

Effectiveness of Salty Sand in Improving the Adobe's Thermomechanical Properties: Adrar Case Study (South Algeria)

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Abstract

Adobe constructions have always existed, particularly in the Sahara's dry and scorching regions. This material has a high thermal inertia and can protect buildings from inclement weather. Its mechanical resistance, on the other hand, is still low and has to be increased. The current research, thus, investigated the effect of sand salinity on the thermal and mechanical properties of adobe. The sand needed to create adobe blocks was purchased from 2 distinct locations. The first one was normal sand while the other one was salty sand rich in SO_4^- sulfate. We considered different ratios of each sand from 10, 20 up to 90 %. The results showed that the adobe made from the sulfate-containing sand improved the compressive strength by about 36 % from 1.91 to 2.58 MPa, and flexural strength by about 71 %, from 0.35 to 0.60 MPa, and reduced the thermal conductivity by 14 % from 0.86 to 0.72 w/mk.

Keywords: Adobe, Arid zones, Mechanical resistance, Normal sand, Salty sand, Thermal conductivity

Introduction

In almost, dry and temperate climates, earth has always been the most common building material [2,3]. Today, at least 30 % of the world's population (about 1.5 billion people) live in houses built on earth [4]. We found that the first prefabricated building elements used by humans were molded earth bricks called Adobe. It is a construction material made from a mixture of sand, clay, and water until it reaches a semi-stable paste state, then formed in wooden molds or by hand, and left out in the open air under the sun to dry [2,5-7].

This material has a positive environmental impact, [8] economical [9] fire-resistant; it absorbs pollutants and encourages self-construction [2,5-7], is recyclable [10], and does not consume energy in its manufacture [11]. Adobe brick building walls are considered load-bearing elements. It resists the compression resulting from the weight of the roof. Therefore, compressive strength in adobe buildings is a significant factor. The walls' average compressive strength is about 70 % of the materials' average compressive strength making up the walls [12]. Increased compressive strength of adobe can result in increased overall strength of walls, building improvement, and building longevity. We also recorded a compressive strength value in existing adobe buildings between 0.2 and 2 MPa. [13,14].

The subject of improving Adobe's compressive strength has always been of great interest to researchers in various parts of the world. Several research pieces have evaluated the effect of adding various materials, natural or synthetic, on the compressive strength of Adobe, for example. We have reported that *P. roxburghii* and *G. optiva* fibers' addition improved the strength by up to 145 - 235 % [15]. Similarly, fonio straw (*Digitaria exilis*) contributed to increase the corrosion resistance of the water and improve the compressive strength [16]. Jové-Sandoval *et al.* [17] noted that pine needles in adobe paste contributed to increasing its strength up to 24 % compared to straw. Marie Giroudon *et al.* [18] compared the addition of the 2 straws, lavender and ocean, and showed that the ultimate compressive strength corresponds to 6 % lavender straw, which is higher than 3 % ocean straw. Moreover, the addition of a small percentage of desulfurization waste improved this strength to 7.5 MPa. [19]. However, the addition of phosphogypsum and natural gypsum waste increased the compressive strength to 4.72 MPa.

[20]. Furthermore, the addition of barley straw brought it to 5.6 MPa [21]. And also. Lime and cocoa ash with clay increased the compressive strength to 5.85 MPa [22]. Jokhio *et al.* [23] noted that the Embedded steel wire reinforcement of adobe brick improved its strength by 3 multiples on the contrary. One study concluded that adding more cellulose fibers could reduce the thermal conductivity, compressive and flexural strength of bricks [24]. Similarly, the addition of straw in Adobe reduced bulk density, bearing capacity and modulus of elasticity [25]. Another study concluded a decrease in the compressive strength of adobe; when they incorporate pig hair at 40 % [26].

While the majority of research have used natural or synthetic elements in adobe paste, these components are not readily available in sufficient quantities to fulfill the demands of earthen building. In this study, we study the influence of the SO₄ sulfate content in the sand and the sand content in the mixture in the adobe on its compressive and flexural strengths and its thermal characteristics. The objective of this study is the exploitation of abundant saline sand deposits in the desert region to improve the compressive and flexural strengths of adobe bricks.

Methodology

Study site description

The province of Adrar is located in southern Algeria. With geographic coordinates 27°52'27 "N, and 0°17'37"W, at an altitude of 257 m **Figure 1**. According to De Marton, its climate has been classified as hyper-arid [27,28], with a stifling summer and a very cold winter. This region includes many saline sites and a large sand reserve. The houses have been built in adobe for centuries.

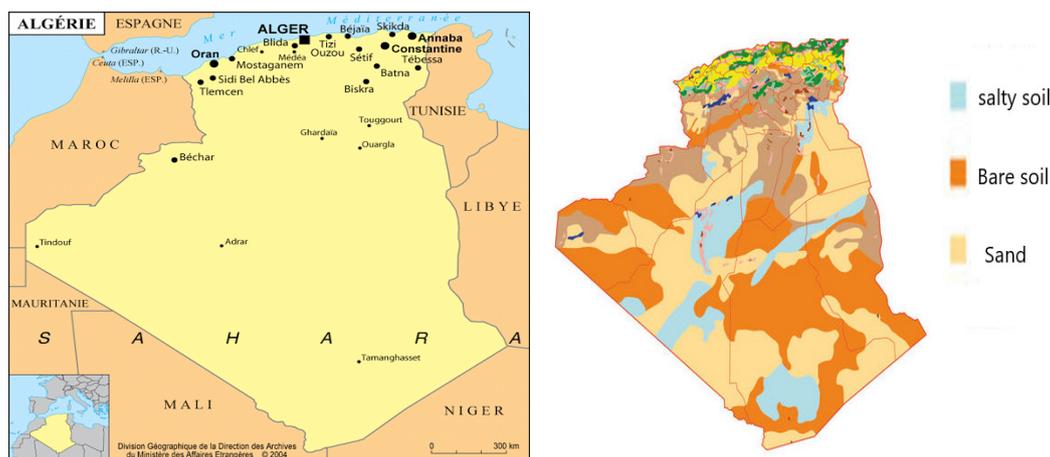


Figure 1 Position of study sites [1].

Materials used

Sand

We have chosen 2 sand resources to carry out this comparative study: One normal sand and the other salty sand, taken from the same region.

The sands previously came from the region of Bouda, in the Wilaya (province) of Adrar, with geographic coordinates 28°0'38.95"N, 0°25'32.95"W for the normal sand. And 28°0'14.89"N and 0°26'20.81"W for the salty sand. We measured the physico-chemical analyses in the LTPO laboratory in Oran.

Table 1 summarizes the results of the different physical properties obtained according to the standards NF. EN 933-8, NF. P94-057 [29,30], we can conclude that the 2 grains of sand, normal, and salty are very clean with an almost total absence of fine clay particles.

Table 1 The physical characteristics of sands.

Physical properties	Salty sand	Normal sand
Wet density	1.58 t/m ³	1.58 t/m ³
Density	2.741 t/m ³	2.61 t/m ³
Fineness modulus	2.31	2.31
Sand equivalent	83 %	87 %

Table 2 presents the results of the various mineralogical properties obtained. These results show a high content of SO₄ sulphate salt in the salty sand compared to normal sand, This presents an environment with high chemical aggressiveness (SO₄ > 12000, class XA3), NF EN 206-1 [29-32].

Table 2 The mineralogical characteristics of sands.

Component	Content (%)						
	SiO ₃	CaO	Al ₂ O ₃	FeO ₃	SO ₄ (mg/kg)	CaCO ₃	CO ₂
Normal sand	89.10	6.20	Nul	1.39	3087.00	4.67	2.05
Salty sand	78.50	3.59	0.37	1.16	17493.00	9.34	4.11

**Figure 2** A) salty sand, B) clay and C) normal sand.

Clay

The clay used; also comes from the region of Adrar (Bouda), with geographical coordinates 27°54'56.66"N and 0°16'40.40"W. We carried out analyses in the LTPOran's laboratory. The results obtained are in the following tables.

Table 3 The physical characteristics of the clay used.

Characteristics	Results
Apparent density	2.64 g/cm ³
Methylene blue (NF 933-9)[33]	VBS = 9.5
Atterberg limits (NF P94-051)[34]	
IP	38.86 %
Wl	64.46 %
wp	25.60 %

The test of methylene blue is made according to the standard NFP 933-9, it consists in controlling the absorption of the injected methylene blue, if the VBS > 8, the soil is classified between argillaceous and very argillaceous, after determination of the Index of plasticity I_p and according to NF P94-051. Suppose $I_p < 40$; the clay is classified as plastic.

Table 4 The Mineral composition of clay from the area of Adrar.

Component	Content (%)						
	SiO ₃	CaO	Al ₂ O ₃	FeO ₃	SO ₄ (mg/kg)	CaCO ₃	CO ₂
	82.10	1.96	3.33	4.41	13720.00	0.93	0.41

The clay has been evaluated according to its chemical constituents; the principal oxides checked are SiO₂, Al₂O₃ and Fe₂O₃, the amount of CO₃ and CaCO₃ is low.

From an industrial point of view, the ratio Al₂O₃/FeO₃ is less than 5.5, which means that this clay is rich in iron and can be used in the manufacture of building materials (bricks, tiles, ... etc.) [35].

Mixing water

The water used comes from the drinking water distribution system of the city of Adrar. The chemical analyses were done in the laboratory of the ANRH of the city of Adrar. **Table 5** shows the chemical analyses of the water used in the adobe mixture. According to the directives of the World Health Organization [36] concerning the potability of water, the pH of the water must be between 6.5 and 9 and the content of sulfate SO₄⁻ must be less than 250 mg/L, chlorides Cl⁻ must be less than 200 mg/L and potassium K⁺ must be less than 12 mg/L and magnesium Mg⁺ less than 150 mg/L. All the results of the analyses obtained, chemical, organoleptic, microbiological, and the parameters related to undesirable substances, related to toxic substances, show that this water is potable.

Table 5 The mineral composition of Adrar's drinking water.

Concentration mg/L	Composition							
	pH	Rs	Ca ⁺	Mg ⁺	Na ⁺	K ⁺	Cl ⁻	SO ₄ ⁻
	7.51	640	51	38	100	7	140	210
	NO ₃ ⁻	HCO ₃ ⁻	NH ₄ ⁺	NO ₂ ⁻	PO ₄ ⁻	MO	SI	
	19.144	119	0.007	0.01	0	1.4	684	

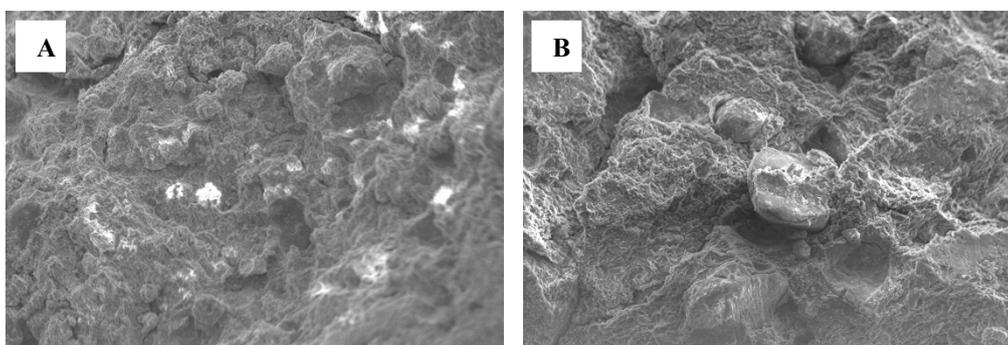
Samples

We prepared several adobe specimens using different sand and clay percentages to study the influence of sand and clay ratios on thermo-mechanical properties. Mixtures in **Table 6** presented 18 variants of adobe samples with various sand percentages (normal/salty) and clay. We counted a total of 90 pieces. The setting occurred in the open air.

Table 6 The compositions of the studied samples.

The Composition	sample	Percentages	Composition	sample	Percentages
Normal Sand	C _d 1	10 % clay +90 % Normal sand	Salty sand	Cs1	10 % clay +90% Salty sand
	C _d 2	20 % clay +80 % Normal sand		Cs2	20 % clay +80 % Salty sand
	C _d 3	30 % clay +70 % Normal sand		Cs3	30 % clay +70 % Salty sand
	C _d 4	40 % clay +60 % Normal sand		Cs4	40 % clay +60 % Salty sand
	C _d 5	50 % clay +50 % Normal sand		Cs5	50% clay +50 % Salty sand
	C _d 6	60 % clay +40 % Normal sand		Cs6	60 % clay +40 % Salty sand
	C _d 7	70 % clay +30 % Normal sand		Cs7	70 % clay +30 % Salty sand
	C _d 8	80 % clay +20 % Normal sand		Cs8	80 % clay +20 % Salty sand
	C _d 9	90 % clay +10 % Normal sand		Cs9	90 % clay +10 % Salty sand

Figure 3 shows 2 images of adobe under a scanning electron microscope; the first image is of an adobe made of normal sand and the second of an adobe made of salty sand. When we mix clay with sand and water, we notice that the normal sand retains the granules with a high adobe percentage. Contrary to the salty sand, the ratio of sand grains in the adobe is slightly low. As salts surround the salty sand grains, most of them dissolve when mixed with water.

**Figure 3** Images according to SEM; A) adobe with salty sand, B) adobe with normal sand.

Mechanical and thermal testing

The uniaxial compression test was performed on simple cylindrical loads at a constant speed until the test piece broke **Figure 4A**. This test aims to determine the compressive strength of the sample (NBNB24.201). Samples used are cylindrical; their height is 10 cm, and their diameter 5 cm. The following formula gives the compressive stress of the specimen;

$$f_c = \frac{P}{A}$$

f_c is the compressive strength (N/cm²), P is the maximum load supported by the specimen, and A is the average gross cross-sectional area.

According to the European standard EN1015-11 [37], the flexural strength is determined by applying a concentrated load on a specimen in the middle of the distance between the 2 supports (**Figure 4B**). In the laboratory of the University of Becher, we tested the specimens of dimensions 40×40×160 mm³, and the flexural strength is determined according to the following equation;

$$R_f = 1,5 \frac{Fl}{bd^2}$$

R_f is the flexural strength (N/mm²),

F is the maximum load applied to the middle of the prism (N),
 l is the distance between the 2 supports (mm),
 b is the average width of the specimen in (mm),
 d is the average length of the specimen in (mm).

We measured thermal characterization tests on specimens of dimensions $100 \times 100 \times 50 \text{ mm}^3$ in the ENPOran laboratory, **Figure 4** using the ISOMET 2104 equipment [38].

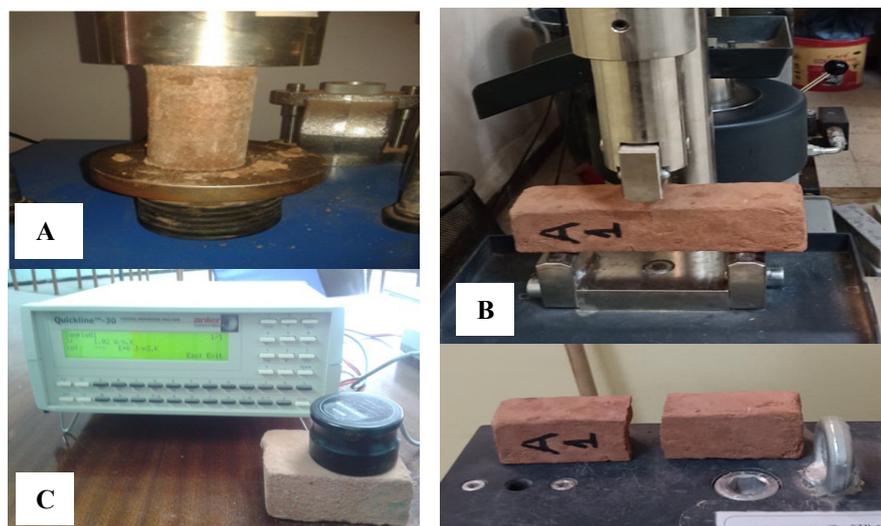


Figure 4 Tests; A) crushing of samples, B) 3-point flexural test and C) measurement of thermophysical characteristics with ISOMET 2104.

Results and discussion

Compressive strength

Figure 5 shows the variation of compressive strength of the samples with the percentage of sand in each mixture; for 2 types of sand. The compressive strength of the adobe prepared with normal sand with 20, 30 and 40 % increased from 1.65 to 1.78, 1.82 and 1.90 MPa, respectively, which presents improvement rates of 6, 10 and 11 %, respectively. However, the mixtures with 60, 70, 80 and 90 % sand contents experienced a decrease in compressive strength from 1.91 to 1.82, 1.78 and 1.45 MPa, respectively, which corresponds to 7, 14, 21 and 31 % compared to the mixture with 50 % normal sand. The highest compressive strength value corresponds to the mixture of 50 % sand and 50 % clay, where its strength reached 1.92 MPa. For the adobe prepared with salty sand, the 20, 30 and 40 % mixtures showed an improvement in strength, from 2.18 to 2.2, 2.28 and 2.49 MPa with ratios of 3, 14 and 18 %, respectively. However, the strength decreased significantly for the 60, 70 and 80 % sand mixtures, from 2.58 to 2.38, 2.23 and 1.91 MPa with ratios of 14, 26 and 34 %, respectively. Note that 2.58 MPa corresponds to the compressive strength of the adobe obtained from the 50 % salt sand +50 % clay mixture.

Comparing the 2 curves of compressive strength, we noted that the salty sand improves the compressive strength of 24, 36 and 30 % for the mixtures of 10, 40 and 80 % compared to the normal sand. Therefore, the optimum mix for compressive strength was 50 % sand +50 % clay for both types of sand. However, increasing the percentage of sand beyond 50 % reduces the compressive strength of the adobe.

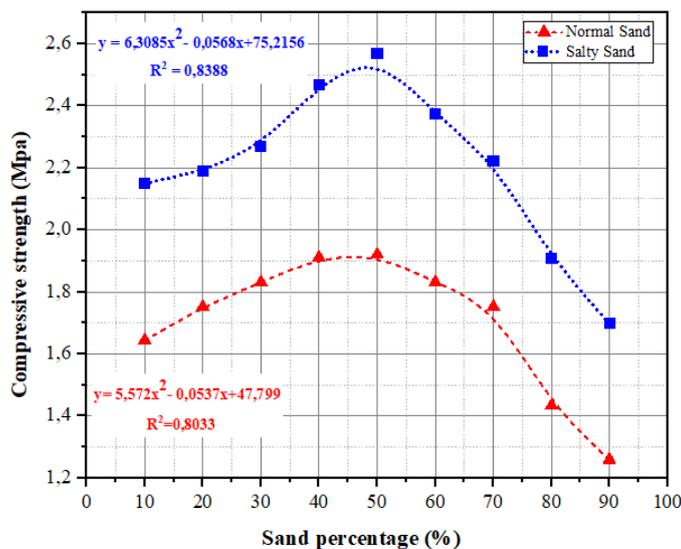


Figure 5 Compressive strength as a function of sand content.

Flexural strength

Figure 6 shows the variation of flexural strength as a function of sand ratios in the adobe mixture in the 2 cases of sand nature; normal and sulfated saline. In the case of normal sand, the flexural strength is semi-stable for the 20, 30 and 40 % ratio mixes ranging from 0.33 to 0.35, 0.35 and 0.37 MPa, respectively, the maximum value was reached at 0.36, which corresponds to the 40 % sand and 60 % clay mix. We then recorded a drop in flexural strength to 0.30, 0.25, 0.09 and 0.03 MPa for the 60, 70, 80 and 90 % sand content, respectively. It was found that the sand content negatively affects the flexural strength.

For the case of salty sand, we recorded a slight increase in flexural strength at 0.55, 0.56, 0.58 MPa for the mixtures of 20, 30 and 40 %, respectively, it was reached for a maximum of 0.6 MPa for the mixture of 50 % sand and 50 % clay, then the flexural strength decreased to 0.5, 0.4, 0.25 and to 0.11 MPa for the mixtures of 60, 70, 80 and 90 % of salty sand, respectively. We noticed that the higher the clay content; the flexural strength is stable and higher than the lowest value of 0.35 MPa required by the New Mexico State Earth Building Materials Code.

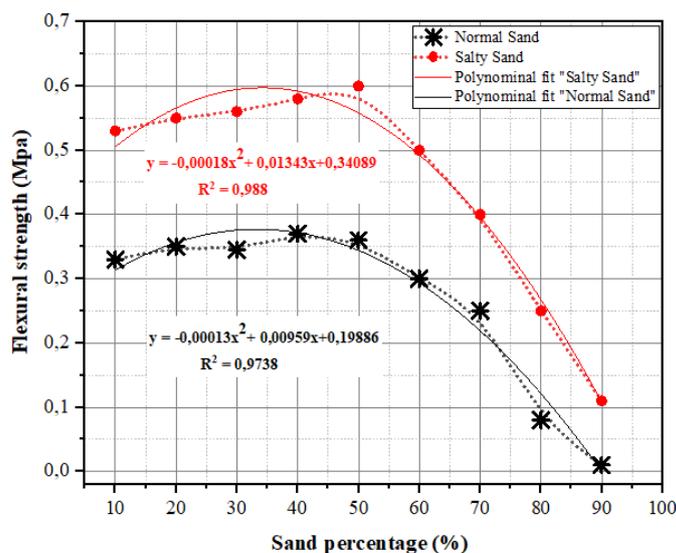


Figure 6 Flexural strength as a function of sand content.

Thermo-physical characteristics

The variation of the thermal conductivity of adobe as a function of the percentage and nature of the sand is shown in **Figure 7**. The thermal conductivity of adobe made from normal sand is almost stable at 15 and 25 %; this mixture has a value of 0.72 W/mk. Then, the thermal conductivity value increases to 0.73, 0.75, 0.95 and 1.05 W/mk for mixtures with 50, 60, 70 and 80 % sand content, respectively. The highest thermal conductivity value equals 1.13 W/mk, corresponding to the mixture containing 90 % of normal sand. As for the adobe/salty sand mixture, we recorded a low thermal conductivity equal to 0.7 W/mk for 10 and 20 % sand contents. This thermal conductivity increases to 0.93, 1.0 and 1.08 W/mk for sand proportions at 60, 70 and 80 %, respectively. The highest thermal conductivity value is 1.1 W/mk, corresponding to the 90 % sand +10 % clay mixture.

Based on these results, we noticed that the salty sand reduces the thermal conductivity of the adobe in a ratio between 3 and 14 %. The proportion of clay in the adobe also contributed to the low thermal conductivity, and on the contrary, the proportion of sand increased the thermal conductivity.

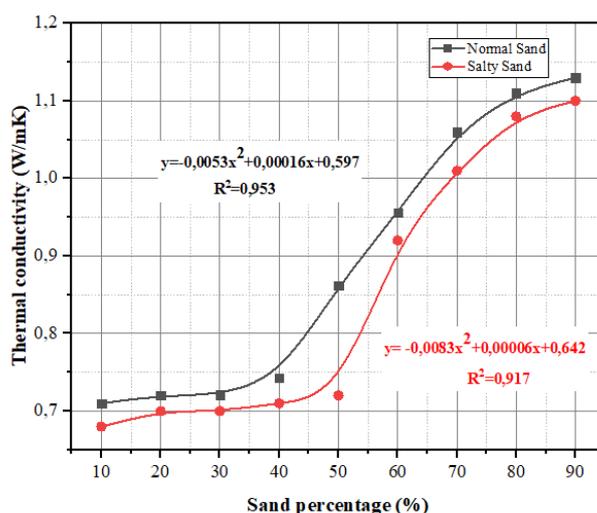


Figure 7 Thermal conductivity of adobe as a function of the sand percentage.

Figure 8 shows the evolution of the specific heat of the adobe as a function of the percentage and nature of the sand. A slight increase does not exceed 3 % for samples with 10, 20, 30 and 40 % of normal sand. Increases, for samples with 60, 70 and 80 % of normal sand, to 1500, 1548 and 1675 kJ/m³K, respectively. The extreme specific heat is 1680 kJ/m³K, corresponding to the mixture of 90 % normal sand +10 % clay.

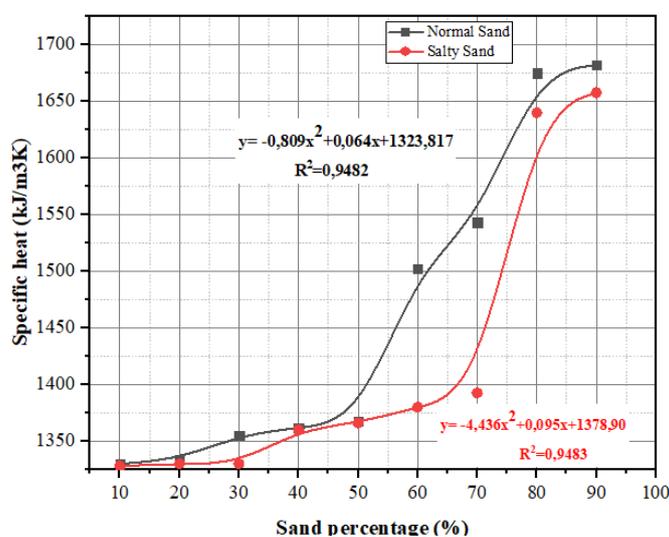


Figure 8 Specific heat of adobe as a function of the sand percentage.

For adobe made with salty sand, the specific heat increased slightly for mixtures of 10 to 50 %, in a ratio not exceeding 4 %. However, it increased progressively as the percentage of clay in the mixtures decreased. As a result, we recorded an improvement of 12 and 24 % for the 2 mixtures with 60 and 70 % sand at 1376 and 1390 kJ/m³K, respectively. The highest specific heat is 1652 kJ/m³K, which corresponds to the 90 % sand +10 % clay mixture.

Comparing the 2 curves in **Figure 7**, we found that salty sand reduces the specific heat by 2 to 8 % and that the high content of salty sand in adobe bricks decreases the thermal inertia.

Comparison with previous studies

Table 7 presents a comparison of different studies and treatments carried out on adobe to improve its compressive, flexural strength and the effect of these treatments on its thermal properties.

Table 7 Comparison with previous studies

Parameter studied	Ref.	Country	Additional material	Improvement / reduction ratio	Quantity MPa
Compressive strength (MPa)	[39]	Brazil	glass fiber reinforced polymer waste	+45 %	1.40 - 2.05
	[16]	Burkina Faso	Fonio straw	+23 %	2.3 - 2.8
	[21]	Algeria	Barley straw	10 % at 1.5 % fiber -45 % at 3.5 % fiber	5.1 - 5.6 5.1 - 2.8
	[40]	China	Clay-silt	22 %	1.39 - 1.70
	[22]	Ghana	Lime &cocoa ash with Safari and <i>Mfensi</i> clay	260 % 642 %	0.8 - 2.07 0.91 - 5.85
	[41]	South Africa	Fibers de sisal	25 %	
	[23]	Malaysia	Embedded steel wire	300 %	1.58
	[42]	North Carolina	Recycled sugarcane Fiber waste	58,61 %	4.79
	[26]	Chile	Pig hair	-40 %	2 - 1.2
	Our study	Algeria	Salty sand	+36 %	1.91 - 2.58
	[43]	Chile	Jute fibers	11 %	2.20 - 2.45
	[44]	Cameroon	Millet waste fibers	38.6 %	4.69
	[45]	Italy	Seagrass fibers	40 %	1.676 - 2.346
Flexural strength (MPa)	[43]	Chile	Jute fibers	20 %	0.55 - 0.66
	[46]	Chile	Chicken feather fibers	7 %	0.54 - 0.58
	[44]	Cameroon	Millet waste fibers	9 %	0.15 - 0.164
	[47]	Denmark	Synthetic fibers of recycled polyethylene	5 %	0.65 - 1.14
	[45]	Italy	Seagrass fibers	46 %	0.411 - 0.6
This study	Algeria	Salty sand	71 %	0.35 - 0.60	
Thermal conductivity (W/m.k)	[39]	Brazil	Glass fiber reinforced polymer waste	-21 %	0.86 - 0.68
	[48]	Burkina Faso	Cement	+27 %	1.1 1.4
	[16]	Burkina Faso	Fonio (<i>Digitaria exilis</i>) straw	-67 %	1.1 - 0.35
	Our study	Algeria	Salty sand	-14 %	0.86 - 0.72

In comparing the different adobe treatments carried out in previous studies, using different additives, natural and synthetic; We have found that most of them have contributed to increasing the compressive strength in variable proportions, from 6 to 3 times, [22,23] or with ratios from 10 to 45 % [16,39-41,43-45]. We have also noted that the additive's percentage merit careful study, and the increase in the percentage of additives up to a specific limit may decrease the adobe strength [21]. Similarly, flexural strength increases by 10 % with the addition of fibers [44,46,47]. It exceeds 46 % in the case of seagrass fibers. We recorded a rate of 71 % with the presence of sulphate. Most studies have shown that the flexural strength only increased at the optimum content of the additions, after which the flexural strength decreased again when the fiber content increased further [49]. Moreover, we found that cement to the adobe increased the thermal conductivity by a significant percentage. Witch contrasts with the various additives decreasing the value of thermal conductivity, improving the efficiency of adobe to insulate houses, especially in hot and dry regions; where adobe is the ideal solution to protect the indoor environment from the aggressiveness of the outdoor climate.

The proportions obtained in our study of adobe with salty sand are encouraging rates, improvement in compressive strength, and increased thermal insulation value.

Conclusions

In this study, we studied different adobe types and combined clay and sand in a desert area. Building materials are supposed to be insulating and must adapt quickly to exceptional climatic conditions. They must also provide good mechanical strength to obtain durable constructions. We proved that: The nature of the sand used is fundamental in this respect. Moreover, the salinity of the sand significantly improves its mechanical properties without having any effect on its thermal behaviors and inertia. We have shown that the salty sand used in the making of adobe is very useful and helps to improve its compressive strength from 1.9 to 2.58 MPa with a rate of improvement of 36 %. Similarly, the flexural strength increases from 0.35 to 0.60 MPa for a rate of 71 %. The adobe has good thermal inertia, and the sulfated salinity of the sand reduces its thermal conductivity by about 14 %. The adobe's high specific heat is critical for retarding the outdoor climate's influence on the building. Using salty sand in adobe, we have not recorded any significant negative impact on this thermal property. The use of salty sand as a substitute for normal sand has no economic cost because salty deposits are abundantly available in desert areas, as are normal sand. All these results recommend using adobe made from salt sand as a building material for new buildings. It is also very encouraging to use it as a material for restoring old adobe buildings known locally as Ksar.

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