# EVALUATION OF DIFFERENT RAW EARTHEN PLASTERS STABILIZED WITH LIME FOR BIO-BUILDING EXPLOITATION

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**Abstract**

The building sector generates around 5-8% of greenhouse gas emissions (GHG)[1] and the disposal of C&D waste at the end-of-life is a high environmental cost. The raw earth is a sustainable construction material with low embedded energy, available locally. It is the most ancient technique of construction, studied in recent years to reduce the environmental life cycle impact of buildings. Clay is responsible for the earth plastic behaviour and represents the binder that keeps together silt and sand grains. Earth sets through drying without chemical reactions, so it could be reinserted into the nature. At the same time, earthen constructions do not withstand weathering and develop lower mechanical performances compared with those which exploit hydraulic binders. We investigated the possibility of improving these characteristics by stabilizing earthen products with the addition of small amounts of lime preserving clay as eco-friendly binder and the full end-of-life recyclability.

Four earths with different binder properties – two kaolin clays, one illite clay and a smectite – were characterized and analysed at the lab scale. The change of the Atterberg limits on adding lime was determined. The clay modification and potential pozzolanic reactions with lime were measured by X-ray diffraction. Two earths were selected to be tested as plasters, adding sand and lime in order to reduce shrinkage and increase water resistance. Cracking and adhesion tests were run for all mixtures. The results show decreasing performances for all the plasters mixtures stabilized with lime, especially in the presence of an expandable clay fraction. The water resistance is improved for the stabilized mixtures that require less sand to reduce cracking and swelling. Lime is better used as a surface finish and plaster, not as stabilizer, because reacting with clay it increases the plastic limit and raises the water demand to obtain a plastic and workable mixture.

**Keywords:**

Raw earth, lime, water resistance, sustainable construction materials, eco-friendly binders.

**List of abbreviations:**

ABS (earth ABS illitic), KSK (Kaolin Serie K), BBZ (Kaolin BBZ), K100 (Silt K100 montmorillonite), PL (Plastic Limit), LL (Liquid Limit), PI (Plasticity Index), AI (Activity Index).

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## 1 INTRODUCTION AND BACKGROUND

The request of more sustainable buildings materials raises the interest in earthen architecture, one of the most widespread in the world: still today one third of human population lives in earthen houses [Minke 2012]. The problems related with the excessive environmental cost of the modern buildings underline some good features of the raw earthen constructions. The environmental advantages include avoiding binder production and raw materials consumption. Raw earth has a very low embedded energy compared with the modern construction technologies. Cement industries is responsible for about 8% of global $CO_2$ emissions [Olivier 2015]. The building sector generates also the C&D (construction and demolition) waste which needs disposal and is still not routinely valorised. In Italy the largest quantity of non hazardous waste is generated from the construction and demolition sector. It produces 43.4% of special non hazardous waste, corresponding with 54.4 million tons [ISPRA 2018]. Using unstabilized raw earth materials allows full recyclability or reuse at the end of life without generating new waste. This low-cost material is frequently obtained directly from the building site when excavating foundation. Building houses with local materials reduces the impact of construction. As Morel demonstrated the impact of transportation decreases by up 453% and the energy embodied in building by 240% [Morel 2001]. These data are estimated by comparing a concrete house and a rammed earth house.

Clayey earth is available everywhere on the planet, even though it has a high spatial variability and it is not a standardized building material. Depending on the earth characteristics, it should be worked with different techniques, such as rammed earth, mud bricks called adobes, soil blocks and so on. For this reason, soil characterization and analysis are very important to evaluate the possibility of using it as such or if it requires any enhancement or stabilisation [Ciancio 2013]. As Jime´nez and Guerrero underline [Jime´nez 2007] a standard protocol and procedure for evaluating the earth doesn't exist. Because of this the first step for using a soil is the analysis of the available material [Avrami 2008]. The earth used as building material is called loam and it's a mixture of clay, silt, sand and occasionally larger aggregates such as gravel or stones. Clay interacts with water behaving as a binder that on drying keeps together silt and grains. This reversible process is the main advantage and weak point of this material. Earth can be reinserted into nature or reused at its end life, at the same time it is not water resistant and it develops low mechanical performances. The aim of this paper is to investigate the possibility of improving earth by adding sand and lime putty for using it as earthen plasters without compromising its properties to be reused. The sand addition is used to constitute the granular skeleton linked and glued by the clay. By doing so, the intrinsic shrinking potential of the clay is controlled. The addition of water needed to obtain a workable mixture may cause a swelling of the clay and thus a shrinkage when the loam mixture dries. If the macroscopic shrinkage is counteracted, cracking occurs which decreases the adhesion of an earthen plaster to the substrate. The optimised size distribution is a good starting point for using earth as a plaster, but it is not the only one criterion [Hamard 2013]. Clay minerals structures can be very different and they affect the plasticity behaviour [Grim 1935]. The clay characteristics have a high influence on the optimal sand quantity. A highly swelling clay is usually very cohesive and a small amount will be sufficient to bind the sand grains. The overall swelling of the mixture will thus be limited and comparable to the one of a not swelling clay [Anger 2009]. The optimal sand amount is usually estimated with a dosage test also called shrinkage or cracking test, a field test realised increasing the sand addition step by step to find the optimum [Emiroğlu 2015]. Adding too much sand causes the mixture to loose cohesion and adhesion capacity. This aspect will be investigated with the adhesion test to measure and compare the adhesion or shear strength of the mixture with the data existing in literature [Hamard 2013; Stazi 2016].

A further concern is the improvement of the mechanical and water resistance. The addition of lime is widely used for soil stabilization reducing swelling, shrinkage and increasing water resistance [Negi 2013]. In this context water resistance relates to soil stability and low erosion. Workability of the earth mixture is determined by the quantity of water added. The mixture must be plastic, comprised within the liquid limit and the plastic limit. The extension of the plastic domain is defined by the Plasticity Index (PI). The Liquid Limit (LL) is the maximum water content above which plasticity is lost and the mixture behaves like a liquid. The Plastic Limit (PL) is the minimum water content that allows workability and the use of clay as natural binder. These two limits are a function of the type of clay which constitutes the earth. The addition of lime putty reduces the plastic range and decreases PI due to increase of the PL. This phenomenon is more evident for the swelling clays (e.g. montmorillonite) and less important for the non-swelling ones (e.g. kaolin) [Hilt 1960]. The increase of the plastic limit implies a higher water demand to make the earth workable. The main concern of a higher water demand is the risk of more extensive cracking when the mixture dries, a problem particularly severe for plasters. This aspect will be investigated, focusing on the interaction of the different clay types with lime [Bell 1996]. The lime addition considered is always less than or equal to 5%, thus allowing clay to always act as the binder in the mixture and allowing the materials to be reused at the end of their life.

A second issue is the thermal conductivity modification, that could be modified by the stabiliser. The thermal conductivity is an important characteristic to attain the necessary insulation performance and to guarantee a low energy consumption for a building. This problem has been briefly investigated with thermal conductivity measurements.

## 2 MATERIALS

Four different soils were analysed: two kaolintitic earths (BBZ, KSK), one smectitic earth (K100) and one illitic earth (ABS). All the soils are supplied by Minerali Industriali Srl (Novara, Italy). ABS and BBZ come from northern Italy, Lozzolo (VC). KSK and K100 come from Sardinina, quarry 'Molino Falzu' Ardara (SS). These earths have been selected as representative of the most common clay typologies in Italy. The materials were dried indoor (25°c and 50% moisture) and crushed to a size smaller than 2 mm. The sand used has a grain-size distribution 0-2 mm, from sand quarries of the river Piave (Dal Zotto Srl). The lime putty is produced by ET, Event and Technologies (Cassolnovo (PV) Italy). For determining the grain-size distribution it was dried indoor (25°C and 50% moisture) and sieved to two millimetres. For subsequent testing the hydrated lime was slaked to a putty with 45% dray matter.

# 3 METHODS AND PROCEDURE

## 3.1 Soil characterization

The soil characterization includes particle size distribution determination by sedimentation and sieving. The percentage of clay, silt and sand is thus determined. Further the Atterberg limits are measured by determining the plasticity range, delimited by the Plastic Limit (PL) and Liquid Limit (LL). The Plasticity index (PI) defines the amplitude of the plasticity range and is given by the difference between PL and LL. The precise mineralogical identification of the clay is done by X-Ray diffraction (XRD).

*Particle size analysis*

Particle size distribution is measured through the sedimentation and sieve analysis, following the European technical specification CEN ISO / TS 17892-4 (European Standard). To thoroughly disperse the clay particles, a 40 g/l solution of hexametaphosphate is used. Particle size distribution has been performed also for the hydrated lime, in order to evaluate the size distribution modifications when adding lime to stabilize the soils. The hydrated lime particles have been dispersed using a different dispersing agent: polynaphthalene sulfonate at the concentration of 2 wt% active matter.

*Atterberg limits*

The determination of LL has performed with the Casagrande spoon following the European technical specification CEN ISO / TS 17892-4 [ASTM 2005]. The PL has performed following the same European standard, by measuring the water content at which the earth begins to crumble when rolled into threads of specified size (3.2 mm) [Andrade 2011].

*XRD analysis on earths minerals*

Powder X-Ray diffraction has been measured on three different samples for each earth. Bulk, un-oriented samples allow the investigation of the overall earth composition. Oriented and glycolated samples are prepared to investigate clay mineralogy. The diffractometer used is a D8 BrukerAdvance, the measurement conditions used are range 5-70° 2θ, counting time 1 sec/step; size 0.02°2θ. Powder samples have been prepared sieving earths to 0.425 mm, in order to remove the coarse fraction (sand and gravel). The preparation of the oriented samples requires silt and clay separation by decantation followed by centrifugation to recover and concentrate the suspension. The fine fraction is dispersed in distilled water (20-30 g/l of clay suspended in a 40 g/l solution of hexametaphosphate). The suspension is prepared in a graduated jar, dispersed by shaking and sonicated for one minute. Afterwards the suspension is allowed to settle for 4 hours. The fraction ≤ 2 μm is retained in the uppermost 5 cm, which are separated and centrifuged to recover a concentrated clay suspension. Few drops of clay slurry was placed on glass slides (Fig.1a) and dried for 24 h at 60°C [Poppe 2001].

The glycolated samples have been prepared starting from the oriented ones. The oriented samples have been inserted into a desiccator filled with 1 cm of ethylene glycol. The desiccator was placed in oven at 60°C for 4-12 hours (the longer times do not adversely affect the specimens). The samples are conserved in the desiccator until the X-ray diffraction measurement [Poppe 2001].

## 3.2 Analysis on the stabilization with lime putty

*Atterberg limits variation*

Based on the characterization results only three soils (ABS, BBZ and K100) have been chosen for studying the lime stabilisation. BBZ was selected instead of KSK because it is almost pure kaolin. The Atterberg limits were measured for investigating the variation of plasticity on adding different lime percentages (1%, 2.5%, 5%). The lime percentage added was calculated on the dry weight of earth, taking good allowance of the water content of lime putty (about 55 w%).

*XRD analysis on mixtures*

XRD measurements were performed on mixtures of earth with lime putty added at 5 wt%. Measurements were repeated at different times (initial time, one month, two months) curing the samples at room temperature in saturated conditions, to quantify the pozzolanic reactions between lime and the earths. A similar procedure with the same curing times is reported by Eades to identify the reaction of hydrated lime with pure clay minerals in soil stabilization [Eades 1960].

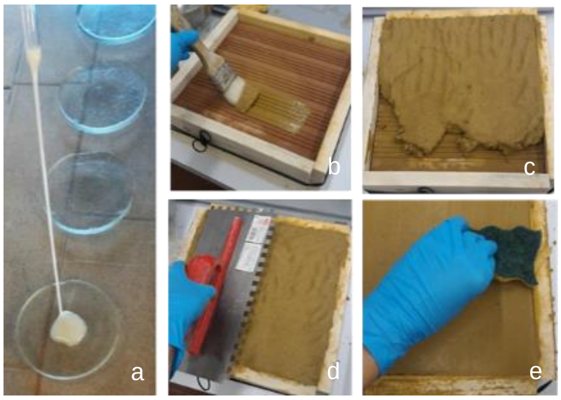


*Fig.1 a) XRD oriented samples preparation, b), c), d), e), shrinkage test preparation.*

## 3.3 Field tests for plasters suitability adding sand and hydrated lime

Finally, only two earths were selected for testing as plasters: ABS and K100. ABS and K100 has been selected based on their plasticity and cohesion yielding a higher adhesion. These earths have been tested with the performance characterization field tests, focusing on the determination of the correct balance between earth and sand and on improving the application properties by adding lime putty.

The optimal sand addition to avoid cracks was determined by the shrinkage test. Once the optimal sand addition was selected the test was repeated by adding 5wt% hydrated lime. The adhesion test was performed with the optimal sand addition, with and without lime stabilisation. The water resistance test was performed on samples prepared for the adhesion test. The observation on the desegregation time was employed to evaluate the contribution of lime in increasing the water resistance.

*Shrinkage test*

The test requires tile sample 1.5 cm thick with a surface of 25x25 cm$^2$. Fired brick tiles were used as support. First the bricks were submerged into the water for 10 min, then a layer of earth slip (barbottina) was laid down on it. The earth slip layer helps the adhesion of the plastering mixture (Fig. 1b). A wooden formwork defines the shape of the tile. The added weight of sand was calculated on the dry earth weight, allowing for the water content of the earths. This correction is particularly important for K100 (w=7%). (Tab.1) The shrinkage and cracking test with addition of lime putty was performed by adding 5 wt% hydrated lime on the dry earth weight. Lime addition is performed on a dry basis, allowing for the lime putty water content (55%). The mixtures were hand mixed for enough time to obtain a good level of plasticity and homogeneity. In the lime stabilization tests, to improve the possible reaction between lime and soil, these two components were first mixed together, and sand was added later. A great care was given to fill uniformly and completely the formworks (Fig.1c). The final step was levelling the surface (Fig. 1d, e) and drying the plaster at ambient conditions (25°C and 50% moisture) for a week. The water content of the plaster samples as prepared and after drying were measured by drying in oven at 105°C for 24 hours.

*Adhesion test*

The same substrate preparation and plaster mixing procedures were adopted for the adhesion test. In this case the formwork is a plastic ring with diameter 5.81 cm and height 1.5 cm. In the internal part of the ring a thin layer of vaseline was applied as demoulding agent, using as a little as possible to avoid contamination of the substrate. The mould filling procedure is the same as for the cracking test (Fig.2 a) and b). After a week all the rings were removed. The brick was fixed in a vertical position on a resistant structure using clamps. A resistant textile strap of the correct dimensions to be fixed on the sample is hung on the plaster disc and carries the loads. Fig.2 shows the instrumentation and the procedure for the test. A load cell was fixed under the ring to measure the load (Fig.2 c).

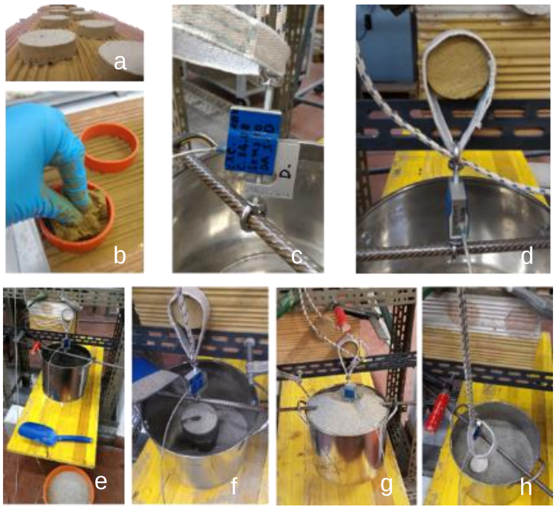


*Fig.2 Adhesion test a) and b)samples preparation, c) load cell d) e) f) g) h) test realization.*

A second rope was used to secure the load cell form falls and impact (Fig.2 d). Under the load cell a load device was fixed to be filled with sand (Fig.2 e). Sand was chosen because it's easy to pour gradually into the load device in a continuous way, till the detachment (Fig.2 g, h). A computer system connected with the load cell was measuring and storing the load data in real time. Discreet loads of 1, 2, 5 kg were used in the initial part of the experiment, to overcome the difficulty of the insufficient capacity of the load device filling it with sand (Fig.2 f). Attention was given to perform load addition with increments as constant and continuous as possible. Similar tests are reported in literature with finite load increments [Hamard 2013; Stazi 2016]. Adhesion strength (τ) is calculated by the detachment load (failure mass $m_f$) and the surface of the sample (*S*).

$$\tau = \frac{m_f \cdot g}{S}$$

Where *g* is gravitational acceleration, equal to 9.81 $m/s^2$, $m_f$ the failure mass (kg) and *S* is the surface area of the specimen ($cm^2$).

*Submersion test*

This test measures the water resistance of the plasters with and without lime putty addition. The samples used in the adhesion test, after the detachment, were used for the submersion test. The water resistance test is only a preliminary approach to water and moisture sensitivity, which would require further testing to evaluate water erosion and plaster absorption softening upon moisture increase [Stazi 2016]. The submersion test simulates an extreme situation where the raw earth is completely submersed in a flood event [Alam 2015]. The sample conditions were observed after 30 s and after 5 min submersion.

### 3.4 Thermal conductivity

The thermal conductivity measurements have been performed on samples of the same composition used for the adhesion and shrinkage test. The specimens were 5 cm wide and about 2 cm thick. After drying for a week (25°C and 50% moisture) all the samples were subjected to the same hygrometric conditions (RH 58%) before the measurements. The samples were regularly weighted in order to ensure stability before testing, because the thermal conductivity evolves according to the material moisture. The thermal conductibility analyser employed is the C-Therm TCI with the Modified Transient Plane Source (MTPS) Technique [Bateman 2009], repeating the measure three times in four different position on one surface of the samples. The measurements have been performed in the LOCIE laboratory, USMB.

## 4 RESULTS

### 4.1 Soil characterization

*Particle size distribution*

The results are summarized in Tab. 1. The earths were classified as silt, with lower percentages of clay and sand. Earth ABS is well graded and it is well adapted for the preparation of earthen plasters.

*Atterberg limits and plasticity chart*

The Atterberg limits reported in Tab. 2 are similar for the two kaolinitic earths BBZ, KSK and for the illitic earth ABS. On the contrary the values for the smectitic earth K100 are higher, similar to those of lime, which has a much finer particle size distribution. K100 and KSK have higher Activity Index (AI=PI/clay fraction), suggesting the presence of more plastic clays. The AI for KSK is higher than for a normal kaolin. We can hypothesize the presence of mixed layer clays, as confirmed by XRD analysis. The classification on the Casagrande plasticity chart (Fig. 3) gives some information about the possible nature of the clay typology. Almost all the earths are inorganic silts of medium or high compressibility. BBZ is classified as medium plasticity inorganic clay. The PI is generally lower than expected for pure clays, possibly due to the presence and contribution of sand to the plastic behaviour.

*Tab. 1 Physical properties of earths and lime.*

| Earth | Clay (%) | Silt (%) | Sand (%) | $D_{50}$ (mm) | $D_{90}$ (mm) | $G_s$ specific gravity | Water content % |
|---|---|---|---|---|---|---|---|
| Diameter (mm) | d<0.002 | 0.002<d<0.06 | 0.06<d<2 | | | | |
| KSK | 14 | 78 | 8 | 0.009 | 0.055 | 2.73 | 1.42 |
| BBZ | 26 | 66 | 8 | 0.004 | 0.055 | 2.69 | 0.50 |
| K100 | 32 | 61 | 7 | 0.007 | 0.05 | 2.74 | 7.46 |
| ABS | 36 | 44 | 20 | 0.015 | 0.13 | 2.78 | 3.08 |
| LIME PUTTY | 51 | 45 | 4 | 0.001 | 0.012 | - | 55 |

*Tab. 2 Atterberg limits and plasticity chart classification of earths and lime putty.*

| Earth | LL (%) | PL (%) | PI (%) | Level of plasticity | Activity Index | Activity level |
|---|---|---|---|---|---|---|
| KSK | 48 | 32 | 16 | Plastic | 1.14 | Normally active |
| BBZ | 40 | 23 | 17 | Plastic | 0.65 | Inactive |
| K100 | 78 | 48 | 30 | Plastic | 0.94 | Normally active |
| ABS | 40 | 30 | 10 | Less plastic | 0.42 | Inactive |
| LIME PUTTY | 80 | 43 | 36 | Very plastic | - | - |

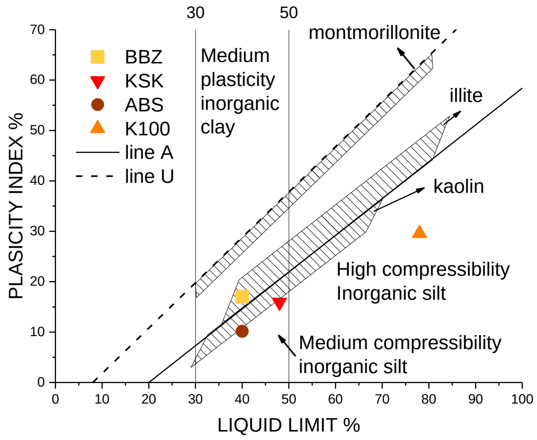


*Fig. 3 Plasticity chart*

*XRD Analysis*

The X-ray diffraction patterns of the bulk non-oriented samples show the abundant presence of quartz in all the earths. The patterns of the oriented and glycolated samples show that the ABS has a mixed clay composition, mostly not swelling illite, with minor fractions of kaolin and interstratified illite/montmorillonite. Earth K100 is predominantly a montmorillonite, highly swelling, with minor fractions of kaolin and illite. KSK contains fractions of expandable clays (interstratified illite/montmorillonite) along with kaolin, thus confirming the results of the plasticity determination showing an AI higher than expected for pure kaolin (Tab 2). Since this earth contains a kaolin which is less pure than the one present in earth BBZ, the latter was chosen for the lime putty stabilization.

### 4.2 Stabilization with lime putty

*Atterberg limits variation*

The stabilization with lime has been performed on BBZ, ABS and K100 earths. Atterberg limits with the lime putty addition are modified in relation to the type of clay mineral present, which reacts differently with lime. The LL increases for BBZ and ABS, while it decreases for K100 (Fig. 4). These changes are in accordance with the values that Bell found for montmorillonite, kaolin and quartz [Bell 1996]. The LL increase for the kaolinitic earth BBZ could be explained by the modification of the affinity of the clay particles surface, due to the action of the hydroxyl ions [Croft 1964 stated by Bell 1996]. Vice versa LL decreases for montmorillonite because lime reduces the swelling capacity of the expandable clay [Basma 1991]. With the montmorillonitic and expansive earth K100 the hypothesis of the modification of the surface affinity seems not to be appropriate.

PL increases for all the earths, the highest value being for K100 (Fig. 4). Hilt underlines that the maximum PL increase is obtained in the montmorillonitic soils, the smallest is observed in the kaolinitic rich soils [Hilt 1960]. This effect which is desirable for soil stabilization can be detrimental for the use of earth as a building material. When PL increases the earth requires more water to be formed in the plastic state, thus it becomes more subject to cracking on drying.

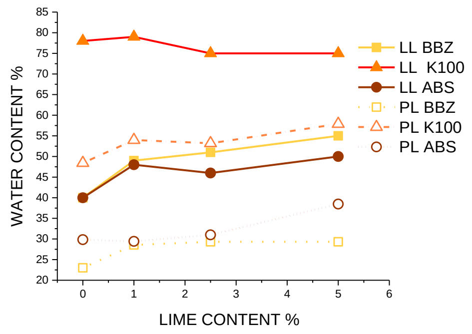


*Fig. 4 LL and PL variation with lime putty addition.*

For K100 the PI (PI=LL-PL) shows a significant decrease, typical of expansive clays [Basma 1991]. The range of plasticity shows a reduction and at the same time a shift towards higher values of water content, as reported in Fig.4. In the plasticity chart the position of K100 is modified by the decrease of PI positioning the earth in the same class but with a decreased compressibility value (Fig. 5). The PI of BBZ increases and combined with increase of LL shifts the position of this earth towards a more plastic behaviour typical of high compressibility inorganic silt. In this case the earth is easily workable in the presence of lime due to the lime induced aggregation and flocculation which cause the clay particles to behave like particles of silt. For ABS the PI has an intermediate behaviour, probably due to the mixed clay composition of the earth. The initial increase is similar to what observed with kaolin, while the final decrease is similar to what observed with the expansive clay minerals of K100. The final shifting is towards values of higher compressibility and plasticity (Fig. 5).

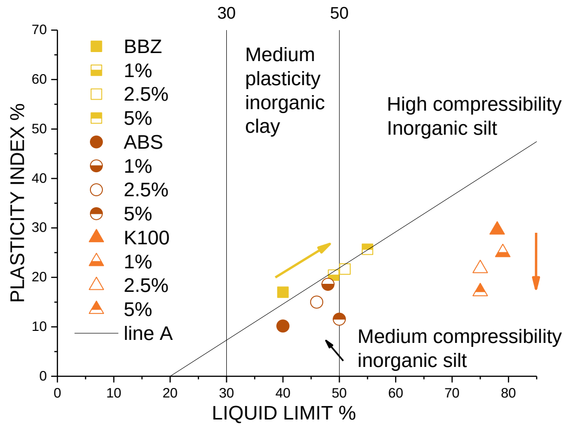


*Fig. 5 Plasticity chart with earths stabilised with different lime percentage.*

*XRD on stabilised earths*

The X-ray analyses were performed on pastes composed of each earth and 5 wt% lime putty at different curing times. The analyses show that after one month the presence of hydrated lime is no longer detected in K100 and ABS. Both these two earths contain a fraction of montmorillonite, which reacts quickly with lime thanks to its high cation exchange capacity. This reaction, caused by the exchange of the adsorbed and interlayer alkaline ions with calcium ions, takes place immediately when lime putty is added [Eades 1960]. Hydrated lime disappears after three months in the BBZ earth, without the appearance of neo formed phases. ABS shows a decreases of the quartz abundance and the possible precipitation of calcium silicate hydrate phases, to be validated with longer curing time. Eades obtained similar results with the same curing times using pure clay mineral and higher percentage of hydrated lime added [Eades 1960]. The presence of mixed clay minerals along with the silt and sand fraction gives less clear results, even if it's still possible to identify the earths that reacts quickly with a small percentage of lime addition.

## 4.3 Field test on plaster mixtures and comparison with lime putty addition

*Shrinkage test*

The field tests on the plaster mixtures were performed on the earths that showed a greater reactivity with lime after one month (K100 and ABS). The plaster realized with earth ABS, characterized by a well graded particle-size distribution and constituted by illite of low activity, shows good results with earth/sand ratio 1 to 3 by weight (Fig 6). Although the ratio 1 to 4 was equally acceptable from the cracking characteristics, the ratio 1 to 3 was chosen because it ensures a better adhesion performance.

*Tab. 3 Water content in the shrinkage test.*

| Ratio | 1:2 | 1:3 | 1:4 | 1:5 | 1:5.5 | lime |
|---|---|---|---|---|---|---|
| | | | Water content % | | | |
| ABS | 18 | 16 | 17 | - | - | 18 |
| K100 | 35 | 29 | 25 | 22 | 20 | 23 |

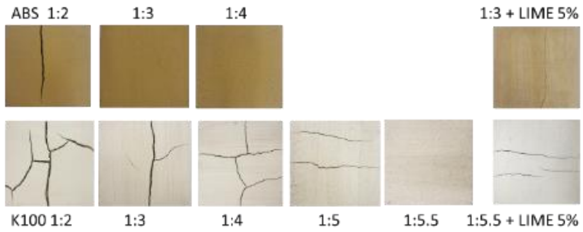


*Fig. 6 Shrinkage test.*

The plaster realized with earth K100 needs more sand to limit shrinkage cracking: it reaches a good result only with the ratio 1:5.5 (Fig. 6). The quantity of sand necessary is higher than with ABS because of the finer particle size distribution and the presence of montmorillonite, highly plastic and swelling.

The addition of lime putty to the mixtures causes an increase in cracking, both for ABS and for K100. This behaviour arises from the increase of PL with the addition of lime (Fig. 4), which raises the water demand to get a material which could be formed in the plastic state. In the Tab. 3 the water content of the mixtures is reported, showing that it is comparable with the increase of PL reported in Fig.4. This is probably the reason of a the greater shrinkage and cracking on drying.

*Adhesion test*

The adhesion tests were performed with the optimized mixtures, with and without lime putty. Six measurements were done for each mixture. In addition to the detachment load, the substrate surface has been examined (Fig. 7). The adhesion surface was found clean only for ABS, while for the other mixtures it is possible to observe plaster residues on the surface.


*Fig. 7 Adhesion surface.*

In Fig. 8 are resumed all the results of the adhesion test. The adhesion values are similar for the two earthen plasters, around 22 kg, equivalent to 81 kPa. The addition of lime putty decreases adhesion, especially for K100, as the graph in Fig. 8 shows. In this earth the montmorillonite clay fraction reacts quickly with lime, losing plasticity and adhesion. The adhesion strength for the stabilized plasters shows values around 53 kPa, as a mean. The adhesion strength registered during all the test lies between 40 and 80 kPa, comparable with literature values [Hamard 2013; Stazi 2016]. The adhesion surface used by Hamard and Stazi is a cob wall or rammed earth wall, very different form the fired brick tiles, which are standard products with an undulating surface. Despite that the adhesion surface used is less porous than an earthen one, the values obtained are higher than the ones obtained from Hamard and Stazi.

The different results could be related with the difference in the loading procedure and in the interface between plaster and support. Fig. 9 reports an example of the loading graph where it is possible to observe how the loading curve depends on the operator and varies between different tests.

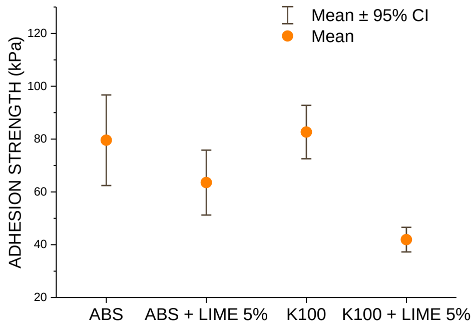


*Fig. 8 Adhesion test results.*

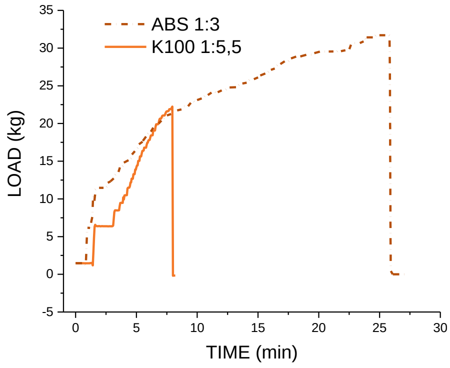


*Fig. 9 Adhesion test: load charge measured by the load cell until the detachment load.*

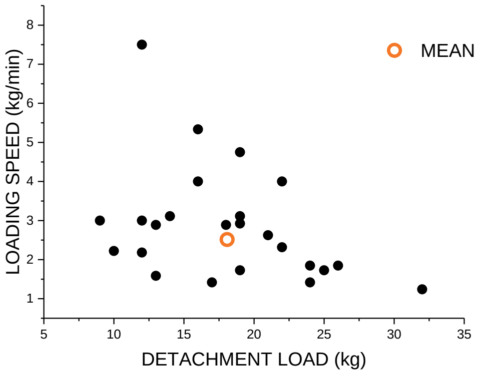


*Fig. 10 Adhesion test results.*

Fig. 10 shows a possible relation between the loading speed and the detachment load, the data are quite dispersed, but it appears that the higher is the loading speed, the lower is the detachment load. The average loading rate is 2.5 kg/min and the average duration of the test is 7 minutes. Comparing the procedure to others, Stazi indicates an increment of 0.125 kg applied each 15 s [Stazi 2016].

The influence of the loading procedure shall be investigated and a standard procedure must be defined allowing a constant loading speed. This would improve the repeatability among different laboratories.

*Submersion test*

In Fig. 11 are reported two pictures of specimens subjected to the submersion test, after 30 s and 5 min. The K100 samples immersed completely in water disintegrate after 30 seconds and lime does not affect the disintegration time. The ABS samples endure longer, thanks to the higher content of clay that has the function of binder. The addition of lime putty for the ABS earth increases the resistance to water. In general, the ABS earth gives a better result, due to the greater content of clay (1:3 ratio) and lime (added as a percentage on the earth).

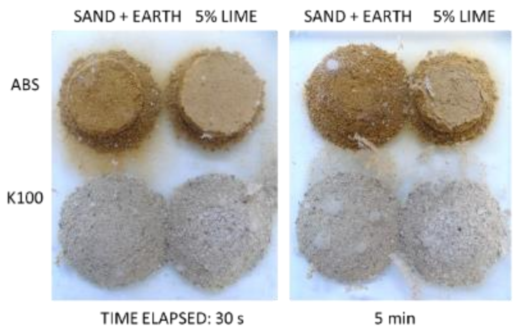


*Fig. 11 Submersion test, the second column in each picture is with the lime addition.*

## 4.4 Thermal conductivity

The thermal conductivity is reduced by the lime addition, increasing the insulation properties of the earthen plasters. This result is clear for K100, as shown in Fig. 12. The measurements on ABS are less precise, due to the difficulty to have a smooth and flat surface with this earth. However with both earths the highest values reached with the earth and sand mixture are higher than ones reached by the stabilized paste. A similar result is obtained by Adam and Jones [Adam 1995] using cement and lime as stabiliser. The values of thermal conductivity for the stabilised earth with lime are lower compared to the one stabilised with cement. Lime addition induces clay flocculation, reducing the material continuity and density. This modification could be the reason of the thermal conductivity decrease. The same behaviour is obtained with the addition of fibres, which increase the thermal insulation [Ashour 2015].

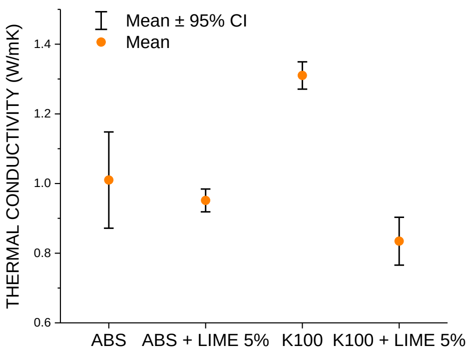


*Fig. 12 Measure of thermal conductivity.*

# 5 CONCLUSIONS

This work emphasizes the importance of performing a complete analysis of the earth, from the particle size distribution to the determination of the clay minerals present. The determination of the optimal grain-size distribution for the plastering mixture obtained by adding sand to earth is the starting point to plaster formulation. None of the earths discussed in this paper can be used as such. Another critical issue concerns the adhesion strength of the plasters, that is governed by the presence clay and by swelling behaviour of the mixture. Lime worsen the behaviour of the plasters regarding both cracking and adhesion. The water resistance improves on lime addition, but the behaviour of the expandable clay fraction upon lime addition needs more investigation. The thermal conductivity decreases with lime addition. This is only a preliminary investigation of the thermal properties of plasters, that would require further analysis.

When using earthen based plasters it is of fundamental importance to fully characterize the earth, to allow a better forecasting of the clay minerals behaviour and to evaluate the possibility of improving its properties by different techniques. Among the earths analysed, ABS is the most suitable for a possible application in bio-building. It has a good particle distribution and requires less sand to be used for the preparation of plaster mixtures for the use in green building.

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