Clay mortars for earth wall plasters in Niger: effect of gypsum, rice husk and rice husk ash on bulk density and compressive strength.

Abstract : Background: Earth walls are still widely built in Niger, but earth materials have modest strength and are sensitive to water. This study assessed three locally available materials, gypsum plaster, rice husk (RH) and rice husk ash (RHA), as additions to clay mortars intended for plastering earth walls.

Methods: A ferruginous clay of low plasticity sampled in Niamey (WL = 42.9%, IP = 19.7%, Fe2O3 = 14.0%) was used. In nine mixes (F0 to F8), the addition replaced 5 or 10% of the dry clay mass. The 4 × 4 × 16 cm prisms were cured for 7 days after casting, including 96 h at 40 °C, and tested in compression at 14 days on six half-prisms per mix; bulk density was determined on the prisms.

Results: The control reached 8.13 MPa. Gypsum alone raised the strength to 10.88 MPa (+34%) at 5% and to 11.27 MPa (+39%) at 10%, with no increase in bulk density. The gypsum–ash blend gave the highest value at 5% (12.19 MPa, +50%) but dropped to 6.13 MPa (−25%) at 10%. The gains obtained with ash alone (+15 and +16%) did not separate these mixes from the control, and raw rice husk lowered the strength by 22 and 45%. Bulk density was not significantly correlated with compressive strength (r = 0.26).

Conclusion: Mix F5, in which 2.5% of the clay is replaced by gypsum and 2.5% by ash, is recommended for interior plasters or plasters sheltered from rain, subject to bond strength tests; F1 (5% gypsum) is the simplest alternative.

Key words:-

Earth plaster, Clay mortar, Gypsum, Rice husk, Rice husk ash, Compressive strength, Earth construction, Niger

Introduction:-

In Niger, walls have traditionally been built with local materials, mainly unfired earth, whose availability, low cost and thermal inertia suit the Sahelian climate. Urbanization and a population growth rate of 3.2 to 3.3% per year since 2020 (World Bank, 2026) have nevertheless increased the use of cement and reinforced concrete, which are chosen for their mechanical strength despite their cost and carbon footprint.

Earth can replace these materials only if its two main weaknesses are reduced: modest mechanical strength and sensitivity to water. This study examines stabilization with gypsum plaster, a fast-setting calcium sulfate binder, combined with two locally available agricultural by-products, rice husk and rice husk ash, with wall plasters as the intended application.

The objective is to measure the effect of these three additions (gypsum, raw rice husk and rice husk ash), alone or combined, at 5 and 10% replacement, on the bulk density and compressive

UNDER PEER REVIEW IN IJAR

strength of mortars made with a local clay. The results are compared with published values for unstabilized earth mortars and plasters, gypsum-stabilized earth, and earth materials containing rice husk, in order to propose a mix that can be prepared with the resources available in Niamey.

Background and literature review

Unfired earth is one of the oldest building materials. Houben and Guillaud (1989) described the main techniques (adobe, rammed earth, cob, compressed earth blocks) and the principles of soil stabilization. In the Sahel, the thermal inertia of thick banco (mud) walls dampens the difference between day and night temperatures, a behavior described for hot, dry climates by Minke (2012).

The sensitivity of earth materials to water and their modest strength are addressed in two ways. The first is stabilization with a binder. Cement is the most widely used, but Van Damme and Houben (2018) question its efficiency in earth in view of the strength gained and its environmental cost, which leaves room for other binders: lime, calcium sulfate binders such as gypsum plaster, and pozzolanic binders. The second is the addition of plant fibers. Millogo et al. (2014) reinforced pressed adobe blocks with 0.2 to 0.8 wt% of kenaf fibers: 0.2 to 0.6% of 30 mm fibers reduced pore size and improved the mechanical properties, whereas 0.8% of 60 mm fibers reduced the compressive strength. For soil blocks reinforced with 0.25 to 1% of agricultural waste fibers, Danso et al. (2015) recommend a content of 0.5%; they also note that the relationships between properties established for binder-stabilized blocks do not apply to fiber-reinforced blocks.

Rice husk ash is a source of reactive silica (Della et al., 2002), whose amorphous or crystalline state depends on the combustion conditions. The review by Laborel-Préneron et al. (2016), based on some fifty studies, compiles data on the physical, mechanical, hygrothermal and durability properties of earth materials containing plant aggregates or fibers, and points out the lack of data on their hygroscopic properties and durability. The fiber contents studied by Millogo et al. (2014) and Danso et al. (2015) remain below 1 wt%, that is, five to ten times lower than the 5 and 10% of rice husk used in the present study. More recently, Nshimiyimana et al. (2020) combined rice husk ash with calcium carbide residue to stabilize compressed earth blocks, and Savadogo et al. (2023) added fermented rice husk to an earth plaster for adobe walls.

Materials and Methods:-

Materials

Clay: the clay was collected from the ground surface on the EMIG campus in Niamey (13.499489° N, 2.085363° E). It was dry to the touch on arrival (water content of 1.48%) and was crushed, ground and passed through a 2 mm sieve to remove coarse particles and organic debris; the retained fraction was ground again until it passed the sieve.

Gypsum: the binder is a commercial gypsum plaster (calcium sulfate hemihydrate) produced by the Egyptian company PLATERIE EL DJABAS, hereafter referred to as gypsum; Table 1 gives

UNDER PEER REVIEW IN IJAR

its properties as supplied by the manufacturer. The molds were filled immediately after mixing, since setting of this gypsum begins after 4 to 6 min according to the manufacturer.

Table 1. Properties of the gypsum plaster (manufacturer's data).

Property	Value
Water of crystallization (H_2O)	4.30%
Compressive strength	13.26 MPa
Flexural strength	3 MPa
Recommended water/gypsum ratio	0.70 to 0.80
Initial setting time	4 to 6 min
Final setting time	8 to 15 min

Rice husk (RH): a by-product of mechanical rice hulling, the rice husk comes from the paddy fields on the right bank of the Niger River in Niamey. It was sieved at 1 mm to remove the fine dusty fraction (only the retained fraction was kept), washed, drained, air-dried for 24 h and then oven-dried at 105 °C to constant mass. It is used as a lightweight plant aggregate.

Rice husk ash (RHA): the dried rice husk was burnt in small batches in a metal pan placed over a charcoal stove (Figure 1b), with the lid partly open, and stirred every 20 to 30 min. Combustion was stopped when the ash was friable and uniformly dark gray. The ash was then cooled, ground and sieved at 0.125 mm. The combustion temperature was not measured; the silica content of the ash, the amorphous or crystalline state of this silica and the residual carbon content, suggested by the gray color, were not determined.

Characterization of the clay matrix

The results of the clay identification tests are given in Table 2. The liquid limit is the value at 25 blows of the regression line fitted to the four cup measurements ($w = -0.1171\ N + 45.83$, where N is the number of blows; $r = -0.99$). With $W_L = 42.9\%$ and $I_P = 19.7\%$, the clay plots above the A-line of the Casagrande chart, whose ordinate is $0.73 \times (W_L - 20) = 16.7\%$, in the field of clays of low plasticity (CL in the USCS). These limits are not sufficient to identify the clay minerals, which were not determined because no X-ray diffraction analysis was performed. The particle size analysis was carried out by dry sieving, without washing or sedimentation: only 1% of the material passes the 0.08 mm sieve, which indicates that the clay aggregates were not dispersed. The coefficients C_u and C_c therefore describe the size distribution of the aggregates in the crushed material, not the particle size distribution of the clay.

Table 2. Identification properties of the clay.

Parameter	Value	Method / Standard
Water content after air drying (w)	1.48%	Oven drying, ISO 17892-1:2014
Coefficient of uniformity (C_u)	4.12	Dry sieving, 20 to 0.08 mm

UNDER PEER REVIEW IN IJAR

Parameter	Value	Method / Standard
Coefficient of curvature (C_c)	2.10	Dry sieving, 20 to 0.08 mm
Liquid limit (W_L)	42.9%	Casagrande cup, 4 points, NF P 94-051
Plastic limit (W_P)	23.2%	Thread rolling, NF P 94-051
Plasticity index (I_P)	19.7%	$I_P = W_L - W_P$

The chemical composition of the clay was determined by energy-dispersive X-ray fluorescence spectrometry (Xenemetrix instrument, rhodium source at 30 kV and 30 µA, measurement in air, quantification by the fundamental parameters method); the contents, normalized to 100%, are given in Table 3. Silica, alumina and iron oxide total 90.9%, followed by CaO (3.1%), TiO_2 (1.9%), K_2O (1.8%) and chlorine (1.1%). The SiO_2/Al_2O_3 mass ratio is 3.8, compared with 1.18 for pure kaolinite: a large part of the silica is therefore located outside the clay minerals, probably as quartz, which X-ray diffraction would confirm or refute. With 14.0% Fe_2O_3, the clay is ferruginous. Three caveats apply to these values: the uncertainty on alumina is high (± 5.1%), sodium is not measured and magnesium is not detected in air, and the loss on ignition was not determined, so the normalized contents overestimate those of the raw material.

Table 3. Chemical composition of the clay by X-ray fluorescence (contents normalized to 100%; uncertainty given by the analysis software).

Constituent	Content (wt%)	Uncertainty (%)
SiO_2	60.7	2.8
Al_2O_3	16.1	5.1
Fe_2O_3	14.0	0.1
CaO	3.1	0.1
TiO_2	1.9	0.1
K_2O	1.8	0.1
Cl	1.1	0.1
Others (14 elements, each below 0.25%)	1.3	–

Mix design

Nine mixes were prepared (Table 4). The control F0 contains clay only (1502 g). In mixes F1 to F8, the addition replaces 5% (75 g) or 10% (150 g) of this clay mass. The total dry mass (1502 g) and the mass of water (296 g, i.e. 19.7% of the dry mass) are the same for all mixes. At equal dosage, the gypsum–ash blend (F5, F6) contains half as much of each constituent as the single-addition mixes.

Table 4. Composition of the nine mixes (masses per batch; the percentage is the fraction of the total dry mass of 1502 g replaced by the addition).

UNDER PEER REVIEW IN IJAR

Mix	Clay (g)	Gypsum (g)	RHA (g)	RH (g)	Water (g)	Total paste (g)
F0 – Control	1502	–	–	–	296	1798
F1 – Clay + 5% gypsum	1427	75	–	–	296	1798
F2 – Clay + 10% gypsum	1352	150	–	–	296	1798
F3 – Clay + 5% RHA	1427	–	75	–	296	1798
F4 – Clay + 10% RHA	1352	–	150	–	296	1798
F5 – Clay + 5% (gypsum + RHA)	1427	37	38	–	296	1798
F6 – Clay + 10% (gypsum + RHA)	1352	75	75	–	296	1798
F7 – Clay + 5% RH	1427	–	–	75	296	1798
F8 – Clay + 10% RH	1352	–	–	150	296	1798

Specimen preparation and testing

The dry constituents (clay, gypsum, ash) were dry-mixed for 2 to 3 min; the rice husk was then added gradually and the water introduced in small amounts. The mass of water (296 g) was set after preliminary trials and applied identically to all mixes. Immediately after mixing, the pastes were placed in lightly oiled 4 × 4 × 16 cm prismatic molds in three layers compacted by hand (pressure with the fingers or a spatula, followed by light tapping on the sides and base of the mold, without vibration), then struck off with a steel rule. Three specimens were cast per mix, 27 in total. Figure 1 shows the main steps, from the treatment of the rice husk to the dried specimens.

UNDER PEER REVIEW IN IJAR



Figure 1. *Experimental steps: (a) washing and draining of the rice husk; (b) burning of the rice husk to produce the ash; (c) casting of the specimens; (d) labeled 4 × 4 × 16 cm specimens after drying.*

The specimens were demolded 24 h after casting, air-dried for 48 h indoors in the laboratory, out of direct sunlight, at 20 to 25 °C, and then oven-dried at 40 °C for 96 h, i.e. 7 days between casting and the end of oven drying. They were then stored in laboratory air until testing at 14 days. Compressive strength was measured on the six half-prisms obtained from the three prisms of each mix, using a laboratory hydraulic press (Figure 2), at a loading rate complying with NF EN 196-1:2016; R_c is the failure load divided by the loaded section of 40 × 40 mm (1600 mm²). In accordance with this standard, the strength of a mix is the mean of the six values of its series, and none of these six values deviates by more than 10% from the series mean. Bulk density was calculated from the mass of each dried prism and the mold volume (256 cm³), since the actual dimensions of the specimens were not measured.

UNDER PEER REVIEW



Figure 2. *Laboratory hydraulic press used for the compression tests.*

Results:-

Bulk density

Bulk densities range from 1443 kg/m³ (F4) to 1641 kg/m³ (F7) (Table 5, Figure 3). For eight mixes, the standard deviation between the three specimens does not exceed 9 kg/m³ (coefficient of variation of 0.6% or less). Six mixes (F0, F1, F2, F3, F5 and F6) lie between 1582 and 1603 kg/m³, within 1% of the control value (1587 kg/m³). F4 (10% RHA) and F8 (10% RH) are 9 and 8% lighter, respectively. F7 (5% RH) is the densest mix, 3% above the control, although rice husk is the lightest constituent of the mix and F8, which contains twice as much, lies 8% below the control. The masses of the three F7 specimens (413, 417 and 430 g, i.e. 1613 to 1680 kg/m³) confirm this mean; they also show the largest scatter of the series (standard deviation of 35 kg/m³), mainly due to the third specimen.

Compressive strength

The control F0 reaches 8.13 MPa. Table 5 gives, for each mix, the mean failure load, the mean strength of the six half-prisms and its change relative to the control. Within each series, none of the six values deviates by more than 10% from the mean of that series (see Specimen preparation and testing): the results of a mix therefore lie between 0.9 and 1.1 times its mean. Comparing these ranges between series, an increase of more than 22% or a decrease of more than 18% relative to the control fully separates the range of a mix from that of the control. This applies to F1, F2 and F5 (increase) and to F6, F7 and F8 (decrease), but not to F3 and F4 (+15 and +16%), whose results may overlap those of the control.

UNDER PEER REVIEW IN IJAR

Table 5. Bulk density, failure load and compressive strength of the nine mixes (bulk density: mean ± standard deviation of the three prisms, calculated from the individual masses and the mold volume; load and R_c: means of the six half-prisms). The last column gives the change in R_c relative to the control F0.

Mix	Bulk density (kg/m³), mean ± SD	Mean load (kN)	Mean R_c (MPa)	Change in R_c vs F0 (%)
F0 – Control	1587 ± 6	13.00	**8.13**	–
F1 – 5% gypsum	1599 ± 5	17.40	**10.88**	+34
F2 – 10% gypsum	1585 ± 9	18.03	**11.27**	+39
F3 – 5% RHA	1582 ± 4	14.90	**9.31**	+15
F4 – 10% RHA	1443 ± 8	15.10	**9.44**	+16
F5 – 5% (gypsum + RHA)	1603 ± 6	19.50	**12.19**	+50
F6 – 10% (gypsum + RHA)	1599 ± 8	9.80	**6.13**	−25
F7 – 5% RH	1641 ± 35	10.20	**6.38**	−22
F8 – 10% RH	1456 ± 9	7.10	**4.44**	−45

Gypsum alone increases the strength by 34% at 5% and by 39% at 10%; ash alone gives +15 and +16%, differences that the scatter does not allow to be separated from the control. The gypsum–ash blend gives the highest mean strength of the series at 5% (12.19 MPa, +50%), but the lowest of the gypsum-bearing mixes at 10% (6.13 MPa, −25%). Raw rice husk reduces the strength at both dosages, by 22% at 5% and by 45% at 10%. Increasing the dosage from 5 to 10% changes the strength little with gypsum alone or ash alone (+0.39 and +0.13 MPa) and reduces it with the gypsum–ash blend (−6.06 MPa) and with rice husk (−1.94 MPa). Figure 3 plots bulk densities and strengths together.

UNDER PEER REVIEW IN IJAR

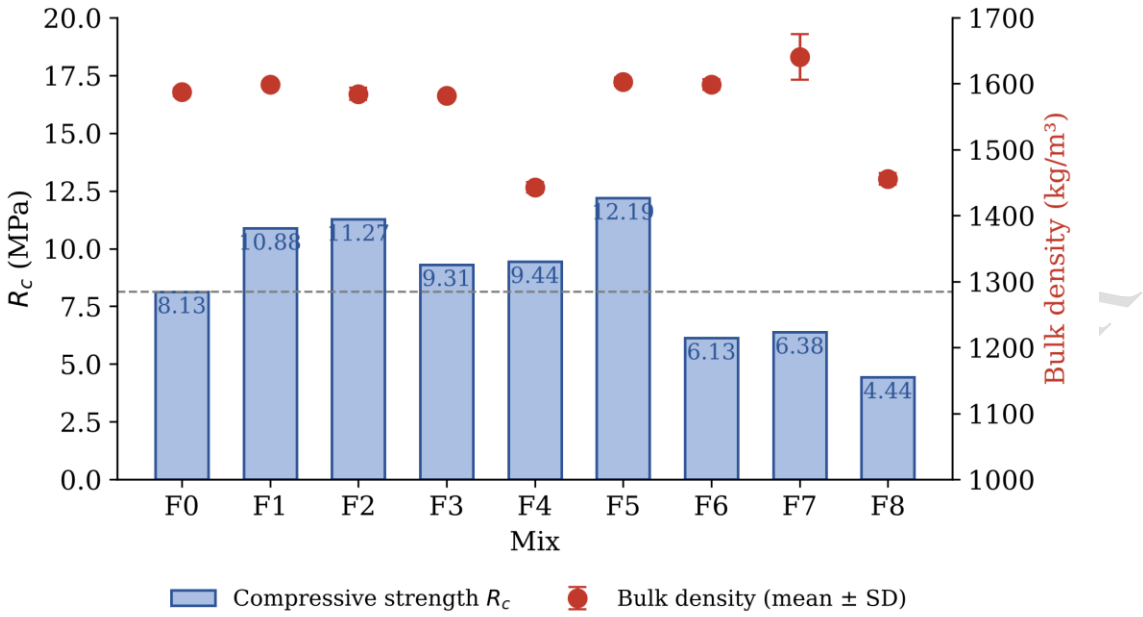


Figure 3. *Compressive strength (bars, left axis) and bulk density (points with standard deviation, right axis) of mixes F0 to F8. The dashed line indicates the strength of the control.*

Discussion:-

Effect of the additions on strength

The strength of the control (8.13 MPa) lies within the range of 2.4 to 15.8 MPa measured by Meimaroglou and Mouzakis (2024) on eleven unstabilized earth mortars tested, as here, on 4 × 4 × 16 cm prisms; in their study, strength increases with the clay fraction and, even more, with the specific surface area of the clay. Gypsum and ash, alone or combined at 5%, increase the strength without changing the bulk density: F1, F2, F3 and F5 remain between 1582 and 1603 kg/m³, like the control. The gain therefore does not result from densification. For gypsum, the most direct explanation is setting: hydration of the hemihydrate forms a network of gypsum crystals that binds the clay grains. Several recent studies point in the same direction. On rammed earth stabilized with 0 to 15% gypsum, Ávila et al. (2025) measured compressive strength gains of up to 130%, reaching 3.2 MPa at 15%. On clay–sand mortars intended for plaster panels, Rocha et al. (2025) obtained increases of 320% in compression and 685% in flexure by replacing 20% of the clay volume with gypsum, and observed that gypsum markedly shortens the setting time. The gains obtained here (+34 and +39%) correspond to lower dosages, 5 and 10% by mass, and start from a stronger control. Conversely, Zak et al. (2016) found no beneficial effect of gypsum on earth bricks and attributed this to the high water content of their mixes and to the rapid setting of the binder; the moderate water content used here (19.7%) and casting immediately after mixing limit both effects.

For ash alone, the gains of 15 and 16% are not sufficient to separate these series from the control, since their ranges of values (mean ± 10%) overlap that of the control. Nor can they be attributed to a pozzolanic reaction, which requires free calcium hydroxide and moist curing, whereas the

UNDER PEER REVIEW

specimens were dried at 40 °C; the clay contains 3.1% CaO (Table 3), in a mineral form that was not determined. The studies in which rice husk ash clearly improves earth blocks combine it with a lime source, calcium carbide residue: Nshimiyimana et al. (2018) obtained 6.6 MPa with 15% of a residue–ash blend at a 7:3 ratio, about three times the strength obtained with the residue alone (2.2 MPa), and Nshimiyimana et al. (2020) reached about 7 MPa by replacing part of the 20% residue with ash, with an optimum at a 16:4 ratio.

The drop of F6 (−25%), with 5% gypsum and 5% ash, is unexpected, since F1 (5% gypsum alone) reaches 10.88 MPa and F4 (10% ash alone) 9.44 MPa; it needs to be confirmed on new specimens. Raw rice husk is used here at contents ten to twenty times higher than the 0.5% recommended by Danso et al. (2015) for plant fibers, and the decrease in strength observed is consistent with the adverse effect reported by Millogo et al. (2014) with 0.8% of long fibers. Savadogo et al. (2023) reported the same trend for an earth plaster: from 0 to 67 vol% of fermented rice husk, compressive strength fell from 3.88 to 0.82 MPa, while linear shrinkage decreased from 4.52 to 0.83%.

Bulk density and strength

Bulk density is often used as an indirect indicator of strength, a denser matrix being assumed to be less porous. In this series, the linear correlation coefficient between the two quantities is 0.26 over the nine mixes and 0.33 over F0 to F5 (Figure 4); with nine points, the value of 0.26 is not significantly different from zero ($p \approx 0.5$). Danso et al. (2015) likewise observed that the relationships between properties established for binder-stabilized blocks do not apply to fiber-reinforced blocks.

F7 is the most marked case: the densest mix of the series (1641 kg/m³) gives one of the lowest strengths (6.38 MPa, −22%). This density is difficult to explain, since replacing 75 g of clay with much lighter rice husk should lower it, as is the case for F8 (1456 kg/m³). The individual masses rule out a transcription error (see Bulk density). As the volume used is that of the mold, denser placement of these specimens or different drying shrinkage remains possible; measuring their actual dimensions would settle the question. Without F7, the correlation coefficient over the other eight mixes is 0.45, still not significant. Bulk density alone therefore cannot predict the strength of these mortars; the type of addition has a greater effect here.

UNDER PEER REVIEW IN IJAR

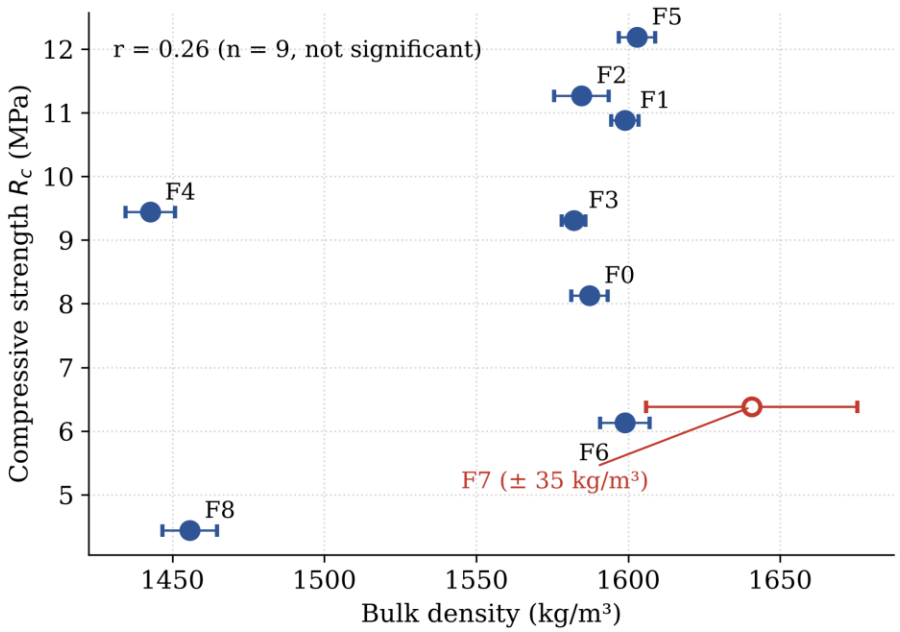


Figure 4. *Compressive strength versus bulk density, with the standard deviation of bulk density (r = 0.26 over nine mixes, not significant). F7 shows the largest scatter of the series.*

Comparison by type of addition

The series combines two variables, the type of addition and its dosage. Figure 5 compares the addition types at equal dosage: at 5%, the gypsum–ash blend (+50%) and gypsum alone (+34%) give the clearest gains, ash alone a moderate gain (+15%) and raw rice husk a loss (−22%). Increasing the dosage from 5 to 10% has no notable effect for gypsum alone and ash alone, and an adverse effect for the gypsum–ash blend and for rice husk. With only two dosages, these results do not locate an optimum dosage; they indicate that, among the mixes tested, F5 gives the highest mean strength without standing clearly apart from F1 and F2: the ranges of these three series (mean ± 10%) overlap.

UNDER PEER REVIEW

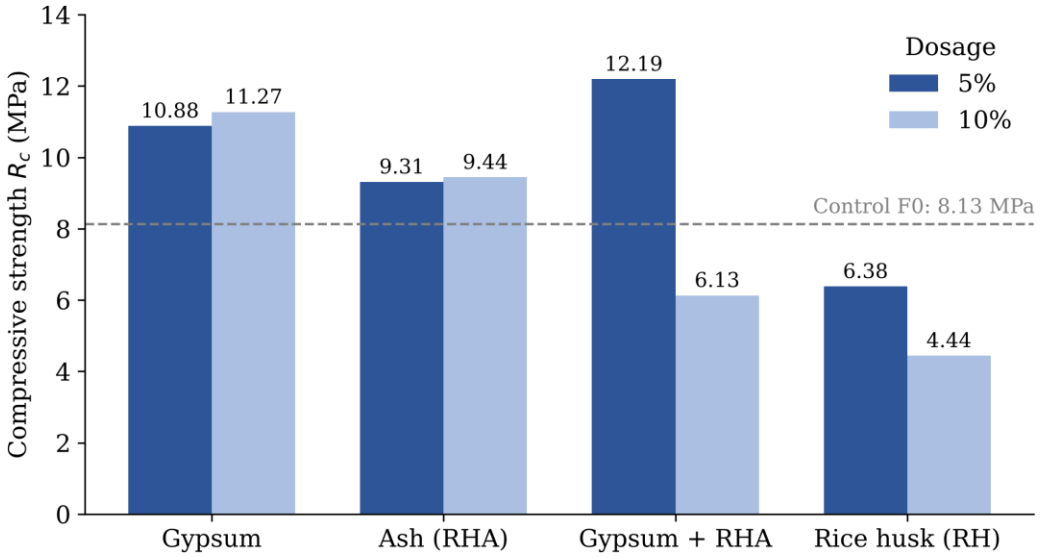


Figure 5. *Compressive strength by type of addition and dosage (5% and 10%), compared with the control F0.*

Recommended mix and relevance for earth construction in Niger

The strengths obtained, from 4.44 to 12.19 MPa, were measured on small specimens dried at 40 °C; they do not directly represent the strength of a plaster exposed to ambient humidity. They exceed the values reported for the control earth plaster of Savadogo et al. (2023), 3.88 MPa, and for the rammed earth with 15% gypsum of Ávila et al. (2025), 3.2 MPa, while remaining within the range measured by Meimaroglou and Mouzakis (2024) on earth mortars tested on 4 × 4 × 16 cm prisms. Differences in preparation and testing between these studies prevent a direct comparison of absolute values; relative gains are more comparable. With only 5% replacement, gypsum alone and the gypsum–ash blend increase the strength by 34 to 50% without making the material heavier, and F5 uses only 2.5% gypsum, half of the addition being an agricultural by-product available in Niamey.

On this basis, mix F5 (2.5% gypsum and 2.5% rice husk ash replacing clay) is recommended for earth wall plasters; F1 (5% gypsum alone), of similar strength, is the simplest alternative to prepare.

This recommendation is subject to three reservations. First, the dosage of the gypsum–ash blend should not exceed 5%, since F6 loses 25% relative to the control; this result needs to be confirmed. Second, gypsum is soluble in water. Rescic et al. (2021) nevertheless obtained, among earth plasters stabilized with lime, gypsum, geopolymers, enzymes or cement kiln dust, the best results with gypsum in water erosion, water absorption, drilling resistance and thermo-hygrometric cycling tests. Until the water resistance of F5 and F1 has been measured, their use should be restricted to interior plasters or plasters sheltered from rain. Third, bond to the substrate, shrinkage and cracking, which matter as much as strength for a plaster, were not measured.

UNDER PEER REVIEW

At the dosages tested, raw rice husk reduces the strength and is not recommended; lower contents, close to those studied for plant fibers, remain to be evaluated. For an earth plaster applied to adobe walls, Savadogo et al. (2023) retain at most 33 vol% of fermented rice husk, since resistance to capillary absorption and water erosion becomes inadequate above 50%.

Limitations of the study

The study is limited to bulk density and compressive strength at 14 days. Bulk density is based on the mold volume rather than on measured dimensions. Thermal performance and durability (water resistance, wetting and drying cycles) were not measured. The mineralogy of the clay and the composition of the ash (silica content, amorphous or crystalline state, unburnt carbon) are not known.

Conclusion:-

Nine mortars made with a ferruginous clay of low plasticity from Niamey (W_L = 42.9%, I_P = 19.7%, Fe_2O_3 = 14.0%), in which gypsum, rice husk ash or raw rice husk replace 5 or 10% of the clay, were tested in compression at 14 days, after 7 days of curing including 96 h at 40 °C. Gypsum alone increases the strength of the control (8.13 MPa) by 34 and 39%; with ash alone, the gains of 15 and 16% do not separate these series from the control, given the ± 10% tolerance of each series. The gypsum–ash blend gives the highest mean value of the series at 5% (12.19 MPa, +50%), close to those of gypsum alone, but loses 25% relative to the control at 10%. Raw rice husk reduces the strength by 22 and 45%. The gains obtained with gypsum are not accompanied by any increase in bulk density, and bulk density is not significantly correlated with strength (r = 0.26). A clay sampled on site, with 5% of its mass replaced by additions available in Niamey, thus reaches 10.9 to 12.2 MPa in the laboratory, and part of the gypsum can be replaced by an agricultural by-product without loss of strength.

Mix F5 (2.5% gypsum and 2.5% rice husk ash) is recommended for earth wall plasters, either indoors or sheltered from rain, and F1 (5% gypsum) is the simplest alternative. This recommendation remains subject to four checks: confirming the drop of F6 on new specimens, recording the six individual values to calculate the standard deviation; measuring the water resistance and erosion of F5 and F1; measuring their bond strength and shrinkage in actual application; and measuring the actual dimensions of the F7 specimens. Further work will also address the characterization of the ash (silica content, amorphous or crystalline state, loss on ignition) and of the clay (XRD, loss on ignition, sedimentation analysis), and the testing of rice husk contents below 1%.

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UNDER PEER REVIEW IN IJAR

Conflict of Interest:-

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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