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Valorization of concrete and brick waste as sustainable alternatives in Lime Mortar: physical, mechanical, and durability performance

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ABSTRACT

It is common knowledge that the construction sector impacts the environment significantly by contributing into waste generation, pollution, and resource depletion. In regards with these issues, countries with an advanced status like Morocco have become clearly noticeable due to the lack of policies in place to handle construction and demolition waste (CDW). The valuation of these wastes is an opportunity to provide sustainable alternatives for traditional construction materials while highlighting the circular economy concept, therefore reducing environment footprint. This research investigates sustainable reuse of recycled concrete aggregates (RCA) and brick powder (BP) as alternatives to natural sand and lime in producing lime mortar. Three different mortar compositions were produced with a constant BP component (30%) along with varying RCA levels (20%, 40% and 60%) and then experimentally tested in terms of density, compressive and flexural strength, porosity, water absorption, and durability after 28 and 90 days. The results show that integrating RCA decreased density and increased porosity; while adding BP improved compactness and water resistance because of BP's pozzolanic properties. The peak performance occurred at a 20% RCA concentration. This concentration provided a superior balance between the important pozzolanic benefits and the greatly diminished weaknesses induced by the RCA. This study confirms the feasibility of manufacturing eco-friendly lime mortars using recycled construction materials. In addition to encouraging ecological sustainability and reducing numerous waste disposal issues, eco-friendly lime mortars offer a sustainable alternative to several conventional mortars with a large potential for the rehabilitation and restoration of the country's historic monuments, thus preserving the cultural heritage.

Keywords: sustainable construction materials, lime mortar, masonry material innovation, mechanical performance assessment, circular economy.

INTRODUCTION

The construction industry generates huge amounts of construction and demolition wastes (CDWs), which significantly impacts the environment. This continuous activity causes a notable effect on the ecosystem, including the depletion of natural resources along with landfills pollution and greenhouse gas emissions (Sulistyaningsih 2020). Around 40% of the world's energy-related carbon dioxide emissions are attributable to this field, with buildings alone responsible for about 28% of these emissions (Ahmed Ali, Ahmad, and Yusup 2020). Due to the significant contribution of the construction industry to the global carbon footprint, efforts toward sustainability should be prioritized within this sector. It is essential to take steps to address this problem by encouraging the reuse and recycling of these materials in favor of promoting a circular economy and sustainable development. Since sand is the second most consumed natural resource globally after water, producing this raw material from CDW will decrease the global demand for natural sand, which is responsible for 85% of the global demand in the construction industry and will help minimizing the environmental impacts from the extraction (The United Nations Environment Programme, 2023). As sand is fine and free from impurities, it ensures the desired properties of a mortar (Stefanidou and Koltsou, 2022). For bricklaying and other masonry applications, three parts sand are used to one part cement or lime. The addition of sand as an aggregate to the binding system is a critical factor in the quality and performance of the final product (Stefanidou and Koltsou, 2022).

One of the traditional binding systems that has been used for centuries in masonry construction, is Lime. It is a limestone-based binder, that has become a forgotten proficiency over time. However, it regained popularity thanks to its environmental benefits, in comparison to other hydraulic binders (Hughes, et al., 2019). Lime produces fewer greenhouse gases and its local production lowers transportation costs and ecological effect, consequent in a more ecologically friendly option. Furthermore, it possesses several helpful physical, aesthetic and health properties. These include its readily achievable adhesion, ease of workability, smoothness across all substrates, important permeability to water vapor coupled with waterproofness, a substantially longer lifespan, and, lastly, its protection against the effects of shear forces, wall deformations and a large range of microorganisms, fungi and molds (Association Technique de L'Industrie Des Liants Hydrauliques (ATILH, 2021). Finally, lime's ability to be reused or recycled makes it an eco-friendly choice and a sustainable material (El-Bichri et al., 2024).

Since, many historic constructions were built using lime mortar as binding material, this material plays a crucial role in masonry's history, and it automatically has a significant connection to the rehabilitation of old constructions now days. Using cement-based mortar in restoration projects can lead to irreparable damage to the structure due to its rigidity. The use of lime mortar in the rehabilitation of old constructions is not only a practical solution but also a preservation of cultural heritage, maintenance of the authenticity and character of historic structures for future generations.

Mechanical behavior of lime-based mortar varies in accordance with several factors, in which the type and proportion of used sand aggregate is primary (Marvila et al., 2019; Raini et al., 2022; Raj and Shrivastava, 2024). This building material is not uniform in composition (homogeneous material). Sand aggregates play a role as inert fillers in the composition of mortars; They reduce the shrinkage phenomena by giving volume to the mortar, increase the resistance by their hardness and their formed structure, and also reduce the quantity of the binder in accordance with their qualities (granulometry, aggregate shape, organic and salt free) (Dibdin 2023). Finally, the choice of sand type depends on the specific application and desired properties of the mortar mixture.

Mortars have historically utilized sands of various origins. Indeed, using sand originating from CDW redress the rarity of good natural sand as well as meeting the sand mining regulation. (Azevedo et al., 2020; Cao et al., 2022; Jesus et al., 2019). Researchers examined the use of recycled sand in mortars, either partially replacing natural sand or employing it entirely as a fine aggregate (Garg and Shrivastava, 2023; Khelafi et al., 2023; Ma et al., 2022). Yet, a few studies, showed that using RA proved to enhance the workability, strength, and durability of mortar (Aalil et al., 2019; Ayat et al., 2022; Letelier et al., 2019; Naciri et al., 2022) showed that mechanical properties of recycled aggregate mortar reach its optimal value along with its high practicability when replacing river sand by 40% of recycled aggregate.

The one-part lime in a mortar holds the mortar together and can be partially replaced, as long as the used material exhibits pozzolanic activity to form calcium silicate hydrates. These hydrates enhance the mechanical properties of the mortar improving its durability and resistance to water absorption (Brzyski, 2018; Pachideh et al., 2020).

On the other hand, Morocco witnessed a high volume of construction activities due to the rapid expansion of urban areas which led to a significant increase in the amount of construction wastes (AFRIK, 2024). Regarding Morocco's tradition and culture, the use of fired clay bricks in construction is deeply rooted because of their availability, low cost of production, and their durability. Consequently, huge amounts of brick wastes are generated and has great potential to be reused or recycled instead of being disposed of in landfills, leading to environmental and economic challenges (David Packer, 2023).

This study aims to investigate the possibility of developing an eco-friendly mortar for practical applications in masonry by using brick dust and recycled concrete aggregate to replace lime and sand, respectively. As mentioned above, lime, known for its ability to improve workability and durability, acts as a constant stabilizing agent in the mortar structure. Several studies have developed lime mortar using recycled aggregates, resulting in reduced durability and mechanical properties (Catalin et al., 2024; Ferreira et al., 2020). Since sand takes up a large portion of mortar, its mechanical and structural properties have a significant impact on overall performance. However, brick dust has been proven to be beneficial for lime mortar (Su-Cadirci et al., 2023). Therefore, based on existing research, this paper evaluates the properties of mortar by varying the amount of natural sand replaced with recycled concrete aggregate while maintaining a constant lime/brick powder ratio. This approach may represent a strategically advantageous decision aimed at achieving optimized and controlled analysis. Incorporating various waste types will reduce the need for primary resources, support circular economy, and might as well create sustainable and durable construction materials (Haigh, 2023; Shukla et al., 2024). Mechanical and chemical properties of different mix proportions are investigated to assess their potential as a sustainable alternative for masonry construction.

MATERIALS AND METHODS

Preparation of raw materials

Local materials from the Fez-Meknes region of Morocco were used to prepare different mortar mix design for the study. Using limestone that is quarried from the surrounding areas of Sefrou (Fig. 1), aerial lime (AE) is produced and ready to be used in mortar and plaster thanks to its high calcium carbonate content (Oliveira and de Souza 2022).

Two types of sand were utilized in this study. One natural sand (NS) originating from Sefrou quarries, which was used as a reference material for reference mortar. The other sand is a recycled sand (RS) obtained from CW at a pipe plant, also located in the Sefrou area; This RA was used in the experimental mixes as a partial replacement for NA (Fig. 3).

On the other hand, brick powder (BP) from brick wastes (BW) were collected, and added to the experimental mixes, serving as a binder replacement for a portion of AE (Fig. 4). BW was crushed using a hammer at first, then Los Angeles apparatus to decrease its size fraction to 0.085.

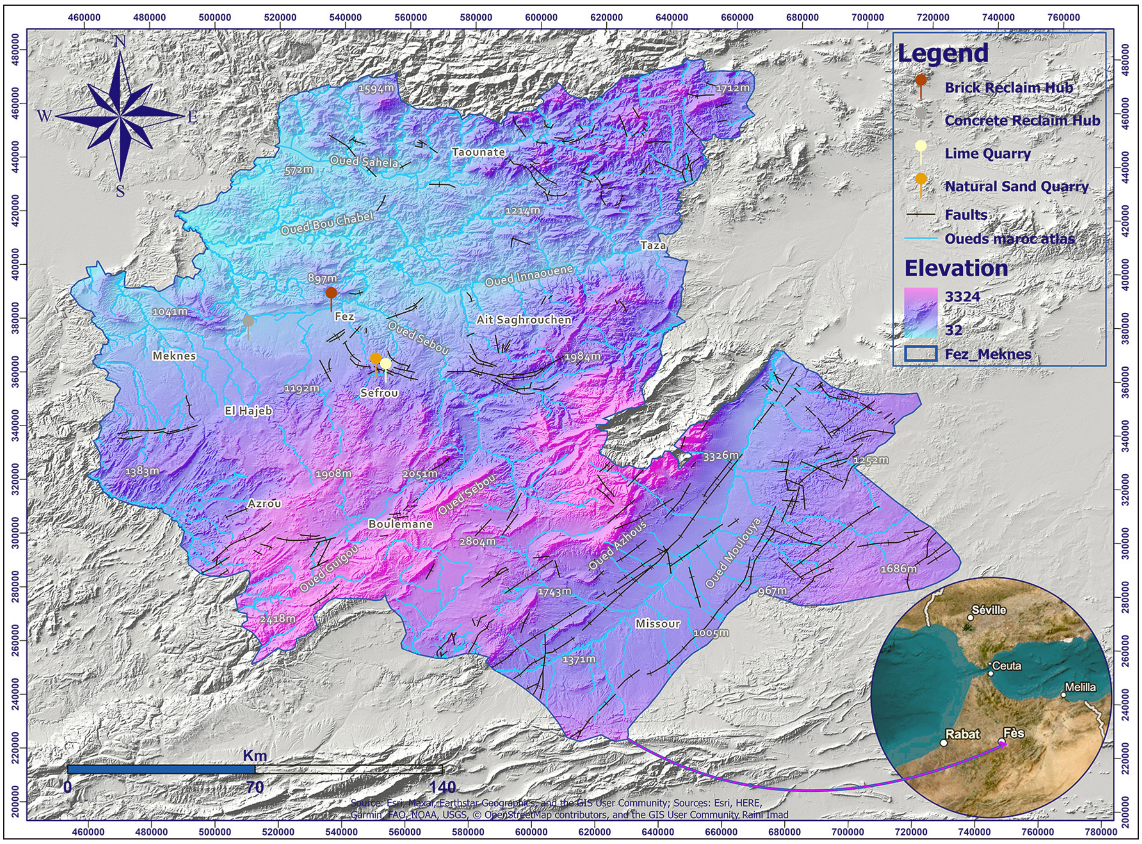

Figure 1. Overview of study area: locating local materials for mortar analysis

Figure 2. Collected lime samples from lime production site

Figure 3. Varieties of sands employed in mortar mixtures; (a) raw natural sand, (b) washed natural sand, (c) recycled concrete sand

After crushing RCA using a hammer, both sands were dried then sieved through a 2mm sieve in accordance with the given procedures in the NM EN 933-1 standard. Also, in pursuit of a suitable level of cleanliness, fine particles were removed by washing the sands, to optimize their fineness.

In order to achieve the desired mixture of the mortar, shape and size of sand particles were characterized conducting a grain size analysis test along with a scanning electron microscopy. Along with this later, X-ray fluorescence (XRF) analysis helped determine the elemental composition and purity of the binder components (lime and brick powder), ensuring optimal chemical properties for the mortar. In line with the potability standard in NM 10.1.353, tap water from RADEEF was used to prepare these later.

Mortars design

After characterizing the raw materials, the effect of RS and BP substitutions on the performance

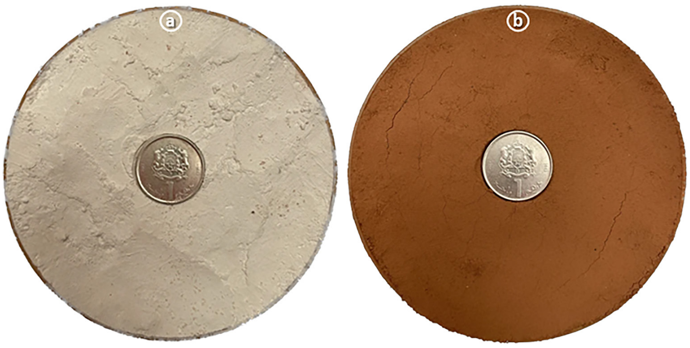

Figure 4. Varieties of binders employed in mortar mixtures; (a) aerial lime, (b) recycled brick powder

Figure 5. Concrete disposal from disposal site for concrete pipes

Table 1. Mortar substitution levels

Binder ibsstitution %	M0	M1	M2	M3	Sand sibstituion %	M0	M1	M2	M3
Lime%	100	70	70	70	Natural sand%	100	80	60	40
Brick powder%	0	30	30	30	Recyled conrete aggregate%	0	20	40	60

and characteristics of three different mortar compositions were investigated. Prism molds with the size of 40×40×160 mm were used to prepare mortar specimens.

Reference mortar M0 was prepared with a binder/sand ratio of 1/3 by volume. Based on literature, significant ratios were chosen to form a group that might yield favorable results (Aalil et al., 2019; Letelier et al., 2019; Ayat et al., 2022; Naciri et al., 2022). For that, sand replacement percentage varied since it makes up around 70% of the mixture altogether, which is a significant amount of the mortar (Table 1). To prevent moisture loss, the mixes were initially covered with

Figure 6. Lime mortar mixture compositions: (a) M1, (b) M2, (c) M3

plastic film until they had undergone initial hardening through drying, setting almost entirely under atmospheric conditions. The ratio of binder to sand stayed constant at 1:3 by volume (Fig. 7), yet a 0.85 water-to-dry-mix ratio was used. This means that each mortar will require between 92 and 94 grams of water in total, depending on how workable each mixture is in the mixing stage, due to the fine particles from the waste.

Test methods

Maintaining a constant lime content while adjusting the sand component allows for a more concentrated analysis of how changes in the latter impact critical properties such as density, strength, etc. Three prismatic samples were prepared for each mortar formulation.

Density

In accordance with the standard NF EN 1015-7, The strength and durability of mortar are greatly influenced by its density. To determine the density of the mortar, weights of the mortars were divided by the volume of the prism after they had been mold-free for 24 hours.

$$\rho = \frac{m}{v} \tag{1}$$

where: ρ (g/cm^3) – density, m (g) – masse, v (cm^3) – volume of the test tube.

Mechanical strength

In accordance with the standard NF EN 196-1, valuable information regarding lime mortars mechanical performance were conducted at different curing ages (28 and 90 days) with a loading

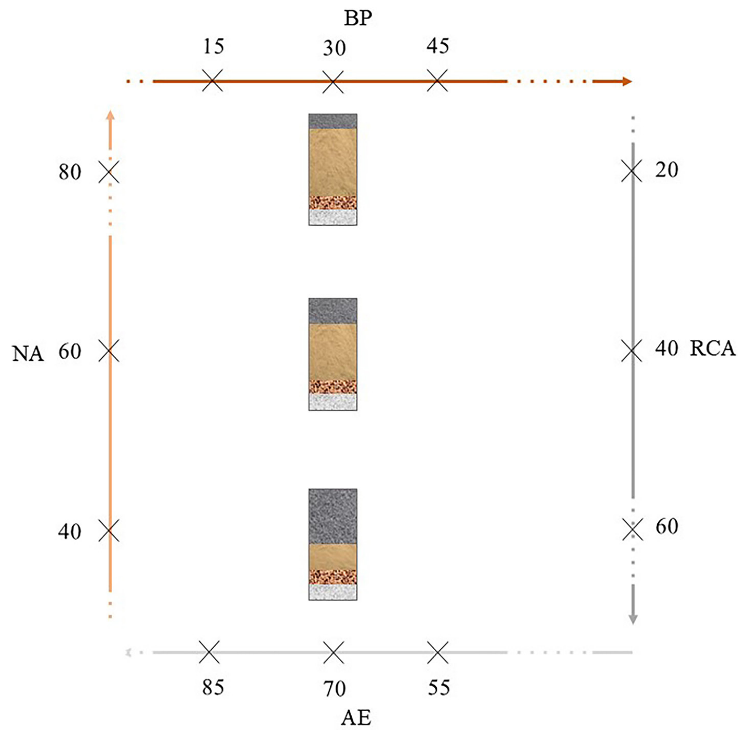

Figure 7. Lime mortar mixture designs: (a) M1, (b) M2, (c) M3

Figure 8. Prism specimens for mortar mix testing

rate of 1N/s. Flexural strength was initially measured, and the remaining broken half prisms were utilized for compression tests, which were calculated using the following formulas:

$$Rc = Fc/A \quad (2)$$

where: Rc (MPa): the compressive strength, Fc (N): the maximum load at fracture, A (mm²): the area of the platens (40×40 mm).

$$Rf = (1.5 \times Ff \times l)/(b \times b \times b) \quad (3)$$

where: Rf (MPa) – the flexural strength, Ff (N) – the peak load, L (mm) – the distance between the supports, b (mm): The side of the prism.

XRF and SEM analysis

X-ray fluorescence (XRF) analysis was conducted to assess the composition of the raw materials. Furthermore, scanning electron microscopy (SEM) analysis was performed at the 'Centre Universitaire Régional d'Interface (CURI)' in Fez, Morocco.

Water absorption by capillarity and porosity

The relationship between capillary absorption and porosity is that the capillary network within lime mortar is directly influenced by its porosity. Water absorption parameter help analyze the durability of the mortar. In accordance with the standard NF EN 1015-18, mortars cured for 28 days were broken into two halves then dried to a constant mass (dry mass M0) in a ventilated oven then weighted. Broken faces were faced downwards and immersed for 24 hours in clean, fresh water to a depth of 5 mm to 10 mm at a controlled temperature of 20 ± 2°C to avoid any contamination. After saturation period, remaining prisms left to drain for 15–30 min and dried their surface then weighted immediately (M3) and to subtract the dry mass (M0). Finally, the water absorption by capillarity was calculated using the following formula:

$$C = 0.625(M3 - M0)kg/m^2 \quad (4)$$

where: C (kg/m²) – water absorption after 24 hours, M3 (kg) – mass of the specimen after 24 hours of immersion in water, M0 (kg) – dry mass of the specimen before immersion, 0.625 – a constant derived from the test method and units, likely accounting for the surface area exposed to water.

The porosity of the lime mortars was examined in compliance with the NM 10.1.149 standard in addition to their absorption of capillary water. In a vented oven, specimens were dried to a constant mass (Wd), just like in the absorption test. However, they were completely submerged in water for 24 hours to achieve saturation. Surface water was eliminated then specimens were weighed to determine the saturated mass (W_s) after this time. The porosity (P) was calculated with the following formula:

$$P = \frac{(W_s - W_d)}{W_s} \times 100 \quad (5)$$

where: P (%) – porosity percentage, W_s (g) – mass of the saturated specimen, W_d (g) – dry mass of the specimen.

RESULTS AND DISCUSSION

Characterizing of raw materials

Particle size distribution and scanning electron microscopy

Sand aggregates have a role of inter fillers when added to mortar, they fill in the spaces in aim to improve the workability and cohesiveness of the mortar (Stefanidou and Koltsou, 2022).

Sand must have a well-graded distribution to provide a smoother and more cohesive mixture.

Figure 9 shows the cumulative particle size distribution curves of natural and recycled sand. Recycled sand shows high percentage of fine particles with size smaller than 0.1 mm as compared with natural sand. The small particles can fit into the interstices between the larger ones, making recycled sand a compact material.

Additionally, the SEM analysis reveals that the RCA has an angular and crushed shape, and NA has a round to angular shape (Fig. 10), which will lead to more gaps between the particles, increasing the surface area and requiring a high-water demand for the mortar mixture.

Fineness modulus and sand equivalent test

The quality of a sand is defined by its property. Based on the sand fraction passing through the 5 mm sieve, the fineness modulus was calculated for both sands, as shown in Table 2, classifying them as coarse for NS and preferable for RCA, respectively. Upholding to the previous values, sand equivalent test was showed values of 98 for NS and 23 for RCA.

While RCS combination has finer aggregates and a low sand equivalent test, which could result in potential problems like higher water absorption, decreased strength, and increased shrinkage in concrete or mortar applications, NS combination, as shown, has coarser aggregate and a high sand equivalent value, which conveys a clean and good particle size distribution.

Further properties of used sands are presented in following table.

X-ray fluorescence analysis

For X-ray fluorescence analysis (XRF), the main chemical components of the brick are silica and alumina with 56.5 % and 16.64 %, respectively.

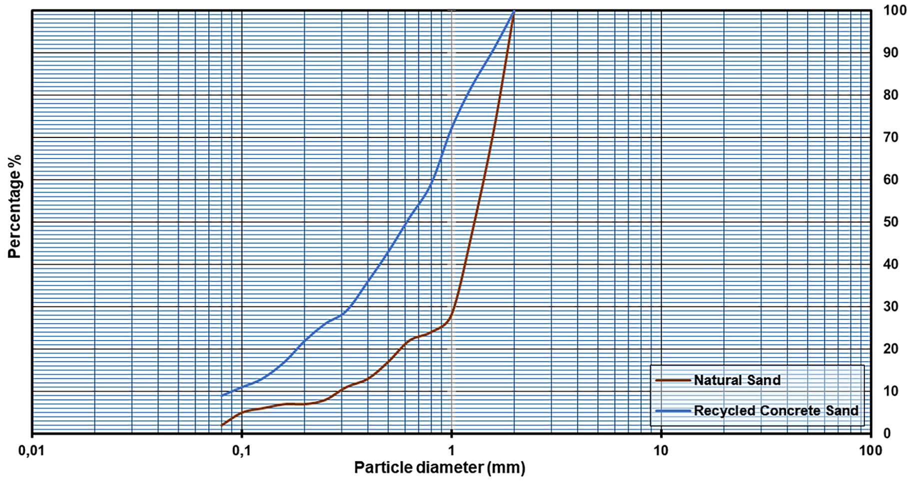

Figure 9. Particle size distribution of natural sand and recycled concrete sand

Characterization of the recycled aggregates

3	Scanning electron microscopy analysis (SEM)

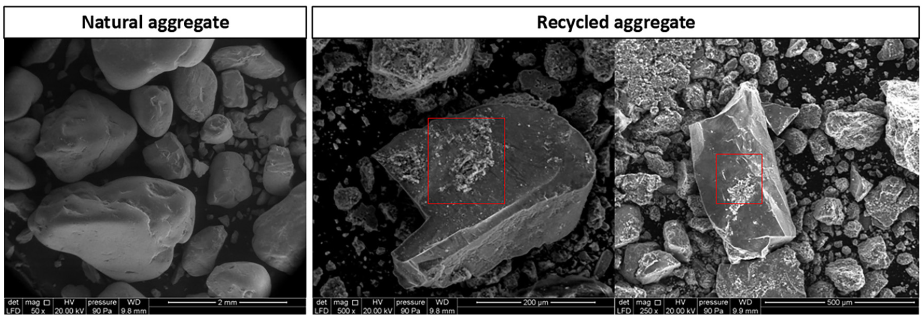

Figure 10. SEM images of aggregate at low magnification

Table 2. Sand fineness modulus

Parameter	Particle diameter (mm)						FM
	%<0,08	%<0,315	%<0,63	%<1,25	%<2,5	%<5	
Natural sand	7	11	22	47	100	0	4.13
Recycled cocnrete sand	17	29	51	82	100	0	3.21
Fineness modulus specification	2.2	>Fine>	2.6	>Preferable>	3.2	>Coarse>	3.6

Table 3. Outline of test results for aggregate properties

Identification tests			
Parameter	Sand equivalent	Bulk density	True density
	EN 10.1.732	EN 1097-6	EN 1097-6
	–	g/cm^3	g/cm^3
Natural sand	74	1.5	2.64
Recycled concrete sand	27	1.23	2.28

In compliance with ASTM C618, brick powders have an oxide element (Al_2O_3+Fe_2O_3+SiO_2) content higher than 70 %, classifying them as pozzolanic materials. The silica and alumina present in fine brick can react with calcium hydroxide in lime to form hydration products, which improve the material's mechanical and durability properties.

Characterizing of mortar mixtures

Compressive strength

The compressive strength for all mixtures increases over time, from 28 days to 90 days, which is typical in lime-based mortars as carbonation and pozzolanic reactions progress. The reference mortar (M0) shows the highest compressive strength at both 28 and 90 days, significantly outperforming the recycled mixtures (M1, M2, M3). M1 exhibited the greatest compressive strength among the recycled mixes after both 28 and 90 days, indicating that a lower recycled concrete aggregate content of 20 % improved strength compared to M2 and M3, which had higher portions of RCA (40% and 60%, respectively) and showed lower compressive strength. The strength decrease can be attributed to the higher porosity and weaker bond strength associated with RCA, as RA tend to possess residual porosity and some cement paste, which likely reduces their ability to bind effectively within the mortar matrix. M0 exhibits a noticeably higher strength increase rate than the recycled mixes, suggesting that RCA might slow down the strength gain process, potentially due to its influence on pore structure as well as matrix connectivity. Furthermore, CS1 benchmark proves that each of the mortar mixtures satisfied the requirements specified by EN 1015-11, thereby confirming their suitability for construction and building applications. All mixes show an increase in compressive strength from 28 to 90 days, likely due to delayed carbonation and ongoing pozzolanic reactions, particularly the slow carbonation of lime and reaction of brick powder with lime. The 30% replacement of lime with brick powder across all mixes doesn't fully offset the weaker matrix formed by RCA in M2 and M3. Unlike, M1, the combination of a lower RCA content with brick powder replacement seems to result in a more favorable matrix, balancing pozzolanic gains with minimized losses from RCA.

Flexural strength

Similar to the compressive strength trends, the reference mortar (M0) has the highest flexural strength at both 28 and 90 days where among the recycled mortars, M1 exhibits the highest flexural strength compared to M2 and M3. All mixtures show a modest increase in flexural strength

Table 4. XRF analysis of raw materials compound

Samples	Chemical compositions (%)								
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	Cl
Lime	0,3	0,2	0,1	41	41	0.11	0,2	0,1	0
Brick	57	17	5,8	9,5	4	2	1,5	1,8	0,6
Natural sand	46	1,2	0,2	29	21	0,2	0,2	0	0,1
Recycled sand	13	2,5	1,5	35	12	0,4	0,2	0,9	0,1

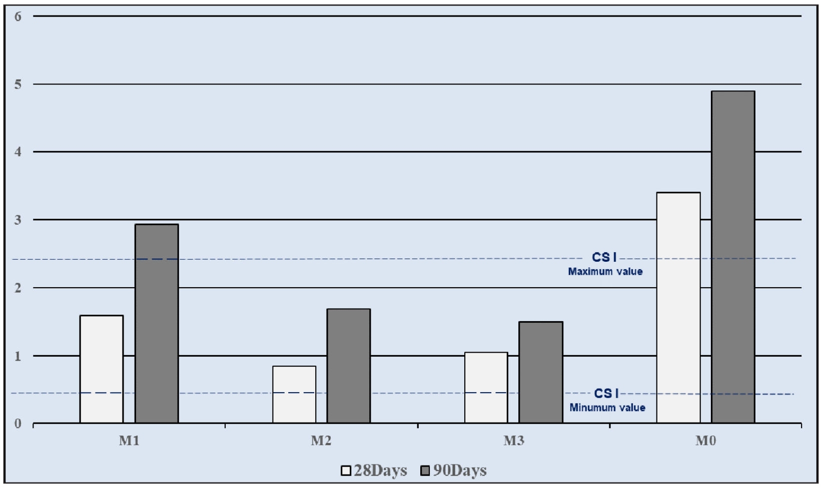

Figure 11. Compressive strengths of mortar mixes at different ages

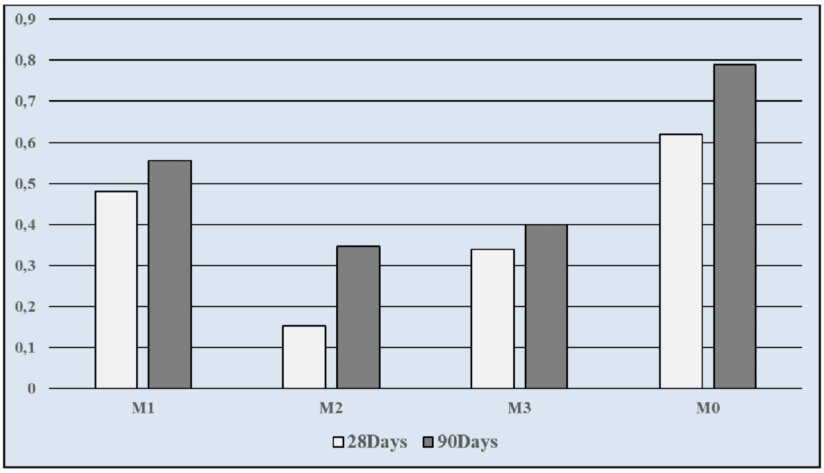

Figure 12. Flexural strengths of mortar mixes at different ages

between 28 and 90 days, which align with the typical behavior in lime-based mortars, where gradual carbonation and pozzolanic activity contribute to continued strength development over time. Brick powder might provide some strength gain, its impact on flexural strength is limited when RCA content is high (as in M2 and M3).

The findings shows that lower RCA content helps maintain better bonding and crack resistance under flexural stress too. Although, higher proportions of RCA weaken the matrix's ability to withstand bending forces resulting in a weaker aggregate bonding and a higher porosity.

Water absorption and porosity

The mortar mixtures (M1, M2, and M3) show a decreasing trend in porosity as the RCA content increases. M3, with the highest RCA content, has the lowest porosity, indicating that replacing natural sand with RCA results in a denser microstructure with reduced open pore space within the mortar.

RCA content may stem from a more compact microstructure, as RCA particles could fill voids more effectively than natural sand, especially when combined with brick powder, which has finer particles that might enhance the binder matrix by enhancing the binder phase's cohesion, which reduces capillary pathways. The pozzolanic reaction of brick powder is likely contributing to a meaningful degree of further pore refinement over time, as it reacts with calcium hydroxide to form additional secondary calcium silicate hydrates. This pozzolanic reaction can fill micropores and lead to a denser, less permeable matrix.

These characteristics – reduced porosity and enhanced density – make M1, M2, and M3 potentially more durable against moisture-related degradation than the reference mortar M0.

Since porosity is a key indicator of the mortar's permeability and potential durability. A lower porosity often correlates with decreased water absorption, as observed in these mixtures. Reduced water absorption enhances the mortar's resistance to freeze-thaw cycles and other moisture-related damage, which is critical in applications exposed to varying environmental conditions.

Therefore, the lower porosity and water absorption in RCA-based mortars may contribute to an extended lifespan, providing greater resistance to weathering and reducing the risk of water-related deterioration.

Density

Findings show that an inverse connection exists between the material density and the RCA content, in other words, as RCA content will increase the total density of the mortar will decrease. It can be seen that the M0 sample is the densest compared to all mixtures and the M3 sample, which contains the most RCA, is the least dense.

The decrease in density at higher RCA content is due to the inherent properties of RCA particles. RCA often contains micro-cracks and thus retained old adhered mortar that leads to a lower intrinsic density than natural sand. Furthermore, the irregular surface texture and porous character of RCA results in a high total porosity which is consistent with existing literature (Liu et al., 2021; Tara Cavalline et al., 2022; Akbarimehr et al., 2024; Catalin et al., 2024), with the effect being most pronounced in M3.

While RCA particles contribute to a more compact structure by filling voids, as discussed previously, they remain less dense on an individual particle level than natural sand. Consequently, mixtures with higher RCA content, such as M3, form a lighter matrix, yet still compact. Nevertheless, the finer particles of brick powder (BP) appear to compensate for some of these drawbacks by enhancing the cohesion within the binder phase. The pozzolanic activity of BP can facilitate the secondary bonding, thereby enhancing the microstructure and help refining the pore structure. This results in reduced permeability and potentially improved durability, even in mixtures with lower overall density.

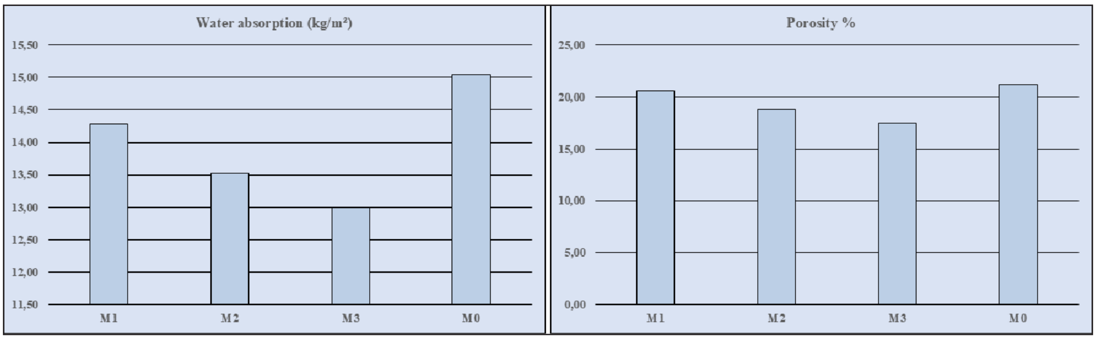

Figure 13. Water absorption and porosity results of mortar mixes at different ages

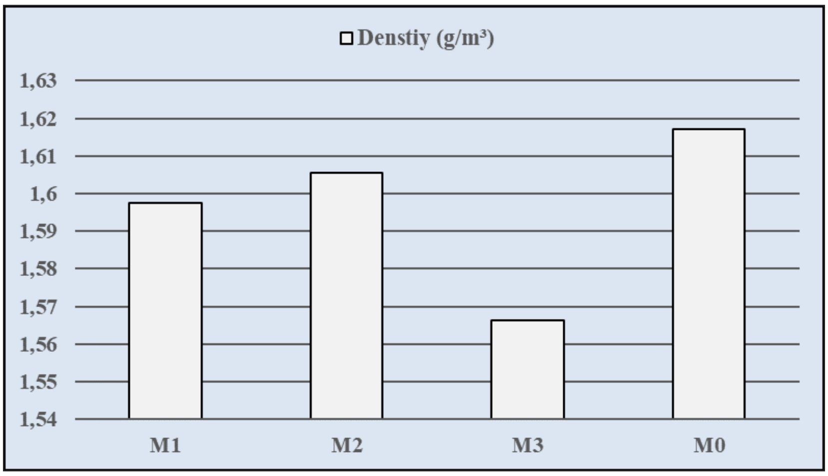

Figure 14. Density results of mortar mixes at different ages

The density results align with trends observed in water absorption, porosity, and mechanical strength. The RCA-BP combination appears to create a microstructure that is compact at the particle-packing level, despite the lower density. While, the matrix is more compact, the mechanical performance is still limited by the microstructural weaknesses of RCA, such as its microcracks and adhered mortar fragments.

CONCLUSIONS

This research points out the possibility of using recycled concrete aggregates and brick powder in lime mortar mixes as a sustainable replacement for traditional construction materials. Sand content variations were examined in conjunction with their interaction with lime, offering valuable insights into optimizing three eco-friendly mortar mixtures to enhance durability and minimize environmental impact.

Research findings indicate that although RCA's inclusion introduces some limitation in mechanical performance, specifically compressive and flexural strength at substitution levels above 20%, the addition of BP reduces these negative effects to a degree via its pozzolanic properties. Mixtures such as M1, which combine RCA and BP in specific proportions, exhibit a balance between sustainability and performance characteristics. This balance renders them appropriate for at least several applications that necessitate moderate load-bearing capacity.

In addition, the study emphasizes environmental benefits of using recycled materials, including reduced solid waste and supporting principles of a circular economy. The water absorption and porosity properties of the recycled mixtures (M1, M2 and M3) were significantly better than those of the traditional mortar (M0), indicating that recycled mixtures represent a sustainable solution to develop comparable and, in several cases, superior durability properties.

Finally, besides their sustainable features, those mortars are promising for the conservation of the cultural heritage by providing ecological materials to use for the rehabilitation of the historical monuments of Morocco. The addition of additives such as plasticizers or pozzolanic enhancers can improve performance through high mechanical strength, durability, and workability, which would expand the range of uses for these novel materials. This research leads to more sustainable construction materials that are both cost effective and durable compared to existing construction materials by addressing their Eco-efficiency along with their functional performance required for modern sustainability efforts.

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