identify the functional groups and the chemical bonds on its surface by PerkinElmer instruments spectrum one. As Figure 1 indicates, the various transmittance peaks observed in the spectrum are related to the specific functional groups, stretching vibration band of C-H bond at $2820\text{--}2970\text{ cm}^{-1}$ and C=C at $1540\text{--}1690\text{ cm}^{-1}$. Also, at $960\text{--}1190\text{ cm}^{-1}$, the peak related to C-S bond resulted from the presence of sulfur which is used in the vulcanization process of rubber.

Figure 1: FTIR spectra for Recycled Rubber particles (RRP).

Particle Size Distribution tests (PSD) for both OPC and RRP were performed by laser diffraction technique using volume-based results of Malvern Mastersizer 2000 (Dry method). As shown in Figure 2, the volume-weighted Mean of the OPC and RRP are $55.9\text{ }\mu\text{m}$ and $944.5\text{ }\mu\text{m}$ respectively.

2.2 Preparation of samples

2.2.1 Dry mixing

Firstly, OPC and RRP at different weight ratios (100/0, 95/5, 85/15, and 75/25 OPC/RRP) were carefully dry blended using mechanical stirring for 30 min, to assure complete homogeneity,

2.2.2 Preparation of cement paste

The different cement pastes were made by mixing the rubberized cement with tap water. The water consistency of each paste should be at a reasonable level to get the optimum fresh and hardened properties. This means the amount of water should be enough to make complete hydration with cement and give the highest compressive strength.

Figure 2: Particle size distribution for a) OPC b) RRP.

Each paste was stirred continuously for three minutes by an electric mixer and assuring the homogeneity of the mixture by visual inspection. The dosage of recycled rubber particles (RRP) was 0 %, 5%, 15%, 25% by the weight of cement.

The resulting mixes were designated as shown in Table 2. The control samples are C-0.3 and C-0.4 for the cement pastes free from the RRP mixed at different W/B ratios 0.3 and 0.4 respectively. The rubberized cement mixtures are defined as “R5-0.3, R15-0.3, and R25-0.3” for the cement pastes containing 5, 15, and 25% by weight of cement and W/B = 0.3 and also in the same way for W/B = 0.4.

2.2.3 Molding

The pastes were molded immediately after the mixing was finished in 2” inches or 50 mm cubic steel mold according to ASTM Designation: C-109/C 109M-07 [34]. Each cube was filled gradually then compacted using a mechanically vi-

Table 1: OPC chemical element analysis.

Constituents	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃ ^{tot.}	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	MnO	Cl	LOI
Constituents (wt %)	13.4	0.46	2.95	4.08	1.57	64.2	0.574	0.275	0.191	0.075	0.202	5.01

Table 2: Mix design of the prepared rubberized cement mixtures.

Sample	W/B ratio	OPC (gm)	wt. RRP (gm)	wt. Water (gm)
C-0.3	0.3	3250	0	975
R5-0.3	0.3	3087.5	162.5	975
R15-0.3	0.3	2762.5	487.5	975
R25-0.3	0.3	2437.5	812.5	975
C-0.4	0.4	3250	0	1300
R5-0.4	0.4	3087.5	162.5	1300
R25-0.4	0.4	2437.5	812.5	1300

brating machine for two minutes to remove any air bubbles to achieve better impaction of the paste.

2.2.4 Curing

According to BS EN 4551-1 [35], the mold was cured in a humid chamber during the first 24 hours at room temperature and then de-molded. The de-molded cubes were immersed in a container filled with tap water for the required curing periods of 1, 3, 7, 14, and 28 days.

2.3 Methods of investigation

2.3.1 Mechanical testing

Compressive strength measurements were carried out on the hardened cement paste using 30 Ton compressive machine manufactured by Lloyd Instruments Ltd, United Kingdom. Three cubes were tested for compressive strength measurements at the various ages of hydration 1, 3, 7, 14, and 28 days and for different W/B ratios at 0.3 and 0.4.

2.3.2 Termination of hydration

Following the compressive strength determination, the hydration of pastes was terminated on the crushed paste cube. This procedure was carried out by rinsing about 20 grams of ground cement pastes from the center of the specimen for at least 1 hour with approximately 150 ml of a 1:1 by

volume mixture of methanol and acetone using a magnetic stirrer, followed by decantation and filtration of the solvent mixture. Finally, the sample was dried in the drier for an overnight period at 80°C to extract moisture [36].

2.3.3 ESEM study

Using Environmental Scanning Electron Microscopy (ESEM), the morphology and microstructure of different hardened cement pastes (0 percent and 25% RRP by weight of cement) prepared with 2 various W/B ratios (0.3 and 0.4) at 28 days curing time were investigated (ESEM). A Quanta FEG 250 scanning electron microscope (FEI Company, USA) was used to capture surface images at the EDRC, DRC, Cairo. ESEM stubs were used to install the samples. The ESEM conditions used were a 10.1 mm working distance and a 20 kV excitation voltage in the in-lens detector.

3 Results and discussion

3.1 Compression behavior of rubberized cement paste

The hydration process after one day is characterized by two stages as shown in Figure 3. The first stage has a sharp increase in strength due to the presence of pores that can accumulate the formed hydration products. This stage was followed by a slight increase in the strength due to the limited pores available for new hydration precipitates.

Generally, it is observed that the compressive strength increases with increasing curing time as shown in Figure 3, Figure 4 and Table 3 and also the percentage of reduction (% R) in compressive strength for all developed pastes has been calculated. This is mostly due to the growth in the amount of calcium silicate hydrates “CSH” and calcium aluminate hydrate (CAH) which accumulated in the open pores resulting a reduction in the porosity of the pastes [37].

Also, it is indicated that the rate of hydration of the Rubberized cement pastes is lower than the control sample. This is attributed to the dilution of cement by RRP which results in decreasing the amount of CSH responsible for gaining strength.

Table 3: Compressive strength (MPa) of the control and Rubberized cement mixtures samples.

Curing Days	Control		Rubberized							
	C-0.3	C-0.4	R5-0.3	% R	R15-0.3	% R	R25-0.3	% R	R25-0.4	% R
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	6.6	5.7	5.5	16.7 %	2.1	68.2 %	1.4	78.8 %	0.4	93.0 %
3	26.9	7.7	17.6	34.6 %	8.4	68.8 %	4.0	85.1 %	2.0	74.0 %
7	40.9	17.3	24.1	41.1 %	9.2	77.5 %	5.9	85.6 %	4.0	76.9 %
14	44.5	19.0	31.2	29.9 %	11.6	73.9 %	5.0	88.8 %	3.0	84.2 %
28	47.8	25.4	33.2	30.5 %	14.2	70.3 %	7.1	85.1 %	4.5	82.3 %

Figure 3: Compressive strength of the hardened cement pastes containing different percentages of RRP at W/B = 0.3 versus curing times.

Figure 4: Effect of W/B ratio on the compressive strength of hardened cement pastes.

As graphically represented in Figure 4, In the case of control and 25% RRP replacement, raising the W/B ratio from 0.3 to 0.4 decreases compressive strength by 46.9% and 36.2 % respectively. This is due to the fact that as the W/B ratio rises, the initial porosity rises, followed by a decrease in compressive strength.

Interestingly, in the case of R25-0.3 and R25-0.4 the specimen gains about 83% of its full strength at the first stage of hydration up to 7 days rather than gaining only about 17% at the later stage. This means that most of the unreacted cement is already hydrated in the first stage due to further dilution as illustrated above. The essence and physical condition of the hydration products produced within the pore system of hardened cement pastes appear to influence the strength results; this achievement will receive further support from the results of the microstructure of the formed hydrates as will be discussed later in this investigation.

3.2 Environmental scanning electron microscope (ESEM)

The control and rubberized cement pastes' ESEM micrographs are shown in Figure 5(a–d) obtained after 28 days of hydration. The development of both fibrous crystals and microcrystalline of cement hydration materials, mostly CSH, CH, and CAH was visible in the micrographs for the pastes [38, 39]. These hydrates form around and between the cement grains, forming obvious binders between the partially hydrated cement grains. The established hydrates had a denser structure that could be clearly seen in C-0.3 than C-0.4, as a high W/B ratio leads to high porosity then lower strength. The role of RRP as a filler appears clearly in the case of R25-0.3 and R25-0.4 micrographs. The high reduction in the strength by 25 Wt. % RRP replacement resulted from decreasing the amount of hydration product and the agglomeration of RRP as illustrated in Figure 5(b and d).

Figure 5: ESEM micrographs for hardened mixtures after 28 days: a) C-0.3 b) R25-0.3 c) C-0.4 d) R25-0.4.

4 Conclusion

It is concluded that the cement replacement with RRP causes deterioration in the strength. However, the new rubberized cement mixture (R5-0.3) can be used in different applications instead of cement type 32.5N. The initial porosity decreases as the W/B ratio decreases, followed by an increase in compressive strength. Utilizing non-biodegradable and recycled materials like rubber could be used as a cement replacement. Thus, a new approach is developed to produce a sustainable building material that might be useful in some industrial applications such as solid and hollow cement blocks, interlock paves and plastering layer.

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