Combined impact of dune sand and crushed brick waste on the characteristics of raw earth bricks

Impacto combinado da areia das dunas e dos resíduos de tijolos triturados nas características dos tijolos de terra bruta

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ABSTRACT
The primary motivators behind the renewed focus on employing locally available materials, recycling industrial waste, and utilizing their characteristics for adobe bricks are cost-effective building materials, thermally efficient, consuming less energy and reducing environmental emissions. In light of this, this study examines how the physical characteristics and mechanical behavior of quicklime-stabilized adobe bricks’ are affected when dune sand (DS) and crushed fired brick waste (CB) are combined. The thermal conductivity of adobe bricks was also studied. According to the data, the compressive and flexural strengths significantly improved with the addition of 40% CB. A slight strength increase was observed with the incorporation of 20% DS, which is not the case for the other types of sand. Addition of 20% DS to the mixtures resulted in a decrease in the TA and Cb. SEM technique confirmed that the use of CB and DS in the adobe bricks preparation procedure resulted in a reduction of voids in the matrix, thereby improving the characteristics, especially their physical characteristics. Additionally, there was an improvement in the apparent density when the M1 combination was included. This
resulted in an increase in the speed at which ultrasonic waves propagated. Similarly, M3 combination helped to reduce the TA and Cb. With regard to M1 combination, it increased the compressive and flexural strength of adobe bricks by 71.75% and 52.23%, respectively, as compared to the RB. Significant increases in elasticity modulus were observed in compression and flexion. The combination of CB and DS slightly increased the thermal conductivity.

**Keywords:** adobe bricks, crushed fired brick waste, dune sand, mechanical characteristics, thermal conductivity, water absorption.

**RESUMO**
Os principais motivadores por detrás do foco renovado na utilização de materiais disponíveis localmente, na reciclagem de resíduos industriais e na utilização das suas características para tijolos de adobe são materiais de construção econômicos, termicamente eficientes, que consomem menos energia e reduzem as emissões ambientais. À luz disso, este estudo examina como as características físicas e o comportamento mecânico dos tijolos de adobe estabilizados com cal viva são afetados quando a areia das dunas (DS) e os resíduos de tijolos queimados (CB) são combinados. A condutividade térmica dos tijolos de adobe também foi estudada. De acordo com os dados, as resistências à compressão e à flexão melhoraram significativamente com a adição de 40% de CB. Observou-se ligeiro aumento de resistência com a incorporação de 20% de DS, o que não ocorre com os demais tipos de areia. A adição de 20% de DS às misturas resultou em diminuição do TA e do Cb. A técnica MEV confirmou que a utilização de CB e DS no procedimento de preparação dos tijolos de adobe resultou na redução de vazios na matriz, melhorando assim as características, principalmente suas características físicas. Além disso, houve melhora na densidade aparente quando a combinação M1 foi incluída. Isso resultou em um aumento na velocidade de propagação das ondas ultrassônicas. Da mesma forma, a combinação M3 ajudou a reduzir o TA e o Cb. Já a combinação M1 aumentou a resistência à compressão e à flexão dos tijolos de adobe em 71,75% e 52,23%, respectivamente, em relação ao RB. Aumentos significativos no módulo de elasticidade foram observados em compressão e flexão. A combinação de CB e DS aumentou ligeiramente a condutividade térmica.

**Palavras-chave:** tijolos de adobe, resíduos de tijolos cozidos triturados, areia de dunas, características mecânicas, condutividade térmica, absorção de água.

**1 INTRODUCTION**

It is important to note that the mud brick, also called adobe brick, is commonly used in earth constructions. This is a technique that is considered one of the oldest. It offers several economic and technical advantages, compared to that which uses compressed earth blocks and rammed earth (Houben; Guillard, 1994). But due of their lack of durability and extreme susceptibility to water, they are regularly criticized (Lan et al., 2020). However, raw earth construction
techniques are still evolving today thanks to the various stabilization processes that exist. The chemical and physical processes involved in these techniques have been widely used to prevent or mitigate the existing shortcomings. The adopted chemical methods consist of adding lime (Venkatarama Reddy; Hubli, 2002; Guettala et al., 2002; Millogo et al., 2008) or cement (Millogo; Morel, 2012) or both to the mixture (Guettala et al., 2002; Nagaraj et al., 2014). It should be mentioned that, over the last few years, mineral additions, as well as cement and lime, have been added in order to improve the mechanical characteristics and durability of mud bricks (Oti et al., 2009a, 2009b, 2010; Sekhar; Nayak, 2018; Vinai et al., 2013; Almeasrar et al., 2023; Siddiqua; Barreto, 2018; Izemmouren et al., 2015). Lime stabilization is a process that includes three short-term reaction phases, namely the action exchange phase, the flocculation phase, and the agglomeration phase. It should be noted that these reactions contribute to improving the characteristics of the treated soil. It was shown that the pozzolanic reaction is the real long-term reaction in lime stabilization. It did turn out that clay minerals dissolve in this reaction's high pH alkaline environment. Soil grains are cemented together by aluminum and calcium silicates, which are created when silica and alumina in clays recombine with calcium (Millogo et al., 2008; Boardman; Glendinning, 2001; Pomakhina et al., 2012). Additionally, it was demonstrated that clay soil with a high concentration of silica, iron hydroxides, or alumina silicates is necessary for lime stabilization. In this context, several authors (Venkatarama Reddy; Hubli, 2002; Izemmouren et al., 2015; Lasledj; Al-Mukhtar, 2008; Venkatarama Reddy; Gourav, 2011; Wild et al., 1986) have shown that the kinetics of the pozzolanic reaction is very slow at room temperature. Its effects can only be appreciated several months and years later. It is noteworthy that the kinetics of the pozzolanic reaction is influenced by several parameters such as the hardening (curing) temperature and the amount of lime in soil. In this regard, Al-Mukhtar et al. (2010) conducted a study for the purpose of examining the influence of temperature on the pozzolanic reaction kinetics within an expansive clay soil stabilized with quicklime. The results they obtained revealed that a curing temperature range, between 20 °C and 50 °C, multiplies the pozzolanic reaction rate six fold. Likewise, the results of the study conducted by Taallah et al. (2016) on blocks of compressed earth stabilized with quicklime and incorporating date palm fibers indicate that the compressive and
tensile strength of blocks subjected to oven hardening is better than that of blocks subjected to other curing (hardening) methods, such as laboratory curing or natural steam-curing. Similarly, Izemmouren et al. (2015) found out that steam hardening of compressed earth blocks stabilized with lime at a temperature of 75 °C, for approximately 24 hours and at atmospheric pressure, gives considerably higher strength values compared to hardening in plastic film at room temperature. With regard to Zaidi et al. (2022), they indicated that the addition of 12% of quicklime to the soil, with oven hardening at 65 °C for approximately nine days, is very beneficial for the stabilization of adobe bricks. In addition, Millogo et al. (2008) investigated the effect of the quantity of lime used on the pozzolanic reaction between lime and soil. They found out that the compressive strength of adobe bricks increases as the amount of added lime rises. However, it turned out that lime contents greater than 10% of the weight of the mixture have no beneficial effect on the compressive strength. The physical soil stabilization methods involve adding natural resources, as well as natural or industrial waste, in the form of fibers or grains (Almeasar et al., 2023; Khoudja et al., 2021; Eslami et al., 2022; Gandia et al., 2019; Layachi et al., 2023). Sand and gravel are natural resources that are generally used to adjust the grain size because each earth construction technique requires its own specific grain size. In this context, Houben and Guillard (1994) suggested that the soil selected for the production of adobe must contain sand and gravel (55-75) %, silt (10-28) % and clay (15-18) %. However, Standard NTE E.080 (2000) recommends the proportions of (10 – 20) % for clay, (15-25) % for silt and (55-70) % for sand. Guettala et al. (2002), they used percentages of 10%, 20%, 30% and 40% of natural sand for the grain size correction of soil. Then, they indicated that the particle size curves of the soils were adjusted to have sand rates of 10, 20 and 30% quite close to the lower limit of the zone recommended for making compressed earth blocks, while the soil corrected with 40% of sand falls outside the recommended limit zone. In addition, Zaidi et al. (2022) conducted a study in which they prepared adobe bricks using soil corrected containing 30% of crushed sand. Moreover, builders’ and demolition debris has been utilized by researchers in a number of studies as recycled fine and coarse aggregates for the creation of mud bricks. In particular, Oti et al. (2010) used waste brick dust as a partial substitute for clay in the production of mud bricks, at different replacement
levels. The incorporation of these wastes up to a percentage of 20% contributed to improving the compressive strength, but also resulted in increasing the water absorption, linear expansion, and weight loss of bricks subjected to several freeze/thaw cycles. This would obviously depend on the percentage of brick dust in the mixture. Similarly, Joshi et al. (2019) noted an improvement in the mechanical strength and durability of adobe bricks manufactured by replacing between 60 and 80% of natural soil with crushed brick waste. Kasinikota and Tripura (2021) found out that water absorption increased as the replacement rate went up, regardless of the particle size of the crushed brick waste. It is widely acknowledged that, in Algeria, the use of dune sand, widely available in the Sahara and extracted at almost zero cost, can offer an alternative solution to the problem related to natural resource depletion (Guettala; Mezghiche, 2011). It has been revealed that the production of fired bricks generates significant quantities of waste, at different stages of the manufacturing process. This waste can also result from non-compliant and damaged bricks. It has been revealed that these brick wastes may be recycled and recovered because this would significantly contribute to partly solving of waste storage, reducing environmental pollution, and preserving natural resources. In this regard, several previous researches have indicated that the addition of waste brick from building construction and demolition wastes to mud bricks increases their capacity absorption. To minimize this absorption, it is highly recommended to combine crushed fired brick waste with dune sand as partial soil substitutes when producing adobe.

By employing local resources, recycling industrial waste (crushed fired brick waste), and taking advantage of their qualities for adobe bricks, this study aims to lower the amount of energy required in rural areas with dry and semi-arid climates. In order to accomplish this objective, our first steps were figuring out the ideal time for the adobe bricks to curing and adjusting the amount of lime added to the soil according to its dry compressive strength. Then, in order to investigate the effects of different sands, with different shapes and origins as well as the dosage of sand on the mechanical strengths, the total and capillary absorption of adobe bricks, the mixture (soil + sand) was replaced with various types of sand; including dune sand (DS), crushed sand (CS), river sand (RS), as well as crushed fired brick waste used as sand (CB). Subsequently, studies were conducted on the combined...
impact of dune sand and crushed fired brick waste on the physical characteristics and mechanical behavior of quicklime-stabilized adobe bricks. Additionally, the thermal conductivity of adobe bricks was examined.

2 EXPERIMENTAL PROCEDURE
2.1 IDENTIFICATION OF MATERIALS USED

The soil used in this study was collected from the southern region of Algeria, at a depth between 0.50 and 1.00 m below the surface, as shown in Figure 1. The chemical composition analysis of this soil was carried out using the X-ray fluorescence spectroscopy (XRF) technique, and the results obtained are reported in Table 1. Moreover, its mineral composition was also investigated using the X-ray diffraction (XRD) approach, and the results obtained are presented in Table 2. As for the physical characteristics, they are given in Table 3. Furthermore, evaluation of the sizes of the different particles constituting the soil and their distribution were investigated using the wet sieving method for coarse fraction, in accordance with Standard NF P 94-056 (1996), and the sedimentation technique for the fine fraction, in accordance with Standard NF P 94-057 (1992), as clearly illustrated in Figure 2.

Figure 1. Materials used in this study: (a) Quicklime, (b) Soil, (c) Crushed fired brick waste, (d) River sand, (e) Dune sand and (f) Crushed sand

![Figure 1. Materials used in this study: (a) Quicklime, (b) Soil, (c) Crushed fired brick waste, (d) River sand, (e) Dune sand and (f) Crushed sand](image)

Source: Authors

Table 1. Chemical composition of soil, quicklime and crushed brick (%)

<table>
<thead>
<tr>
<th>Components</th>
<th>Soil</th>
<th>Quicklime</th>
<th>Crushed brick</th>
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</thead>
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<tr>
<td>SiO₂</td>
<td>35.32</td>
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<td>CaO</td>
<td>24.11</td>
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<td>Al₂O₃</td>
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<td>Fe₂O₃</td>
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<td>MgO</td>
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Table 2. Mineralogical analyses of soil (%)

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<th>Kaolinite</th>
<th>Orthoclase</th>
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Table 3. Physical characteristics of soil and different sands

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<th>Properties</th>
<th>Soil</th>
<th>Dune Sand (DS)</th>
<th>Crushed Sand (CS)</th>
<th>River Sand (RS)</th>
<th>Crushed Brick waste (CB)</th>
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<td>Apparent density (kg/m³)</td>
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<td>1442</td>
<td>1632</td>
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<td>Specific density (kg/m³)</td>
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</table>

Source: Authors

Figure 2. Particle size distribution of soil, Crushed sand (CS), Dune sand (DS), Crushed fired brick waste (CB) and River sand (RS)

The stabilization of soil in this study was carried out using quicklime (see Figure 1). Its chemical characteristics are listed in Table 1.

It was shown that significant losses occur at each stage of the fired brick manufacturing process at the brick factory. These losses mainly occur during the loading, packaging and storage of bricks as shown in Figure 3.
The recovered fired brick waste is then crushed using the Los Angeles apparatus to produce coarse aggregates that are then sieved in order to obtain a homogeneous particle size, as shown in Figure 1. Furthermore, it is useful to remember that the chemical composition of soil and the physical characteristics of its particles are presented in Table 1 and Table 3, respectively.

The particle size curve of crushed fired brick waste (CB) is shown in Figure 2, while Figure 4 presents the scanning electron microscopy (SEM) image and energy-dispersive x-ray (EDX) spectra of CB.

In this study, three sand types were used: crushed sand (CS), dune sand (DS) and river sand (RS), as illustrated in Figure 1. It should be noted that the physical characteristics of the sands used are consistent with AFNOR Standards (1996); they are summarized in Table 3.

In addition, the data relating to the particle size analysis of sands are illustrated in Figure 2, while the SEM and EDX results of dune sand (DS) are illustrated in Figure 5. The concoctions' mixing water, or tap water, is obtained from the public network.

This water satisfies Standard NF P 18-404's criteria for quality.
Figure 4. SEM (G=5000) and EDX of crushed fired brick waste

Figure 5. SEM (G=5000) and EDX of dune sand

2.2 MIXTURES NOMENCLATURE, SAMPLES PREPARATION AND EXPERIMENTS

In order to carry out the present work, 24 mixtures were prepared to be used in two distinct phases. During the first phase, the mixture (soil + sand) was replaced by different types of sand, including DS, CS, RS, as well as CB used as sand, with mass percentages: 0% (the reference brick (RB)), 10%, 20%, 30%, 40% and 50%. However, in the second phase, the crushed fired brick waste was combined with the dune sand to formulate the mixtures M1, M2, M3. Table 4 presents the different proportions used in the mixtures prepared for the experiments carried out in this study.
Table 4 Composition of mixtures with mass percentages

<table>
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<tr>
<th>Mixture</th>
<th>Soil (%)</th>
<th>Crushed brick waste (%)</th>
<th>Dune Sand (%)</th>
<th>Crushed sand (%)</th>
<th>River Sand (%)</th>
<th>Quicklime (%)</th>
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</table>

Source: Authors

Cubic samples with dimensions (10×10×10) cm³ and prismatic samples with dimensions (4×4×16) cm³ were carefully prepared, going through several stages: The first step involved collecting the soil in the form of lumps and then sifting it through a 2 mm mesh sieve to obtain a homogeneous texture. The resulting product was then subjected to drying, at a temperature of 65 °C for 24 hours, while ensuring that this soil was completely dry. The second step sought to optimize the amount of lime added to the soil based on its dry compressive strength. This involved incorporating different amounts of quicklime into the soil. In this regard, Millogo et al. (2012) indicated that adding different quantities of quicklime to the soil allowed detecting an optimal quantity of lime beyond which the compressive strength started decreasing due to formation of C-S-H which resulted from the reaction between lime and clay minerals as well as to the high
concentrations of calcite and the portlandite. Afterwards, the prepared samples were placed in the oven for periods of 3, 5, 7 and 9-day to determine the optimal curing period of the adobe bricks. This heat treatment favored the acceleration of hydration and the pozzolanic reaction between lime and clay. Figure 6 clearly shows that the most interesting results were observed with a lime content of 10% and a curing period of 7-day.

Figure 6. Effect of lime dosage and curing time on the compressive strength of adobe bricks

In the third step, various materials such as soil, quicklime and sands were carefully mixed, for a period of 2 minutes, using a mortar mixer, in order to obtain a homogeneous composition and to ensure that all soil and sand grains are covered with quicklime. Then, the amount of water that was previously established in order to achieve a spread diameter of (160 ± 10) mm was slowly added, according to the flow table test of Standard BS EN 459-2 (2010). The mixing operation was continued for a period of 2 minutes until a good plasticity composition was obtained, and until the resulting paste was completely homogenized. Then, this paste was manually deposited in the molds, in three identical layers, and carefully compacted. It should be noted that the internal surface of the molds was previously lubricated in order to prevent any fracture of the samples during unmolding. Afterwards, the samples were covered with a plastic film and allowed to air dry for 48 hours. They were subsequently placed in airtight plastic bags (Almeasars et al., 2023), and cured in an oven at 65 °C for 7-day, after which they were ready to be tested. Three samples were used on
average for each test. All tests were carried out with bricks having dimensions (10×10×10) cm³. However, the flexural test and the evaluation of the mechanical behavior were performed using bricks with dimensions (4×4×16) cm³.

3 RESULTS AND DISCUSSIONS
3.1 EFFECT OF DIFFERENT SAND TYPES ON THE MECHANICAL STRENGTHS AND WATER ABSORPTION

3.1.1 Dry compressive strength

Figure 7 illustrates the influence of the dosage of different sand types on the dry compressive strength (DCS). The results obtained allowed observing that the mixture containing 40% of crushed fired brick waste (CB) showed a maximum DCS value, which represents an increase of 80.86%, compared to the strength of RB.

As illustrated in Figure 4, this strength improvement is certainly due to the shape and roughness of the CB particles, which promoted better adhesion between the aggregates and the lime-soil matrix. Kasinikota and Tripura (2021) attributed this strength increase to the pozzolanic reaction that generally occurs between fine particles, i.e. those with a diameter less than 0.15 mm, usually present in CB and lime.

The analysis of bricks containing crushed sand and river sand (BCS and BRS) indicated an increase in DCS reaching up to 30%, depending on the dosage of these two sands. However, it was found that, beyond this proportion, the DCS begins to decrease. It is worth mentioning that the DCS increase for BCS and BRS was around 78.13% and 46.92%, respectively, over a dosage range extending from 0% to 30%.

On the other hand, the lowest DCS value was obtained by adding dune sand (DS), with an optimum rate of 20%. This DCS value is 9.33% higher than that of RB. This small increase in DCS is due to the uniform and spherical shape of the grains of the sand used, as shown in Figure 5. The compressive strength decrease of bricks, containing different types of sand added with optimal rates, is attributed to the deficit in fine particles of the soil because the cohesion between the sand and soil grains is ensured by these particles.
As a result, the minimum plasticity required for the manufacture of adobe bricks is insufficient. It is noteworthy that the DCS values of the adobe bricks tested were found consistent with the strength requirements specified by the New Mexico State Standards for Adobe Construction (Walker, 1991) (2 MPa) and by the Standards New Zealand (1998) (1.3 MPa).

### 3.1.2 Flexural strength

The variation in flexural strength (FS) is shown in Figure 8. It is clearly noted that this strength increases with the addition of CB, reaching 3.85 MPa at 40% dosage. This improvement corresponds to an increase of approximately 91.54% with respect to that of RB. Figure 1 clearly indicates that the angular shape of the crushed fired brick aggregates and the rough texture of the crushed brick generally promotes a robust bond between the brick aggregates and the mixture matrix (soil + lime), which helps to increase the flexural strength (Silva et al., 2009). These results are in good agreement with those reported in similar previous works (Joshi et al., 2019).
Furthermore, after the addition of CS, the flexural strength results are almost similar, except that the optimum of this strength is detected at 30% of CS, which is certainly due to the angular shape of CS.

However, it should be noted that the smooth and flattened shape of the RS particles and the rounded shape of the DS grains caused a reduction in the flexural strength of the bricks as compared to those of the bricks incorporating CB and CS. However, these strengths were greater than that of RB. Similarly, the optimum compressive strength was achieved by adding 30% and 20% of RS and DS, respectively.

### 3.1.3 Total and capillary absorption

The previously recorded results, relating to the compressive strength and the flexural strength of bricks incorporating various types of sand, were used to determine their optimal values which were then utilized to determine the total absorption (TA) and the capillary absorption coefficient (Cb) of the bricks under study. Figure 9 presents the variation of Cb and TA for the four types of sand. Analysis of the data at hand showed that B40CB gives the highest Cb and TA values. These values reached 10.27g/cm².min¹/² and 16.53%, respectively. In addition, the increase (%) was approximately 17.64% for Cb and 12.21% for TA with respect to RB. This increase is certainly due to the water absorption that was found higher for brick waste aggregates (Junior et al., 2022). In this regard, the results reported by Kasinikota and Tripura (2021) showed that whatever the size
and quantity of CB particles, the water absorption of the compressed earth blocks increased as the replacement rate went up. However, low TA and Cb values were obtained for B30RS, followed by B20DS, then by B30CS. Likewise, the Cb values decreased by approximately 38.14%, 31.27%, and 12.37% for B30RS, B20DS and B30CS, respectively, with respect to the RB values. Likewise, the TA decreased by approximately 35.5%, 28.71%, 35.5% and 10.38%, respectively, compared to the values found for RB.

Figure 9. Effect of sand type on the capillary absorption and total of adobe bricks

The findings of the first phase showed that fired brick waste can be used as a substitute for conventional sands such as crushed sand and river sand. These findings were also confirmed by the mechanical strength results. However, a challenge still remains regarding the high water absorption capacity of bricks incorporating these two types of sand, because it exceeds that of RB. For the purpose of reducing this absorption capacity, it is highly recommended to combine brick waste with dune sand which is known for its water absorption capacity lower than that of soil and CB.

3.2 COMBINED EFFECT OF CRUSHED FIRED BRICK WASTE AND DUNE SAND ON PHYSICAL CHARACTERISTICS

3.2.1 Apparent density

The apparent density was measured for the different mixtures and the results obtained are presented in Figure 10 which shows that the values obtained
vary between 1543 kg/m³ and 1800 kg/m³. It should also be noted that the density of mixture M1 increased by 16.65% with respect to that of RB. This increase is explained, on the one hand, by the apparent densities of CB and DS which are higher than that of raw earth and, on the other hand, by the formation of new hydrates C-S-H after the addition of CB, which led to lower porosity, as clearly shown in Figure 11.

This same figure presents the SEM-EDX images of the different mixtures. It also shows that the structure of the M1 mixture is denser than that of RB and those of the M2 and M3 mixtures. Similar trends have been reported in the study conducted by Joshi et al. (2019) on adobe bricks. They replaced the excavated natural soil by 70% of masonry demolition waste and crushed bricks and hence observed an increase in dry density from 1670 kg/m³ to 1810 kg/m³.

Fortunately, the densities of all mixtures remained within the acceptable range regarding the adobe bricks. These density values, as reported by researchers, are between 1540 kg/m³ and 1950 kg/m³ (Joshi et al., 2019).

Figure 10. Combined effect of crushed fired brick waste and dune sand on the apparent density and propagation speed of adobe bricks

3.2.2 Propagation speed of ultrasound waves

The test carried out here was primarily intended to detect the presence of voids or cracks within the prepared adobe bricks. Analysis of the results of the ultrasound propagation speed test, as presented in Figure 10, revealed that the lowest wave propagation speed value was observed in the RB mixture. On the
other hand, the M1 mixture presented the highest wave propagation speed value which was found equal to 2005 m/s. It was also observed that the wave propagation speed increased as the quantity of fired brick waste went up. It was indeed shown that this increase was around 14.63%, 10.92% and 7.08% for mixtures M1, M2 and M3, respectively, with respect to RB. These increases could be attributed to the decreased amount of CB that was replaced by dune sand. As shown in Figure 11, this replacement resulted in the formation of voids within the mixtures. These findings are consistent with those reported for the apparent density. It has in fact been observed that the higher the density of the adobe bricks, the greater the wave propagation speed.

![Figure 11. SEM images (G=5000) of brick adobes: (a) RB, (b) M1, (c) M2, (d) M3](image)

Source: Authors

### 3.2.3 Total absorption

The total absorption (TA) of the different mixtures was measured and the results obtained are presented in Figure 12 which explicitly shows that the water absorption decreases with increasing DS rate. It was also seen that the TA of mixtures M1, M2, and M3 decreased by approximately 9.30%, 15.13%, and 25.66%, respectively, with respect to that of RB. This could be attributed to the progressive reduction of soil in the mixtures following its replacement by the combination of CB and DS. It should also be remembered that the absorption capacity of DS is lower than those of soil and CB, as illustrated in Figure 9. It is also worth emphasizing that the maximum water absorption value of 13.36 % was
recorded for the M1 mixture. In addition, the Australian standard proposed by Walker (1991) indicates that the water absorption capacity of bricks must be below 20%. Fortunately, the total absorption values of all mixtures tested in the present work turned out to be below this threshold percentage.

![Figure 12. Combined effect of crushed fired brick waste and dune sand on the total absorption of adobe bricks](image)

Source: Authors

### 3.2.4 Capillary absorption

The results of the capillary absorption test are illustrated in Figure 13. It is easily noticed that the M3 mixture presents the lowest absorption coefficient C_b value which is equal to 5.81 g/cm².s⁻¹; it is 22.84% lower than that of RB. It should be noted that this C_b is more than twice that found for adobe brick containing 30% crushed sand.

![Figure 13. Combined effect of crushed fired brick waste and dune sand on the capillary absorption of adobe bricks](image)

Source: Authors
This result is similar to that found in the study conducted by Khoudja et al. (2021). Similar to the total absorption, it was noted that the coefficient \( C_b \) decreased as the quantity of brick waste replacing dune sand increased. In this analysis, the \( C_b \) values can be considered as representing low capillarity, which is consistent with the recommendations of Standard XP 13-901 which requires \( C_b \) values less than 20.

### 3.3 Combined Effect of Crushed Fired Brick Waste and Dune Sand on Mechanical Behavior

#### 3.3.1 Dry Compressive Strength

Figure 14 illustrates the variation in dry compressive strength (DCS) of bricks for the different mixtures under study. For this, samples with dimensions (10×10×10) cm³ were used to measure the DCS. It was in fact observed that the DCS of the prepared mixtures increased as the percentage of CB went up, in comparison with RB. Indeed, a straightforward increase in compressive strength was easily observed. This increase was of the order of 71.75%, 53.75%, and 44.19%, respectively, for mixtures M1, M2 and M3, with respect to that of RB. The highest compressive strength value was recorded for mixture M1, with an average of 7.54 MPa, while the lowest, of approximately 4.39 MPa, was obtained for RB. In comparison with the study carried out by Khoudja et al. (2021), it was noted that the dry compressive strength values of adobe bricks incorporating the combination of dune sand and waste bricks were higher than that of adobe bricks containing 30% sand crushed, as reported in (Khoudja et al., 2021).

![Figure 14](image-url)
3.3.2 Mechanical behavior of adobe bricks under compression

Figure 15 and 16 illustrate the mechanical behavior of various adobe brick mixtures under compression. The mechanical behavior was investigated by examining the stress-strain curves obtained from half samples of dimensions (4x4x16) cm³, via the three-point flexural test. As for Figure 16, it depicts the effect of different mixtures on the mechanical behavior of the samples under compression. Additionally, Table 5 summarizes the mechanical parameters obtained from the stress-strain curves, including the average of the maximum stress and ultimate strain, as well as the apparent modulus of elasticity. Analysis of the stress-strain curves presented in Figure 16a suggests that all adobe bricks exhibited quasi-linear elastic behavior, followed by a brittle failure. It was seen that strains increased as a function of the applied stress. Regarding Figure 16b, it shows that the maximum compressive stress values were observed in the following order: the M1 mixture came first, followed successively by the M2 and M3 mixtures. However, the minimum value was recorded for the RB. This interpretation is quite consistent with that made for the results presented in Figure 14. Furthermore, Figure 16c presents the elastic modulus results of the different mixtures prepared. It was noted that the modulus of elasticity follows the same trend as the compressive strengths. It was indeed observed that the elastic modulus values varied between 225.22 MPa and 363.20 MPa, which correspond to deformations of 2.54% and 3.33%, respectively (see Table 5). It should be pointed out that increasing the percentage of CB in the mixtures resulted in an increase in their modulus of elasticity. This increase corresponds to approximately 61.26%, 37.70%, and 17.73% for the mixtures M1, M2 and M3, respectively. According to Joshi et al. (2019), this elastic modulus augmentation could primarily be attributed to the presence of a fraction of CB whose particle size is similar to that of natural sand. The elastic modulus of the mixtures M1, M2 and M3 were found to exceed those of the reference mixtures which contain 30% crushed sand and 11% lime that were examined in the study carried out by Khoudja et al. (2021).
Figure 15. Experimental Scene: Mechanical behavior of adobe bricks under compressive of a brick sample

Source: Authors

Table 5. Compressive mechanical parameters

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Compressive strength (MPa)</th>
<th>Apparent modulus of elasticity (MPa)</th>
<th>Ultimate strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>10.83</td>
<td>363.20</td>
<td>2.54</td>
</tr>
<tr>
<td>M2</td>
<td>10.34</td>
<td>310.13</td>
<td>2.58</td>
</tr>
<tr>
<td>M3</td>
<td>9.83</td>
<td>265.16</td>
<td>3.05</td>
</tr>
<tr>
<td>RB</td>
<td>9.43</td>
<td>225.22</td>
<td>3.33</td>
</tr>
</tbody>
</table>

Source: Authors

Figure 16. Combined effect of crushed fired brick waste and dune sand on the mechanical behavior in compressive: (a) Stress-strain curves; (b) Compressive strength; (c) Modulus of elasticity

Source: Authors
3.3.3 Mechanical behavior of adobe bricks under flexural

The three-point flexural test was carried out in order to determine and analyze the mechanical characteristics of adobe bricks of dimensions (4x4x16) cm³ that were manufactured with the different mixtures presented in Figure 17.

Regarding Figure 18, it shows the way the various mix combinations may affect the flexural mechanical characteristics of adobe bricks.

Close examination of Figure 18a clearly indicates that the RB, as well as the other bricks, exhibited an essentially linear elastic behavior until reaching the maximum load, after which a sudden rupture occurred.

It was also noted that the combination of fired brick waste and dune sand led to an increase in flexural strength, as compared to the RB, as presented in Figure 18b and Table 6.

This increase was of the order of 52.23%, 30.34%, 19.4% for mixtures M1, M2 and M3, respectively, in comparison with RB.

Table 6. Flexural mechanical parameters

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Flexural strength (MPa)</th>
<th>Apparent modulus of elasticity (MPa)</th>
<th>Ultimate strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>3.06</td>
<td>490.25</td>
<td>1.38</td>
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<tr>
<td>M2</td>
<td>2.62</td>
<td>469.23</td>
<td>1.45</td>
</tr>
<tr>
<td>M3</td>
<td>2.40</td>
<td>425.69</td>
<td>1.61</td>
</tr>
<tr>
<td>RB</td>
<td>2.01</td>
<td>380.63</td>
<td>2.00</td>
</tr>
</tbody>
</table>

Source: Authors
Figure 18. Combined effect of crushed fired brick waste and dune sand on the mechanical behavior in flexural: (a) Stress-strain curves, (b) Flexural strength and (c) Modulus of elasticity

Source: Authors

On the other hand, it was observed that the ultimate deformation of the bricks under study decreased as the percentage of crushed brick waste (CB) increased, which explains the increase in the fragility of bricks as the CB content went up. Figure 18c and Table 6 present the results relating to the modulus of elasticity, for the different mixtures. It is noteworthy that the trend seen for the modulus of elasticity is similar to those observed for the compressive and flexural strengths. The values of this modulus were found to fluctuate between 490.25 MPa and 380.63 MPa. Increases of about 28.79%, 23.30% and 11.83% were observed for mixtures M1, M2 and M3, respectively, in comparison with that of RB.

3.3.4 Thermal conductivity

Figure 19 illustrates the variation in thermal conductivity (TC) for the different mixtures. It is worth mentioning that the presence of CB and DS in the bricks incorporating raw earth and lime resulted in increases in TC. It was found
that the thermal conductivity of the M1, M2 and M3 mixtures increased, respectively, by 24.07%, 16.66% and 11.11%, with respect to that of RB whose thermal conductivity is equal to 0.54 W/m.C°. This increase may be explained by the fact that the porosity of the BR is higher than that of the M1, M2 and M3 mixtures. It was also revealed that the porosity factor does affect the thermal conductivity (TC) of the samples, because closed pores reduce the TC, due to the low thermal conductivity of air (Chen; Liu 2013). Finally, Figure 19 clearly shows that the thermal conductivity follows the same trend as the direction of the apparent density and ultrasound propagation speed.

4 CONCLUSIONS

An experimental procedure was carried out to assess the combined effect of crushed fired brick waste and dune sand on adobe bricks characteristics. In light of the obtained results, the most important conclusions can be identified as follows:

A slight strength increase was observed with the incorporation of 20% DS, which is not the case for the other types of sand. Addition of 20% DS to the mixtures resulted in a decrease in the TA and Cb. These decreases were estimated at 34.75% and 24.74%, respectively.

Incorporation of CB and DS during the adobe bricks preparation process helped to decrease voids in the matrix, which improved the bricks’ characteristics in general, notably their physical characteristics, as the SEM technique indicated. Moreover, the apparent density, incorporating the M1 mixture (30CB+10DS), were
improved by 16.65%, thus leading to an increase of approximately 14.63% in the propagation speed of ultrasonic waves. Likewise, the M3 mixture (20CB+20DS) contributed to reducing the TA and Cb lower than that of RB by 25.66% and 22.84%, respectively.

With regard to the M1 mixture, it increased the compressive and flexural strength of bricks by 71.75% and 52.23%, respectively, as compared to the RB. It was also noted that the elastic modulus significantly increased by 83.4% in compression and 52.23% in flexion.

Combination of CB with DS led to a slight increase in the thermal insulation of adobe bricks as their thermal conductivity increased by 23.20% with respect to that of adobe bricks stabilized with lime only. But this slight loss of thermal insulation capacity seems very small, compared to the other gains obtained for the other studied characteristics.

Reducing the cost of construction materials, increasing thermal and energy efficiency, and protecting the environment are all achieved by using locally accessible resources, recycling industrial waste, and using its qualities to make mud bricks.

Future studies for improving these findings:

Study of heat treatment to accelerate the pozzolanic activity of crushed fired brick waste.

Durability study of raw earth bricks subjected to steam treatment.
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