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Earth-based construction material field tests characterization in the *Alto Douro Wine Region*

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Abstract: The *Alto Douro Wine Region*, located in the northeast of Portugal, a UNESCO World Heritage Site, presents an abundant vernacular building heritage. This building technology is based on a timber framed structure filled with a composite earth-based material. A lack of scientific studies related to this technology is evident, furthermore, principally in rural areas, this traditional building stock is highly deteriorated and damaged because of the rareness of conservation and strengthening works, which is partly related to the non-engineered character of this technology and to the knowledge loosed on that technique. Those aspects motivated the writing of this paper, whose main purpose is the physical and chemical characterization of the earth-based material applied in the *tabique* buildings of that region through field tests. Consequently, experimental work was conducted and the results obtained allowed, among others, the proposal of a series of adequate field tests. At our knowledge, this is the first time field tests are undertaken for *tabique* technology. This information will provide the means to assess the suitability of a given earth-based material with regards to this technology. The knowledge from this study could also be very useful for the development of future normative documents and as a reference for architects and engineers that work with this technology to guide and regulate future conservation, rehabilitation or construction processes helping to preserve this important legacy.

Keywords: *Alto Douro Wine Region*; *tabique*; traditional building techniques; field tests; composite earth-based material

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1 Introduction

One of the most traditional Portuguese building technologies used for sheltering and housing widespread in different parts of the country is *tabique*, Pinto *et al.* [1] a variation of worldwide known traditional timber framed with infill panels technology, [2]. The *Alto Douro Wine Region* (hereinafter referred to as '*Alto Douro*'), a sub-region of the *Trás-os-Montes e Alto Douro Region*, located in the northeast of Portugal, is rich in terms of *tabique* building heritage. Nevertheless, the majority of these buildings exhibit an advanced stage of deterioration, [3], which has lead to building collapse, demolition or replacement by other building technologies such as reinforced concrete structures. It is evident that construction or rehabilitation works are sparse, this scenario is most probably related to the non-engineered character of this construction technology and the subsequent absence of normative documents but is also related to the massive desertification of the northeast of Portugal, as a result of littoral urbanization.

This traditional building technique had a significant incidence until early XX and has gradually been replaced by others, nowadays the building industry is dominated by a solution consisting of a reinforced concrete framed structure with fired brick masonry and concrete slabs. This technology is sustainable, minimizes environmental impact by reducing the need for resources used to produce building materials, incorporates important skills and knowledge from the past, is an important aspect of the *Alto Douro* landscape UNESCO´s World Heritage Site classification, [4] and represents a unique building heritage.

Studies regarding this technology, although initiated in 2008 [5], have at this stage analysed some aspects of *tabique* buildings located in the *Trás-o-Montes e Alto Douro Region*, as materials characterization [1, 3, 5–7], building state of conservation [1, 5], *tabique* walls typologies [8], numerical modelling [9], thermal insulation [10, 11], fire resistance and rehabilitation works. The present work follows the study presented in [1, 3, 5, 12] and relative to laboratory tests applied to characterize the earth-based material (EBM) present in *tabique* walls. In this paper the same properties such as grain size, plasticity, organic or lime content will be assessed but through field tests that are commonly referred in the literature. This study will define the properties of a given EBM suitable for this technology and at the same time define the field tests which are adequate to characterize this material. Field tests are not exact, but they can be performed on site relatively quickly and are usually exact enough to estimate the composition and the properties of the EBM. This type of information is largely disseminated by different authors in respect to others building technologies, as rammed earth, compressed earth blocks (CEB) or adobe, [13, 14], but to our knowledge, there has been very little research about the characterization of the EBM used in *tabique* buildings or variations of it as wattle and daub in England or himiş and bağdadi construction in Turkey, [2]. Probably, this is due to the complexity of the analysis and because the EBM apparently do not have a load-bearing function as in the others earth-based technologies. In this context, the present work will, therefore, fill this gap. This paper is structured as follows: firstly, *tabique* walls structures, components and the composite earth-based material (CEBM) are described; secondly, traditional earth-based material field tests are reviewed; thirdly, the characterization of *tabique* EBM samples of the *Alto Douro* is performed; fourthly, results are presented and discussed and a series of adequate field tests to characterize the EBM applied to *tabique* buildings is proposed; finally, the main conclusions of this research work are drawn.

2 *Tabique* buildings and the earth-based material

Previous research by Pinto *et al.* [1], Cardoso [3] and Carvalho *et al.* [5], on this region indicates that most *tabique* constructions are residential single family detached houses with two storeys (ground and first storey). Usually, the ground floor is used as a storage room or for business and the first floor is used for housing. Those buildings have exterior stone masonry walls on the first floor level, (Figure 1), and *tabique* exterior walls at the first floor while *tabique* partition walls can be found in any floor levels. This technology applies traditional building materials as stone, wood, steel nails and a CEBM defined as raw earth with additions of hydraulic lime, straw, dried onion foliage, wood shaving or corn cob.

A *tabique* building component as a wall, (Figure 1), is formed of a timber structure made up of vertical boards connected by laths (horizontal slats) which are connected with metal nails, [6]. This structure is then filled and coated with a CEBM, [1, 3, 5, 8].

Figure 1: *Tabique* building and wall.

High quantities of CEBM are applied and the deterioration of *tabique* elements is principally due to CEBM loss, furthermore, the CEBM is of paramount importance since it provides sound and thermal insulation and fire resistance. Usually a revetment is applied in the outer face of exterior *tabique* walls, as metal plates, a lime render, schist tils or ceramic tiles to increase the waterproofing and to prevent the deterioration of the CEBM. In the following section a list of test methods are presented and later used to access some of the *tabique* EBM properties.

3 Earth characterization tests review

A literature review was made to access the tests commonly used for the characterization of the EBM applied in timber framed building technologies with infills. Surprisingly a lack of scientific studies was noticed, despite some studies recently initiated [1, 3, 5], or presented by Aedo & Olmos [15] and Cyted [16] in France and South America, respectively. Currently there are several published works on earth characterization but in respect of other technologies, such as adobe, rammed earth and CEB, using their standards and normative documents. For this reason, the literature review initiated was reoriented on these technologies. Grain size, plasticity, chemical and mineralogical composition of the earth are the properties mostly evaluate trough testing methods, Houben & Guillaud [17], Minke [18], Doat et al. [19]. Those tests can be performed in laboratories and give quantitative results, nevertheless some of these are field tests with the advantage that they can be performed in the field, relatively quickly and with simple equipment. In those tests, the results regarding the EBM properties are qualitative. In the following section some field tests frequently adopted which were found in the literature review are applied for the characterization of *tabique* EBM.

4 Experimental work

In order to identify and characterize EBM traditionally used in *tabique* buildings, an experiment was carried out using material samples collected from *tabique* buildings located in the *Alto Douro*. Grain size, plasticity and chemical field tests were performed at the Geotechnical and Construction Material Laboratory of the Polytechnic Institute of Coimbra. In the following subsections materials, methods and results are presented and discussed.

4.1 The materials

In the scope of this study, fieldwork based on technical visits and collection of information and samples performed by Cardoso [3] in the municipality of *Lamego* in the *Alto Douro* allowed the collection of several EBM samples. EBM samples were collected from six *tabique* buildings located in Lamego municipality, [3, 12], a portion of each of these samples is illustrated in Figure 2.

Figure 2: *Tabique* building studied.

These *tabique* buildings are rural *tabique* dwellings of two floors with exterior and partition *tabique* walls. In each building, one EBM sample with an average weight of one kilogram was collected and the adopted sample designation correspond to C2, C3, C4, C5, C6 and C7, (Figure 2). The sampling locations can be found in [3, 12].

4.2 Methods

To study the granulometry, plasticity, cohesion and chemical content, the following field tests were performed:

- Particle size characterization tests, which consist of a: tactile and visual test, particle size characterization test and field sieving test.
- Plasticity test, consisting of a: shine test, dropping ball test, adhesion test, wash hands test, nibble test, dry strength test, consistency test and ribbon test.
- Chemical characterization tests, allowing the identification of the presence of clay, organic matter or hydraulic binders as lime, consisting in a: colour test, acid test and smell test.

In the next subsection field tests and results are presented, firstly the results regarding grain size and plasticity tests and finally those relative to the chemical sample's content.

4.2.1 The equipment

The field tests are manual and need simple equipment for example a spoon, a brush, a plastic container, three ASTM series sieves and a spatula illustrated in Figure 3.

Figure 3: Equipment used in the grain size characterization.

4.2.2 Grain size characterization

The tactile and visual test, particle size characterization test and field sieving test were applied to all six samples.

In the tactile and visual test, the simple observation and touch of the samples allow characterization of the samples granulometry. If it feels rough and has no cohe-

(a) Particle size characterization test **(b)** field sieving test

Figure 4: Samples granulometric characterization tests.

sion when moist the soil is sandy, if it feels slightly rough and is moderately cohesive when moistened the soil is silty, if, when dry, it contains lumps or concretions which resist crushing and finally if it becomes plastic and sticky when moistened then the soil is clayey [17].

In the particle size characterization test, the manual separation of the visible (particles with diameter less than 0.08 mm) and invisible particles (particles with diameter greater than 0.08 mm) was made, two different portions of earth-based material were obtained, (Figure 4-a)).

The field sieving test was performed with the use of three sieves of the ASTM series, in order to obtain three different portions of EBM: gravel, sand and silt/clay. The results are presented in Figure 4-b).

The results of the tactile and visual test, (Table 1), allow us to conclude that the EBM samples studied have a fine texture and are classified as silty EBM. Only sample C4 is classified as clayey as a result of the plastique behaviour when humidified.

Table 1: Tactile and visual test results.

Sample	Tactile and visual test	Classification
C2	Slightly rough	Silty EBM
C3	Slightly rough	Silty EBM
C4	Plastic and sticky	Clayey EBM
C5	Slightly rough	Silty EBM
C6	Slightly rough	Silty EBM
C7	Slightly rough	Silty EBM

The particle size characterization test results, (Table 2), indicates that the EBM samples have silty and clayey granulometry, since there is a huge proportion of invisible particles whose shape can not be distinguished with human visual acuity. with the eyes.

Finally, the field sieving test classifies all the EBM samples as silty/clayey, (Table 3).

The previous field tests globally classify the EBM samples as silty. Those results are similar to the ones obtained with the laboratory tests [3, 12]. As referred to previously,

Table 2: Particle size characterization test results.

Sample	Characterization by size (mm)		Results
	% < φ 0.08 mm	% > φ 0.08 mm	
C2		85	15 Silty/Clayey
C3	85	15	Silty/Clayey
C4	70	30	Silty/Clayey
C5	90	10	Silty/Clayey
C6	90	10	Silty/Clayey
C7	95	5	Silty/Clayey

Table 3: Field sieving tests.

Sample	Field sieving test		Classification	
	$\varphi \geqslant 2$ mm	0.074 mm < φ <2 mm	$\varphi \leqslant 0.074$ mm	
C2	10	55	45	Silty/Clayey
C3	15	55	40	Silty/Clayey
C4	12	50	38	Silty/Clayey
C5	8	52	40	Silty/Clayey
C6	10	50	40	Silty/Clayey
C7	11	45	44	Silty/Clayey

those field tests have been widely used in the earth construction context, but to our knowledge, this is the first time they have been applied to *tabique* technology.

4.2.3 Plasticity characterization

In order to evaluate the samples plasticity, the nibble test, washing hands test, shine test, dropping ball test, adhesion test, water retention test, dry strength test, consistency test and ribbon test were performed in C2, C3, C4, C5, C6 and C7 EBM samples.

In the nibble test, a very small quantity of the EBM samples is crushed lightly between the teeth, a sandy soil grinds between the teeth and produces a disagreeable sensation, if it can be ground between the teeth, without a disagreeable sensation the soil is silty. Clayey soils, on the other hands, gives a sticky, smooth or floury sensation [17]. In the washing hands test, a humid EBM sample is rubbed between the hands, if the grains can be distinctly felt, it indicates sandy or gravelly soil, if the sample is sticky, but the hands can be rinsed clean fairly easily the EBM is silty, if the EBM has a soapy feel and the hands cannot be rinsed easily the EBM is clayey, [17]. Figure 5 illustrates the hands aspect after this operation.

As indicated in Table 4, the nibble test and washing hands test classified the EBM samples as silty, except for sample C4 who was classified as clayey.

For the preparation of the samples for the shine test, dropping ball test, adhesion test, water retention test and

Table 4: Nibble and washing hands tests results.

Sample	Nibble test	Classification	Washing hands test	Classification
C2	Can be ground	Silty	Rince easily	Silty
C3	Can be ground	Silty	Rince easily	Silty
C4	Sticky	Clayey	Cannot rince easily	Clayey
C5	Can be ground	Silty	Rince easily	Silty
C6	Can be ground	Silty	Rince easily	Silty
C7	Can be ground	Silty	Rince easily	Silty

Figure 5: Washing hands test.

consistency test, a moist portion of each EBM sample is formed into a 3 cm ball diameter so that it sticks together but does not stick to the fingers, Figure 6 illustrates these ball samples.

Figure 6: EBM balls.

For the shine test, the EBM balls are cut in half with a knife and the cross section of the ball is observed. A shine cross section indicates clay content, a dull cross section indicates higher silt or sand content, (Figure 7-a)). In the dropping ball test, (Figure 7-b)), the balls are dropped from a height of 1.5 m into a flat surface, if the ball flattens only slightly and shows few or no cracks, it has a high binding force due to a high clay content, this is the case for the six samples.

Table 5 presents the plasticity test results of the shine test and dropping ball test.

As it can be observed the shine test classified the sample as silty earth and the dropping ball test as clayey earth. Since the dropping ball test results are different from the shine test and the other previous tests and also regarding the laboratory tests realized in [12], we recommend not to use this test to characterize EBM applied in *tabique* technology.

In the adhesion test, a spatula is inserted in each ball, (Figure 7-c)), if the spatula penetrates with difficulty and EBM sticks to it upon withdrawal the EBM is extremely clayey, if the spatula can be pushed into it without difficulty but a bit of EBM remains on the spatula upon withdrawal the EBM is moderately clayey, if the spatula can be pushed into the mass without encountering any resistance at all, even if the spatula is dirty upon withdrawal the EBM contains only a little clay [17]. The results regarding the adhesion test are presented in Table 6.

The plasticity evaluation of samples C2, C3, C4, C5, C6, C7 was concluded with the dry strength test, consistency test and ribbon test. For the dry strength test, we form three pats of EBM for all six samples. The pats were put in an oven until they were completely dried, (Figure **??**-a)). Then we observe how easy the pats are to pulverize between the thumb and index finger. If the pat pulverizes easily, the EBM is silty or fine sand and has a low clay content, if the pat can be crushed to a powder with little effort, the EBM is silty or sandy clay, finally if the pat is hard to break and will not pulverize, the EBM has a high clay content, [17].

In the consistency test, (Figure **??**-b)), the EBM samples are formed into a ball. If it crumbles before forming a ball, then the EBM as a high silt or sand content. If the ball can be crushed between the thumb and forefinger only with a lot of force, the clay content is high. If the ball cracks and crumbles, then the EBM as a low clay content, [16]. In

(a) Shine test **(b)** Dropping ball test **(c)** Adhesion test, sample C4

Figure 7: Shine, dropping ball, adhesion and water retention tests.

Table 5: Shine and dropping ball test.

Sample	Shine test	Classification	Dropping ball test	Classification
C2	Dull	Silty	No cracks	Clayey
C3	Dull	Silty	No cracks	Clayey
C4	Shiny	Silty	No cracks	Clayey
C5	Dull	Silty	No cracks	Clayey
C6	Dull	Silty	No cracks	Clayey
C7	Dull	Silty	No cracks	Clayey

(a) Dry strength test samples **(b)** Consistency test, sample C4 **(c)** Ribbon test, sample C4

Figure 8: Dry strength, consistency and ribbon test.

Table 6 the results obtained from the adhesion test and the dry strength test are presented.

The adhesion test classified the EBM samples as sandy. Nevertheless in this test it is very difficult to measure the variation of the force applied to the spatula, since it is a manual operation. This generates questions about the precision of the results. The dry strength test classified almost all the samples as silty-clay. We observed that when the pats broke they divided into three parts, except sample C4 which broke into four parts.

For the ribbon test, (Figure **??**-c)), each EBM sample is carefully rolled in the form of a sausage with the maximum length that the EBM sample will support. A long ribbon is indicative of the high clay content, a short ribbon on the other hand indicates a low clay content.

The results of the consistency test and ribbon test are presented in Table 7. We observed that the ribbon length varies between 16 cm and 26 cm, which in means they correspond to medium plasticity.

In the consistency test, only C4 sample presented a medium plasticity behaviour. This result was already observed in the laboratory tests results presented in [12].

Since the results of the consistency test do not allow a clear classification of the samples we recommend not to use them. Furthermore, as the dropping ball test, the plasticity results of consistency and ribbon test are not corroborated with the results obtained in the laboratory tests presented in [12] or with the previous field tests, for these reasons we do not recommend them to be used in EBM applied in *tabique* technology.

Table 6: Adhesion and dry strength test results.

Sample	Adhesion test	Classification	Dry strength test	Classification
C2	No resistance	Little clay	Divided in 3 parts	Silty/Clayey
C3	No resistance	Little clay	Divided in 3 parts	Silty/Clayey
C4	Small resistance	Moderately clay	Divided in 2 parts	Clayey
C5	No resistance	Little clay	Divided in 4 parts	Silty/Clayey
C6	No resistance	Little clay	Divided in 3 parts	Silty/Clayey
C7	No resistance	Little clay	Divided in 3 parts	Silty/Clayey

Table 7: Consistency and ribbon test results.

Sample	Consistency test	Classification	Ribbon test (cm)	Classification
C2	Indeterminate	–	26	High plasticity
C3	Indeterminate	–	20	Medium plasticity
C4	Soft	Medium plasticity	25	High plasticity
C5	Indeterminate	–	20	Medium plasticity
C6	Indeterminate	–	16	Medium plasticity
C7	Indeterminate	–	20	Medium plasticity

4.2.4 Chemical characterization tests

It is common practice in the *Alto Douro* region to use EBM enriched with hydraulic lime in the *tabique* walls since lime is does not exist in that region. Which means lime can be present in the EBM applied in *tabique* constructions or rehabilitation. In order to define the lime content, one drop of a 20% solution of chloridric acid, presented in Figure 9, is added the samples using a glass or a timber rod.

Figure 9: Acid test samples.

The efflorescence indicates the presence of lime, if there is no efflorescence, the lime content is less than 1%. If there is a weak, brief efflorescence, the lime content is between 1% and 2%; if the efflorescence is significant though brief, the lime content is between 3% and 4%; and if the efflorescence is strong and long lasting, the lime content is more than 5%. The acid test results presented in Table 8 reveals that the samples do not react with the chloridric acid thus they do not have lime in their composition or if they have it is in a very small quantity. The results are the same as those obtained with EDS analysis results reported in [3, 12].

Table 8: Acid test results.

Sample	Classification
C2	Without reaction, < 1% lime
C3	Without reaction, < 1% lime
C4	Without reaction, < 1% lime
C5	Without reaction, < 1% lime
C6	Without reaction, < 1% lime
C7	Without reaction, < 1% lime

Finally the colour test and smell tests were performed to identify organic matter in the samples. EBM without organic matter is odourless, however it acquires a musty smell if it contains deteriorating humus or organic matter. The test results of the colour and smell of the samples are indicated in the Table 9. Those results indicate that almost all the samples do not have organic matter in their composition as expected since the samples were extracted at a sufficient depth.

Table 9: Colour and smell test results.

Sample	Colour test	Classification	Smell test	Classification
C2	Dark	Organic matter	Odorless	No organic matter
C3	Clear	No organic matter	Odorless	No organic matter
C4	Clear	No organic matter	Odorless	No organic matter
C5	Clear	No organic matter	Odorless	No organic matter
C6	Clear	No organic matter	Smells musty	Organic matter
C7	Clear	No organic matter	Odorless	No organic matter

Table 10: Field tests proposal.

Particle size characterization	Particle size characterization test	Plasticity	Nibble test
	Expeditious sieving test		Washing hands test
	Tactile and Visual test		Shine test
Chemical composition	Smell test		Dry strength test
	Colour test		
	Acid test		

Table 9, show that the colour test and smell test present opposite results, those differences should be due to the expeditious nature of those tests.

5 Field tests proposal

The exhaustive experimental work realized regarding the EBM samples characterization allows us to evaluate whether the field tests are adequate to validate when a given EBM can be used in *tabique* construction. This was accomplished following two criteria: firstly comparing theme with laboratory tests results and secondly comparing the field test results between them. In this context a proposal is made relative to field tests that can be used for the selection of EBM in rehabilitation and *tabique* constructions. This proposal is similar to the ones done by several authors and can be found in [13], [18] and [19] but regarding other technologies and is presented in Table 10.

The field tests proposal is of paramount importance since it will complement the research and results published but regarding other earth-based technologies, furthermore it can be used in practical construction applications.

As referred to throughout the analysis the dropping ball test, adhesion test, consistency test and ribbon test were considered not adequate because the results obtained were too different from the laboratory tests [12] and from the other field tests.

6 Conclusions

The field test literature is rich and abundant for BTC, adobe and rammed earth techniques but almost non-existent for *tabique* technology. Based on that a series of field tests is proposed to select the EBM adequate to *tabique* construction. This proposal is based on the results similarity between the granulometry, plasticity and chemical composition properties obtained with field tests and laboratory tests. Globally the particle size characterization and plasticity tests classified the EBM as silty/clayey and the chemical composition tests defined a EBM without organic matter or lime content. The mechanical properties should therefore be those corresponding to a silty clayey soil. Those field tests will allow the determination of whether an EBM has the properties needed to build structural components as *tabique* walls used in future rehabilitation works and construction of new *tabique* constructions in Lamego municipality and eventually in other places in the country. The field tests applied are simple, empirical and user dependent for this reason we recommend to repeat them several times and not to take the first result. They should be used as guidance in the early stages of the selection procedure, later in the design stage, more accurate laboratory tests should be performed. At our knowledge, this is the first time an experimental work based on field tests has been performed in *tabique* EBM. This information can give guidance to the development of standards and be a requirement for the future development of numerical tools for the structural stability analysis of these *tabique* buildings.

We should be aware that the environmental issues and the use of eco-friendly materials are gaining an increasing interest worldwide and presently, the building industry has been recalling earth-based building technologies as a modern building solution due mostly to its recognized sustainability, low environmental impact. Adopting tabique construction would contribute to a more sustainable building industry besides it has good thermal and acoustic properties and is high durability, as the existing *tabique* buildings reveal.

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