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Experimental Investigation of Mortars with Diverse Sand Types

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Fine aggregates, particularly river sand (NS) and crushed sand (CS), play a key role in concrete production. However, the excessive extraction of river sand has become a serious environmental concern, encouraging the search for sustainable alternatives. This study investigates the feasibility of incorporating recycled sand (RS), obtained by crushing and grinding standard concrete cylinders (16 × 32 cm), as a partial replacement for NS and CS in ternary mortar mixtures, with substitution levels ranging from 20 % to 100 %. Mortars were prepared with a fixed water-to-cement ratio, and their fresh and hardened properties were evaluated in terms of workability, bulk density, water absorption (immersion and capillarity), and compressive strength at 3, 14, and 28 days. The results show that mortars containing up to 40 % RS maintain mechanical and physical performances comparable to those prepared with natural sand. Beyond this threshold, compressive strength decreases and water absorption increases. A strong correlation (R^2 = 0.98) was observed between dry density and water absorption, confirming the consistency of the results. Overall, the findings demonstrate that recycled sand produced from laboratory concrete specimens can be effectively used as a sustainable alternative in mortar production, contributing to resource conservation and reducing the environmental footprint of the construction sector.

Keywords: compressive strength, consistency, absorption, mortar, recycled sand.

1. INTRODUCTION

Concrete remains the most widely utilized construction material in modern civil engineering. Its manufacture requires substantial amounts of fine aggregates, particularly river and crushed sands. In recent times, the unsustainable extraction of river sand has raised significant environmental concerns, leading many governments to adopt regulatory measures aimed at curbing or eliminating illegal sand mining [1].

Crushed sand is generally produced by grinding stones using artificial processes. In addition to depleting natural resources, the manufacturing of crushed sand also contributes significantly to CO_2 emissions. [2]. On the other hand, recently, it has been reported that Construction-related waste generated during the demolition process of old or abandoned structures, has contributed to relatively large proportions of the total quantity of waste. It has been noted that, in numerous developing nations, landfilling is still the primary method of managing construction and demolition waste, which inevitably leads to contamination of water, atmosphere and soil, as well as saturation of discharges [3]. The construction sector has been reported to account for approximately 39 % of global CO_2 emissions [4], while the industrial sector consumes more than 50 % of natural resources [5]. These figures highlight the urgent need for sustainable practices in construction materials. In this regard, the use of alternative cementitious materials [6] and the reuse of solid waste from the demolition of buildings represent effective strategies. Such approaches are highly beneficial to the environment, as they significantly reduce the demand for natural aggregates and lower CO_2 emissions generated by the extraction and transportation of raw materials.

Several research projects have assessed using recycled sands to replace natural ones in concrete manufacturing, either completely or partially. In this context, Khatib [7] carried out experimental investigations to evaluate the effect of using recycled fine sands, in place of natural ones at different proportions, on concrete's mechanical performance. They then found out that when natural sands were replaced by recycled ones at rates of 25 % and 100 %, compressive strength declined by 15 % and 30 %, respectively. Regarding Evangelista et al. [8], they indicated that no significant compressive strength reductions could be observed for recycled sand substitution percentages up to 30 %. As for Khoshkenari et al. [9], it was found that incorporating recycled sand into the mix reduced the concrete's mechanical properties. However, this reduction can be offset by the incorporation of fine natural aggregates of size between 0 and 2 mm. Regarding Parreira et al. [10], they suggested that incorporating a superplasticizer in recycled sand-based concrete improved its mechanical properties beyond those of control concrete. However, Fan et al. [11] presented two categories of recycled sand with different fineness moduli. According to the test findings, the use of recycled sand with its relatively low fineness modulus and minimal water absorption capacity contributes to maintaining the concrete's mechanical properties.

Regarding Jesus et al. [12], the results demonstrated that mortars incorporating CDW, finely ground to 0.149 mm, as a replacement for 20 % natural sand, saw their mechanical

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resistance increase. For their part, Azevedo et al. [13] replaced natural sand with the mentioned above waste at the rates of 25, 50 and 100 % to produce mortar. They then found out that the 25 % substitution rate was the most appropriate to achieve mortars with better compactness and the highest mechanical strengths.

Even though recycled sand has been the subject of considerable research, its integration into concrete applications remains limited, primarily due to its specific physical properties, which tend to compromise compressive strength and workability [14].

This study explores the feasibility of substituting crushed sand (CS) and natural sand (NS) with recycled sand (RS) in ternary mortar compositions, with replacement levels varying between 20 % and 100 %. The study evaluates compressive strength, consistency, water absorption and densities.

The results indicate that adding recycled sand reduced mortar workability and increased water absorption, largely attributable to the elevated internal porosity of the recycled particles. Higher absorption and lower density were noted for all substitution rates. Moreover, compressive strength dropped significantly when the replacement rate exceeded 40 % by weight.

2. EXPERIMENTAL DETAILS

2.1. The materials used

A Portland cement of type CEM II/A-L 42.5 N, sourced from the Ain Touta cement plant (Algeria), was used in this study. Its Blaine fineness is 3371 cm²/g. The detailed chemical composition is given in Table 1.

Table 1. Chemical composition of the cement employed

%	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	P.A.F
CEM II	20.34	5.37	3.0	61.69	1.80	2.20	5.03

Three types of sand with a 0 – 5 mm fraction were used for the preparation of the mortar mixes (see Fig. 1).

Fig. 1. Photograph of the three types of sand used in this study

Natural Wadi sand (NS) was locally collected from the Lioua region (Biskra-Algeria) and is mainly silica-based. Crushed quarry sand (CS) was sourced from the Ain-Touta region (Batna-Algeria) and is limestone-based. Recycled sand (RS) was obtained by crushing and grinding ordinary concrete specimens (16 × 32 cm) and consists of residual cement paste and aggregate fragments. The particle size distribution curves of these sands are presented in Fig. 2.

2.2. Composition and methods

Mortar compositions were prepared using a cement-to-sand ratio of 1:3 by weight. In these mortars, crushed sand (CS) and natural sand (NS) were partially or fully replaced by recycled sand (RS) at substitution levels ranging from 20 % to 100 %, as detailed in Table 2. The water-to-cement ratio (W/C) was maintained at 0.7 for all mixes.

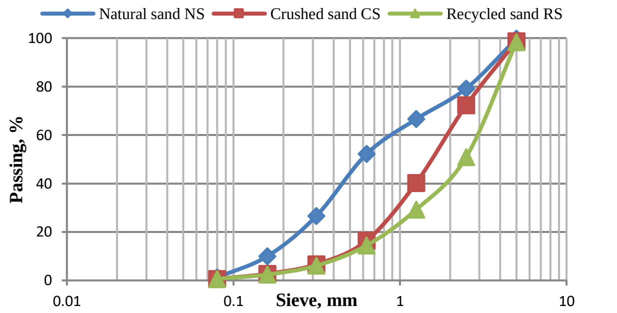

Fig. 2. Granulometric analysis of sands used in this study`

Table 2. Mix design of the studied formulations

Mix	% natural sand (NS)	% crushed sand (CS)	% recycled sand (RS)	C, g	W/C
1	100	0	0	450	0.7
2	0	100	0	450	0.7
3	40	40	20	450	0.7
4	33.33	33.33	33.33	450	0.7
5	30	30	40	450	0.7
6	20	20	60	450	0.7
7	10	10	80	450	0.7
8	0	0	100	450	0.7

Mortar prisms measuring 4 × 4 × 16 cm³ were cast according to the EN 196-1 specification [15]. After casting, all samples were cured in water until testing.

Mechanical tests were carried out after 3, 14, and 28 days of curing, whereas capillary water absorption was measured at 28 days following water curing. Workability was evaluated using a mini-slump test, following the European specification EN 1015-3 [16]. The test involved filling a mini-cone. The cone was subjected to 15 successive jolts by raising the shaking table to a height of 10 mm and allowing it to drop freely. After this, the cone was carefully removed. Measurements of the mortar spread were taken along two perpendicular axes, and their average was recorded as the representative value.

Regarding the water absorption test by immersion, it involved putting the mortar test pieces of dimensions (4 × 4 × 16) cm^3 in the oven and then weighing them until they reached a constant weight. They were next immersed completely in water for a period of 72 hours, i.e. until the material was saturated, in conformity with the requirements of the European Standard EN 13369 [17]. The absorption coefficient by immersion A_b is given by the following relationship:

$$A_b = \frac{M_a - M_s}{M_s} \times 100, \qquad (1)$$

where M_s and M_a are the dry and saturated masses of the sample, respectively.

The capillary water absorption test involved recording, through successive weighings, the mass of water retained by pre-dried specimens. This method can also serve as an indirect means of characterizing capillary porosity. The mortars' capillary absorption was assessed after being water-cured for 28 days. The literature presents a range of procedures for testing. In the present study, it was decided to adopt a variant of the operating method proposed by AFREM (AFPC-AFREM) [18].

It is worth emphasizing that three samples of dimensions $(4 \times 4 \times 16)\ \mathrm{cm}^3$ were prepared from each formulation. This test was performed to assess the rate at which unsaturated mortar samples absorb water through capillary action when exposed to water without any applied pressure. The absorption rate can be determined using the following formula:

$$Ca_t = \frac{M_t - M_0}{A}, \quad (2)$$

where Ca_t is the absorption coefficient at maturity t, kg/m²; A denotes the sample's cross-sectional area, m²; M_0 represents the specimen's initial mass, kg; M_t corresponds to its mass measured at time t, kg.

3. RESULTS AND DISCUSSIONS

3.1. Workability test

Fig. 3. presents the spreading results of mortars incorporating recycled sand at various replacement levels. The workability of the mortars was assessed using the flow table test in accordance with EN 1015-3 [16], in which fresh mortar is subjected to 15 drops from a specified height, and the resulting spread diameter is measured.

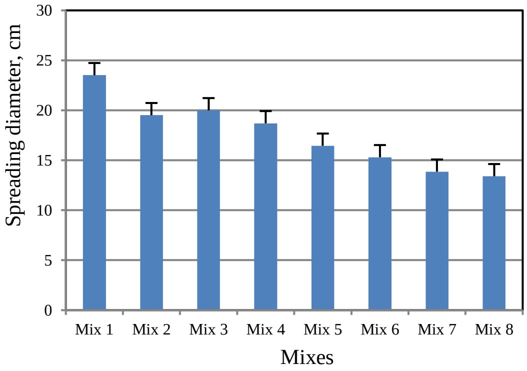

Fig. 3. Spreading diameter of the different mixes

The measured spreading diameters ranged from 13.4 to 23.5 cm. Mix 8, containing 100 % recycled sand, exhibited the lowest spreading diameter, demonstrating that high recycled sand content significantly reduces mortar workability. A decrease in flowability of approximately 18 % was observed at a recycled sand content of 40 %, reaching up to 43 % at full replacement. This reduction is primarily attributed to the higher water absorption of recycled sand compared to natural aggregates. In this context, Gomes et al. [19] reported that adjusting the water content to achieve a spreading diameter between 16 and 17.6 cm corresponds to excellent workability.

3.2. Fresh density

The fresh density of the mortar was determined in accordance with EN 1015-6 [16] by filling a container of known volume with fresh mortar, compacting it in two layers, striking off the surface, and weighing the filled container. The density was then calculated as the ratio of the net mass of mortar to the container volume.

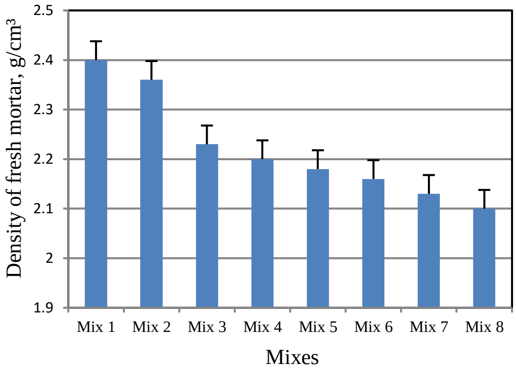

Fig. 4. Bulk density of fresh mortar

As shown in Fig. 4, the apparent density decreases progressively with increasing proportions of recycled sand (RS). For a mortar containing 40 % RS, the density decreases by approximately 9 % compared with the mix with 100 % natural sand (NS), while a full replacement with 100 % RS results in a reduction of about 12.5 %. This reduction is mainly attributed to the lower intrinsic particle density of RS compared with NS. These findings are in agreement with previous studies [20 – 22], which similarly reported that the use of recycled sand leads to lower fresh densities due to its inherent material properties.

3.3. Density in hardened state

The 28-day bulk density of the hardened mortar specimens is illustrated in Fig. 5. The determination was carried out following the procedure described in EN 1015-10 [16]. After curing for 28 days under water at 20 ± 2 °C, the specimens were first surface-dried with a damp cloth and then oven-dried at 105 ± 5 °C until a constant mass was reached. The bulk density was calculated as the ratio of the dry mass to the apparent volume of the specimen, the latter being obtained from its geometrical dimensions (40 × 40 × 160 mm prisms). This parameter provides valuable information on the compactness and porosity of the mortar: higher bulk density generally indicates better packing of particles and lower void content. The results clearly highlight the effect of recycled sand incorporation on the compactness of the mixtures, with a gradual reduction in density observed as the substitution level increases.

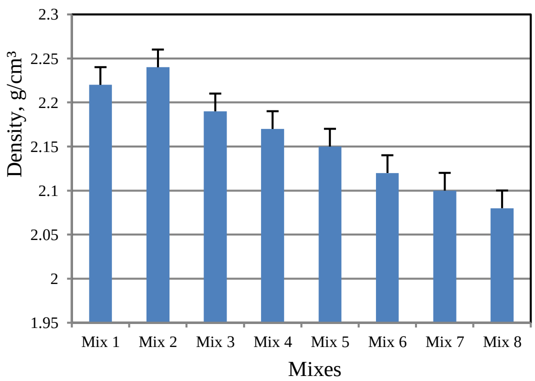

Fig. 5. Bulk density of hardened mortar

As shown in Fig. 5, mortars incorporating recycled sand exhibit slightly lower hardened bulk density compared to those made with natural aggregates. In the present study, replacing 40 % of natural sand with recycled sand led to a density reduction of approximately 3.2 %, while full replacement (100 % recycled sand) resulted in a decrease of about 6.3 %. These trends are consistent with the literature: Cuenca-Moyano et al. [23] reported that the use of pre-soaked recycled fine aggregates in masonry mortars caused a reduction in hardened density, particularly at high replacement levels, and Plaza et al. [24] observed similar decreases in density with increasing amounts of recycled fine aggregate derived from crushed concrete blocks. The agreement between these findings and the present results confirms the reliability of the observed trend and highlights the influence of the lower intrinsic density and higher porosity of recycled sand particles on the microstructure of mortars.

3.4. Water absorption test by immersion

A 28-day immersion test was performed to evaluate the internal porosity of the mortars, in accordance with the procedure described in NF EN 13369 [17]. After curing, the specimens were first oven-dried at 105 ± 5 °C until reaching a constant mass, then fully immersed in water at 20 ± 2 °C for 24 hours. The water absorption by immersion was calculated as the percentage increase in mass relative to the dry mass. This parameter provides an indirect assessment of the open porosity and permeability of the hardened mortar. The corresponding results are presented in Fig. 6, highlighting the effect of recycled sand incorporation on the material's pore structure.

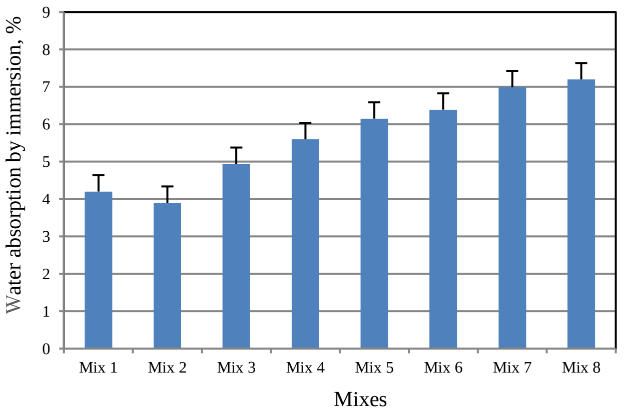

Fig. 6. Water absorption by immersion of mortar samples

Fig. 6 shows that the water absorption by immersion increased with the recycled sand content. This trend can be attributed to the higher porosity and absorption capacity of recycled sand particles compared to natural or crushed sand. Similar findings have been reported in previous studies [25], confirming that the use of recycled fines generally enhances water uptake due to their porous microstructure. In the present work, the maximum absorption rate was recorded after (72 ± 2) hours of immersion, reaching 7.2 % for Mix 8 (100 % RS), whereas the lowest value of 3.9 % was obtained for Mix 2 (100 % CS). It is generally accepted that high-quality concretes and mortars should exhibit water absorption values below 10 % [26]. Accordingly, all the mixtures tested in this study remained within this limit, indicating that despite the higher absorption associated with recycled sand, the mortars produced still meet the requirements for good quality materials.

3.5. Water absorption and density

In general, recycled aggregates are characterized by lower bulk density and higher water absorption compared to natural aggregates [27], mainly due to the porous cement paste residues attached to their surfaces. This residual paste, being considerably less dense than natural aggregates, contributes to the overall reduction in density. As a result, the density of recycled materials decreases progressively with increasing amounts of attached cement paste [28].

Fig. 7. shows a strong linear relationship between dry density and water absorption expressed by the regression equation $y = -21.491x + 52.066$, with a coefficient of determination $R^2 = 0.98$. This high correlation indicates that as dry density increases, water absorption decreases markedly, confirming that a denser microstructure reduces porosity and improves the compactness of the mortar matrix. Similar trends have been reported in the literature: Xu et al. [29], observed an inverse relationship between dry density and water absorption in mortars with $R^2 = 0.94$, while Usman et al. [30], reported comparable findings with $R^2 > 0.95$. Wan et al. [31], further demonstrated that low-density mortars exhibited higher water absorption, reinforcing the inverse correlation. These results confirm that the observed relationship holds consistently, regardless of the recycled material's size, type, or source, supporting the previous interpretation of the mortar's microstructural behavior.

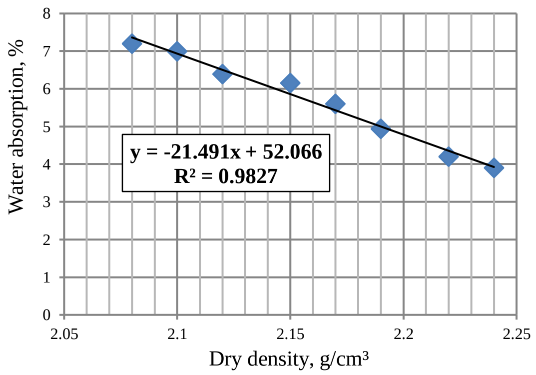

Fig. 7. Correlation between dry density and water absorption

3.6. Capillary water absorption test

Capillary water absorption is widely recognized as a key parameter for evaluating mortar durability. Previous research has shown that mortars with high capillary absorption generally display lower resistance to long-term deterioration [32]. This behavior is explained by the fact that water, often containing dissolved salts and aggressive agents, can penetrate through the capillary pore network and reach deeper layers of the material, thereby accelerating degradation mechanisms such as leaching, carbonation, or sulfate attack [21]. It is therefore important to emphasize that capillary absorption is strongly influenced by the internal structure of the mortar. A dense and well-compacted matrix, characterized by a finer and less interconnected pore system, significantly limits water ingress and thus improves durability [33].

In this study, capillary absorption was determined according to the AFPC-AFREM recommendations [18]. The capillary water absorption test was carried out on prismatic mortar specimens (40 ×40 × 160 mm) after 28 days of curing. Prior to testing, the specimens were oven-dried at 105 ± 5 °C until constant mass was reached, then cooled in a desiccator to prevent superficial moisture uptake. The lateral faces were sealed with an epoxy coating so that water could only penetrate through the bottom face. The specimens were placed in a tray with a constant water level of approximately 5 mm in contact with the base. The mass increase due to water uptake was periodically recorded at fixed time intervals (15, 30, 60 min, 2, 4 and 24 h).

The results were expressed in terms of capillary absorption (mm³/mm²), calculated as the volume of water absorbed per unit surface area. The absorbed water was then plotted as a function of the square root of time (√t), which highlights the kinetics of capillary suction.

Fig. 8 presents the capillary water absorption values for all tested mixtures. The results indicate that water absorption increases progressively with higher replacement rates of natural aggregates by recycled sand.

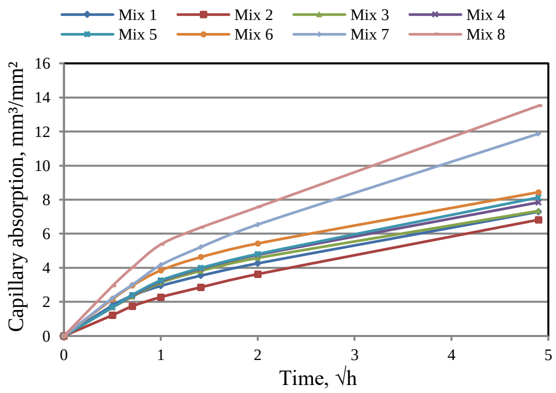

Fig. 8. Change in the capillary water absorption of mortars

Water absorption generally increases with respect to the square root of time. However, the graph reveals two distinct phases in the curve, each exhibiting a different trend:

1. The initial segment of the curve, which displays a steep slope, corresponds to the rapid absorption of water into the larger capillary pores. This stage is known as initial absorption.
2. The second portion, showing a more moderate slope, represents the slower penetration of water into finer pores, a process commonly referred to as sorptivity.

This figure shows that the mortars under study have almost constant initial absorption values for a replacement rate between 20 and 40 %. The mortar with the highest capillary absorption rate corresponds to Mix 8 (100 % RS).

3.7. Compressive strength test

The compressive strength of the mortars was defined as the maximum load at failure divided by the cross-sectional area of the specimen. Tests were carried out on 40 × 40 × 40 mm³ mortar prisms, in accordance with EN 196-1 [15]. Each specimen was first subjected to a flexural strength test, producing two halves, which were then tested under compression. The loading was applied using a universal testing machine at a constant rate of 2.4 kN/s, as specified in EN 196-1 [15]. The results after 3, 14, and 28 days of water curing are presented in Fig. 9, showing the influence of recycled sand proportion on the development of compressive strength.

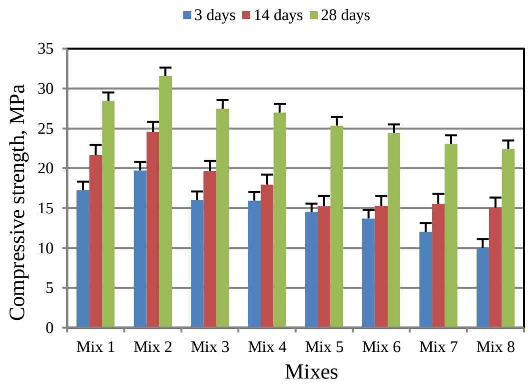

Fig. 9. Development of the compressive strength of mortars for different mixes

Fig. 9 shows that recycled sand-based mortars develop lower compressive strength compared to the control mix prepared with natural sand, the difference increases proportionally with the level of recycled sand used in the mixture. The experimental results show a reduction in 28-day compressive strength by 3.37 %, 5.09 %, 10.82 %, 14.09 %, 18.91 % and 21.16 % for the recycled sand replacement rates of 20 %, 33.33 %, 40 %, 60 %, 80 % and 100%, respectively.

In comparison, Khatib [7] reported that replacing fine natural aggregate with crushed concrete resulted in strength reductions of 15 – 30 %, the strength loss was limited to approximately 10 %. Evangelista et de Brito [8], found that substitution levels of up to 30% fine recycled concrete sand do not compromise the mechanical properties of masonry mortars. More recently, Mora-Ortiz et al. [21] indicated that recycled mortar aggregates can provide acceptable performance up to a 60 % replacement, depending on the mix design and curing conditions, while Kępniak & Łukowski [34] observed that strength reductions become less significant over longer curing periods, allowing satisfactory performance even at higher replacement levels (up to 80 %).

These observations are consistent with our results: within the 20 – 40 % substitution range, strength losses remain relatively low (< 11 %), aligning with Khatib's findings, Evangelista & de Brito's 30 % threshold. Beyond this range, compressive strength declines more noticeably. Therefore, the 40 % substitution limit identified in our study represents a balanced compromise between resource sustainability and mechanical performance, while taking into account the type, origin, and quality of the recycled sand.

4. CONCLUSIONS

This study evaluated the feasibility of incorporating recycled sand (RS) as a sustainable alternative to natural sand (NS) and crushed sand (CS) in mortar production, with substitution levels ranging from 20 % to 100 %. Mortar mixtures were prepared and tested for workability, bulk density (fresh and hardened), water absorption (immersion and capillarity), and compressive strength at 3, 14, and 28 days. The main findings can be summarized as follows:

1. The incorporation of RS significantly reduced mortar workability. At substitution levels between 20 % and 40 %, the flow diameter decreased by about 15 – 30 % compared with the reference mix, while at 100% RS replacement, the reduction reached approximately 43 %, mainly due to the higher water absorption capacity of recycled sand.
2. The use of recycled sand reduces both the fresh density and the hardened bulk density of mortars. Reductions of about 9 % (40 % RS) and 12.5 % (100 % RS) were observed for fresh density, while hardened bulk density decreased by approximately 3.2 % and 6.3 % at the same replacement levels. These reductions are attributed to the lower intrinsic density and higher porosity of recycled sand compared with natural sand.
3. The incorporation of recycled sand increased water absorption from 4.2 % for mortars with 100 % natural sand (NS) and 3.9 % with 100 % crushed sand (CS) to 7.2 % for mortars with 100 % recycled sand (RS), reflecting the higher porosity of recycled particles. Nevertheless, all mixtures remained below the 10% threshold generally required for good-quality mortars, confirming that recycled sand can be employed as a sustainable alternative without compromising material performance.
4. A strong linear correlation ($R^2 = 0.98$) was established between dry density and water absorption. At 100 % RS, absorption by immersion increased from 4.2 % NS to 7.2 %, representing nearly a 70 % increase, while capillary absorption nearly doubled. At substitution levels between 20 % and 40 %, absorption values remained close to those of NS mortars.
5. The reduction in compressive strength is proportional to the level of recycled sand incorporation, reaching 10.82 % at 40 % replacement and up to 21.16 % at full replacement (100 %). Within the 40 % substitution range, losses remain relatively limited (< 11 %), confirming that 40 % replacement represents the most balanced compromise between sustainability and mechanical performance, depending on the type, origin, and quality of the recycled sand.

Overall, the results confirm that recycled sand can replace natural sand up to 40 % without significant performance loss, providing a viable pathway for sustainable mortar production. This promotes resource conservation and construction waste valorization. Future research should investigate the long-term durability and performance of RS-based mortars under different exposure conditions.

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