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Experimental Investigation on Using Electrical Cable Waste as Fine Aggregate and Reinforcing Fiber in Sustainable Mortar

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ABSTRACT

Challenges posed by industrial solid waste, particularly Electrical Cable Waste (ECW), have been increasingly recognized due to their environmental implications and substantial decomposition timelines. ECW, a byproduct of aggressive demolition and reconstruction in Iraq, has seen limited investigation regarding its potential use as an aggregate substitute and fiber additive in concrete applications. This study endeavors to repurpose ECW as a partial replacement for natural sand and as fiber reinforcement, with a focus on both short-term and long-term performance. A fixed ratio of natural sand was substituted with ECW (10%), and waste fibers were integrated at varying concentrations (0.5%, 1%, 1.5%, 2%, 2.5%, and 3%). For comparative purposes, a control mix devoid of ECW and fibers was also examined. Evaluations were conducted on the flow rate, along with compressive strength, flexural strength, and density at intervals of 7, 28, and 360 days. Results indicate that despite a reduction in flowability and a decrease in hardened density to under 2000 kg/m^3, inclusion of ECW can yield a sustainable lightweight mortar without significant compromise on strength. This study thus underscores the potential of waste repurposing as a viable solution for waste management and environmental enhancement. Additionally, this approach can help mitigate natural resource depletion, such as that of natural sand, fostering a move towards sustainable construction practices.

1. INTRODUCTION

Human civilization is overgrowing and the environment is affected accordingly [1, 2]. As a result, proper attention must be paid to protecting natural resources and the environment. Among all construction materials, concrete is by far the most widely utilized [3]. The concrete industry is the most important source of CO_2 emission and the most important consumer of depleted natural resources (virgin materials) [4-7]. Therefore, to maintain the sustainable concept, two important methods must be taken into account: recycling waste materials and lowering emissions of carbon dioxide. One of the wastes that can be employed in the concrete industry is electrical waste. Cable waste (plastic) is a new material that has to be recycled due to the increasing population and the increase of this waste. Many researchers have studied plastic waste from different sources and its ability to be used in the concrete industry [8]. Da Silva et al. [9] investigated the feasibility of using waste plastics to partially replace aggregates in the cement slurry at 5%, 10% and 15% with sizes ranging from 1-2 mm. The experiment results showed a decrease in compressive and flexural strength due to the weak bond between the aggregate and the cement matrix. Mustafa et al. [10] investigated plastic waste as natural sand replacers in 0%, 5%, 10% and 20%. Experimental results showed improved strength and higher energy absorption under static and shock loads.

The effect of recycled plastic fibers on concrete was studied and reported by Kim et al. [11]. According to their findings, the modulus of elasticity and compressive strength dropped as the percentage of fiber in the material increased. On the other hand, dry shrinkage cracks delayed the recycling of the reinforced plastic fibers compared to control samples (without fibers). Foti [12] reported plastic fibers reinforcing concrete (waste bottles) and found that when plastic fibers are added, they can have a good effect on the hardness of concrete. In addition, it increased concrete plasticity and improved the crushing performance of concrete samples. The research that was carried out by de Oliveira and Castro-Gomes [13] investigated the viability of incorporating fibers derived from recycled bottles into cement mortar. The findings revealed a discernible rise in both the material's compressive and flexural strengths and a notable improvement in the material's toughness. Spadea et al. [14] conducted research to determine whether or not recycled nylon fibers might be used as mortar reinforcement. Recycled plastic reinforced mortar with only 1% fibers was shown to boost tensile strength by as much as 35% and toughness by as much as 13 times. According to the findings, the mechanical characteristics of mortar suffered due to the high fiber content (1.5%). The results showed that the high fiber content (1.5%) caused a decrease in the mechanical properties of the mortar. Al-Hadithi and Hilal [15] used plastic waste fiber at 0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2% by volume in self-compacted concrete. They found the compressive strength increased for all mixtures with fiber up to 2% by volume; thereafter, the strength declined. The flexural strength results showed the benefit of utilizing waste plastic fiber. Al-Tulaian et al. [16] investigated the utilization of recycled plastic waste fibers in cement mortar and its effect on flexural toughness, plastic shrinkage cracking and flexural strength. The investigation involved fiber content and length. Laboratory experiment results showed that the flexural toughness increased from 26 to 61 times, and flexural strength increased from about 6% to 84% for mortars reinforced with recycled plastic waste fibers. Plastic shrinkage cracks presented a clear width reduction when using recycled plastic waste fibers. Aziz et al. [17] evaluated the utilization of waste plastic fibers (WPF) in concrete with percentages ranging between (0% to 1%). Compressive strength was improved with a mixture without fibers (reference mix) up to (0.75%). At the same time, the flexural strength increased as waste plastic fiber content increased.

Based on the literature reviewed, it is apparent that the impact of plastic waste on the properties of concrete or mortar is conflicting. The variations in the source of the waste, the percentage added to the mixture, and the method of addition (as fiber or a substitute for natural aggregate) may account for this discrepancy. As a result, more research is required to understand this type of waste better. Moreover, according to the literature, limited studies have dealt with using locally produced Electrical Cable Waste, simultaneously, as a sand replacement and fiber reinforcement in mortar. Moreover, few studies have examined the mechanical performance of these residues in the short and long term (7 to 360 days). Therefore, this research aims to utilize the waste plastic extracted from the waste electrical cables in two ways: first 10% of waste plastic was used as a partial substitution for sand. Second, use the plastic wire that encases the cable inside as a fiber at 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% by weight. Flow rate and mechanical properties for mortar are examined at 7, 28, and 360 days. It is believed that the results of this study are promising in producing an environmentally friendly mortar with characteristics almost similar to the reference mixture by reusing the waste and eliminating its environmental damage through its inclusion in the concrete technology.

2. EXPERIMENTAL PROGRAM

This work utilized ordinary Portland cement type II (CEM II/A-L 42.5R) to cast all mortar formulations. This cement confirms the limitations of Iraqi Standard No. 5 [18]. Table 1 displays the cement's chemical composition as well as its physical and mechanical characteristics. Locally available fine aggregate (natural sand) was employed. The fineness modulus, absorbance, and density of the sand used were, respectively, 3, 1.2% and 2.65 g/cm^3, while grain size ranged between 1.18 mm and 0.15 mm. Table 2 shows the sieving analysis of the fine aggregates conforming to Iraqi Standard No. 45 [19]. All mixes were cast and cured using tap water. A superplasticizer (Glenium 54), Type F and G from BASF company, was added in a constant proportion for all mortar mixtures. Glenium 54 is conformed to ASTM C494 [20] and is based on a modified polycarboxylic ether. Electrical Cable Waste (ECW) is employed as a fine aggregate substitute at a fixing rate of 10%. ECW was collected from waste cables after cleaning and then cut into small pieces and sieved within the range of 1.18 mm to 0.15 mm and then become ready for replacement with natural sand (see Figure 1). The density of ECW was 1300 kg/m^3. Moreover, in this study, waste fibers were also used in different proportions to improve the mechanical characteristics of mortar. Waste plastic fibers were gained from waste cables by cutting them to a length of (3 cm) with an aspect ratio of 23.

Table 1. The chemical composition and physical characteristics of the cement

Oxides	Content, %
SiO_2	20.3
CaO	62.9
Fe_2O_3	3.8
SO_3	1.75
Al_2O_3	4.7
MgO	3.2
Insoluble residue	1.15
Loss on Ignition	3.0
Free CaO	0.8
Initial setting time (min)	54
Final setting time (hr)	3.7

Table 2. The gradation of the natural sand

Sieve Opening (mm)	Iraqi Specification No.45	Percentage Passing, %
	Grading Zone III	Natural Sand
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

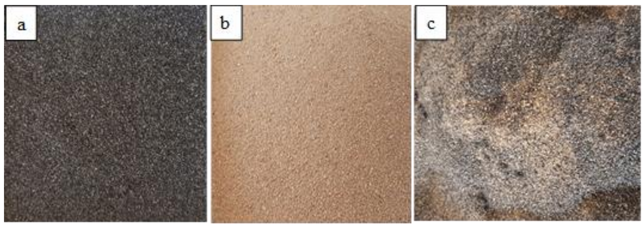

Figure 1. (a) Natural sand, (b) Electrical Cable Waste (ECW) aggregate and (c) mixing of the two types

Seven mixtures were made to assess the fresh and mechanical properties of mortar under laboratory conditions. The water-cement ratio (w/c) and the superplasticizer dose were fixed for all mixtures (0.38 and 3.5% by weight of cement, respectively). All mixtures comprised 90% natural sand and 10% electric cable waste. The reference mixture was devoid of waste fibers while the other mixture contained waste plastic fibers in percentages of 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% by weight of cement, respectively. Table 3 outlines the mix proportion details for the mortars.

Six and a half minutes was the period of mixing the mortar. All mortar components were dry-mixed at 140 rpm for 30 seconds. Then, the superplasticizer and water were added and mixed at low speed for 2 minutes. After a half-minute pause, the ingredients were mixed at 285 rpm for two minutes. Finally, the waste fibers were gradually added and mixed at a high-speed rate for another 1.5 minutes. After mixing immediately, the flow rate was determined for the fresh mortar according to ASTM C1437 [21]. Standard molds (40×40×160 mm^3) were used for pouring the fresh mortar. An electric vibrator was utilized to compact the specimens. After twenty-four hours, the molds were eliminated, and the samples were put away in a water tank until the test day (7, 28, 360 days). Compressive and flexural strengths, as well as bulk density, of the hardened mortar were determined. Bulk density was determined by dividing the prisms' mass by their geometrical dimensions [22], while compressive and flexural strengths were assessed in line with BS EN 196-1 [23].

Table 3. Proportions mix details for mortar (g)*

Mix Designation	Cement	Fine Aggregate	ECW**	Fiber	W/C	SP
M	500	1237.5	137.5	0	190	17.5
M 0.5%F	500	1237.5	137.5	2.5	190	17.5
M 1%F	500	1237.5	137.5	5	190	17.5
M 1.5%F	500	1237.5	137.5	7.5	190	17.5
M 2%F	500	1237.5	137.5	10	190	17.5
M 2.5%F	500	1237.5	137.5	12.5	190	17.5
M 3%F	500	1237.5	137.5	15	190	17.5

* The proportions were calculated for three mortar prisms (40 m×40 m×160 m)

** ECW: Electrical Cable Waste

3. RESULTS AND DISCUSSION

3.1 Flow rate

Figure 2 illustrates the flow rate findings of mortars. It can be seen from the results that the presence of ECW aggregate and fiber led to a decrease in the flow of soft mortar. The higher the waste proportion, the greater the reduction in the flowability of the mixture. The mixture ECW10F0.5 recorded a flow of 158 mm or 21.3% reduction (the lowest reduction), while the mixture ECW10F3 recorded a flow of 121 mm or 39.5% reduction (the highest reduction) compared to a flow of 200 mm for the reference mixture (free of residues). In general, a variety of influences can affect the workability including the shape and size of the plastic aggregate and the fibers used [24]. Consequently, the angular and irregular shape of the shredded plastic can lead to a decrease in the fluidity of the mixture [25]. Moreover, the waste fibers tend to intertwine together in the center of the spread of the flow, adding friction between them and the aggregate [15], which contributes to obstructing the mortar flowability.

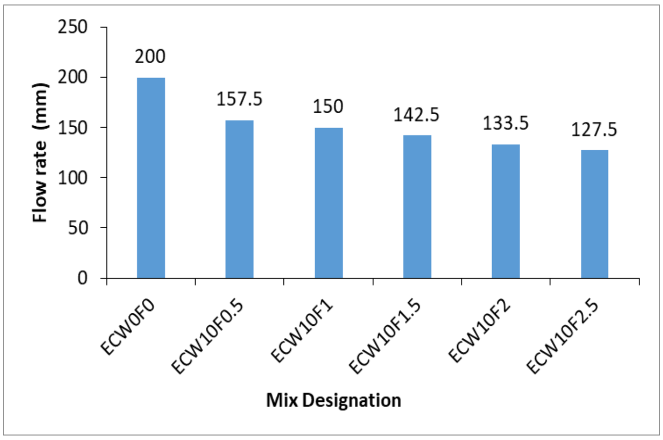

Figure 2. Flow rate results of ECW and waste fibers-based mortars

3.2 Compressive strength

Figures 3-5 illustrate the findings of the compressive strength test conducted at 7, 28, and 360 days. The results showed that, at the age of 7 days (Figure 3), the mixture ECW10F0.5 recorded a slight decrease in compressive strength (4.9%), and then this reduction diminished as the content of waste fibers in the mixture increased, up to 1.5%, where the compressive strength was almost equal to the reference mixture. (Free of any addition or replacement). Then, the compressive strength tended to decrease whenever the percentage of waste fibers exceeded this amount, as the mixture ECW10F3 recorded a decrease in strength of 13.2% lower than the control sample.

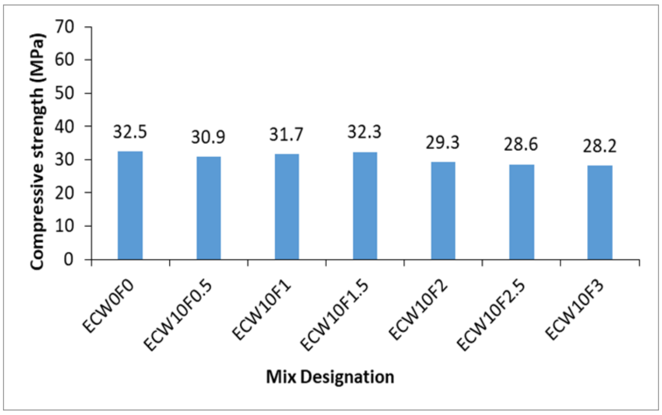

Figure 3. Compressive strength results of ECW and waste fibers-based mortars at 7 days

Moreover, at 28 days, Figure 4 showed that the compressive strength of mortars with fiber ratios ranging from 0.5 to 1.5 was equal to that of the reference sample. After that, the compressive strength decreased proportionally with the increase of the fiber content so that the ECW10F3 mixture recorded a value of 42.5 MPa (12% reduction) compared to 48.3 MPa for the plain mortar.

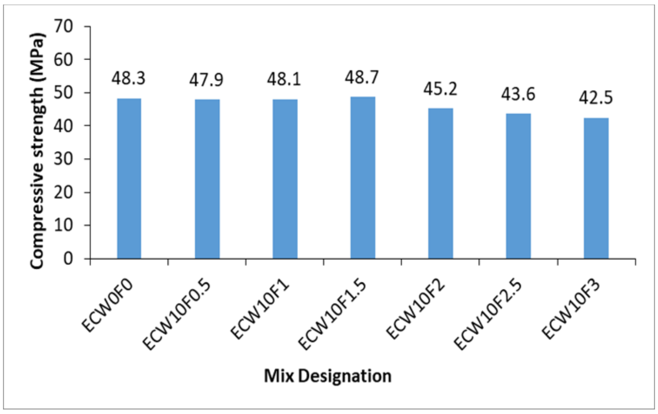

Figure 4. Compressive strength results of ECW and waste fibers-based mortars at 28 days

On the other hand, at the age of 360 days, displayed in Figure 5, the change of compressive strength with the increase of fiber percentage was similar to that at the age of 7 days but with different proportions. Where it was discovered that there was an 11.3 percent drop in compressive strength from the control mixture at a fiber content of 0.5%, then the reduction decreased until it reached 2.8% decline at a rate of 1.5%; thereafter, the reduction grew again with an arise in the fiber content and recorded 18.4% reduction at 3% fiber.

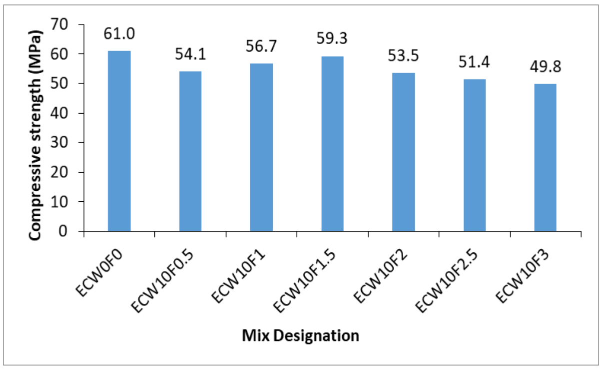

Figure 5. Compressive strength results of ECW and waste fibers-based mortars at 360 days

The decreased modulus of elasticity in ECW aggregates compared to normal aggregates may explain the drop in compressive strength [26, 27]. Moreover, the poor adhesion strength between the plastic surface and the cement paste may also decrease the compressive strength [28]. The presence of waste fibers has reduced the negative impact of plastic waste. By increasing the waste fibers to a certain level (1.5%), the compressive strength was almost equal to the reference mixture. This enhancement can be clarified according to Al-Hadithi and Hilal [15], who stated that the fibers close to the microcracks actively block the cracks from spreading further. As a result, the cracks that emerge inside the matrix are forced to follow a zigzag pattern. This increases the demand for more energy in the future, increasing the ultimate load. However, the high content of the fibers also caused the compressive strength to go down, and the reason for this is that at a higher content, more entrapped air enters the mixture, as a result of the reduction in flowability of the fresh mortar [29], and thus the compressive strength decreases.

3.3 Flexural strength

The results of the flexural strength are displayed in Figures 6-8. It was observed that flexural strength was generally lower when ECW was employed as an aggregate in the mortar. The low value of flexural strength in the presence of ECW aggregates may be due to the poor bond between the cement paste and these wastes and the poor flowability of the mortar containing it [30]. It was also observed that this effect diminished as the fiber content in the mixture increased. At seven days (Figure 6), it was found that the flexural strength dropped by 21.2% from the reference mixture and that this reduction decreased as the percentage of waste fibers increased up to 2%. After this ratio, the strength value exceeded the control sample by 1.4% and 5.7% for the mixtures ECW10F2.5 and ECW10F3, respectively. This behavior can be explained as follows: The presence of waste fibers in the concrete works to resist the expansion of cracks through bridging when tensile loads are applied, which causes an increase in the flexural strength of the ECW-modified mortar [31]. At 28 days (Figure 7), the results showed a behavior similar to the age of 7 days, where the decline in flexural strength decreased with the growth in fiber content, but up to 1%. After this ratio, a continuous positive effect was recorded compared to the control mixture. The percentages of improvement were 6.3, 7.5, 13.8 and 20% for the mixtures ECW10F1.5, ECW10F2, ECW10F2.5 and ECW10F3, respectively. On the other hand, at the age of 360 days (Figure 8), the results showed a similar trend to the earlier ages in that the flexural strength improves with the growth of the fiber content. Still, the total strength (equal to that for the control) did not recover even at 3% fiber, in contrast to the early ages (7 and 28 days), where some fiber levels recorded values that exceeded the reference sample. However, the ECW10F3 mixture decreased slightly, 2.7% lower than the fiber-free mix.

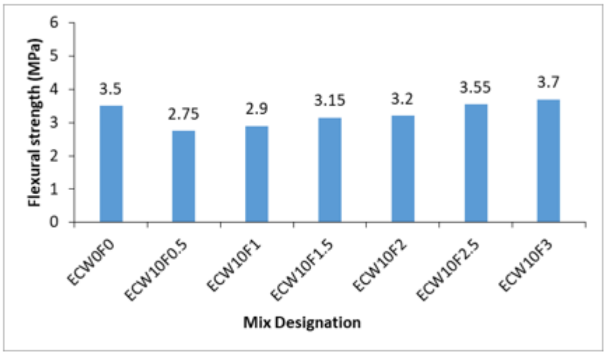

Figure 6. Flexural strength results of ECW and waste fibers-based mortars at 7 days

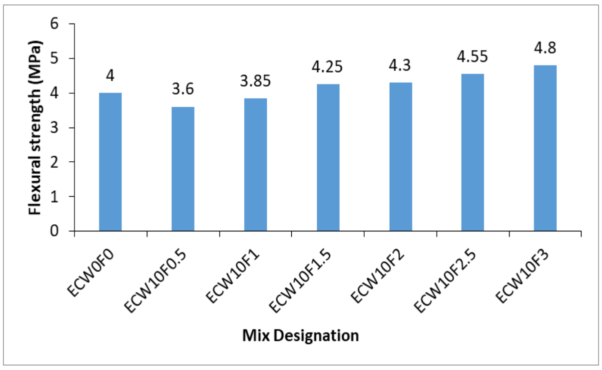

Figure 7. Flexural strength results of ECW and waste fibers-based mortars at 28 days

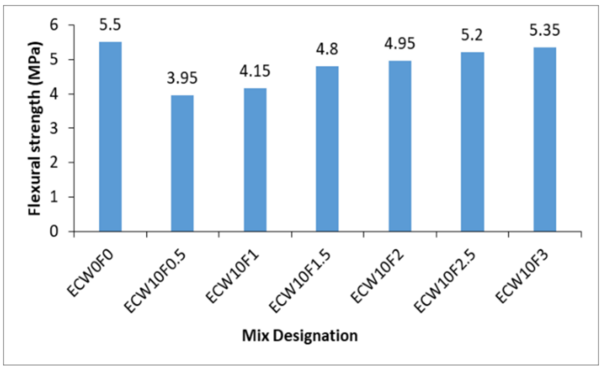

Figure 8. Flexural strength results of ECW and waste fibers-based mortars at 360 days

3.4 Bulk density

Figures 9, 10, and 11 present the results of bulk density measurements of mortars after 7, 28 and 360 days, respectively. In general, the results indicated a decrease in the density of the hardened mortar in the presence of ECW and WF compared to the reference sample. Moreover, the density was reduced by increasing the fiber content in the mix for all examination ages (7, 28 and 360 days). The ECW10F0.5 mixture recorded a reduction of between 19.5 and 21.2% at seven days compared to the plain mortar, while the density was 12.1 to 15% less than the reference mixture at the age of 360 days. Moreover, it is noted that the decrease in density was not significantly affected by the mortar age, as the change in density for most admixtures (at a certain proportion of fiber) between the ages of 7 and 360 days was less than 2%. The reason for the low density of mortar is that the density of ECW is less than that of the natural aggregates. Moreover, it can be seen from the figures that the reduction in density was dropped in the presence of fiber and that this drop was proportional to the increase in the fiber content in the mixture. Reducing the decline in density is an indication of an improvement in the compressive strength property due to the direct proportion between the density and the compressive strength [32].

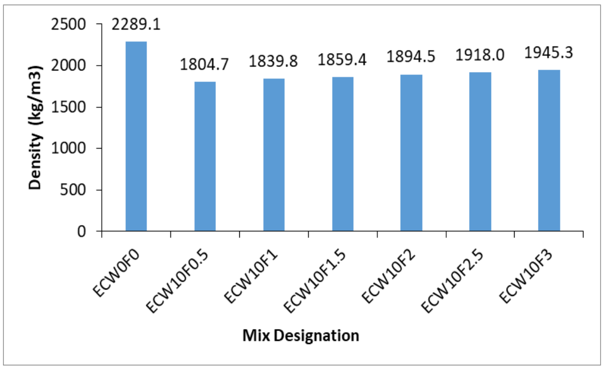

Figure 9. Bulk density outcomes of ECW and waste fibers-based mortar mixtures at 7 days

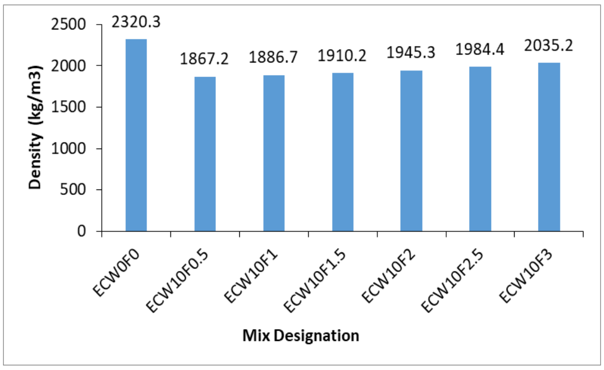

Figure 10. Bulk density results of ECW and waste fibers-based mortars at 28 days

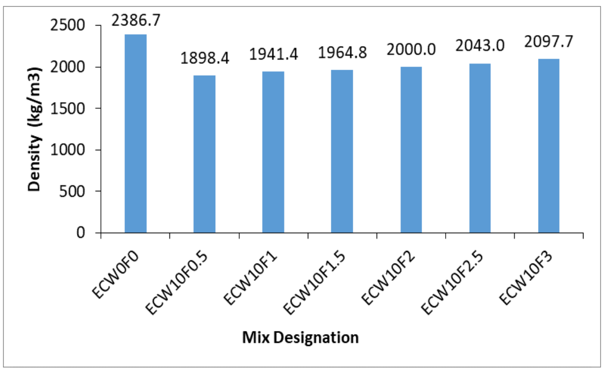

Figure 11. Bulk density results of ECW and waste fibers-based mortars at 360 days

In addition to the above, it is worth saying that Reusing plastic waste can have long-term effects on the environment and the economy. Since plastic waste does not readily decompose, it can harm the environment. However, reusing it in other industries, particularly construction, can solve this problem. This approach offers two benefits. Firstly, it eliminates the need for landfill areas, which reduces the cost of transportation and disposal and helps governments manage waste more efficiently. Secondly, it transforms plastic waste from a harmful substance into a helpful resource, which can help to reduce its environmental damage. Additionally, using plastic waste as an alternative to natural aggregate (such as sand) can reduce the depletion of natural resources, contributing to sustainability. However, further research is necessary to evaluate the environmental impact and how much it can be reduced when incorporated into concrete technology.

4. CONCLUSIONS

Based on the current experimental inquiry, it can be deduced the following:

- The combined use of ECW as a partial substitute for natural sand and as a fiber reduces the flowability of the fresh mortar. The decrease in the flow rate is proportional to the percentage of fiber addition.
- The presence of waste fibers improved the compressive strength of the mortar containing 10% ECW to a certain level, after which the strength decreased gradually. The best percentage of fiber addition was 1.5%, as it recorded a value almost equivalent to the reference mixture at ages 7, 28 and 360 days.
- The addition of waste fibers mitigated the negative impact of ECW on the mortar's flexural strength. The mixture ECW10F3 recorded a change in flexural strength of 5.7, 20 and -2.7% in 7, 28 and 360 days, respectively, compared to the control specimen, which is considered the best compared to all other mixtures.
- Replacing the natural aggregate with 10% ECW reduces the density of the hardened mortar. Still, the increase in the fiber content of the mixture within the range of 0.5% to 3% has contributed to the regression of this decrease from 20.5% to 12.1% at the age of 360 days.

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NOMENCLATURE

ECW	Electrical Cable Waste
WPF	Waste plastic fiber
CEM II/A-L	Portland cement type
w/c	Water to cement ratio
SP	Superplasticizer