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Durability of rammed earth walls exposed for 20 years to natural weathering

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ABSTRACT

This paper presents a study on the durability of different types of stabilised and unstabilised rammed earth walls. These rammed earth walls were constructed and exposed for 20 years to natural weathering, in a wet continental climate. None of these walls have shown complete collapse to date. A method to measure the rammed earth walls erosion by stereo-photogrammetry has been developed. The result shows that the mean erosion depth of the studied walls is about 2 mm (0.5% wall thickness) in the case of rammed earth wall stabilised with 5% by dry weight of hydraulic lime and about 6.4 mm (1.6% wall thickness) in the case of unstabilised rammed earth walls. The stabilisation enables to not use any plaster to protect the walls. In the case of the unstabilised rammed earth walls, an extrapolated lifetime longer than 60 years can be assessed. This shows a potential for the use of unstabilised rammed earth in the similar climatic conditions with this study. The method of stereo-photogrammetry used to measure the erosion of rammed earth walls on site may also help to calibrate and develop more pertinent laboratory test to assess the durability of rammed earth wall.

1. Introduction

Earthen materials in general and rammed earth in particular are ancient materials used for construction since time immemorial. Some earthen structures built centuries back are still performing satisfactorily. The most famous example is the Great Wall of China which was built approximately 2000 years ago using local materials: rammed earth, stones, baked bricks and wood. Although earthen constructions offer advantages such as thermal comfort [1], local employment creation and a minimal impact on the environment [2], earthen material was abandoned in the 1950's in Europe. Past history shows that as far as strength is concerned, rammed earth is not suited for the construction of very tall structures, but can certainly be used for load-bearing structures 2–3 stories high. Nevertheless, the problem of durability still raises questions, since, on one hand, we have 100-year old buildings with a satisfactory performance: the examples are the case the Horyuji Temple in Japan which a part was built with rammed earth approximately 1300 years ago and is still in good condition today [3], or the case of traditional rammed earth houses in France which were built more than 100 years ago and are still used today, Fig. 1; on the other hand, earthen material is very sensitive to water. Yet this drawback is also an advantage, since it can be easily recycled, obviously making it environmentally friendly. This paper presents a study on the durability of rammed earth walls.

From the above examples, we see with an appropriate design, a suitable roof, a basement avoiding capillary rise of water from the soil, etc., traditional rammed earth houses (without cement or lime) show satisfactory durability. However, in order to comply with the standards applied to industrial materials, more stringent durability criteria are expected from rammed earth. Several types of durability tests (spray test, drip test, wet to dry strength ratio, etc.) are proposed for earthen materials in general and rammed earth in particular [4]. Since unstabilised rammed earth could not pass these tests, it was systematically abandoned and replaced with stabilised rammed earth (using cement, lime, etc.). However, several studies have shown that the above tests are too severe and unrealistic. Heathcote [4], Guettala et al. [5], and even Ogunye and Boussabaine [6] advise against using these types of tests. Losing confidence in the adequacy of the existing tests given by several earth building standards (such as NZS 1998 [7]), many researchers have tried to develop different types of durability tests. Ogunye and Boussabaine [8] described a “rainfall test” in laboratory simulated conditions, and Hall [9] described a “climatic simulation chamber”. Further information on the in-situ walls from which we can develop new tests or calibrate existing laboratory tests become necessary [6]. Guettala et al. [5] studied small earthen wall specimens left for 4 years on a site without protection, and Heathcote [4] studied the durability of a small scale house. This paper presents

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Fig. 1. 150 years old rammed earth house in the South East of France.

Fig. 3. General view from the south of the walls on the site.

a study of the durability of rammed earth wall specimens exposed for 20 years to natural climatic conditions in France (Western Europe).

2. Details of the experimentation

The wall specimens were built in 1985 in the framework of the Rexcoop program, and controlled by the French Scientific and Technical Building Center (CSTB), near Grenoble, in a French Alpine valley, at an altitude of 212 m. The climate is described in Fig. 2, thanks to data from a national meteorological station at the site [10]. The annual rainfall is about 1000 mm, the direction of prevailing winds is NE-SW and the maximum wind speed is 21 mm/s.

This area is particularly rich in vernacular rammed earth constructions, with approximately 300,000 houses over 50 years old, according to Michel and Poudru [11]. The traditional rammed earth construction is popular in this region by a combination of several factors: cultural, social, economic, etc. But the main reason comes from the principle of using available local materials. First, amount of clay in the soil show that it should be compacted by rammer. Secondly, wood is very available in this region, which allows to manufacture formworks. So, the rammed earth technique becomes an optimum choice in the traditional construction of this region.

A total of 104 earthen wall specimens were built (Fig. 3) using rammed earth, straw-earth, compressed earth block (CEB) masonry, and vibrated-compressed block masonry. Different types of soils were used for each of these construction techniques. Different types of surface protection methods were tested. This paper focuses on the durability issues of only the rammed earth walls. Fig. 4 shows a map of the rammed earth specimens indicating their positions at the experimentation site. More information on the construction of these wall specimens is given in Rubaub and Chevalier [12].

2.1. Construction details of the rammed earth wall specimens

The rammed earth wall specimens were erected on a concrete foundation with a 250 mm base exposed above ground level. A bituminous painted layer was installed on top of the base to prevent water from capillary rise from penetrating the rammed earth wall test specimens. Local soil from a nearby site mixed with a cultivator, with the larger stone particles removed by hand, was used for the rammed earth wall specimens. The water content of the soil was about 10%. The metal formwork was assembled according to the wall dimensions (1000 mm $\times$ 400 mm $\times$ 1100 mm

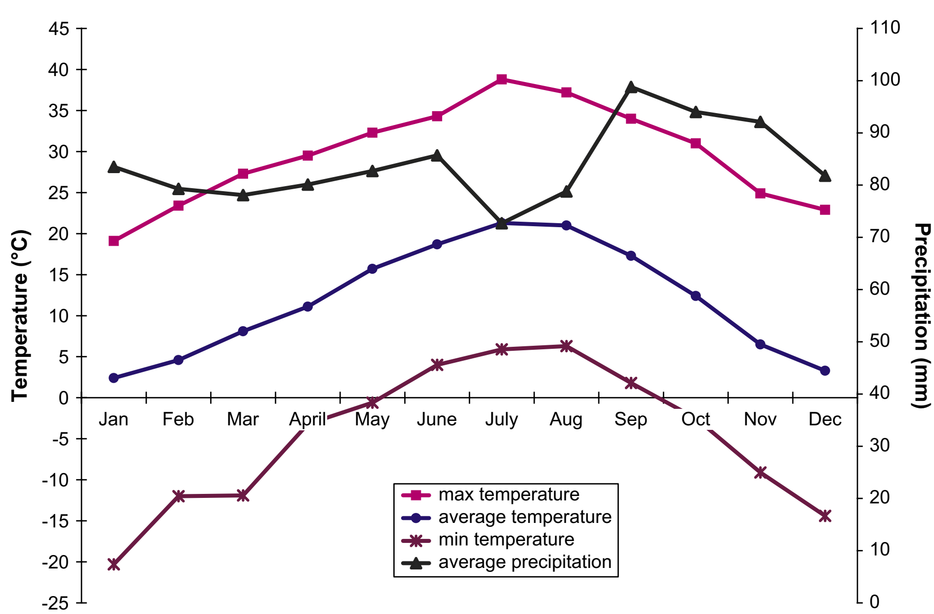

Fig. 2. Climate on test site, averaged over the period 1971–2000.

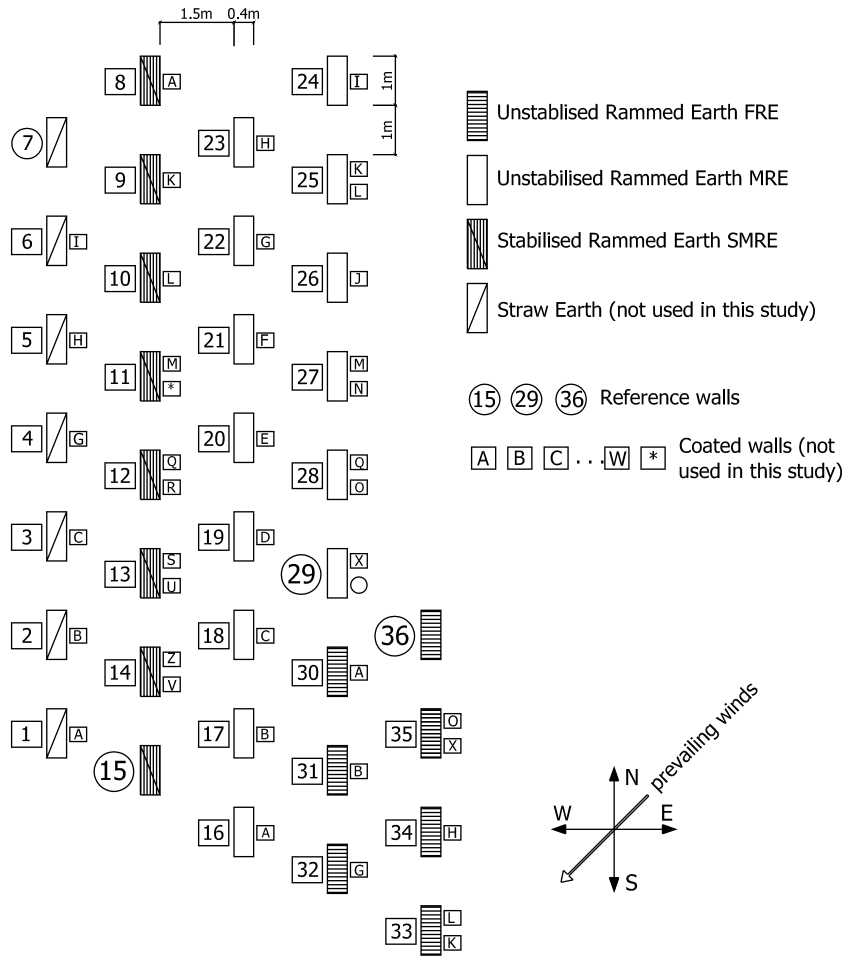

Fig. 4. Plan showing the location of various rammed earth specimens with protective coating details. Several walls were protected by 2 different coating types on each half. The numbers are the wall numbers.

high). Wetted soil was poured into the metal mould in 150 mm layers and then compacted with a pneumatic rammer. There was no control of the density of the specimen. Ramming was stopped when the mason heard clear beats due to the contact between the rammer and the earth. This obviously required the experience of the mason. The process continued up to the top of the wall specimen. Three types of specimens can be identified based on the soil source and the stabilisers used (Fig. 4), as indicated below:

- Fine soil from Verpillière, called FRE (Fine Rammed Earth). The grain size distribution of this soil is given in Fig. 5. The mineralogical analysis of this soil shows that it contains Quartz, Feldspath, … and 16% of clay particles (less than 2 μm). The clay fraction is composed of Illite (40%), Kaolinite (20%) and Smectite (40%). The Atterberg's limits are: $W_L = 27\%$, $W_P = 19\%$, thus $I_P = 8$.
- A mixture of FRE (50%) and a non-argillaceous soil from Morestel (50%), called MRE (Medium Rammed Earth). The Morestel soil contains essentially gravel and sand where Quartz is 76%. The grain size distribution of the mix soil MRE is given in Fig. 5.
- MRE stabilised with 5% (by dry weight) of natural hydraulic lime, called SMRE (Stabilised Medium Rammed Earth).

The location of these walls along with the surface protection methods adopted is shown in Fig. 4. Initially, 7 FRE walls were constructed, in which the soil contained too much clay and a high natural water content. Considerable shrinkage was observed in the specimens the day after dismantling the formwork. Similarly, poor linkage between the different compacted layers was observed. These initial problems led to the use of another type of soil referred to as MRE. It was also attempted to use 5% hydraulic lime to produce SMRE-type specimens, assuming that the lime would stabilise the clay and make the material less sensitive to moisture changes.

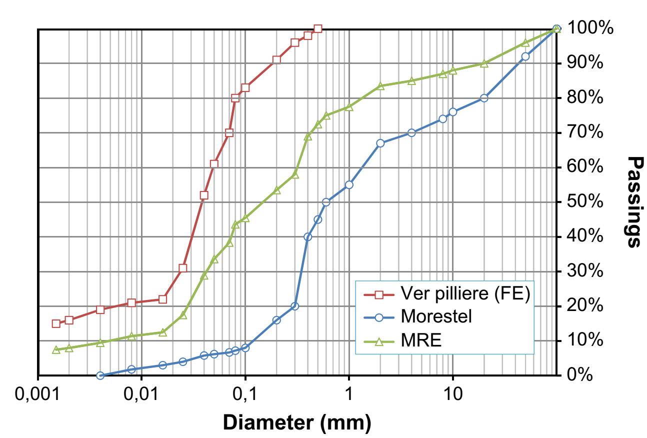

Fig. 5. Grain size distribution of the earths: Clay ≤ 2 μm ≤ silt ≤ 63 μm ≤ sand ≤ 2 mm ≤ gravel ≤ 60 mm ≤ stone.

2.2. Types of protection

All of the rammed earth walls were protected from rainwater entering from the top of the specimen by an asbestos cement roof, as shown in Fig. 3. For each type of rammed earth walls (FRE, MRE and SMRE), a reference wall was built without any protection layer. On other walls, several protective coatings were applied (plaster, paint, impregnation). In this paper, we shall only study the durability of the reference walls by measurements of their erosion after 20 years exposed to natural weathering.

3. Limitations of the study

Except for the case of the exterior walls, the tested walls are not directly representative of normal earthen buildings. Indeed, they have two outer surfaces, whereas in a house or a barn, the interior atmosphere (without rain) is different from the external one subjected to weathering. The insulation against capillary rise from the foundation is made with a bitumen painted layer, whereas in vernacular earthen buildings the stone masonry basement is more or less permeable to ground water. Finally, the surface of the tested walls is obviously smaller than a house facade and the relationship between the overhang of the roof and the house wall height is not the same, approximately 1/15 in the tested walls, and varying between 1/20 and 1/10 in practice.

Consequently, we shall use this study as a relative comparison between various systems, not directly transposable to vernacular construction where empiricism remains necessary. On the other hand, the natural exposure conditions of these experiments give data that cannot be obtained by the experiments simulated in the laboratory mentioned in previous sections.

4. Reference walls

4.1. SMRE reference wall no. 15 (Fig. 6)

This is the rammed earth wall stabilised with 5% by dry weight of hydraulic lime. After 20 years, there are no significant changes in rammed earth quality except for some minor vertical cracks at the wall edges which have occurred during construction when the formwork was removed. This type of crack can be prevented by proper construction detailing.

4.2. MRE reference wall no. 29 (Fig. 7)

This is the unstabilised rammed earth wall made with the mix soil (MRE). On this wall, half of the southern side is left without any protection as a reference (right half on Fig. 7) and half of the northern side is protected with impregnation (as indicated in Fig. 4). Wall 29 is relatively eroded when compared with wall 15, especially the top two-thirds of the wall portion.

4.3. FRE reference wall no. 36 (Fig. 8)

This is the unstabilised rammed earth wall made with fine soil (FRE). The multiple cracks on the rammed earth surface appeared the day after installing the wall due to considerable shrinkage (as discussed earlier), but they are located only on the wall surface.

These qualitative conclusions are not sufficient to evaluate the durability of these rammed earth walls, hence the erosion measurement of the reference walls is presented in the next section.

Fig. 6. Reference wall no. 15 made with SMRE (stabilised rammed earth).

Fig. 7. Unstabilised reference wall no. 29 made with MRE (unstabilised rammed earth), facing West.

Fig. 8. Reference wall no. 36 made with FRE (unstabilised rammed earth).

5. Erosion measurement with the stereo-photogrammetric method

5.1. Principle of the stereo-photogrammetric method

Two photos taken from 2 different viewpoints (Fig. 9) can be superimposed to become a "relief". When viewed with a stereoscope, the relief appears. This work was done in the 3S Laboratory in Grenoble (data stereoscope and processing). Further details of the technique are given by Desrues and Duthilleul in Ref. [13]. The displacements determined by this process have an accuracy limited by the scale factor. The measurements on the images allowed an accuracy of ± 0.005 mm. The wall was 1.1 m high, and was represented by 60 mm on the slide, giving a scale factor of 18.3. The resulting accuracy of the displacement measurement was ± 0.092 mm.

5.2. Principle and hypotheses of erosion measurement

The vertical and horizontal profiles of the walls are plotted from the 3D image of the relief (Fig. 10). To obtain the erosion during the 20 years of exposure, it is necessary to compare the difference between the current relief and the initial relief after the wall manufacturing process. The initial relief soon after construction in 1985 is not available because no record was made at that time. However, it is possible to propose hypotheses on the initial state of the surfaces.

The formwork used for the installation consisted of steel plates, causing us to believe that the original wall surface was flat. It can be assumed that the "reference line" corresponding to the initial position of the wall surface is a line that touches the "summits" of the profile, Figs. 11 and 13. It should be noted that during the examination of the walls condition, pebbles could still be found on the surface of the walls, whereas the "fleur de pisé" had been watched. In practice, the presence of pebbles on the surface of the rammed earth is common due to the use of earth containing coarse gravel during construction. The mason only controls the concentration of big pebbles on the surface where fine particles of earth cannot fill the spaces between the pebbles, creating holes on the surface. With a length long enough for each profile (around 1 m), a number of non-eroded parts of the wall surface can be observed. By observing the profiles and tracking them, it is possible to determine the non-eroded positions of the wall surface, since the footprints of the formwork on which the reference line passes are still visible.

The measurement on the photos is performed manually with an optical stereoscope. It is therefore not possible to obtain the entire surface of the wall in relief, but only relief profiles, where each point is measured manually. The mean distance between 2 consecutive points is about 3.5 mm. Then from these profiles and a calculation of the standard deviation, we can obtain good relief accuracy for the entire wall surface and therefore the eroded volume. Note that manual processing allows us to obtain the profiles with better accuracy. It also allows us to study the erosion mechanisms in detail, especially near a pebble, by zooming in on the zone of study. Moreover, manual processing makes it possible to treat discontinuities in an appropriate way that gives more discretion in the development of the method.

5.3. Erosion measurement results

Here we quantify the erosion, without specifying the mechanisms which lead to this erosion. The areas of eroded earth in

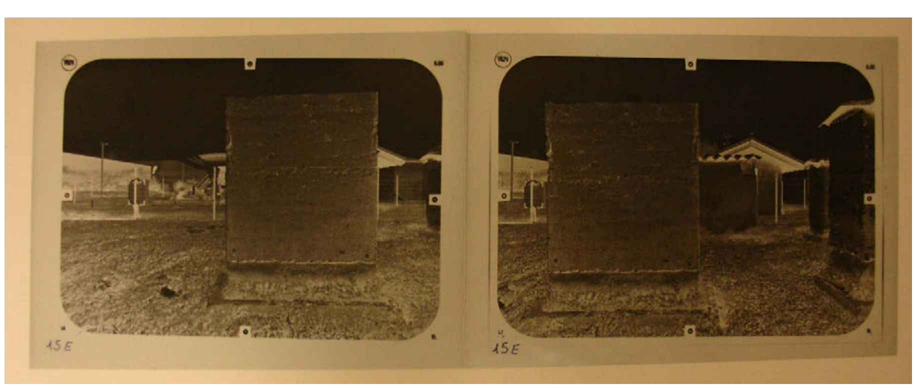

Fig. 9. Two photos taken from two different viewpoints on the same facing East of the wall no. 15. Left: photo taken from a point at left of the wall. Right: photo taken from a point at right of the wall.

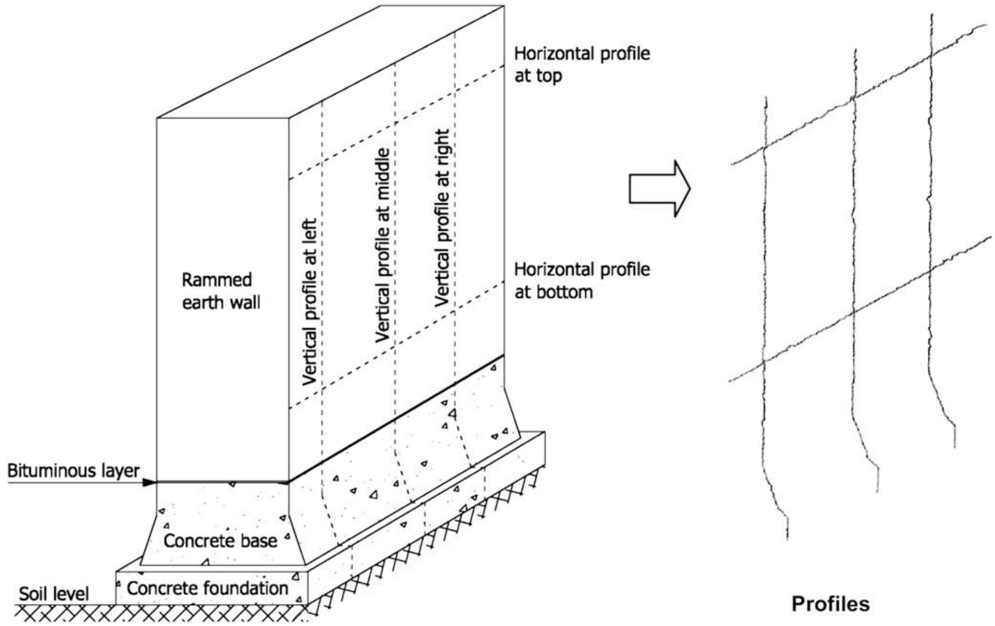

Fig. 10. Vertical and horizontal profiles of a wall.

Table 1 are calculated from the profiles and divided by the profile length to obtain the eroded material on a meter length. This enables us to compare the erosion values of different profiles. To obtain the volume of eroded material, one simply multiplies the measured eroded area by the size of the wall in the respective direction.

The east and western faces are biggest, so more profiles can be realised. The east face is attacked by prevailing winds, so it is worst than western face. Therefore only results on the East face are presented here.

5.3.1. Heterogeneity of erosion for the same wall

For most of the walls we observe that the upper part is less eroded because it is protected by the roof. Fig. 12 present an example of the roof role. In rain, the roof protects only the head and a part at the top of the wall. From Fig. 13, we measure that only about 20% (218 mm) of wall height is well protected by the roof. The eroded area covers 2890 mm^2 at the top and 6213 mm^2 at the lower part in the case of wall no. 36 and 2196 mm^2 at the top and 2446 mm^2 at the lower part in the case of wall 15. However, this is not true for wall no. 29, and the reasons are discussed later.

However, the erosion heterogeneity of a rammed earth wall is observed not only with the different zones across the height (protected by the roof or not) but also from the heterogeneity of each wall layer. There is a variation in density across the height of each compacted layer. Indeed, having been in direct contact with the rammer, the upper part of the layer is denser and therefore less eroded. The lower part is less dense due to the spread of the stress and compaction energy under the rammer during the compaction. Therefore, the lower part of each compacted layer is more eroded (Fig. 13). This heterogeneity causes variations in eroded volumes across the height of each compacted layer. Because of this heterogeneity, horizontal profiles cannot be used to estimate the eroded material of a wall. Only vertical profiles will be used because they pass though the entire height of the wall. With the vertical profiles, the heterogeneities due to the different zones (well protected by the roof or not) and the diversity of density in each compacted layer can be avoided to obtain the representative depth of erosion.

The stabilised rammed earth wall no. 15 has not eroded much in general (2 mm erosion on average) and the erosion between the upper and lower parts is not very different.

The unstabilised rammed earth wall no. 29 (FRE) presents an aspect rather difficult to understand: the top and middle parts of the wall (i.e. the upper two-thirds) have eroded more, while the lower part of the wall has not eroded as much. This may be attributed to construction defects in the walls such as non-uniform compaction across the height. Moreover, the top portion of the walls is protected by the small roof covering on top, yet shows more erosion. It should be noted that wall no. 29 has one half with no protective layer and that the other half is painted by impregnation. It is possible that the painted part has obscured its behaviour by encouraging water retention [14].

The top portion of the unstabilised rammed earth wall no. 36 (MRE) is well protected by the roof and shows very little erosion compared to the unprotected part (Fig. 13).

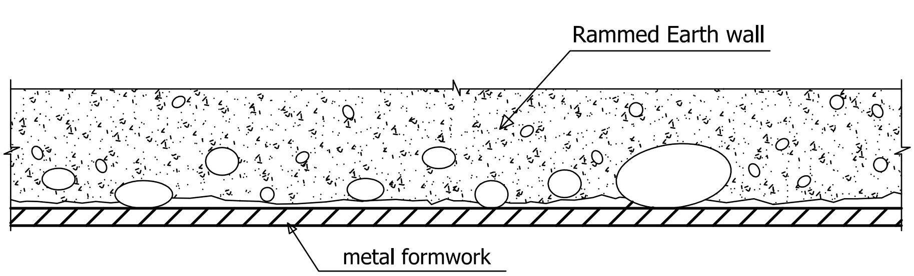

Fig. 11. Hypothesis of the reference line determination.

Table 1
Summary of eroded material measurement on the East face of the reference walls.

	Wall 15 (Stabilised MRE)				Wall 29 (Unstabilised MRE)		Wall 36 (Unstabilised FRE)	
Vertical profiles	Left	Middle1	Middle2	Right	Left	Right	Left	Right
Area of eroded material/1 m length (mm^2)	2156	1755	1730	2181	5750	Impregnation	5861	6831
Maximum erosion depth (mm)	7	5	6	5	18		21	17
Mean area of eroded material/1 m length (mm^2)		**1960**			**5750**		**6350**	
Deviation from mean (%)		13					11	
Horizontal profiles	Top		Bottom		Top (half at left: reference)	Bottom	Top	Bottom
Area of eroded materail/1 m length (mm^2)	2196		2446		6628	3111	2890	6213
Maximum erosion depth (mm)	6		5		14	8	12	18

Note: a half of wall no. 29 is the reference, the other half is painted by impregnation.

5.3.2. Heterogeneity of erosion for the different walls

For the reasons we mentioned above, only the results on vertical profiles are used to compare among the walls.

The erosion of the rammed earth wall no. 15 stabilised with NHL (1960 mm^2/1 m length) is less than the unstabilised rammed earth walls, while the difference in erosion values of two unstabilised walls is low (5750 mm^2/1 m length in the case of FRE wall no. 29 and 6350 mm^2/1 m length in the case of MRE wall no. 36). The maximum material loss of these non-stabilised rammed earth walls is 6350 mm^2/1 m length, corresponding to a mean erosion depth of 6.4 mm on the whole surface, which corresponds to 1.6% of the total wall thickness.

5.3.3. Durability evaluation of the studied walls

Unlike the industrial building materials (for example, steel or reinforced concrete) in which erosion has to be very limited to ensure its mechanical performance, in the case of rammed earth walls, erosion is tolerable. Indeed, being load-bearing walls, traditional rammed earth walls (about 50 cm thickness in general) are loaded by stresses of 0.1–0.3 MPa at the wall base, while the compression strength of unstabilised rammed earth is about 1 MPa [15,16]. This means that load-bearing rammed earth walls are overdesigned and constructed with safety factor between 3 and 10. So, when a rammed earth wall is eroded to 10% wall thickness (corresponding to 5 cm), there is still a safety factor of at least 2.7 for this wall.

However, on the aesthetic side, erosions to 5% wall thickness (corresponding to 2.5 cm) seems acceptable for occupants. Therefore, we assume that the lifetime of rammed earth wall is obtained when the erosion depth is 5% of wall thickness. The calculation of the lifetime of the walls is done in this study following these assumptions.

In general, we can see the erosion of a rammed earth wall is not a linear function of time. During the first time after construction, the wall shows more erosion on the surface, and then the erosion stabilises [17]. The reason for this may be that the non-linearity is due to the loss of compaction energy in contact with the formwork during manufacture because of friction. There is a loss of compaction energy by friction on the formwork, therefore the earth which

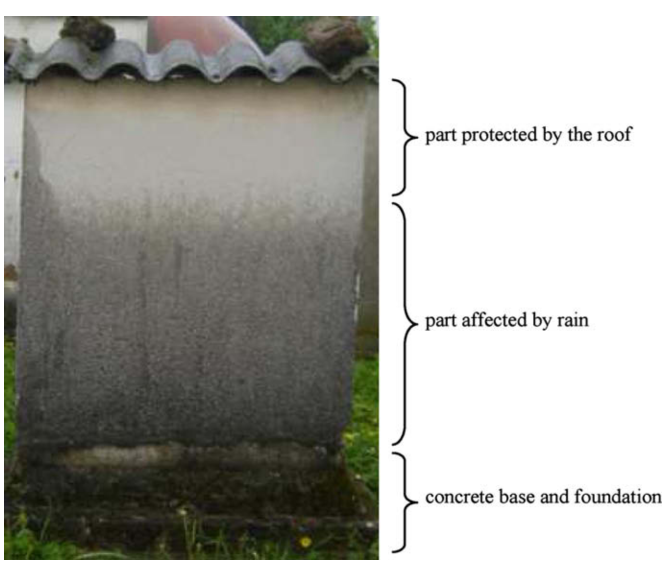

Fig. 12. The photo shows the wall no. 23 in the rain. The roof protects only the head and a part at the top of the wall against the rain.

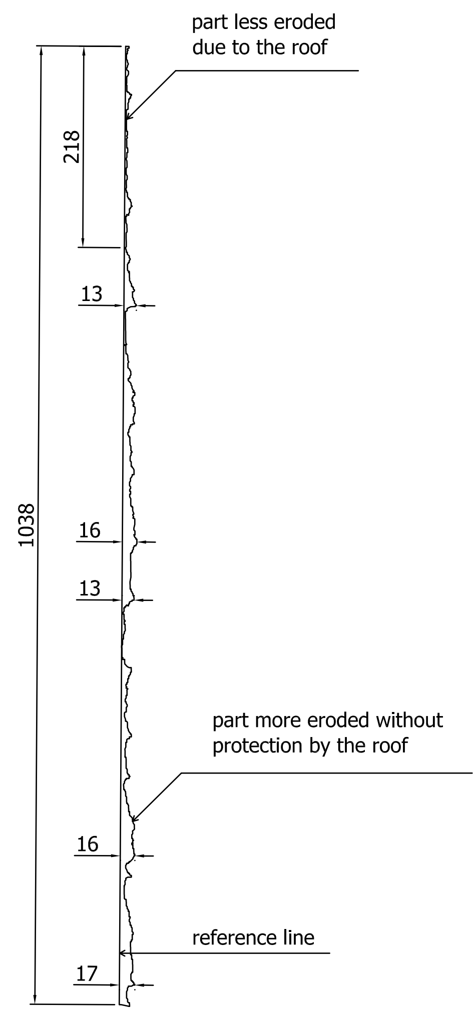

Fig. 13. Difference of erosion between upper and lower parts of wall 36 presented on a vertical profile.

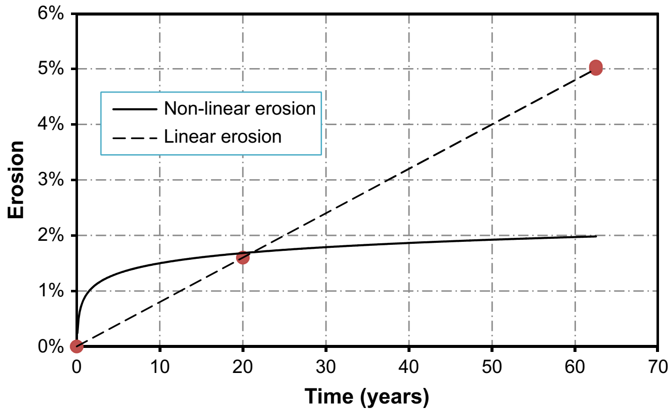

Fig. 14. Difference between linear and non-linear erosions with time.

was in contact with the formwork was less compacted and therefore more eroded.

However, there have not been studies researching this non-linear function. In this study, we have only data at the initial time (time = 0; erosion = 0) and at the time of this study (time = 20 years; erosion = 1.6%, case of unstabilised rammed earth). So, it is impossible to estimate exactly the lifetime of these walls by a non-linear function. Therefore we must try with the linear function. If we use the linear function of time for the erosion of the unstabilised rammed earth walls, 62.5 years should be required before these walls are eroded to 5% thickness (Fig. 14). The non-linear erosion curve in Fig. 14 is only an example of the non-linear possible behaviour of erosion that is often observed empirically in reality [17], but there is still no scientific researches giving an exact function. However, with this non-linearity aspect of erosion depending on the time, we can see that lifetime of these unstabilised rammed earth walls may be much longer than 62.5 years.

6. Concluding remarks

Although there are still some differences between the context of this study and the walls of real houses (2 surfaces exposed; insulation against capillary rise reassembled by a layer of bitumen, etc.), an "in-situ test" with a large time scale gives data that laboratory tests cannot give.

After 20 years of on-site exposure to weather, the material loss due to wall erosion is measured by an innovatory method using the stereo-photogrammetry. The erosion measurement is equivalent to a mean thickness of about 2 mm (corresponding to 0.5% wall thickness) in the case of the rammed earth wall stabilised with 5% (by dry weight) of natural hydraulic lime. Therefore the stabilisation enables to not use any plaster to protect the walls. In the case of the unstabilised rammed earth walls, the erosion measurement is about 6.4 mm (corresponding to 1.6% wall thickness) which led to an extrapolated lifetime longer than 60 years. This show a potential for the use of unstabilised rammed earth in the similar climatic conditions of this study (precipitation annual about 1000 mm).

The erosion measurement of the unstabilised rammed earth in this "in-situ test" confirms the durability of traditional unstabilised rammed earth walls which have undergone more than 100 years of weathering (the old house in Fig. 1 is an example.)

In similar conditions of this study, the stabilisation by cement or lime is inadequacy. First, the stabilisation does not enable the recycling of the material that is not a positive point in sustainable development. In addition, the use of cement or lime meets also the economic problem and the availability of these materials in the market in some countries and regions. That is why the development of new suitable tests to evaluate the durability of rammed earth following different climatic conditions is also important to decide whether the stabilisation is necessary.

The method of stereo-photogrammetry used to measure the erosion of rammed earth walls on site may also help to calibrate and develop more pertinent laboratory test to assess the durability of rammed earth wall.

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