# A methodology for the mix design of earth bedding mortar

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**Abstract**

Earth masonry is a good alternative to more conventional materials in order to reduce the environmental impact of building materials. However earth construction techniques mostly rely on bricklayers' experience, which is a hindrance to industrial development of this traditional know-how. This article proposes a methodology for the mix design of unstabilized earth bedding mortar based on mechanical criteria of the masonry and rheological criteria of fresh mortar. A test to characterize the shear strength of the masonry interface is specially investigated. The mechanical performances of the formulated mortar are then validated with laboratory scale characterization.

**Keywords**

Earth masonry, unstabilized earth mortar, mechanical characterization, on site characterization

## 1. Introduction

Earth construction techniques have been used worldwide for millennia. In a time of environmental crisis, it is a good alternative to conventional materials thanks to its very low embodied energy [1]. However, the lack of knowledge about the mechanical behavior of earth material makes it difficult to promote. Research is still necessary to develop it for construction purpose and enhance building codes.

Traditionally, earth masonry is made of bricks (adobes, compressed earth bricks, extruded bricks…) and an earth mortar composed of sand, clayey earth, and water. An important effort has been made to characterize bricks, but they are most often prepared with addition of fibers and/or stabilizers [2, 3], or historical adobes [4, 5]. Extruded earth bricks with no fibers and no stabilizers are still poorly known from the mechanical point of view [6-8]. However, it is an interesting product for the development of earth masonry. Indeed, it can be produced industrially, it has good mechanical performances compared to traditional adobes or rammed earth, and it also has good thermal performances [9]. Furthermore, unfired clay brick masonry as a heterogeneous material as well as earth mortars, for their part, have received very little attention [10-12].

More than 30 years of research has led to a good, yet uncomplete, comprehension of general masonry behavior, mostly directed to fired bricks and stone masonries [13], that are much more resistant and for which the difference of performances between bricks and mortar is more pronounced. In vernacular constructions, the use of unstabilized earth mortar is widespread because it is locally available, economical, and presents good compatibility with the bricks [14]. However, questions persist about earth mortars, how to design the mixture, as well as its mechanical performances and the performances of the interface with the bricks. In particular, there is a strong need for the development of mix design methodologies and simple tests that could be used on site. Indeed, until now, most knowledge about earth construction techniques relies on the know-how and experience of skilled bricklayers, which is a hindrance to the industrial development of such techniques [15, 16]. As an evidence, there are few national regulations about earth masonry and mortars [17-19].

The present article focuses on the development of a methodology for the mix-designing of a mortar used in earth masonry. Two clayey earth coming from different French regions were studied: one from the North of France, the other one from the South-West. First, a methodology of design was proposed, based on three criteria: the shear strength of the interface brick/mortar, the development of cracks when drying, and the workability of fresh mortar. In a second part, the mechanical performances of the optimized mortars were determined at laboratory scale (compressive strength, indirect tensile strength and shear strength at the interface).

## 2. Materials and procedures

### 2.1 Materials

#### 2.1.1 Raw material

Two types of extruded bricks (Br1 and Br2) and earth mortars (M1 and M2) coming from two French brick factories were studied in this paper. Br1 comes from the North of France and Br2 from the South-West. As noticed by Maillard [20] and Aubert [21], the direction of extrusion has a strong impact on the characteristics of extruded bricks and it is thus essential to know precisely the conditions of extrusion. Br1 was extruded transversally to the laying direction and presents a rough surface. It is important to note that no vacuum was applied during the preparation of Br1 in contrary to what is common during industrial extrusion process. Br2 was extruded under vacuum and longitudinally to the laying direction; it presents a smooth surface. The photography of the two bricks and the description of the manufacturing processes are presented on Figure 1.

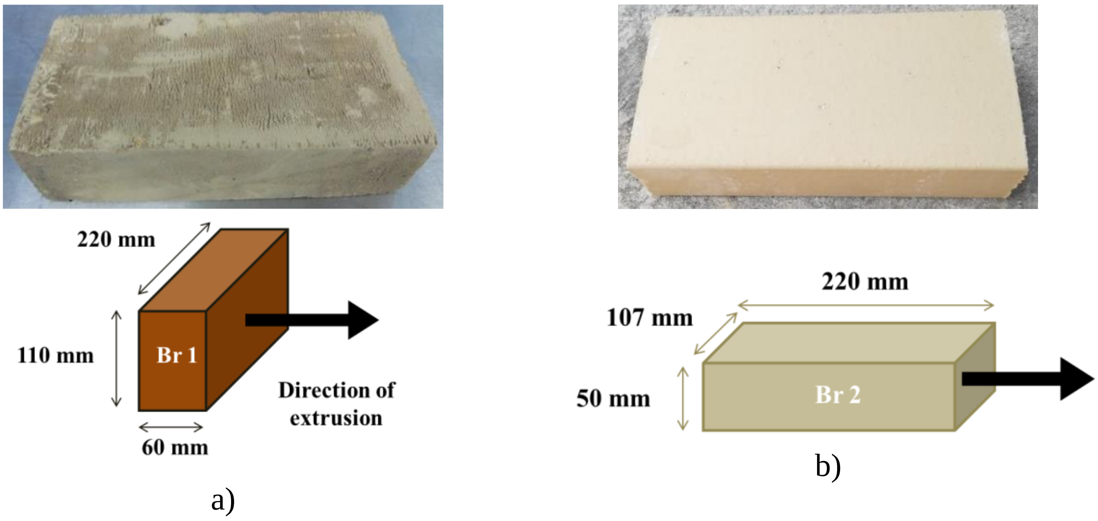



Figure 1: Photography and manufacturing process of the two bricks : a) brick 1, b) brick 2

The earth mortars M1 and M2 were made from clayey earth E1 and E2, coming from the same quarries as the bricks. In order to improve workability and prevent cracking, earth E1 and E2 were then mixed with siliceous sand and water to obtain mortars M1 and M2.

The main characteristics of the bricks and earth for the mortars are presented in Table 1. The bulk density of bricks was determined according to standard DIN 18945 [17]. The compressive strength was measured according to standard NF EN 772-1 [22]. The samples were entire bricks positioned perpendicularly to the laying direction, and vertically in order to decrease the aspect ratio that has a great effect on the compressive strength of earth bricks [23]. For each type of bricks, 6 specimens stored at 50% relative humidity (RH) and 20°C were tested with a press at a charge rate of 0.05 MPa/s.

The indirect tensile strength was determined with a three point bending test on entire bricks parallel to the laying direction, under the same moisture and temperature conditions (6 specimens were tested for each type of brick).

The geotechnical characteristics of the soils contained in the materials were determined by measuring the Atterberg limits (standard NF P94-051 [24]) and the methylene blue value $V_b$ (standard NF P94-068 [25]).

The size distribution of the soil mixtures was analysed using two techniques: the coarser fraction (>80 mm) was analysed by wet sieving, and the finer fraction by means of hydrometer analysis (standard NF EN ISO 17892-4 [26]). The results show that the earth E1 is poorer in clay, which explains that the plasticity index and the methylene blue value $V_b$ are lower.

Finally, a qualitative mineralogical study of the clay minerals contained in the two soils was carried out using XRD on oriented aggregates with three preparations: air dried or natural, after glycolation and afterheat treatment at 500°C. The results show that the two soils have similar qualitative mineralogical compositions. Both soils are composed of quartz, calcite, goethite, feldspars and, as clay minerals, illite, chlorite and montmorillonite.

Table 1: Main physical and geotechnical characteristics of Br1, E1, Br2 and E2

| Sample | Br1 | E1 | Br2 | E2 |
|---|---|---|---|---|
| Bulk density (kg.m$^{-3}$) | 1715 | - | 2080 | - |
| Compressive strength (MPa) | 2.5 | - | 7.6 | - |
| Indirect tensile strength (MPa) | 1.0 | - | 2.6 | - |
| Sand content (>2 mm) | 2.7 | 0.3 | 1.3 | 1.7 |
| Gravel content (<2 mm) | 20.8 | 8 | 50.7 | 37.8 |
| Silt content (<0.063 mm) | 56.1 | 77.8 | 28.7 | 38.6 |
| Clay content $C$ (<0.002 mm) | 20.4 | 13.9 | 19.4 | 21.9 |
| Liquid limit $W_L$ (%) | 35 | 32 | 45 | 46 |
| Plastic Limit $W_p$ (%) | 23 | 24 | 28 | 31 |
| Plasticity Index $I_p$ (%) | 12 | 8 | 17 | 15 |
| Methylene blue value $V_b$ (%) | 2.2 | 1.7 | 3.5 | 4.1 |
| Index of clay activity $A_{CB}$ (100*$V_b/C$) | 10.8 | 12.2 | 18 | 18.7 |
| Nature of clay minerals | Illite, montmorillonite, chlorite | | | |

### 2.1.2 Composition of mortar

For each type of mortar M1 and M2, a panel of sand:earth ratio that gave an acceptable workability and scarce cracking was tested. Five volume ratios sand:earth were tested for M1 (2:1, 1.5:1, 1:1, 1:1.5 and 1:2) and four for M2 (3:1, 2:1, 1.5:1 and 1:1). The mortars were mixed 24h before the tests and stored in large hermetical boxes in order to avoid water evaporation. This procedure allows good water absorption in clay layers. Before the test, the consistency of fresh mortar was adjusted by adding water if necessary. Finally, the water content was controlled by drying a sample of mortar at 50°C. Before being tested, all the samples were stored in controlled moisture conditions (50% HR and 20°C) since the moisture content has a strong impact on mechanical performances [27].

## 2.2 Procedures

### 2.2.1 Methodology of mix design of earth mortar

As underlined earlier, the methodology of mix design of earth mortars from a given clayey earth is not yet established. The ratio of earth, sand and water required to obtain a resistant and workable mortar is currently a bricklayer skill. For this reason, a methodology of mix design is proposed in this paper and presented in Figure 2. Some advice were given by a skilled bricklayer to prepare mortars M1 and M2. He showed the qualitative differences between a usable mortar and a mortar that would be too dry or too sticky to work with. In a second time, two objective criteria based on laboratory tests were established to better evaluate these subjective observations: one based on the shear strength at the interface of brick and mortar and another on the workability of fresh mortar. These criteria are the most important for the resistance of a wall and during the construction phase.

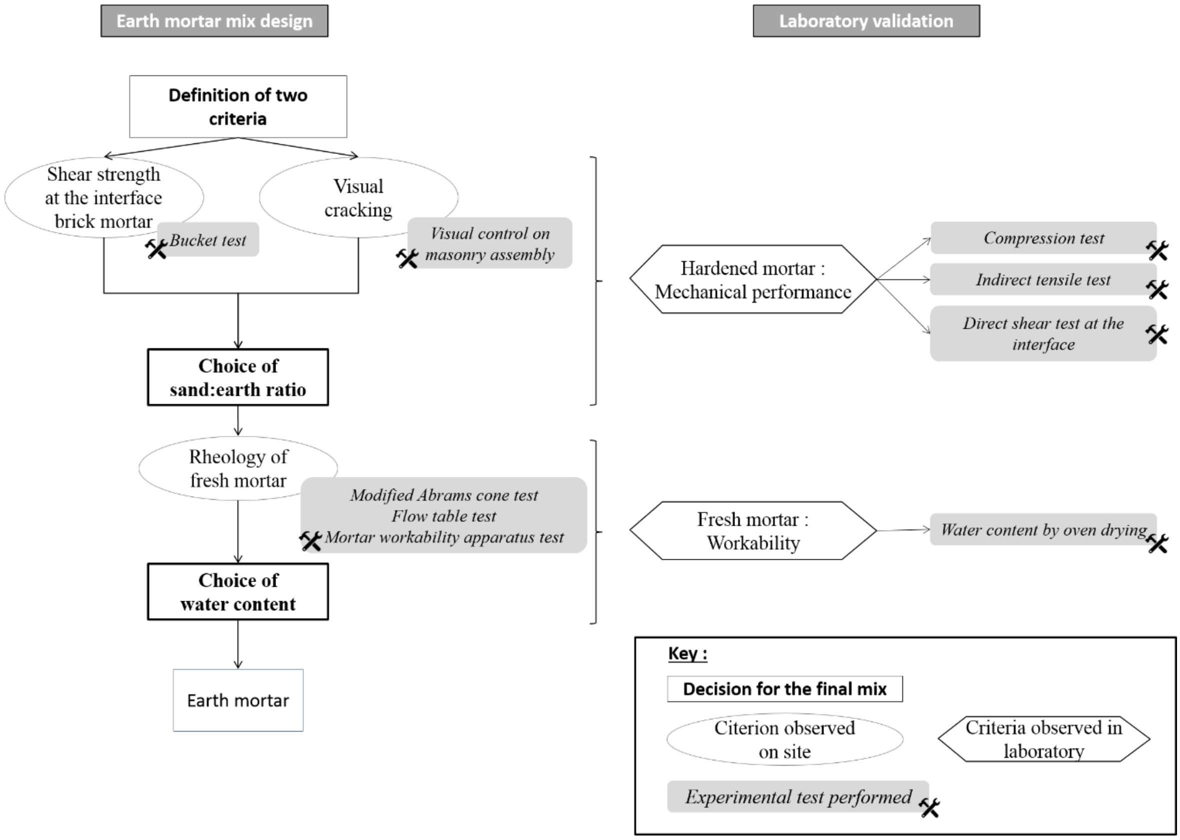



Figure 2: Methodology for the mix design of earth mortars

The article is aimed at explaining the methodology and the different steps – figured by the grey cells on figure 2 - to choose an optimized mix of sand, earth and water.

## Visual cracking

Assemblies of two bricks and two joints of mortar were prepared for each mortar mix design as shown on Figure 3. This test was inspired by the French professional guidelines for earth plaster [28], and it was already developed by Hamard et al. [29]. Indeed, when it comes to plaster, very scarce to no cracking is acceptable at the surface, which gives a criterion for the sand:earth ratio. Though the current mortar is a bedding mortar and not plaster, it seemed interesting to study whether this criterion could be adapted to the design of bedding mortar. A wet sponge was spent on the bricks to avoid diffusion of water from fresh mortar to bricks. The top layer was meant to visually follow the development of cracks during drying shrinkage. The assemblies were stored at 50% RH and 20°C until the mass stabilized.

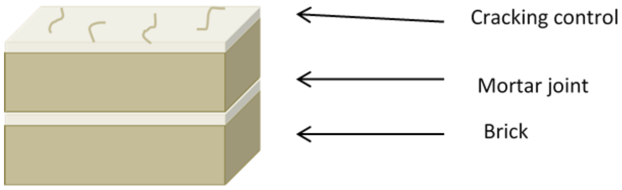



Figure 3: Assemblies used to follow cracking during drying shrinkage

**Shear strength at the interface of brick and mortar**

A very simplified test was implemented to estimate the shear strength at the interface of brick and mortar, which was called the "bucket test". It was also inspired by the French professional guidelines for earth plaster [28] and it is presented on Figure 4. This test used the same assemblies than the ones used for the visual cracking control.

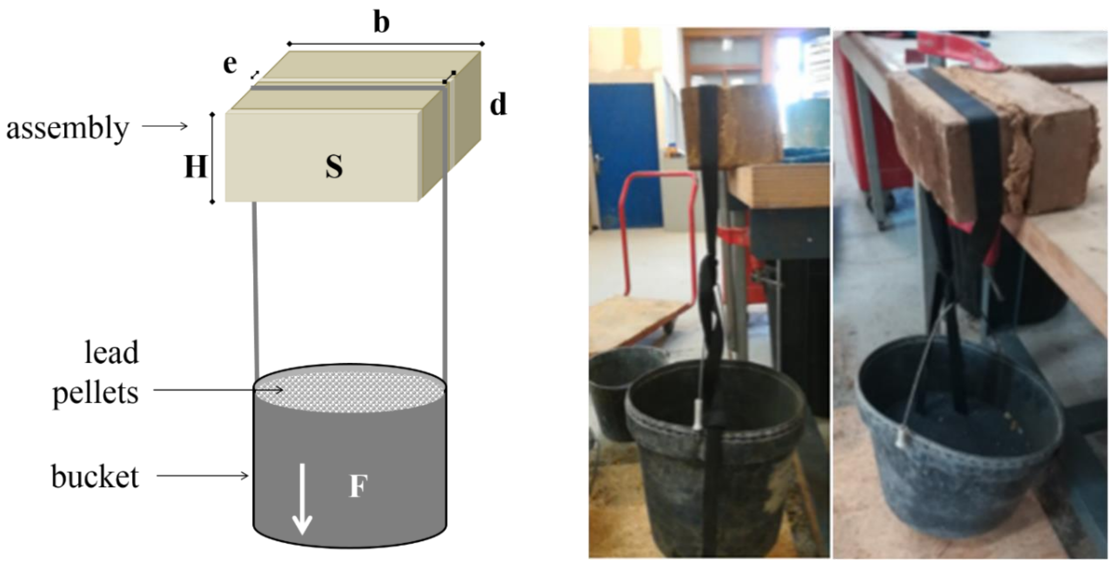
For each mix design, 3 samples were tested. The test consists in shearing the joint interface, and determining the mass required to break it. The bottom brick is fixed to the table with clamps, and a strap allows to localize the load as close to the interface as possible. The bucket is eventually filled up with lead pellets. When the failure occurs, the bucket is weighted to determine the corresponding load $F$.

The shear strength $\tau$ (MPa) of the interface can then be calculated according to equation 1.

$$\tau = \frac{F}{S} \quad \text{equation 1}$$

with :

- $F$ : the load applied with the strap (N)
- $S$ the shear surface (m²).



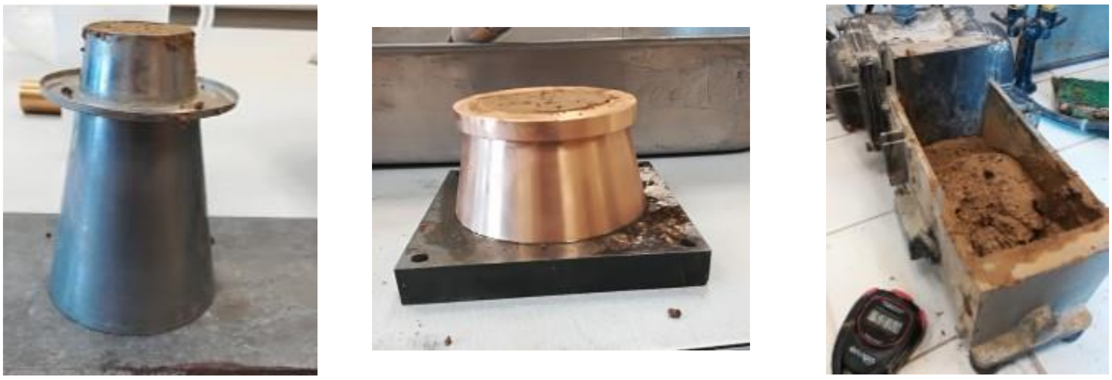

a) b)

Figure 4: "Bucket test" for the shear strength of the interface brick-mortar : a) scheme of the test, b) photography of the device

**Rheology of fresh mortar**

Once the sand:earth ratio optimized using the two previous tests (visual cracking control and bucket test), a minimum and a maximum water content were determined for each mortar to obtain a good workability (according to the experience of the skilled bricklayer). For each water content, rheological characteristics were measured using three rheological tests, all inspired from the cement paste procedures (Figure 5):

- the first test was based on a modified Abrams cone and it was inspired from the Australian standard AS 2701.5 [30] and from the procedure developed by Schwartzentruber [31] for concrete equivalent mortars. The modified Abrams cone is similar to the usual Abrams cone used for concrete but twice smaller in a homothetic ratio of its dimensions. Addressing the diameter of aggregates and the small slump, this cone of 15 cm height seemed adapted to earth mortar. Before the test, the cone must be lubricated with formwork oil and filled up with three layers of mortar. Between each layer, the mortar was stitched with 15 shots of a metallic needle of 16cm of diameter. The excess of mortar was finally removed. The cone must be raised vertically in 2 seconds. The slump was finally measured at the highest point of the cone.
- the second test was performed according to standard NF EN 1015-3 [32], with a conical mould and a flow table,
- the third test used a mortar workability apparatus and the flow was measured according to standard NF P 18-452 [33].



a) b) c)

Figure 5: Rheological tests on fresh mortar : a) modified Abrams cone test, b) flow table test, c) mortar workability apparatus

**2.2.2 Laboratory mechanical characterization of earth mortar**

After the optimisation of the composition of earth mortars, the mechanical characteristics of the optimised mortars were measured at laboratory scale. Such tests were meant to validate that the methodology provided good mortars. However, they would not be systematically necessary when formulating an earth mortar.

**Hardened state: compressive strength measurements**

Compressive tests were performed on cylindrical samples according to a procedure inspired from the standard NF EN 196-1 [34]. The dimensions of cylinders were 35 mm of diameter and 85 mm of height. Those dimensions ensured an aspect ratio of 2 and thus a low lateral confinement. The metallic mould was filled up in two layers and vibrated during 30 seconds after each layers to obtain a proper surface state. In order to speed up the drying phase, the mould was stored in an oven at 30°C during one week, so that the mould can be removed and the samples stored in a room at 20°C and 50% RH until the mass stabilized. Before the test, the samples were capped with a thin layer of paraffin in order to regularize the surface. 6 specimens of mortar M1 and M2 were tested using a load rate of 0.05 MPa/s.

**Hardened state: indirect tensile strength measurements**

The tensile strength was indirectly determined by a three point bending test, according to standard NF EN 1015-11 [35]. For each mortar, 6 parallelepiped specimens (4x4x16 $cm^3$) were prepared with the same procedure used for compression tests on cylindrical specimens: the moulds were filled up in two layers with 30s of vibration between each layer. The samples were stored at 30°C for drying before removing the mould and then stored at 20°C and 50% RH until the mass stabilized. The standard suggests a loading rate from 10 to 50 N/s. Nonetheless, given the poor tensile strength of earth mortar (1 MPa to 4 MPa, [8, 36-37]) it was decided to load at a rate of 2.5 N/s so that the test lasted around 2 minutes and dynamic phenomena did not interfere.

**Hardened state: shear strength at the interface brick-mortar**

Finally, a shear test at the joint interface was performed in order to validate the bucket test developed earlier. It was inspired by the triplet test of standard NF EN 1052-3 [38]. As the sample preparation and the test represent a lot of work, it could only be performed for brick Br2 and mortar M2 in the present paper. Indeed, the samples require a long time to be prepared: the sawing of the bricks, the polishing of the surface to ensure parallelism, and above all, the drying of fresh mortar. Regarding research and schedule constraints, a priority was accorded to prisms of type 2 because this masonry is studied in the scope of a larger research project of mechanical modelling of earth masonry. Though incomplete, it seemed still interesting to discuss the results and the validity of such an experiment that can be an alternative to the triplet test – this latter being quite complicated to develop.

It was adapted to squared samples of dimensions $60 \times 60 \text{ mm}^2$ in order to use a direct shear press (Figure 6). Two layers of bricks of 20 mm height were jointed with 1 mm of mortar and the samples were stored at 50% RH and 20°C until the mass stabilized. During the drying process, a load of 2.7 kPa was applied on the assembly. The press was adjusted so that the shear plane would localise at the interface between brick and mortar. A vertical confinement $N$ was applied, then the top part of the shear box was pulled with a strength $T$ measured with a dynamometric ring. Three different values of vertical load $N$ were applied: 56 kPa, 236 kPa and 417 kPa, corresponding to 5%, 30% and 50% of the compressive strength of mortar. For each vertical load, three samples were tested. The rate of displacement of the upper part of the shear box was 0.1 mm/min.

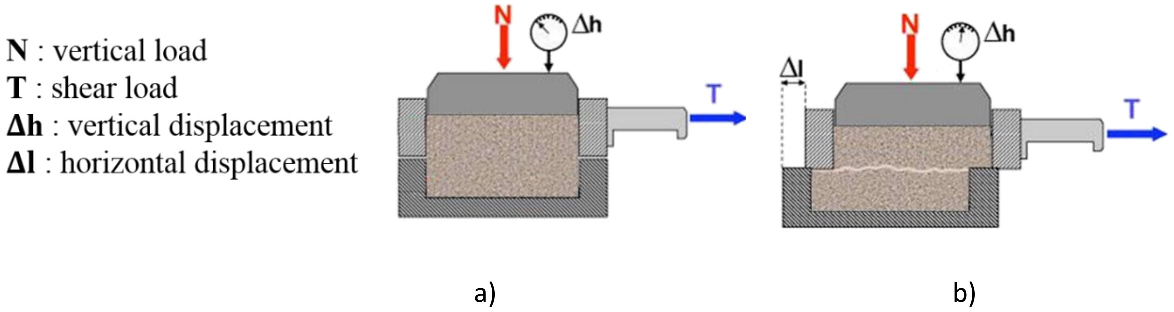


Figure 6: Principle of the direct shear test (from INPL-Nancy) : a) before the test, b) at the end of the test

The shear strength $\tau$ (MPa) at the interface is calculated according to eq. 2:

$$\tau = \frac{F}{S} \qquad \text{equation 2}$$

with :

- $F$: the shear strength (N)
- $S$: the corrected shear surface (mm²)

Such a procedure enables to establish the Mohr-Coulomb law of friction (eq. 3) at the interface between brick and mortar.

$$\tau = \tan\Phi \times \sigma + c \qquad \text{equation 3}$$

with :

- $\tau$ : the shear stress (MPa)
- $\phi$ : the friction angle (°)
- $\sigma$ : the confinement stress (MPa)
- $c$ : the cohesion (MPa)

**Fresh state: water content by oven drying**

To complete the previous procedures, the water content of mortar was systematically controlled by drying a sample of each mix design in an oven at 50°C.

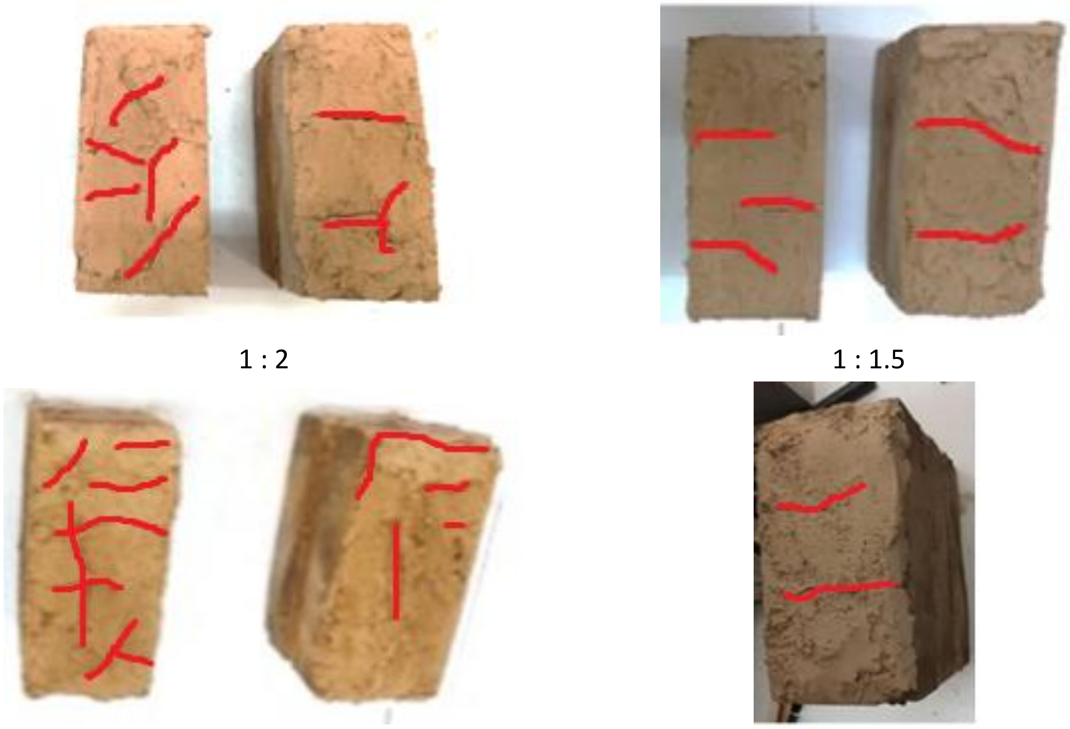
## 3. Results and discussion

### 3.1 Mix design of earth mortar

#### 3.1.1 Optimization of the sand:earth ratio based on workability, cracking and shear strength

Different ratios of sand and earth were tested using the amount of water giving a constant workability measured using the modified Abrams cone test equal to 13.5±0.5cm. This value of slump ensures a good enough workability of fresh mortar during the building phase.

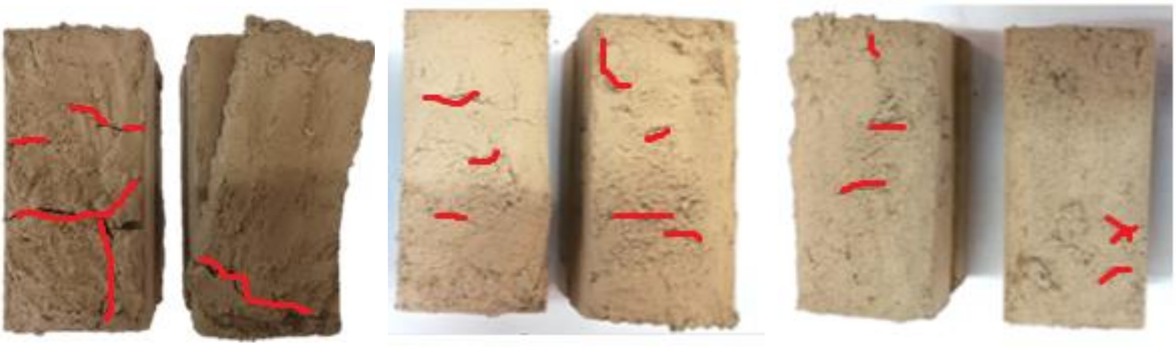
Figure 7 shows the surface of the brick assemblies after the drying of mortar. Although not for earth plaster, scarce cracking is acceptable in the design of bedding mortar. However, here, the upper layer of mortar allows comparing two different mix designs but gives no clue on the actual crack development in the joint since the drying shrinkage is restrained by the adjacent bricks. It appeared that an important amount of sand could either lead to important cracking or none. Large amount of sand gives a mortar that is hard to apply so that the bound with the brick is weak and the mortar may crack at the interface between a well bounded part and a part of poor adhesion. On the contrary, the drying shrinkage of clay contained in the mortar always lead to important cracking in the mortars rich in earth.



1 : 2      1 : 1.5

1 : 1      1.5 : 1

a) Mortar M1



1 : 1      2 : 1      3 : 1

b) Mortar M2

Figure 7: Surface of the assemblies after the drying of mortar for different sand:earth ratios

The results obtained for the various tests are presented in Table 2. About workability, the mortar is here described as either “too pasty” or “too sandy”. “Too pasty” means that the mix sticks to the trowel. On the contrary, “too sandy” means that the mix crumbles.

Table 2: Workability, cracking and shear strength of the preliminary mix designs of mortar for each water content and corresponding slump

| | Sand : Earth ratio | Water content (%) | Slump (cm) | Workability | Cracking | Shear strength (kPa) | COV (%) |
|---|---|---|---|---|---|---|---|
| M1 | 1.5 : 1 | 21.6 | 13.4 | Workable | Important | 7.1 | 34 |
| | **1 : 1** | **19.7** | **13.5** | **Workable** | **Scarce** | **19.2** | **68** |
| | 1 : 1.5 | 22.5 | 13.6 | Too pasty | Important | 11.2 | 29 |
| | 1 : 2 | 25.4 | 13.9 | Too pasty | Important | 21.4 | 28.7 |
| M2 | 3 : 1 | 18.5 | 13.5 | Too sandy | None | 8.5 | 1.5 |
| | **2 : 1** | **19.2** | **13.4** | **Workable** | **scarce** | **14.7** | **39.4** |
| | 1 : 1 | 23.9 | 13.8 | Too pasty | important | 21.1 | 28.7 |

It was expected that the strength of the interface would decrease with the increase of sand amount since clay is the active component in the cohesion of mortar. Though the tendency seems clear for M2, it is not as clear for M1. Another interesting point is that due to the process of extrusion, the state surface of bricks Br1 is quite rough whereas Br2 is very smooth. Higher shear strength for interfaces of type 1 could come from the better bound between mortar and a rough brick. Furthermore, the failure surfaces were various : sometimes failure happened at the interface between brick and mortar, sometimes, it could happen in the joint. No obvious link can be established between the type of failure and the value of the strength. These differences of failure could explain the very high variability of results. This variability might also come from the fact that there is no confinement pressure perpendicular to the prism, and several mechanical phenomena are likely to happen : shear stress, but also tensile stress due to the bending moment involved by the excentricity between the strap and the joint. When estimating the tensile stress with a simplified cantilever model, it appears that the tensile stress and the shear stress are likely to be similar. Given that the tensile strength of masonry interface is also a weak point, it is highly likely that the value of the shear strength is reduced by the combined effect of tension. In spite of such variability, the bucket test reveals to be an interesting track. Indeed, it could contribute to fufill the need for the development of simple tests that could be used on site in order to design earth mortar.

In order to choose the good mix design of mortar, both shear strength and workability must be addressed. For mortar M1, the ratio 1:2 is the most resistant. However, it is too pasty. This is the reason why the mix design 1:1 was finally chosen. For the same considerations, the mix design 2:1 was chosen for mortar M2. This final choice also reveals that the cracking state is not determining. Though  cracking is an important parameter when designing a plaster, since there are some aesthetics requirement for plasters, it is not necessary to follow the cracking due to drying shrinkage when designing a joint mortar.

### 3.1.2. Optimization of the water content of fresh mortar based on a rheological criterion

For the same sand:earth ratio, the water content of fresh mortar was increased from a dry mixture to a liquid mixture. The results of three rheological tests performed on fresh mortar are presented in Table 3.

Table 3: Rheological characteristics of fresh mortar for different water contents

| | Workability | Water content (%) | Slump (modified Abrams cone) (cm) | Flow (flow table) (cm) | Workability (mortar apparatus) (s) |
|---|---|---|---|---|---|
| M1 1 : 1 | Too dry | 17.5 | 14.3 | 14.3 | > 120 |
| | Minimum | 18.4 | 14.3 | 15.2 | > 60 |
| | **Good** | **22.0** | **13.3** | **15.3** | **> 60** |
| | Maximum | 23.0 | 13 | 15.8 | 56 |
| | Too wet | 24.0 | 11.5 | 16.9 | 27 |
| | Too wet | 25.5 | 9.5 | 17.8 | 10 |
| M2 2 : 1 | Too dry | 16.6 | 14.6 | 11.1 | > 120 |
| | Minimum | 18.7 | 14 | 15.0 | > 120 |
| | **Good** | **20.6** | **13.6** | **15.4** | **> 60** |
| | Maximum | 22.0 | 13 | 15.8 | 59 |
| | Too wet | 23.9 | 9.5 | 18.3 | 24 |
| | Too wet | 28.4 | 5.5 | 20.8 | 6 |

As related by Gelard [16], there is no guideline existing for the rheology of fresh mortar. Here, it can be noticed that the workability apparatus test is not designed for earth mortar. Indeed, in the case of cement mortar for which the test was designed, the flow in the apparatus lasts around 30 s. Here, for the water content that is of interest, it lasts more than 60 s. It means that the variability of duration of flow around interesting water contents would not be precise enough to compare close water contents. The slump test and the modified Abrams cone test give interesting results. Though both mortar M1 and M2 do not have the same clay content, it seems that a slump between 14 cm and 13 cm, or a flow between 15 cm and 16 cm, ensure good workability. Moreover, the modified Abrams cone seems more adapted to site work, in order to check the water content when preparing mortar to build a wall for example. Those recommendations are consistent with the observations made by Walker and Stace [39] and Pkla et al. [40].

Finally, according to the shear resistance of the masonry and to the workability of mortar, a final design was selected to prepare mortar 1 and mortar 2 (table 2). Mortar 1 M1 is made of a volume sand:earth of 1:1, with a water content of 22.0 %, which corresponds to a slump of 15.3 cm. Mortar 2 M2 is made of a volume sand:earth of 2:1, with a water content of 20.6 %, which corresponds to a slump of 15.4 cm.

### 3.2 Laboratory mechanical characterization of earth mortar

#### 3.2.1 Hardened state: compressive strength of earth mortar

The results of compressive tests on cylindrical samples of mortar M1 and M2 are presented in Table 4.

Table 4: Compressive strength of the earth mortars M1 and M2

| | $f_m$ min (MPa) | $f_m$ max (MPa) | $\overline{f_m}$ mean (MPa) | COV (%) |
|---|---|---|---|---|
| M1 1 : 1 | 1.64 | 3.06 | 2.10 | 27.1 |
| M2 2 : 1 | 0.65 | 0.90 | 0.79 | 13.0 |

Mortar M2 is approximatively three times less resistant than M1. Compared to other values of the literature [37, 40], the mortars present average performances. It should be reminded that mortar M1 is formulated with a larger ratio of clay, and the present results seem to support the correlation between clay content and strength established by Heath et al. [6].

**3.3.2 Hardened state: tensile strength of earth mortar**

The tensile strength was determined by indirect three point bending test. Table 5 shows the indirect tensile strength of mortars M1 and M2. Once again, mortar M1 is more than twice more resistant than mortar M2. Furthermore, the ratio between the compressive strength and the indirect tensile strength is not constant, in comparison with cement paste where this ratio is usually close to 10. Laou [41] found the same variability of ratios for different mix designs of mortar and different water contents. This result puts into perspective the usual recommendations to use $f_{tm} = 0.1\, f_m$ as a value for the tensile strength of mortar that is widespread in the design of stone and brick masonry [42]. With earth mortar, it appears that this ratio is not valid: more studies are necessary for unstabilized earth mortars before drawing conclusions for building codes.

Table 5: Indirect tensile strength of mortar M1 and M2

| Mortar type | $f_{tm}$ min (MPa) | $f_{tm}$ max (MPa) | $\overline{f_{tm}}$ mean (MPa) | COV (%) | Ratio $f_m/f_{tm}$ (-) |
|---|---|---|---|---|---|
| M1 1 : 1 | 1.01 | 1.29 | 1.16 | 8.7 | 2.6 |
| M2 2 : 1 | 0.40 | 0.63 | 0.51 | 15.5 | 1.6 |

It can be interesting to compare the strength of the mortar with the strength of the brick. The properties of the bricks can be found in Table 1. The brick of type 1 appears to be less resistant than the one of type 2. However, the ratio of strengths for masonry 1 is much less than for masonry 2. Indeed, Br1 and M1 are about as strong in compression and indirect tension. On the contrary, Br2 is 10 times more resistant than M2 in compression and 5 times in tension. Though no direct conclusion can be drawn, it would present interest to study the consequence on the compressive strength of global masonry, to see the effect of difference of resistance of the components.

### 3.3.3 Hardened state: shear strength at the interface brick-mortar

Finally, it was proposed to test the shear strength of the interface between brick and mortar at a laboratory scale to support the "bucket test" proposed during the preliminary studies of mix design. Here, a better control of the mechanical solicitation is ensured thanks to the use of direct shear test device. This test could only be performed for mortar M2 for technical reasons. Some failure surfaces are presented on figure 8.


a)

b)

Figure 8: Failure surfaces of Br2 and M2 submitted to direct shear test: a) failure at the interface and detachment of mortar, b) failure at the interface.

When repeated for three values of normal stress, the curve $(\tau, \sigma)$ of figure 9 can be obtained, using the Mohr-Coulomb criteria (eq. 1). The friction angle $\phi = 42°$ and the cohesion $c =$ 14 kPa.

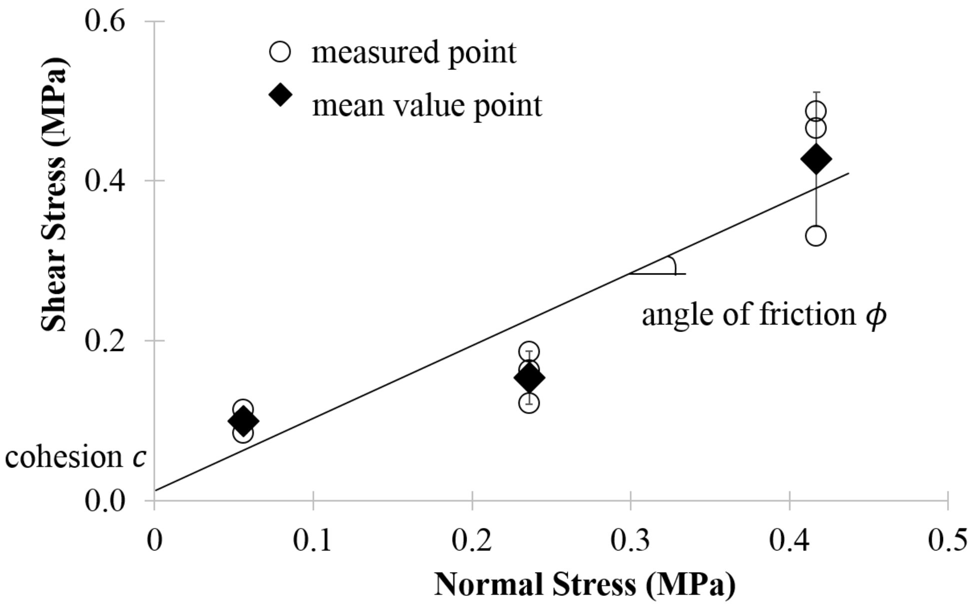



Figure 9: Mohr-Coulomb law for M2 and Br2 assemblies.

In fact, the cohesion $c$ corresponds to the initial shear strength, i.e. the shear strength under no confinement. It is interesting to notice that the preliminary test developed earlier, the bucket test, gave a shear strength at the interface of 14.7 kPa, which is very close to 14 kPa. However, the high variability of both the bucket test and the direct shear test must be reminded here. For this reason, a more complete campaign with different sand:earth ratio, different water content of fresh mortar, and other types of earth should be led to conclude on the validity of the bucket test.

The present cohesion and friction angle are within the orders of magnitude that can be found in the literature ([37, 43-46]) However, the quality of adobes and types of tests of those references are always different, might it be a triplet test with or without confinement, or a direct shear test realized at a reduced scale (such as the present test) or at full scale. Yet, the cohesion ranges from 10 kPa to 160 kPa and the friction angle from 29° to 50°. Otherwise, standard DIN 18946 [18] requires an initial shear strength of 200 kPa for masonry interfaces. Here, it appears that for earth masonry, this requirement can hardly be fulfilled.

### 3.3.4 Fresh state: water content by oven drying

The control of water content by oven drying at 50°C are systematically presented in the description of the mortar in tables 2 and 3. This procedure enables to have precise results on the water content, rather than calculating if from the added amount of water during the preparation of mortar.

## 4. Conclusions and perspectives

This article focused on the development of a methodology for the mix design of unstabilized earth mortar for masonry purpose, tested on two clayey earth from France. It was based on two mechanical criteria on assembled masonry and a rheological criterion on fresh mortar. As a preliminary study to determine the sand:earth ratio, assemblies of two bricks and two layers of mortar were prepared. The top layer of mortar enabled to visually follow the development of cracking while drying. Moreover, a test called "the bucket test" was developed to characterize the shear strength at the interface between brick and mortar. The interest of such test is that it can be used easily on site to design an earth mortar from any clayey earth and sand. In a second phase, three rheological tests were used on fresh mortar to determine the optimized water content of fresh mortar to ensure both strength and workability of the mortar. It appears that mortar workability apparatus was not adapted to earth mortar. Flow table and modified Abrams cone can be used. Since it is more adapted to site constraints, the modified Abrams cone with a slump between 13 cm and 14 cm seems to be the best option to define the water content of fresh mortar. Finally, it can be concluded that sand:earth ratio and water content of fresh mortar must be chosen as a compromise between shear strength of the assembled material, which is the dimensioning criteria for structural purpose, and the workability of fresh mortar for the bricklayer. Further investigation must be performed to conclude on the importance of the cracking development, since it does not seem as influent as for plaster mix design.

The mortars designed thanks to the previous methodology have reasonable mechanical performances checked at laboratory scale (compressive and tensile strength). This information tends to validate the methodology. A direct shear test, similar to the well-known triplet test, was also proposed to support the bucket test. It gave interesting results: the initial shear strength was close to the shear strength determined with the bucket test. Moreover, the cohesion and friction angles are similar to what can be found in the literature. However, the variability of the results and the fact that it was applied to a sole material, encourages to further investigate the validation of the bucket test.

As a perspective, the present study is an initial draft for the mix design of mortar from any earth and sand. It should be completed with more experimental tests on other types of earth and different water content of fresh mortar, since this parameter has a strong influence on the performances of the assembly. The bucket test should be performed on those other mix in order to draw conclusions. A way to improve this test would be to confine the sample while drying, in order to be more accurate to the real drying conditions in a wall. A more exhaustive experimental campaign might enable to build up abacus to help the mix design of mortar. Furthermore, the direct shear test seems to be an interesting mean to validate the bucket test, adapted to site constraint. However, the direct shear test must be completed with further tests on interface M2/Br2 and with tests on interface M1/Br1. Finally, the present results are the basis of a wider research project that focuses on the development of a non-linear constitutive law to model the mechanical behavior of earth masonry. The mortar designed here will be used for the construction of a full scale wall submitted to a cyclic in-plane shear test.

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## 6. Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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