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Evaluating the Morphology and Physicomechanical Properties of 'Green' Cement Paste with Fine Rubber Particles

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Abstract. The major goal of this research is to develop a green cementitious composite that may be utilized in practical construction applications using waste fine rubber particles (WRP). WRPs are generated from grinding waste tire rubber as a partial replacement for ordinary Portland cement (OPC). OPC/WRP were blended with the ratios of 100/0, 95/5, 85/15, and 75/25 weight%, then mixed with water. The Physicomechanical properties: workability, compressive strength, morphology, and microstructure of the hardened composites were measured after 28-days of hydration. A mechanism of the workability of rubberized cement composite was suggested.With changing properties closer to a light-weight material and with decreasing compressive strength upon waste rubber addition, the results direct the possible applications towards plastering.

Keywords: ordinary Portland cement (OPC), Physicomechanical properties, waste fine rubber particles (WRP), green cement.

1. Introduction

In an effort to ensure climate resilience through climate action, the National Committee for Climate Change was activated in 2007 at the Egyptian Ministry of Environment to develop mitigation and adaptation strategies for sectors and ministries concerned. A lot of research [1] related to environmental impact on all fronts has started since and Egypt has lately announced to host the 27th session of the Conference of the Parties (COP 27) to the UN Climate Change Conference 2022 UNFCCC[2].

Heavily-polluting construction materials are among the biggest drivers of Egypt's CO_2 emissions, with cement among the top polluters [3-7]. The use of 'green' cement (as per definition of "green" may include using low-carbon production processes and recycling industrial waste), is anticipated as the future for the cementitious construction industry.

In Egypt, waste tire rubber is one of the most hazardous materials disposed of in landfills, which litter the landscape and provide a severe fire threat once ignited, emitting hazardous chemicals. Through soil, water, and air pollution, stored tires pose a number of environmental, economic, and health problems. Every year, Egypt produces 20 million trash tires. The volume of old tires is becoming a serious concern for waste management as manufacturing increases and disposal choices decrease[8].

Several Researchers utilized Rubber Particles obtained by crushing waste rubber tires in developing new polymeric composite materials[4, 9-12]. The crumbed tire rubber particles are sieved, segregated, and used to partially replace coarse aggregates [13] or fine aggregates [14] in concrete [15] and mortar [16]. In confident cases, powder or ash was ground and sieved from tire granules, which can be used as cement replacement [17, 18]. Rubber fibers are also used as a partial replacement for mineral aggregates [19]. The crumbed rubber applications in concrete were classified according to various sizes, 1–6 mm as a fine aggregate while 6–19 mm as a coarse aggregate[20]. Fernández-Ruiz M.A. and Gil-Martín L.M. characterized the mechanical behavior of concrete in which the cement was replaced by 5 and 15% ground tire rubber (GTR). It was concluded that GTR reduced the durability, mechanical properties such as compressive strength, and flexural strength. Nevertheless, it gave a good energy dissipation in the quasi-static reversed cyclic loading test [18, 21]. Wang Y. incorporated fiber scrap tire rubber (FSTR) into cement paste (FSTR-

CP) to investigate its performance against the fresh and hardened properties. The results revealed that the FSTR-CP has a lower density, acceptable workability, and higher ductility[22].

Generally, workability is an essential parameter for binding material to show its availability in mixing, casting, transportation, and consolidation processes. The workability of paste, mortar, and concrete can be measured by different techniques such as mini-slump test, one of the most important and simplest tests, Here, the workability of cement paste can be evaluated by measuring the spread area (pancake diameter), the widespread area means high workable paste, and vice versa. Generally, when the rubber content increased, the slump value decreased due to its irregular shape, degree of fineness. Bleeding was not observed the in concrete because fine rubber absorbed more water than sand [23, 24]

In this paper, the potential of fine waste crumbed rubber to improve the Physicomechanical performance of rubberized cement composites is demonstrated. These mixtures resemble low density mixtures compared to the traditional ones. This work paves the way to many important possible applications with this material being light-weight as well as providing a light sound barrier to decrease noise transmission in urban or residential environments. The results have the potential to be combined into the interior and exterior plastering layers in building systems.

2. Materials and Experimental work

2.1 Materials

The materials appropriated in this framework were: (i) Ordinary Portland cement (OPC; type:42.5N), which was supplied from Torah Company, Helwan, Egypt and (ii) waste fine rubber particles (WRP) delivered from the local market, Egypt.

2.2 Experimental work

2.2.1 Chemical composition

X-ray fluorescence (XRF: Xios, model PW-1400) was utilized to identify the oxide composition of OPC.

2.2.2 Particle size distribution

Particle size distribution (PSD) was performed by Malvern Mastersizer 2000 (Dry method).

2.2.3 Preparation of cement paste specimens

Four dry blended powders (DBP) of 3250 gm namely C-0.3, RCP5-0.3, RCP15-0.3, and RCP25-0.3 were prepared by replacing OPC with different percentages of WRP (0, 5, 15, and 25% by weight of OPC respectively) in a ball mill for 1 hour to achieve high homogeneity and the mix design of the prepared samples was clarified in Table 1. By combining the dry-blended mixture with tap water, several cement pastes were created. An electric mixer was used to stir each paste continuously for three minutes, with visual examination to ensure homogeneity and no agglomeration occurred. The control sample is C-0.3, which is made up of cement pastes that are free of WRP. For cement pastes having 5, 15, and 25% by weight of cement, the rubberized cement mixtures are specified as "RCP 5-0.3, RCP 15-0.3, and RCP 25-0.3." respectively, as shown in Table 1. All mixtures are blended at a constant W/B ratio of 0.3, with a constant water content of 974 gm.

Table 1 Prepared rubberized cement mixtures

Sample	C-0.3	RCP 5-0.3	RCP 15-0.3	RCP 25-0.3
OPC Wt. (gm)	3250	3087.5	2762.5	2437.5
WRP Wt. (gm)	0	162.5	487.5	812.5

2.2.4 Mini slump test

The effect of different doses from WRP (0, 5, 15, and 25%) on the workability of cement paste was determined using the mini-slump test according to ASTM C1611 as shown in Figure 1. The fresh paste was poured into Abram’s truncated conical cone, which has 19 mm top diameter, 38 mm bottom diameter, and 57 mm highest. The cone was removed vertically, and the spread diameter was measured in two perpendicular directions. A high W/DBP ratio is used to give a remarkable difference in the spread area between pastes.

Figure 1 the mini-slump cone

2.2.5 Compression test

After the mixing process, the pastes were molded in a 50 mm cubic mold followed by curing in 99 % relative humidity at 23 ± 2°C overnight. The hardened specimens were de-molded then the curing process was completed under tap water till the time of testing. Mechanical compressive test performed at 28-days of hydration under uniaxial strain rate is shown in Figure 2 on a set of three cubes of hardened specimens. The compressive strength was measured by using Lloyd universal testing machine (30 ton) according to ASTM: C-109/C 109M-07[25]. The mechanical behavior of the developed composites investigated at constant strain rate = 0.5 mm/min.

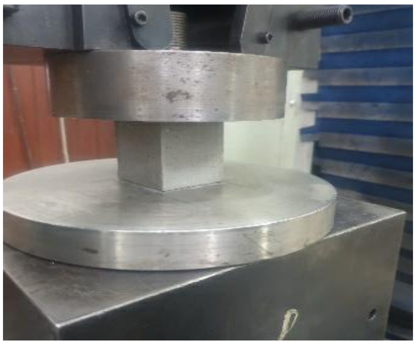

Figure 2 *Compression test for test specimen using Universal Testing M/C*

3. Results and Discussions

3.1 XRF analysis

The OPC constituents Wt.% are SiO_2, 13.4; TiO_2, 0.46; Al_2O_3, 2.95;Fe_2O_3,4.08; MgO, 1.57; CaO, 64.2;Na_2O ,0.574; K_2O, 0.275; P_2O_5, 0.191; MnO, 0.075; Cl, 0.202; loss on ignition, 5.01. The ratio of silica (SiO_2) to alumina (Al_2O_3) In a good grade cement should be between 2.5 to 4 and the ratio of Calcium oxide (CaO) to the total oxides of silicon, aluminum, iron (SiO_2+Al_2O_3+Fe_2O_3) should be close to 2. The average composition of OPC is CaO, 50-60%; SiO_2, 20-25%; Al_2O_3, 5-10%; MgO, 2-3%; Fe_2O_3, 1-2%.

3.2 Particle size distribution analysis

The particle size of OPC grains was measured, with a d_{50} of 55.9 µm while the particle size of waste rubber particles was largerwith a d_{50} of 944.5 µm.

3.3 Mini slump analysis

The workability of the fresh pastes that contain different percentages from WRP has been expressed by the calculated spread area as shown in Figure 3 a, b. The spread area of different pastes with various rubber doses (0,5,15, and 25%) was represented in

Figure 3c. It is clarified that as the doses of WRP increase, the spread area decreases. The reduction in the spread area of rubberized cement pastes with 5, 15, and 25% WRP w.r.t control (0% WRP) is 4.94, 11.32, and 40.8% respectively.

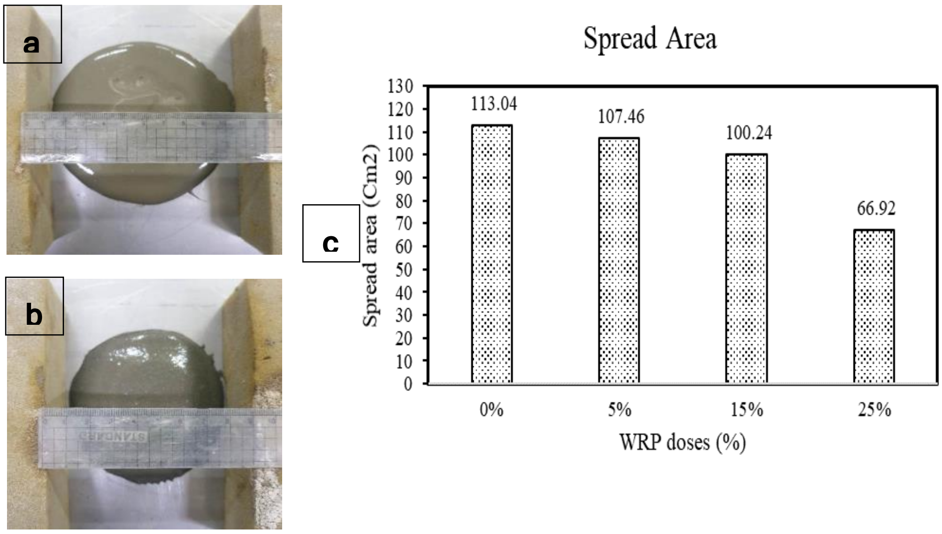

Figure 3 the workability of the fresh paste a) Spread diameter of Control sample (C-0.3) b) Spread diameter of RCP25-0.3 c) the workability of the specimens using mini-slump

The reduction in the spread area may be due to the rougher surface and higher friction coefficient of WRPs than OPC particles that cause higher flow resistance. The size of particles is the main reason behind the high roughness of WRPs: as the fineness of WRP increases, the surface roughness increases.

On a flowability basis, the fresh paste needs high free water content to be workable for a long time. The presence of a high amount of very fine rubber which has a high surface area leads to high free water adsorption. The reduction in spread area values is considered acceptable for the application that doesn't need high workability or flowability as a plastering layer.

The schematic drawing, as shown in Figure 4, illustrates the phenomenon of decreasing the workability or flowability of rubberized cement paste (RCP) with increasing the WRP doses. It also explains the effect of the surface charges and their role on the formation of the attractive forces between the cement particles and WRP particles and the repulsive forces between WRPs and itself to form the air voids in the fresh rubberized cement paste. This phenomenon may lead to an increase in the frictional forces between the layers of RCP and obstruct the slipping of the layers on each other which results in decreasing the flowability of the fresh rubberized cement paste.

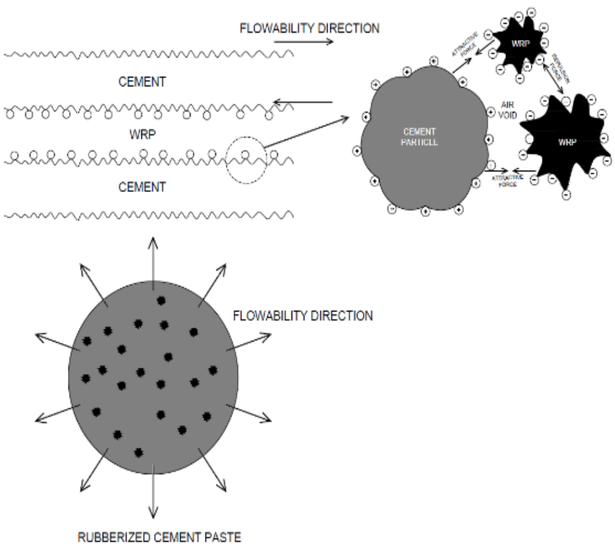

Figure 4 Schematic on the effect of surface charges on the flowability of rubberized cement paste

3.4 *Mechanical behavior of the rubberized cement composites*

The compressive stress-strain curve of rubberized cement mixtures under uniaxial strain rate is shown in Figure 5. The stress-strain behavior of RCPs has been dominated by the WRP dosages in which the maximum compressive strength was dramatically decreased as the WRP dosages increased. The compressive strength of RCP5-0.3, RCP15-0.3 RCP25-0.3 decreased by 30.5, 70.29, and 85.15% compared to C-0.3.The decrease in mechanical strength is related the increase in rubber doses on the expense of the main binding material (cement) where the WRP has low compressive strength.

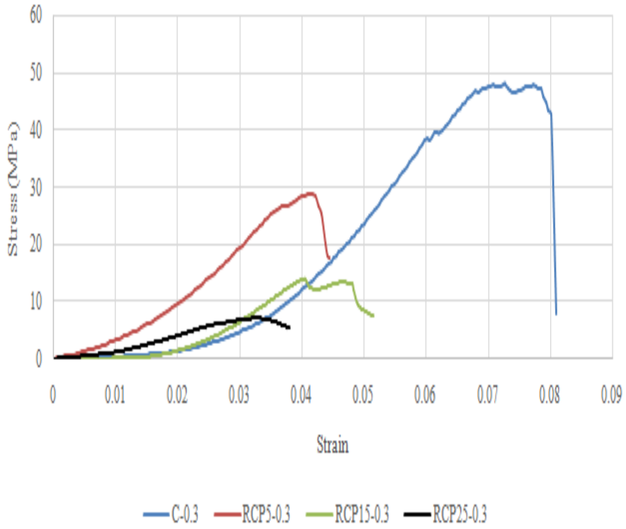

Figure 5 Compressive strength behavior of the developed RCPs at 28 days

Based on the stress-strain behavior at 28 days, some of the mechanical characteristics of developed RCPs have been investigated as shown in Table 2 at constant uniaxial strain rate = 0.5 mm/min such as toughness, modulus of elasticity, strain at failure, and compressive strength. Compared to the control sample (C-0.3): The toughness of RCP5-0.3, RCP15-0.3, and RCP25-0.3 decreased by 63.86, 83.56, and 92.87 %, respectively. The modulus of elasticity of RCP5-0.3, RCP15-0.3, and RCP25-0.3 decreased by 20.43, 36.56, and 68.82 %, respectively. The strain at failure of RCP5-0.3, RCP15-0.3, and RCP25-0.3 decreased by 46.83, 39.24, and 51.9 %, respectively. The compressive strength of RCP5-0.3, RCP15-0.3, and RCP25-0.3 decreased by 39.41, 70.62, and 85.15 %, respectively.

Table 2 Mechanical characteristics of developed rubberized cement composites at 28 days

C/CS Sample	Toughness (MJ/m^3)	Modulus of Elasticity (GP_a)	Strain at failure	Compressive strength (MP_a)
C-0.3	1.685	0.93	0.079	47.80
RCP5-0.3	0.609	0.74	0.042	28.96
RCP15-0.3	0.277	0.59	0.048	14.04
RCP25-0.3	0.120	0.29	0.038	7.10

3.5 *The morphology and microstructure of the rubberized cement composites*

The morphology and microstructure of the hardened blended cement pastes (RCP5-0.3 and RCP25-0.3) are shown in Figure 6 and Figure 7 obtained after 1, 7, and 28 days, respectively. All micrographs are on the same magnification scale 3000x(40µm). During the early age of hydration (1day), the ESEM micrographs displayed the formation of ill-crystalline hydrates; these hydrates (mainly as Calcium silicate Hydrate (CSH), Calcium Aluminate Hydrate (CAH) and ettringite) are shown with small hexagonal crystals of Calcium Hydroxide (CH). The quantities of both amorphous and microcrystalline hydrates increased with increasing ages of hydration from 1 to 28 days. Later at 7 days (Figure 6 and Figure 7 (b)) and at 28 days (Figure 6 and Figure 7 (c)), the

ESEM micrographs showed the formation of a dense structure of almost nearly amorphous hydrates within the limited pore system of the hardened paste.

These ESEM micrographs displayed a less dense structure caused by the strong cement dilution by WRP that resulted in decreasing the amount of hydration products that are responsible for filling the pores. Evidently, when WRP replaced the cement, it led to decreasing the porosity [26] due to its filling effect. These results are compatible with the Physicomechanical properties of obtained pastes, partial cement replacement with WRP caused noticed reduction in the compressive strength of the RCPs.

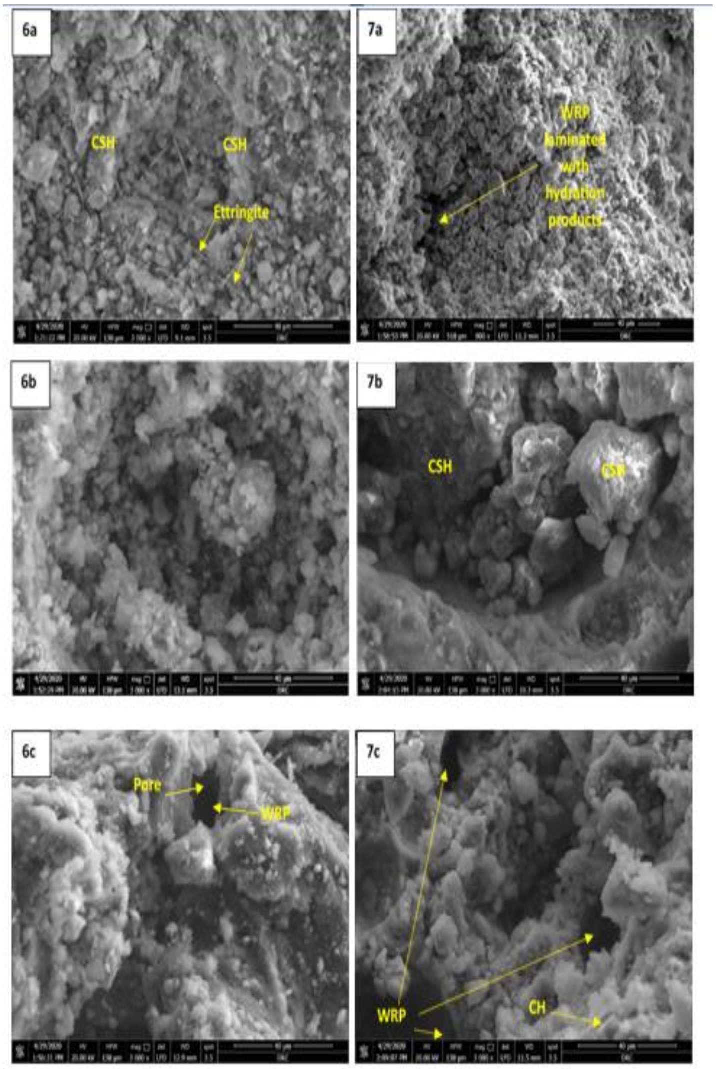

Figure 6 Morphology and microstructure of the hardened5% rubber addition cement paste at various ages of hydration (6a) 1 day, (6b) 7 day and (6c) 28 days

Figure 7 Morphology and microstructure of the hardened 25% rubber addition cement paste at various ages of hydration (7a) 1 day, (7b) 7 day and (7c) 28 days

Conclusion

In line with the Egyptian environmental movement, this paper presents a study of the effect of embedding waste rubber particles into cement on the properties of the new green cementitious composites. The following conclusions can be made:

- Increasing the doses of WRP led to a decrease in the workability of fresh cement pastes. The spread area decreased by 4.94, 11.32, and 40.8% when the cement was replaced by 5, 15, and 25% respectively.
- The compressive strength RCP5-0.3, RCP15-0.3 RCP25-0.3 decreased by 30.5, 70.29, and 85.15% compared to C-0.3 under uniaxial compression loading.
- The ESEM micrographs displayed a less dense structure for rubberized cement pastes caused by the strong cement dilution by WRP.
- As an outlook, the suggested formula can be used as light-weight material with many useful plastering properties.

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