Workability of Sustainable Cement Sand Mortar Made with Waste Fine Aggregates

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ABSTRACT

This study investigates the application of the Circular Economy (CE) principles in cement–sand mortar by partially replacing natural fine aggregates with recycled materials. The aim is to promote sustainable construction practices while reducing ther environmental impacts associated with sand mining and waste disposal. Three types of recycled aggregates were evaluated: Recycled Concrete Aggregate (RCA),

Crushed Brick (CB) aggregates (CBA, CBB, CBC, CBD), and crumb Rubber Aggregates (RB10, RB20, RB40). Each replaced 15% of the sand content by mass for the mineral wastes and by volume for the rubber, across three water-to-cement (w/c) ratios: 0.4, 0.5, and 0.6. The workability was assessed using the flow test as illustrated in [17]. The results revealed that the mortars with RCA and brick aggregates exhibited low workability at lower w/c ratios due to the high water absorption and the rough particle textures of the aggregates. In contrast, Rubberized Mortars (RB) showed excellent flowability across all ratios, attributed to rubber's non-absorptive nature. Increasing the w/c ratio improved the flow in all mixes, though the rubber aggregates consistently outperformed others. The findings highlight the feasibility of using recycled waste materials, particularly rubber, to produce workable, eco-friendly mortars, supporting the shift toward a more sustainable construction industry.

Keywords-circular economy; recycled aggregates; cement–sand mortar; workability; sustainable construction

I. INTRODUCTION

The CE is commonly defined as an economic model centered on reducing, reusing, and recycling resources to promote resource efficiency and economic prosperity [1]. Authors in [2] stated that rapid urbanization contributes to higher greenhouse gas emissions and resource depletion, driven by the increased cement production. Adopting CE approaches can reduce the construction industry's contribution to global warming and lessen its overall environmental footprint. As the demand for new infrastructure rises, the construction industry's consumption of natural resources has surged dramatically. A large amount of construction waste is produced every year [3]. Cement mortars are essential in construction. They are used for finishing, repairs, protective concrete covers, ferrocement elements, brick masonry joints, and shielding porous materials from the environmental effects [4]. Cementitious mortar consists primarily of fine aggregates, often riverbed sand, combined with hardened cement paste and interfacial transition zones. Given the high volume of aggregate in the mixture, its characteristics play a critical role in determining the mortar's physical and mechanical performance [5]. The construction of large-scale projects, like buildings, highways, hydropower dams, and nuclear power plants requires massive quantities of sand, ranging from hundreds to tens of thousands of tons, with usage reaching up to tens of millions of tons globally, according to UNEP [6]. The global sand consumption could have reached more than 4 billion by 2060 [6]. Authors in [7] noted that intensive sand mining negatively impacts the physical, biological, and chemical environment. Its consequences involve river widening, harm to the aquatic ecosystems, including both marine flora and fauna, chemical contamination, and a decline in the overall water quality.

The incorporation of plastic waste in mortar not only enhances the workability but also reduces the density and helps mitigate the plastic disposal challenges [8]. Similarly, ground ceramic waste has been used as a sand replacement in cement–sand mortar, improving the mechanical properties, reducing the pore size, and enhancing the durability by lowering the gas permeability and water absorption [9]. Phosphate mine waste has also been applied as a fine aggregate substitute, resulting in higher compressive strength and reduced water absorption [10]. In [11], mineral wool and rice straw were added to cement–sand mortar, improving the insulation performance while maintaining acceptable mechanical strength. Waste brick and geo-cement aggregates have likewise been shown to provide comparable or even superior flexural and compressive strengths relative to natural aggregates [12, 13]. The primary aim of this study is to apply the CE strategy in cement–sand mortar by replacing natural fine aggregates with recycled alternatives, including waste concrete aggregates, different types of brick aggregates, and crumb rubber of varying sizes. In all mixes, 15% of the natural sand was replaced with waste aggregates. An experimental program was conducted to compare the workability of mortars incorporating these different recycled materials. This study is particularly significant as it addresses the urgent need for sustainable construction practices by applying the CE principles in mortar production. Its novelty lies in the comparative evaluation of multiple recycled aggregates, especially crumb rubber, which improves workability while reducing the environmental impacts. By exploring effective alternatives to natural sand, this research contributes valuable insights into the development of eco-friendly building materials and supports the broader shift toward sustainable construction.

II. TEST PLAN

Three categories of recycled aggregates were considered. The first is RCA, produced by crushing waste concrete. The second category comprises CB aggregate, subdivided into four types of CBA, CBB, CBC, and CBD, representing different sources or processing methods. The third category includes rubber aggregates derived from waste rubber products, prepared in three gradings labeled as RB40, RB20, and RB10. In these mortar mixes, mineral waste aggregates (RCA, CBA, CBB, CBC, and CBD) were used to replace 15% of the sand content by mass. For the rubber aggregates (RB40, RB20, and RB10), 15% of the sand was replaced by volume to account for the differences in density and physical properties. The goal was to create more sustainable mortar mixes that reduce the reliance on virgin sand while managing the waste materials effectively. A key property evaluated in this study was the workability, which is essential for the practical mixing, placing, and finishing of mortar. To assess this property, flow tests were performed following a standard method presented in [16] for measuring the spread of hydraulic cement mortar. As summarized in Table I, a total of 27 different mixes were prepared to systematically examine the effects of the aggregate type and w/c ratio on workability. Three w/c ratios were used: 0.4, 0.5, and 0.6. To clearly identify each mix, a consistent three-part naming convention was adopted: the first part indicates the mix type (CM for control or the recycled aggregate designation), the second denotes the fixed 15% fine aggregate replacement level, and the third specifies the w/c ratio. This experimental design enables a detailed investigation of how different recycled aggregates and varying w/c ratios affect the mortar workability. The findings aim to support the development of sustainable construction materials that help reduce the waste disposal burdens and the environmental impact of the natural resource extraction.

TABLE I. SUMMARY OF ALL SAMPLES TESTED IN THIS WORK

No.	Mix ID	Natural sand kg/m^3	Recycle fine aggregate kg/m^3	Water kg/m^3
1	CM-00-04	1067	-	192
2	CM-00-05	1067	-	240
3	CM-00-06	1067	-	288
4	RCA-15-04	907	160	192
5	RCA-15-05	907	160	240
6	RCA-15-06	907	160	288
7	CBA-15-04	907	160	192
8	CBA-15-05	907	160	240
9	CBA-15-06	907	160	288
10	CBB-15-04	907	160	192
11	CBB-15-05	907	160	240
12	CBB-15-06	907	160	288
13	CBC-15-04	907	160	192
14	CBC-15-05	907	160	240
15	CBC-15-06	907	160	288
16	CBD-15-04	907	160	192
17	CBD-15-05	907	160	240
18	CBD-15-06	907	160	288
19	RB40-15-04	907	43	192
20	RB40-15-05	907	43	240
21	RB40-15-06	907	43	288
22	RB20-15-04	907	39	192
23	RB20-15-05	907	39	240
24	RB20-15-06	907	39	288
25	RB10-15-04	907	36	192
26	RB10-15-05	907	36	240
27	RB10-15-06	907	36	288

III. MATERIALS

In the present study, all cement–sand mortar compositions were prepared using the "Hybrid Innovative Eco-Friendly Cement" developed by Siam Cement Group (SCG), known for its sustainable formulation and reduced environmental impact compared to conventional Portland cement. The fine aggregate used in the control and modified mixes consisted of locally sourced natural river sand. The sand exhibited a specific gravity of 2.42 and a bulk density of 1481 kg/m³, while only particles passing through a No. 4 sieve (4.75 mm aperture) were utilized to ensure consistency in particle grading and to eliminate the coarser materials that could alter the workability or mechanical properties of the mortar. The inorganic waste materials comprised concrete waste aggregates RCA and brick waste aggregates, specifically categorized as CBA, CBB, CBC, and CDC, which were obtained from demolished infrastructure and construction debris. Only those particles passing through a No. 8 sieve (2.36 mm aperture) were selected for incorporation into the mortar as replacements for the natural sand. In addition to the recycled construction materials, rubber-based waste from the automotive and industrial sectors was also incorporated in the form of finely graded rubber particles. The finest grade, designated as RB40, consisted of rubber particles passing through a No. 50 sieve (300 µm) and retained on a No. 200 sieve (75 µm). The intermediate grade, RB20, included particles passing through a No. 16 sieve (1.18 mm) and retained on a No. 100 sieve (150 µm). The coarsest fraction, RB10, comprised particles that passed through a No. 4 sieve (4.75 mm) and were retained on a No. 16 sieve (1.18 mm). These gradations were specifically chosen to analyze the effects of the particle size on the workability and mechanical performance when used as volumetric replacements for natural fine aggregates.

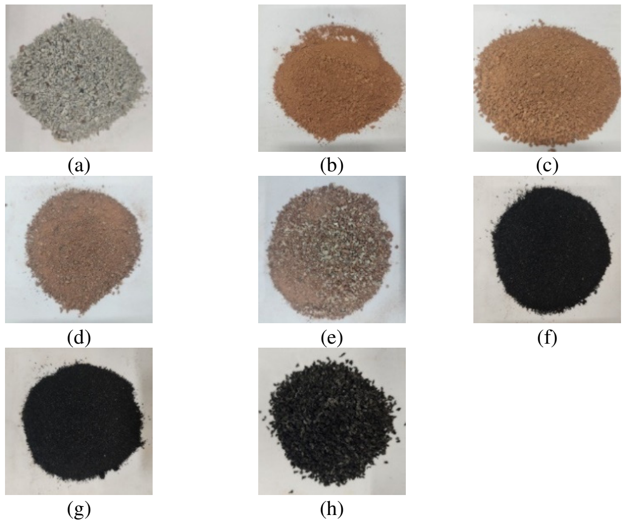


Fig. 1. Waste fine aggregate used in this experiment: (a) RCA, (b) CBA, (c) CBB, (d) CBC, (e) CBD, (f) RB40, (g) RB20, (h) RB10.

IV. SAMPLE PREPARATION & MIXING

All mortar mixes were prepared using ordinary SCG hybrid cement, natural river sand, and the selected recycled aggregates. The recycled concrete and brick aggregates (RCA, CBA, CBB, CBC, and CBD) were dried to remove moisture, while the rubber aggregates (RB40, RB20, and RB10) were cleaned to remove any foreign materials. For each mix, 15% of the natural sand was replaced with recycled aggregate, by mass for mineral waste and by volume for rubber aggregates. The materials were weighed accurately based on specified w/c ratios of 0.4, 0.5, and 0.6. Mixing was performed manually to simulate typical site practices. Dry materials were first blended thoroughly to ensure an even distribution of the recycled aggregates before water was gradually added. Mixing continued by hand until a uniform and workable mortar was achieved. The prepared samples were then tested immediately for workability using the [16] flow table test.

Fig. 2. Mixing of mortar, (a) materials and (b) mixing.

V. WORKABILITY TEST

The flow test described in [16] was performed using a mini cone mold, with the equipment specifications following those in [17]. The mold had a top diameter of 70 mm, a bottom diameter of 100 mm, and a height of 50 mm. The flow table measured 254 mm in diameter with a drop height of 12.7 mm. During testing, the mortar mix was placed in the mini cone mold, which was then lifted vertically. The table dropped 25 times within 15 s. The flow was determined by measuring two perpendicular diameters of the spread, and the average of these values was recorded as the flow of the mortar.

Fig. 3. Flow test equipment.

VI. RESULTS

The flow characteristics of cement-sand mortars incorporating various replacement materials were evaluated at three w/c ratios: 0.4, 0.5, and 0.6. The results, measured in mm, revealed considerable differences in workability depending on the type of aggregate or the replacement material used. As shown in Figure 1, 100 mm of flow was observed at a w/c ratio of 0.4 for the Control, RCA, and all CB mixes, indicating an insufficient water content to initiate the flow in these mortar systems. This suggests that a w/c ratio of 0.4 is inadequate for workable consistency when using traditional or high-absorption aggregates. The Control Mix (CM), made with conventional aggregates, began to exhibit flow at a w/c of 0.5, reaching 165 mm, and increased to 220 mm at a w/c of 0.6, as shown in Figures 2 and 3. This reflects the expected trend of enhanced workability with increased water content. However, the complete lack of flow at 0.4 highlights the limited lubrication capacity in mixes containing only cement and sand without supplementary or flow-enhancing materials. The mortar containing Recycled Coarse Aggregates (RCA) also showed 100 mm of flow at a w/c of 0.4 (Figure 1) and only achieved 115 mm at w/c 0.5 and 190 mm at w/c 0.6. These lower flow values compared to the control mix are attributed to the high porosity and rough surface texture of RCA, which absorbs a significant portion of the mix water, reducing the amount of free water available for lubrication. This behavior confirms the need for water adjustment or admixture usage when incorporating RCA in mortar applications. Similarly, the Ceramic-Based (CB) aggregate mixes (CBA, CBB, CBC, and CBD) showed very low flow (100 mm) at the lowest w/c ratio of 0.4 (Figure 1), underscoring the limited workability of these mixes under low water conditions. At higher w/c ratios, however, some CB mixes showed moderate to good flow values. For example, CBC and CBD achieved 195 mm and 200 mm, respectively, at a w/c of 0.6 (Figure 3), approaching the flow level of the control mix. CBB, on the other hand, had the lowest flow among ceramics at 0.6 (160 mm), likely due to the angular and porous characteristics of the ceramic particles that increase the internal resistance. In contrast, the RB mixes (RB10, RB20, and RB40), which incorporated ground rubber by volume, displayed substantial flow even at the lowest w/c ratio. As portrayed in Figure 1, RB10 achieved 130 mm of flow at a w/c of 0.4 and increased to 270 mm at a w/c of 0.6 (Figure 3), which was the highest flow across all mixtures. RB20 and RB40 also maintained high flow values across all w/c levels, exceeding 250 mm at a w/c of 0.6. Although the rubber particles are angular in shape, their non-absorptive nature plays a crucial role in enhancing the workability. Because crumb rubber does not absorb water, a greater amount of free water remains available to lubricate the cement paste and fine aggregates, resulting in a significantly better flow behavior compared to the other mixes.

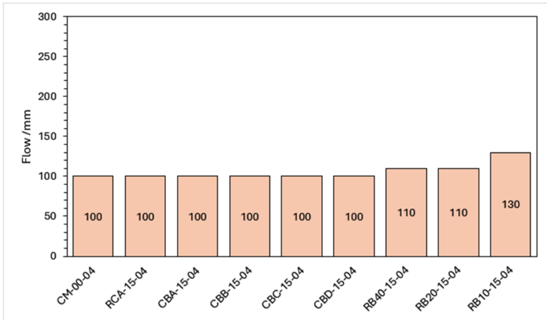


Fig. 4. Flow of mortar with w/c ratio of 0.4.

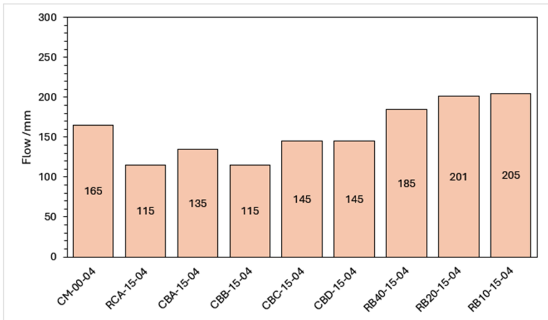


Fig. 5. Flow of mortar with w/c ratio of 0.5.

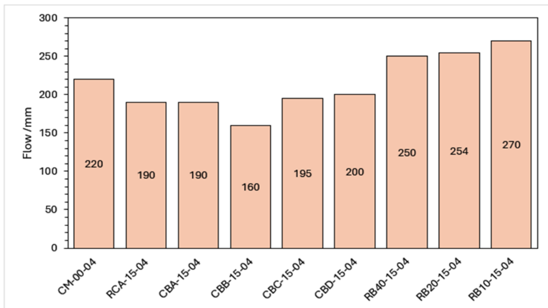


Fig. 6. Flow of mortar with w/c ratio of 0.6.

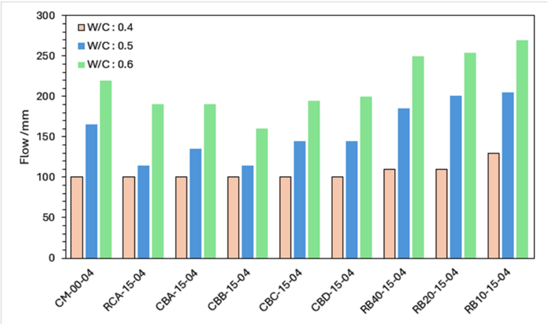
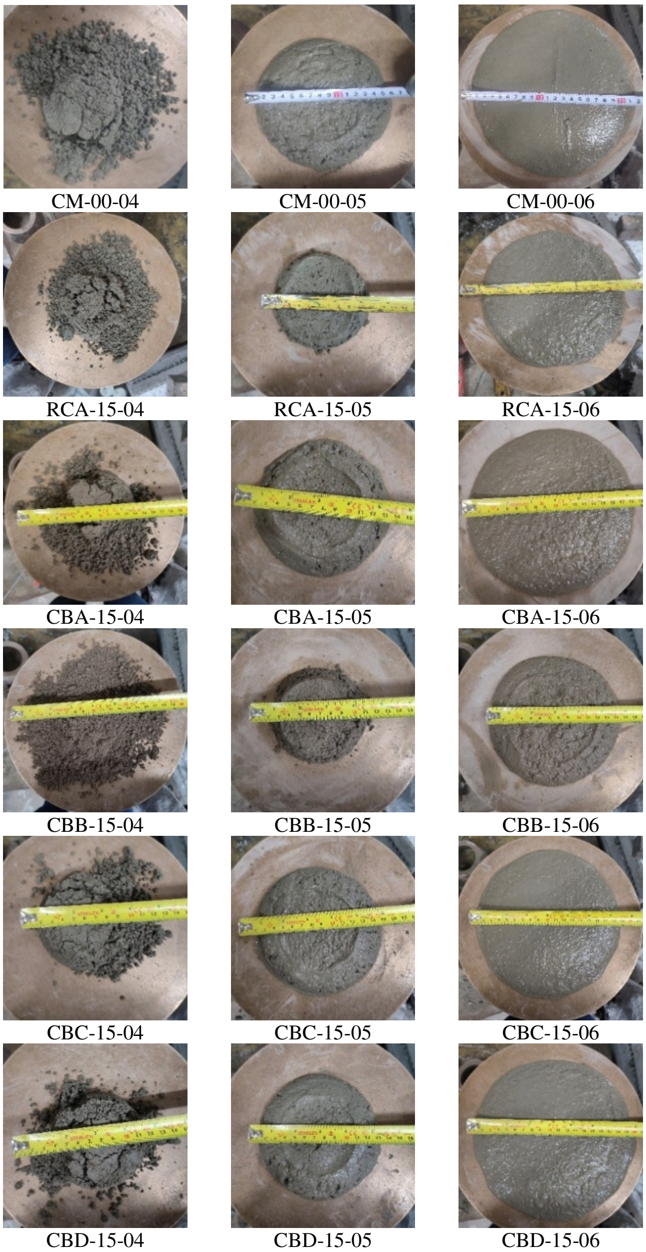


Fig. 7. Flow of mortar with different w/c ratios.



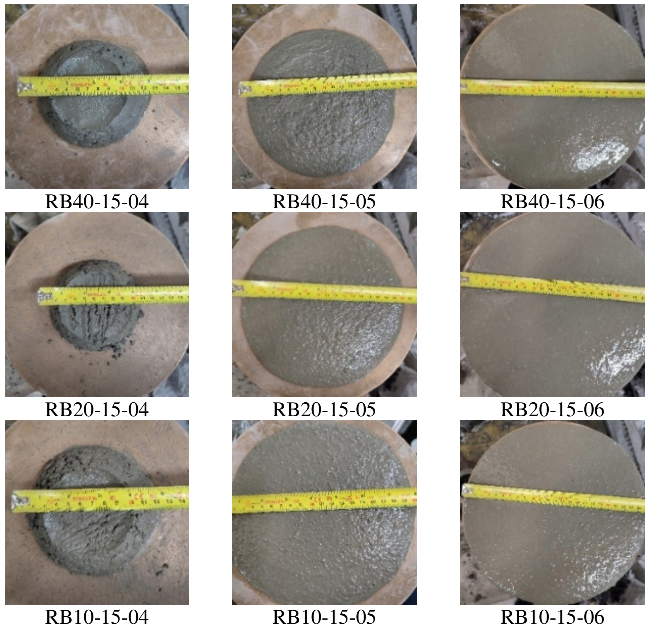


Fig. 8. Flow patterns of mixed designs observed in this work.

VII. DISCUSSION

This study provides important insights into the flow behavior of cement–sand mortars with different recycled aggregates across varying w/c ratios. The control mix with natural aggregates showed the expected trend: workability improved as the water content increased, reaching a flow of 220 mm at w/c = 0.6. In contrast, mortars with RCA and CB aggregates exhibited poor flowability, stagnating at 100 mm at w/c = 0.4. This limitation is linked to their high porosity and rough surface textures, which absorb water and reduce lubrication, a behavior complying with the findings in [14, 15]. Although some ceramic mixes performed moderately better at higher w/c ratios, they still fell short of the control. In sharp contrast, RB (RB10, RB20, RB40) demonstrated excellent workability, exceeding the 250 mm flow at w/c = 0.6. This superior performance is attributed to the non-absorptive nature of the crumb rubber, which preserves free water for paste lubrication. Overall, these results highlight the strong potential of rubber as a sustainable aggregate in mortar production while underscoring the need to carefully consider the aggregate type to balance the workability and performance.

VIII. CONCLUSIONS

The flow performance of cement-sand mortar incorporating recycled and alternative aggregates was evaluated at water-to-cement (w/c) ratios of 0.4, 0.5, and 0.6. Based on the results, the following conclusions can be drawn:

- RCA mortars exhibited limited workability, with 100 mm flow observed at a w/c of 0.4, and reduced flow values noted at higher w/c ratios compared to the control mix. The reduced flow is attributed to the high-water absorption capacity and roughness of RCA, which decreases the amount of free water available for lubrication.

- CB aggregate mortars also showed 100 mm flow at a w/c of 0.4, indicating poor workability under low water conditions. While the flow improved at higher w/c ratios, the performance varied among the ceramic mixes. CBC and CBD approached the flow values of the control at w/c 0.6, whereas CBB consistently showed the lowest flow, likely due to its angular and porous texture.
- The RB mixes, containing coarse crumb rubber, demonstrated superior flow across all w/c ratios. Unlike the RCA and CB mixes, the RB mortars exhibited measurable flow even at a w/c of 0.4. The enhanced workability is attributed to the non-absorptive nature of the crumb rubber, which retains free water in the mix and improves the paste mobility. RB10 recorded the highest flow of all mixes, reaching 270 mm at a w/c of 0.6.

Overall, increasing the w/c ratio improved flowability in all mortar types. However, the degree of improvement was highly dependent on the physical and absorptive characteristics of the aggregate. RB consistently outperformed the RCA and CB mixes in terms of flow, highlighting their potential for applications requiring enhanced workability. In contrast, the RCA and CB aggregates require careful water adjustment or admixture incorporation to achieve comparable performance.

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