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Early and long-term performance of green mortar made from the waste of electrical cables

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Abstract. The disposal of solid waste has become one of the critical issues facing governments due to its environmental impact due to the difficulty of its decomposition. Electric cable waste (ECW) is one of these wastes. Its production increased in Iraq over time due to the demolition and reconstruction of residential and commercial homes. Therefore, reusing it in other industries, such as concrete technology, is a promising solution. Limited studies have studied the utilization of these local wastes as a replacement for natural sand in the short and long term. Therefore, the aim of this study is to investigate the properties of mortar incorporating recycled ECW as a partial replacement for sand. The fine aggregate (natural sand) was replaced by weight with ECW ranging from 0 to 25 % in the step of 5 %. Flow rate, as well as mechanical properties (compressive strength, flexural strengths, and density), were executed at 7, 28, and 360 days. It was found that the best performance was obtained at a replacement ratio of 5 % of ECW with mechanical strengths close to or slightly less than the reference sample and a 17 % reduction in density. However, regarding sustainability, it is possible to produce a lightweight structural mortar with a density lower than 1700 kg/m^3 and a compressive strength of 36 MPa at 360 days when replacing the natural sand with 25 % ECW.

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1. *Introduction*

Pollution is one of the great challenges that face humans. For that, researchers are looking for an eco-friendly solution to withstand serious problems, such as accumulating waste and non-biodegradability in addition to maintaining (natural) resources from consumption [1–5]. Recently, the world's growth and the development of electrical waste are as well-developed along one side. Electrical waste includes different materials, such as copper, aluminum, lead, iron, and plastic. The waste will react to produce a chemical toxic, which leads to spoiling human health and affects adversely the environment. The reuse of electrical cable waste (ECW) as a full or partial replacement for building substances is one of the promising solutions [6]. Plastics have wide-ranging applications, such as construction, packaging, healthcare applications, transportation, and electrical/electronic materials. Polyvinyl Chloride commonly (PVC) wire insulations are acquired from scrap vendors [7].

It is supposed that the reuse of the solid residue in concrete technology leads to less environmental damage and less demand for landfills on the one hand, as well as converting it into valuable materials on the other hand [8, 9]. Many previous works have used this plastic waste in concrete technology. For example, Lakshmi and Nagan [10] examined the concrete compressive strength in the existence of electronic plastics. The compressive strength declined by 2.59 % when using 1 % 5 cm waste plastic. In contrast, the compressive strength increased from 6 to 11 % when the volume of waste plastic was reduced to 3 cm. Tensile strength was also improved by 4.5 % when embedding 3 cm of waste plastic compared to 5 cm. Raghatate Atul [11] reported that by incorporating waste e-plastics into concrete, mechanical properties were improved and the compressive strength was boosted by up to 20 %. However, the splitting tensile strength showed a marginal increase of 0.8 % after a 20 % substitution. Gull and Balasubramanian [12] explored the ability to use waste plastics (insulation wire) as fibers after shredding them into defined shapes with a size range of 3–5 cm. Samples were treated for 7, 14, and 28 days. The results revealed that at 1% e-plastic, the compressive strength increased by 5.9 and 10.6 % after using 4 and 3 cm sizes of waste plastic, respectively. In contrast, the reduction was 2.59 % with a size of 5 cm. However, at the same percentage addition, the tensile strength improved by 2.3 % for 5 cm of e-plastic and increased by 4.6 % for 4 cm in 28 days. Grinys et al. [13] investigated concrete's mechanical, fracture, and microstructural properties containing 5 % ECW. Bulk density reduced 6.1–6.3 % in 5–10 % of waste electrical cables compared to conventional concrete.

Manjunath [14] investigated the ability to use electrical waste in concrete as fine and coarse aggregate with different replacement ratios: 0, 10, 20, and 30 %. Results showed that the compressive strength of 10 % e-plastic gave an improved performance. In contrast, by increasing the proportion of the e-plastic content of coarse aggregate to 20 %, the concrete's mechanical properties (compression, tensile, and flexural strengths) showed a decrease related to the reference mixture. The mechanical characteristics of the concrete were reduced when the e-plastic was used as a fine aggregate throughout the curing stages. Yildirim and Duygun [15] studied the effect of Waste Electric Cable Rubber (WECR), in which sand replaces concrete at 5, 10, and 15 % of the total volume. It was recorded a rise in the concrete workability due to the poor adhesion between the WECR and the cement paste. The mechanical properties recorded a decline in their performance. An increase in WECR reduces the mechanical strengths of the concrete at 3, 7, and 28 days, leading to a decrease in adherence, especially at 15 % WECR.

Based on the existing literature, few research have used locally sourced ECW as a fine aggregate during the early and long-term periods. Moreover, waste aggregates (e-plastics) have a lighter weight than conventional natural aggregates, which is important for reducing the unit weight of the mortar. Thus, the main objectives of the current study include the production of environmentally friendly structural lightweight mortar by reducing the amount of fine aggregate (natural sand) in the mixture and replacing it with ECW. Furthermore, it aims to study its mechanical properties in the short and long term. Moreover, this research aims to recommend the best-performing substitution ratio for future research to better understand the behavior of this waste as an alternative to the natural resources in the construction sector. Therefore, in the present research, ECW in proportions of 5, 10, 15, 20, and 25 % substituted the sand in mortar. The flow and mechanical characteristics of mortars were studied at 7, 28, and 360 days. The reuse of this solid waste in the construction sector (especially concrete technology) as an alternative to raw materials contributes to enhancing sustainability by reducing the consumption of natural resources as well as limiting its environmental damage, in addition to reducing the need for landfill spaces.

2. Methods

Commercially available Ordinary Portland cement (CEM II/A-L 42.5R) was used, conforming to Iraqi specification No. 5 [16]. The chemical composition and physical and mechanical characteristics of cement are given in Table 1. Natural sand with a fineness modulus of 3, water absorption of 1.2 %, bulk density of 1650 kg/m^3 and specific gravity of 2.65 was provided by local quarries and employed as a fine aggregate. It conforms with the Iraqi specification No. 45 [17]. The particle size of the sand was ranged between 1.18 and 0.15 mm as illustrated in Table 2. The local tap water was used for mixing all ingredients. Superplasticizer type A and F, Glenium 54 (manufactured by BASF Company), was utilized to adjust the flowability of the mortar mixtures. Glenium 54 complies with ASTM C494 [18]. ECW was replaced with sand at different percentages. ECW was collected from waste cables. The outer wire sheaths, which consisted of plastic only (did not contain copper or aluminum), were shredded into small pieces and then, ground with a grinder. After that, they were sieved within the range 1.18–0.15 mm, to be ready for substitution with natural fine aggregate (sand), as presented in Fig. 1. The density of ECW is 1048 kg/m^3.

Table 1. The properties of the utilized cement.

Oxides	Content, %
CaO	62.9
Al_2O_3	4.7
Fe_2O_3	3.8
SiO_2	20.3
MgO	3.2
SO_3	1.75
Insoluble residue	1.15
Loss on Ignition	3.0
Free lime	0.8
Physical properties	
Setting time (min)	
Initial	54
Final	**222**
Compressive strength (MPa)	
3 days	**28.2**

Table 2. The sieve analysis outcome of the fine aggregate.

Sieve opening (mm)	Iraqi standard (No. 45)	Passing percentage, %
2.36	85–100	100
1.18	75–100	100
0.60	60–79	71.8
0.30	12–40	35.1
0.15	0–10	3.7

Different blends were cast to investigate mortar's fresh and mechanical properties with and without ECW. The mixture that served as the control was composed entirely of natural sand, while the other mixtures incorporated ECW by 5, 10, 15, 20, and 25 %, respectively, as a substitute for sand. The water/cement and superplasticizer dosages were 0.38 and 3.5 %, respectively. Table 3 shows the proportions mix details for mortar in this work.

Table 3. Mix proportions details of mortars in grams (for three prisms with dimensions of 40×40×160 mm³).

Mix designation	Cement	Fine aggregate	ECW aggregate	Water/Cement	SP*
ECW0	500	1375	0	190	17.5
ECW5	500	1306	69	190	17.5
ECW10	500	1237.5	137.5	190	17.5
ECW15	500	1169	206	190	17.5
ECW020	500	1100	275	190	17.5
ECW025	500	1031.5	343.5	190	17.5

* SP – superplasticizer

A mechanical mixer that complied with ASTM C305 [19] was used for mixing the mortar components. The mixing period was five minutes. Firstly, the dry materials were mixed for 0.5 minutes at a low-speed rate (140 rpm). The water and superplasticizer were supplemented with the mixer, and all ingredients were blended for two minutes at 140 rpm. Then, the mixer was paused for half a minute. After that, the mixer was operated for final mixing at 285 rpm for two minutes. After mixing directly, the flow test of the fresh mortar was conducted following ASTM C1437 [20]. The fresh mixtures were cast 40×40×160 mm³ standard molds and vibrated using an electrical vibrator. Molds were removed after 24 hours, and the specimens were stored in a water tank (at room temperature) until the test time. Many tests were conducted for the hardened mortar, including flexural strength, compressive strength and bulk density at 7, 28, and 360 days. The density was determined by dividing the mass of the prism by its geometric volume [21], while the compressive and flexural strengths were determined following BS EN 196-1 [22].

Figure 1. ECW aggregate.

3. Results and Discussion

3.1. Flow Rate

Fig. 2 shows the results of flow rates for all mixtures. Overall, the results reported that the existence of ECW aggregates reduced the flow rate of the mortar mixtures. The greater the percentage of substitution with natural sand, the higher the reduction rate. The decreasing values ranged from 2.5 % for ECW5 to 50 % for ECW25 compared to the control mixture (ECW0). The sharp edges and irregular shape of ECW grains may be the reason for reducing the flow of mortar, as this reduces the fluidity within the fresh mixture and increases the friction between its components [23]. When the waste content in the mixture increases, the friction between the components also increases, which results in a proportional decrease in flow. The literature has also revealed similar findings [24].

3.2. Compressive Strength

Figs. 3, 4, and 5 display the compressive strength of mortar mixtures after 7, 28, and 360 days, respectively. In general, the results showed that replacing the fine aggregate with ECW led to a drop in the compressive strength of the hardened mortar and that the decline grew as its proportion in the mixture increased. In other words, the lowest strength reduction was recorded for the ECW5 mixture, while the highest decrease was recorded for the ECW25 mixture. This behavior has been observed for all early and late ages. The reduction rates ranged from 6.92 to 45.54 %, from 4.55 to 37.06 %, and from 2.3 to 40.82 % for ECW5 and ECW25 mixtures at 7, 28, and 360 days, respectively. The softer waste strength compared to surrounding cement paste and its low compressive strength compared to the natural sand may explain the reduction in compressive strength [13].

In addition, this phenomenon occurs due to the enlargement of plastic particles and the weakening of the bonding force between the cement paste and the plastic aggregate surface. Plastic is also a hydrophobic substance, which limits the amount of water needed for the cement hydration [25, 26]. Similar results have been documented in the existing literature [13, 15, 27].

Moreover, it was observed that the decrease in compressive strength at 28 and 360 days is less than that at 7 days age compared to the control mixture. The reason for this may be that, over time, the hydration increases, which enhances the bond between the matrix and the ECW particles and, as a result, leads to a reduction in the strength losses.

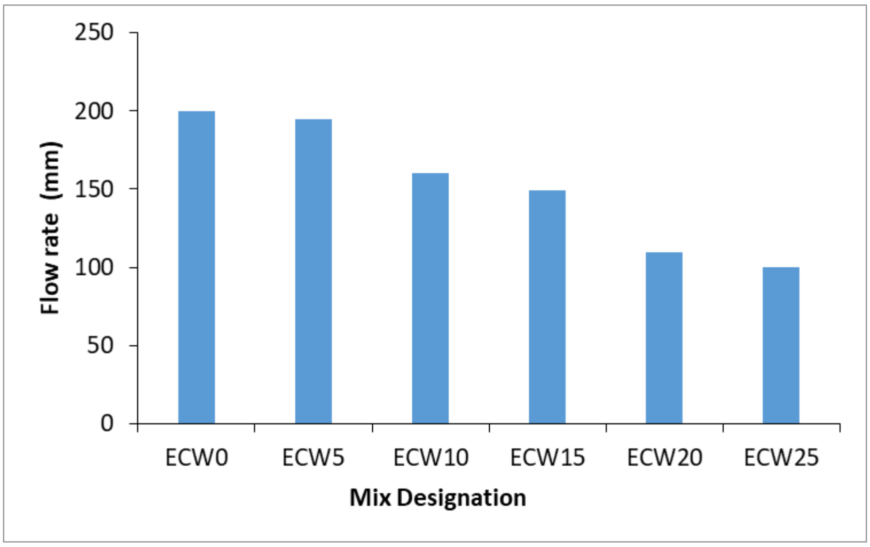

Figure 2. Flow rate results of fresh mortar mixtures.

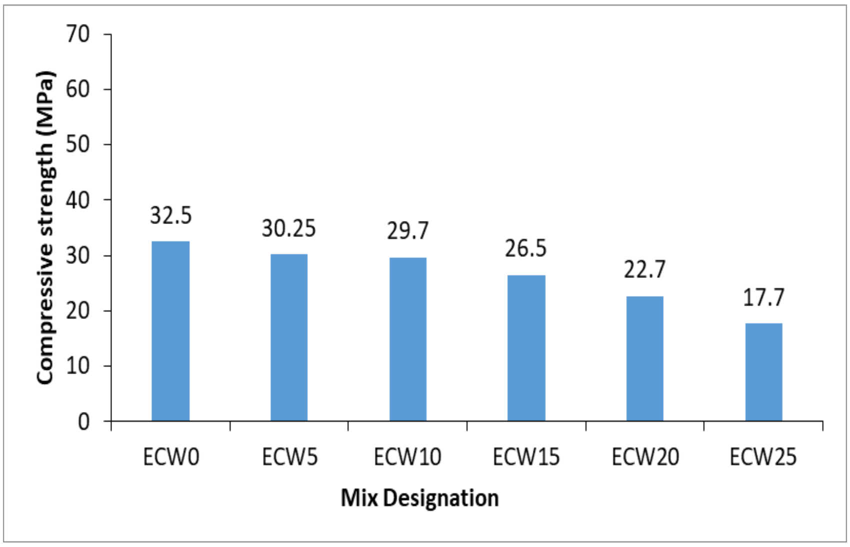

Figure 3. The 7-days compressive strength findings of ECW mortars.

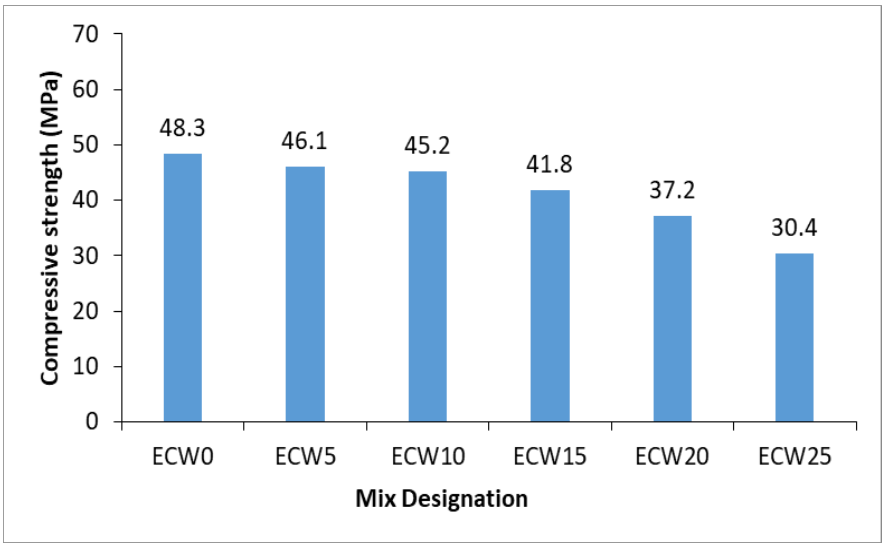

Figure 4. The 28-days compressive strength findings of ECW mortars.

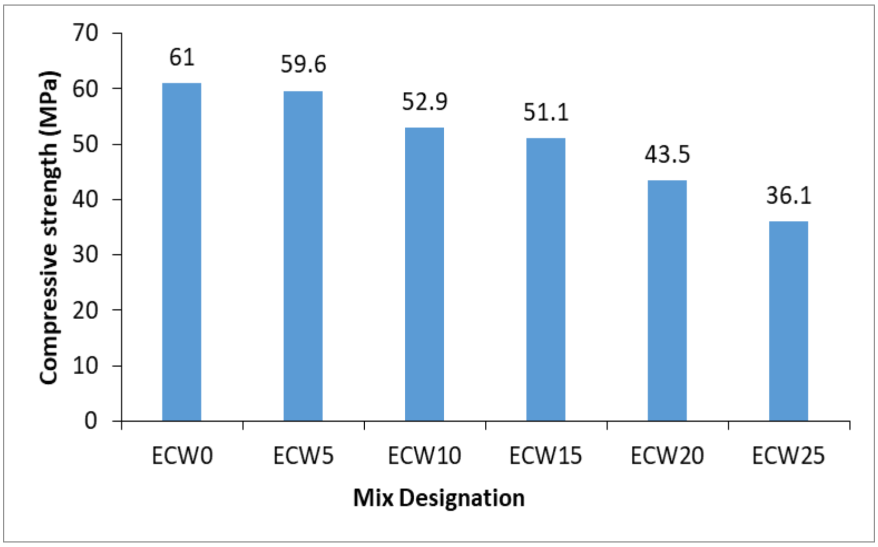

Figure 5. The 360-days compressive strength findings of ECW mortars.

3.3. Flexural Strength

Figs. 6 to 8 display the results of flexural strength examination. The results of the flexural strength showed a comparable tendency as in the compressive strength, where the strength decreased when using ECW. The higher the amount of waste in the mixture, the lower the flexural strength. The minimum decreasing rates were given by ECW5, 10, 15, and 5.56 % at 7, 28, and 360 days, respectively. In contrast, the highest drop percentages were found in ECW25: 50, 43.75, and 22.22 % in the same periods mentioned above. Comparable trends were obtained in previous works [13, 15, 27]. Among the reasons for the low flexural strength may be due to the flexible and unbreakable nature of the waste under loading [28]. The poor workability of the mixture and the weakness of the interfacial transition zone (ITZ) between the cement paste and the waste may be another reason for the low value of the flexural strength [29].

Moreover, it is noted that the decrease in flexural strength is higher than that in compressive strength for the same replacement values. The reason for this is that the flexural strength is more affected by the structure of voids and cracks inside the ITZ compared to the compressive strength [30]. Therefore, the effect on the flexural strength is greater.

3.4. Bulk Density

The bulk density results of the hardened mortars are illustrated in Figs. 9 to 11. Results disclosed that the density decreased after using ECW as a substitute for aggregates. Also, the reduction in density is proportional to the replacement rate. These results are agree with Yildirim and Duygun [15] and Ruiz-Herrero et al. [27]. The reason for reducing the density is due to the low density of these wastes (1048 kg/m^3) related to the natural aggregate (1650 kg/m^3). Similar findings for plastic waste were found in the literature [27]. Moreover, when observing the behavior of the density with age, it is noted that the reduction percentage of the given replacement percentage is almost constant regardless of the age of the examination (early or late). For example, the percentage of reduction for the ECW5 mixture (the lowest replacement percentage) was about 17 % for all ages, as well as for the ECW25 mixture (the highest replacement percentage), it was about 30 % for ages 7, 28, and 360 days, which indicates the homogeneity of the distribution of the substance in the mixture.

It is also noted that at the age of 360 days, by replacing 25 % of the waste, the density value was 1664.1 kg/m^3 compared to 2386.7 for the reference mixture. Upon observing the corresponding compressive strength value (36.1 MPa), it can be reported that a lightweight structural mortar has been produced.

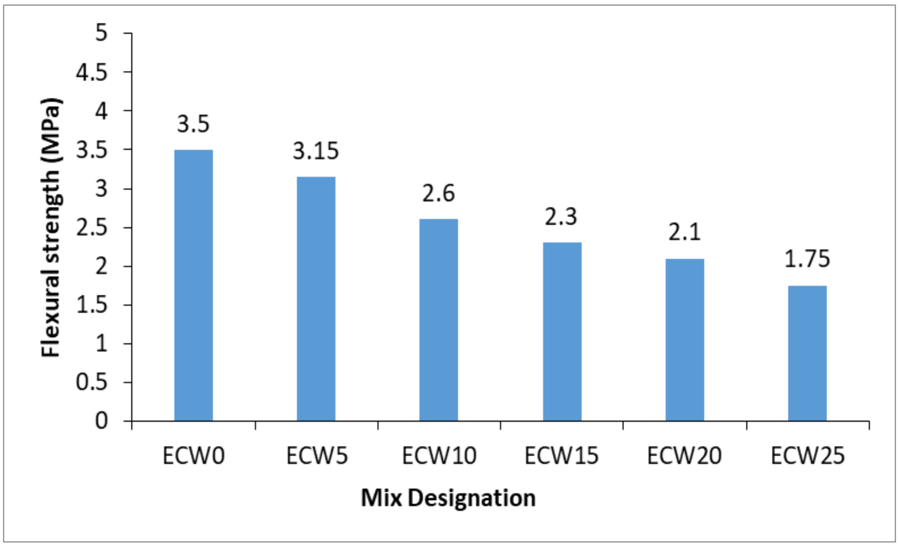

Figure 6. The 7-days flexural strength findings of ECW mortars.

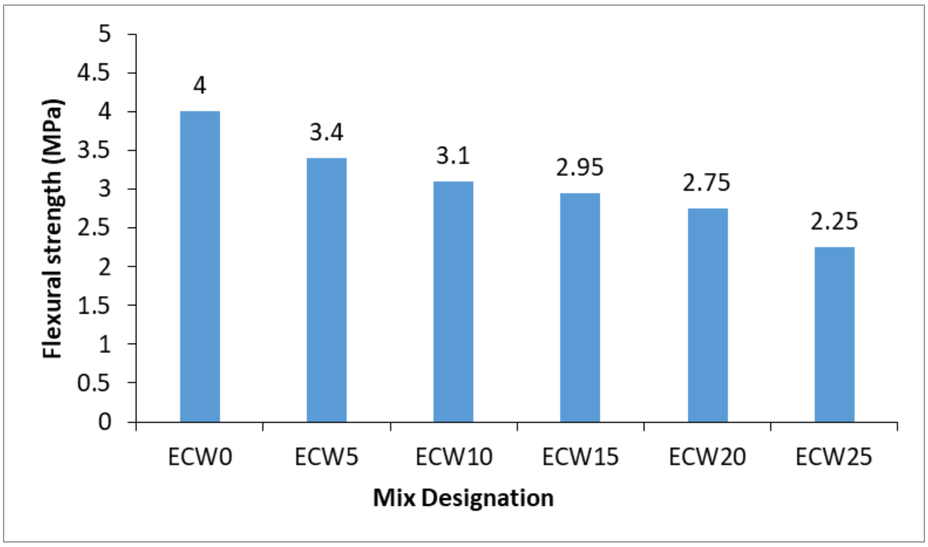

Figure 7. The 28-days flexural strength findings of ECW mortars.

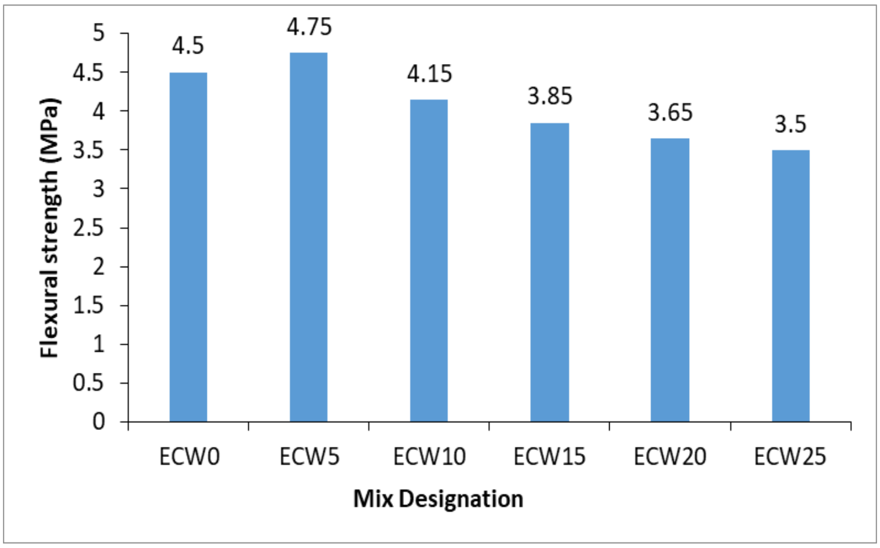

Figure 8. The 360-days flexural strength findings of ECW mortars.

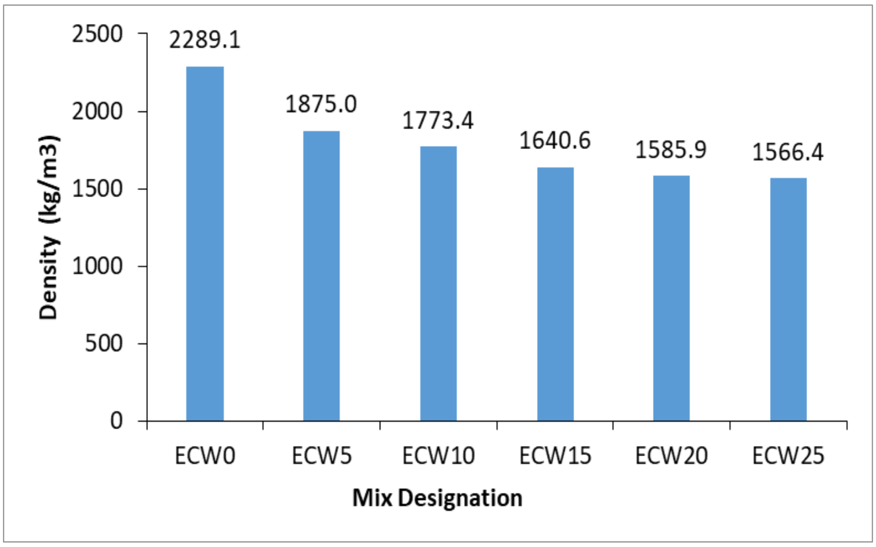

Figure 9. Density results of ECW mortars at 7 days.

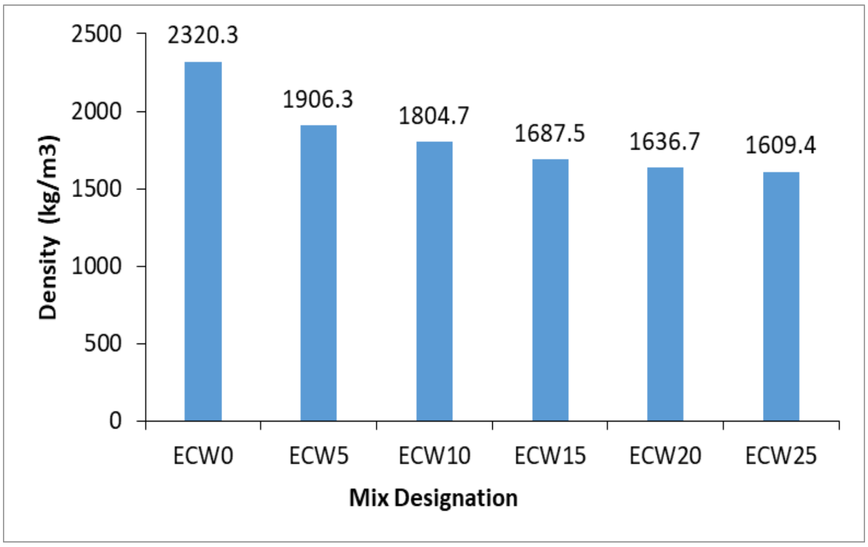

Figure 10. Density results of ECW mortars at 28 days.

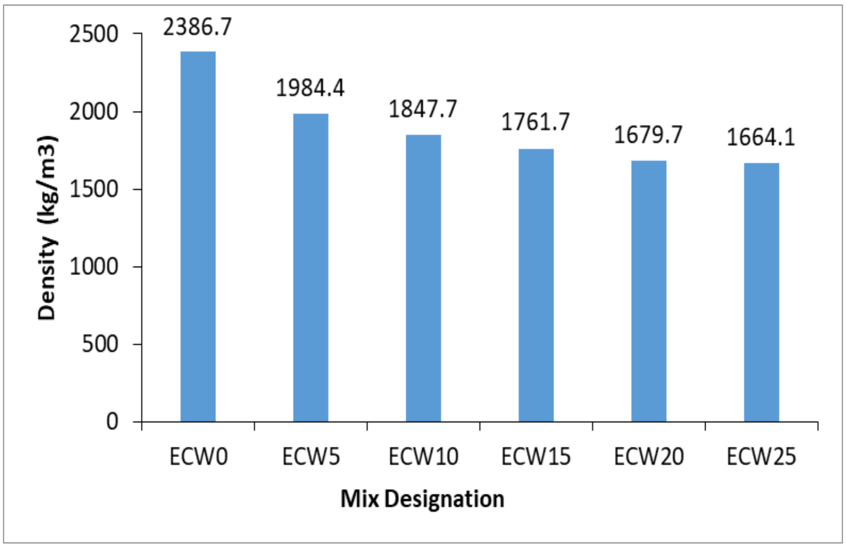

Figure 11. Density results of ECW mortars at 360 days.

3.5. Correlation

For mortars containing ECW ranging from 0 to 25 %, the compressive strength-flexural strength, compressive strength-dry density, and compressive strength-flow rate relationships have been developed for each testing age (7, 28, and 360 days) as shown in Table 4 and Figs. 12 to 14. A polynomial equation (X^2) relationship was chosen for all the after-mentioned properties. The results revealed that a strong correlation between the compressive strength – flexural strength and compressive strength – flow rate have been recorded with a correlation coefficient (R^2) of not less than 0.91 for each corresponding age, which indicates that these properties are directly related to the compressive strength. That is, with an increase in the compressive strength, the density and flexural strength increase proportionally. Moreover, a good relationship was observed for the compressive strength with the density for ages 7, 28, and 360 days, with R^2 values in the range of 0.856 to 0.916.

Table 4. The equations and corresponding correlation coefficients of the developed equations for ECW-based mortars.

Age (days)	Relationship type					
	Compressive strength-flexural strength		Compressive strength-dry density		Compressive strength-flow rate	
	Equation	R^2	Equation	R^2	Equation	R^2
7	$Y = 0.008X^2 – 0.292X + 4.4452$*	0.940	$Y = 6.2181X^2 – 271.97X + 4467.9$	0.916	$Y = 0.3451X^2 – 10.11X + 168.64$	0.938
28	$Y = 0.0042X^2 – 0.2447X + 5.9026$	0.917	$Y = 4.2181X^2 – 300.83X + 6890.5$	0.878	$Y = 0.3127X^2 – 18.688X + 377.81$	0.950
360	$Y = 0.0016X^2 – 0.1038X + 5.2147$	0.927	$Y = 1.6518X^2 – 138.07X + 4516.4$	0.856	$Y = 0.0932X^2 – 4.8087X + 149.61$	0.991

Y – compressive strength; X – other property

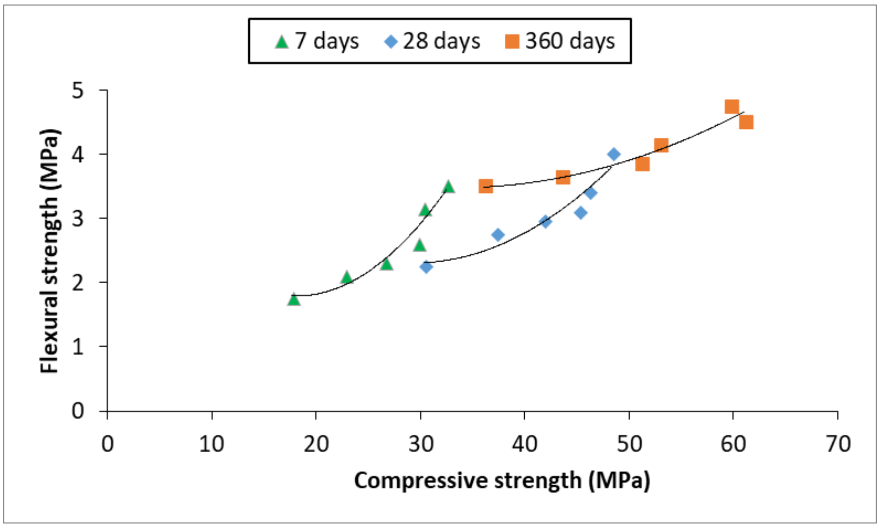

Figure 12. The compressive strength and flexural strength correlations of ECW-based mortars for 7, 28, and 360 days.

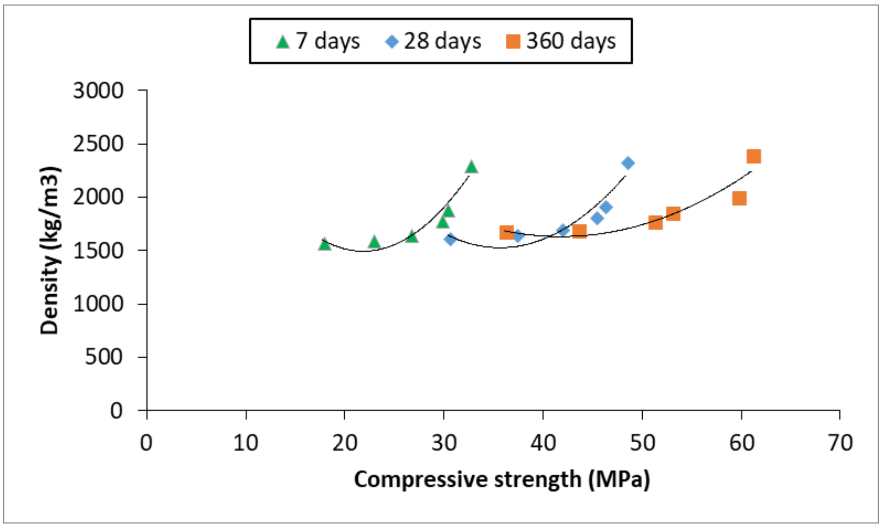

Figure 13. The compressive strength and density correlations of ECW-based mortars for 7, 28, and 360 days.

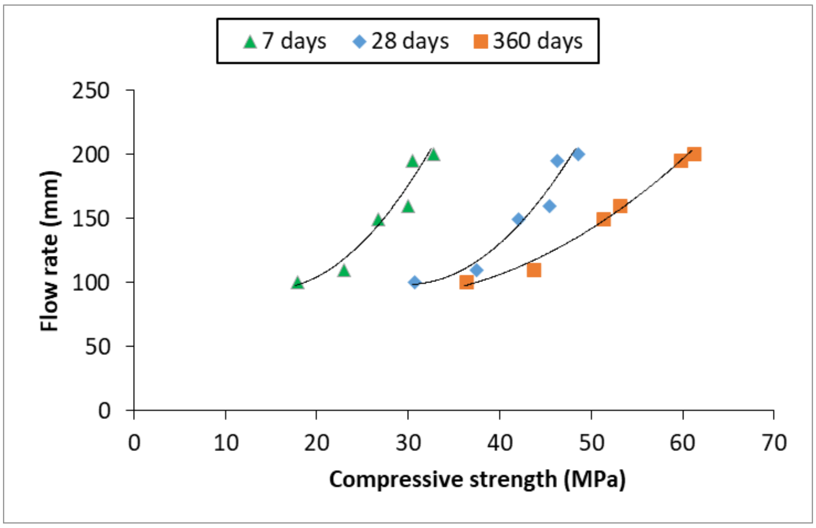

Figure 14. The compressive strength and flow rate correlations of ECW-based mortars for 7, 28, and 360 days.

4. Conclusion

In this experimental study, the influence of ECW was investigated as an alternative to the natural sand in mortar at early and late ages. Through the flowability and mechanical characteristics results, the following have been concluded:

1. The presence of ECW as sand replacement material can reduce the flowability of flesh mortar and the reduction rate increases with the ECW content in the mix.
2. Replacing sand with ECW contributed to reducing the mechanical properties of mortar for all ages (7, 28, and 360 days). The lowest reduction percentage was for ECW5 (2.3 and 15 % for compressive and flexural strength, respectively, at 360 days). On the other hand, the ECW25 mix recorded the highest reduction amount, reaching 40.82 % in compressive strength and 22.22 % in flexural strength at the age of 360 days.
3. ECW caused a decrease in solid density of approximately 17 % at a 5 % replacement rate and about 30 % at a 25 % replacement rate compared to the reference sample for all ages of examination. This indicates the production of lightweight mortar suitable for structural applications.
4. The correlations developed between the compressive strength property and each flow rate, flexural strength, and density revealed good second-order polynomial equations with a correlation coefficient (R^2) between 0.856 to 0.991.

In summary, considering all the tests carried out, the best performance of using ECW was at a 5 % substitution ratio with flow values and strengths equivalent to or slightly less than those of the reference mix with a density value of lower than 2000 kg/m^3. Moreover, it is possible to obtain a lightweight, structural, and environmentally friendly mortar with a density of less than 1700 kg/m^3 when replacing 25 % of the natural sand with ECW. It can be utilized for different construction purposes, as its compressive strength is 36 MPa at 360 days.

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