PAST AND PRESENT OF THE EARTHEN ARCHITECTURES IN CHINA AND ITALY

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Front-page image captions

1. TECLA (Technology and Clay) 3D printed house by WASP and Mario Cucinella Architects, Massa Lombarda, Ravenna, ITALY (2021)
2. Ruins of a vernacular building in Sant'Omero, Abruzzo, ITALY (by Dalila Fortunato and Anna Jaroszewski, 2020)
3. Ruins of Gaochang ancient city, Xinjiang Province, CHINA (by Fabio Fratini and Loredana Luvidi, 2016)
4. Keziergaha beacon tower (Han Dynasty) in Kuche city, Xinjiang province, CHINA (by Center of Conservation of Xinjiang Cultural Heritage, 2020)

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EARTH MATERIALS: CHARACTERIZATION AND TRADITIONAL/INNOVATIVE TECHNIQUES OF CONSERVATION

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INTRODUCTION

The word "earth" commonly designates what must be correctly called soil, namely the surface layer that covers the Earth's crust and is formed through weathering of the rocky substrate due to rain, thermal cycles, salt crystallisation, growth of plant, the metabolism of microorganisms, etc. These agents through chemical, physical and biological actions determine the transformation of the rock in another material, the soil, which has compositional, physical and mechanical characteristics completely different from the original rock material.

A solid portion (mineral component and organic component), a liquid portion and a gaseous portion compose the soil. Along its formation, it differentiates in a series layers called horizons:

- the superficial horizon that contains 5%-10% of organic substance;
- an underlying eluviation horizon made of residual minerals (quartz), clay minerals and insoluble organic substances (humic acids) in which the meteoric water leaches the alkaline and alkaline earth elements towards the underlying illuviation horizon;
- the underlying illuviation horizon where the inorganic fraction prevails strongly with respect to the organic fraction and it is enriched of alkaline and alkaline earth metals.

In the following, the characteristics that mostly influence the behaviour of the "earth" in the masonries will be considered, namely the composition of the mineral component and the physic mechanical characteristics (Fratini, 2011).

THE MINERALOGICAL CHARACTERISTICS OF AN EARTH

The mineral component of an earth consists of a fine-grained fraction mainly composed of *clay minerals* belonging to the Phyllosilicates class (which dimension is below 4 μm) and a coarse-grained fraction (silt, sand and gravel fractions) composed of quartz, feldspars, carbonate, iron hydroxides and rock fragments (Fig. 1).

Fig. 1 Particular of an earth, it is possible to recognize the different grain fraction and the organic component

The clay fraction is very important in the earth, because it is the binder that allows the realization of earthen artefacts. It is also true that the behaviour of clay minerals affects the durability of the earthen building and in particular because these minerals are strongly influenced by the interaction with water.

Genetically the clay minerals form through chemical physical alteration of feldspars in exogenous environment or through hydrothermal phenomena with loss of Na, K, Ca, Mg and consequent enrichment in Al and Si. From the chemical point of view they can be classified as silico-aluminate hydrates containing Mg^{2+}, Fe^{3+}, Na^{+}, K^{+}.

The word *Phyllosilicates* comes from *filos*, leaf in Greek, with clear reference to their most common habit which is tabular. The crystal lattice is characterised by the various combination of *tetrahedral layers* (constituted by Si-O tetrahedra) and *octahedral layers* (gibbsitic and brucitic layers). These layers, depending on their composition, can establish more or less strong bonds among them and give rise to particles of different granulometry. This results in a very different mechanical behaviour. For example, kaolinite has a typical particle size of about 1 μm, with rather strong bonds and therefore it gives rise to a stable clay, less sensitive to the action of water. On the other hand, smectite gives rise to particles of a few nanometers (1 nm = 10-3 μm), and has weak bonds between the layers that in presence of water tend to break (swelling behaviour). Water can interact with the clay minerals because the octahedral and tetrahedral layers despite being generally neutral, have a positive charge in the interior and negative charge on the external surface. This feature leads to establishing very strong bonds with water molecules which, being dipolar, are electrically attracted to the surface of the clay particles. The water that is immediately in contact with the particles therefore becomes an integral part of their structure and is defined as "adsorbed water".

Moving away from the surface of the particles, the bonds gradually become weaker until the water takes on the characteristics of "free water" or "interstitial water". Even taking into account the presence of adsorbed water, the clay particles are negatively charged on the surface of the flakes and positively charged on the edges (neutral environment). Therefore, they tend to manifest repulsive forces, to which are added the Van der Waals forces, attractive on the long distance and repulsive at short distance.

This means that if the clay particles are surrounded by a fluid with a high concentration of positive ions (for example, in the marine environment), the superficial negative charges will tend to neutralize and therefore the repulsion effect will be lower and the particles will tend to aggregate with consequent sedimentation. On the contrary, in an environment that is poor in positive ions (for example in freshwater), repulsion forces tend to prevail and the clay particles will tend to remain in suspension.

Therefore, in earth rich in clay, the particles may also not be in direct contact with each other while retaining the material characteristics of continuity, favouring the flow of interstitial water and consequently making this type of earth susceptible to swelling.

From the mechanical point of view, earths are considered as pseudo-coherent rocks and can be divided into the following two categories:

- *fat earths*, consisting of a high % of clay minerals, retain a large amount of water and lose it slowly by evaporation, have high plasticity, strong cohesion of the dried product but at the same time cracking in the shrinkage phase;
- *lean earths*, consisting of a high % of coarse fraction, retain a low amount of water and lose it quickly, have low plasticity, low shrinkage in drying, low cohesion of the dried product.

The type of porosity that develops during shrinkage is different for the two kinds of earths: fat earths display mainly a cracking macroporosity while lean earths, where the coarse fraction acts as framework contrasting shrinkage, display mainly an intergranular porosity.

The characteristics of the dried product depends also on the kind of clay minerals: the presence of swelling clay minerals (smectite, vermiculite) can increase the shrinkage with strong cracking and worsening of the mechanical characteristics. The presence of non-fibrous dispersed organic materials can increase the plasticity and could cause cracking problems. The regularity during drying allows developing balanced cohesive forces that hinder the formation of cracks. Therefore, in order to have good mechanical characteristics in the dried product, we need a quantity of clay minerals such as to produce a good cohesion (i.e. a low intergranular porosity) but also to avoid the development of cracking during shrinkage.

THE CHARACTERIZATION OF EARTH MATERIALS

The study of the *mineralogical composition* is carried out by X-ray diffraction, an analytical method that allows recognition of phases with crystalline structure present in a material.

In particular, the clay minerals are studied by analysing the granulometric fraction below 4 μm (obtained by separation from the bulk through sedimentation) on oriented powder samples meaning that the clay minerals are oriented according to the lattice baseline planes. This preparation is needed because these minerals are characterized by different distances between the lattice baseline planes and the orientation makes it possible to better investigate this distance thanks to special heat treatments and absorption of substances (e.g. ethylene glycol).

The determination of *calcium carbonate content* is performed through the method of calcimetry.

The *organic matter content* can be determined gravimetrically by attack with hydrogen peroxide.

The *content of soluble salts* can be determined according to the following methods:

- gravimetric method (the amount of all ionic species is obtained);
- ion chromatography (the amount of individual ionic species is obtained)

The *grain size distribution* can be determined through different methods. A common grain size classification is according to the Wentworth scale: gravel (diameter > 2 mm), coarse sand (0.2 - 2 mm), fine sand (0.02 - 0.2 mm), silt (0.002 - 0.02 mm) and clay (< 0.002 mm).

Sieving methods, operating at dry or wet conditions, are used for the study of the coarser fraction (gravel and sand).

In order to study the fine fraction (silt and clay) (< 0.075 mm according to ASTM or < 0.063 mm according to BS and AFNOR standards), the *Sedimentation method* can be used which is based on the separation of the sample suspended in a liquid placed in a cylinder where the particles tend to settle at different speeds due to gravity according to Stokes Law. Different measurement methods can be used:

- *pipette method*: it consists in sampling the material in suspension at a depth s and time t;
- *densimeter method* with hydrostatic balance: the grain size distribution is determined through the measurement of the progressive reduction of the density of an earth suspension, caused by the sedimentation of the particles;
- *optical methods*: are based on the principle that particles diffract a light ray according to an angle that is higher the smaller the particles.

Study of plasticity: Atterberg limits

"Earth" may occur in one of the following four states, depending on the content of water: liquid, plastic, semi-solid, solid. In fact, for low values of water content, the forces among the clay particles prevail and the material has a consistent aspect (solid or semi-solid depending on the water content). With increasing water content, the pore volume increases, the forces among particles becomes negligible and the material loses its formability assuming the characteristics of a very viscous fluid.

The characteristics of plasticity are measured in the laboratory by tests for determining the content of water to which an earth passes from a liquid to a plastic state and solid state. These are the *limits of consistency or Atterberg limits*:

- *liquid limit* (WL): minimum water content for which the earth runs due to a little pressure (on the order of 2-3 kPa) and behaves like a viscous fluid;
- *plastic limit* (WP): minimum water content for which the earth may be deformed plastically without splintering;
- *shrinkage limit* (WS): water content below which the earth does not undergo more reduction in volume when it is dried.

The *activity of the clay fraction* is determined through the *method of methylene blue*. The principle consists in quantifying the capability of ionic absorption of an earth by measuring the amount of methylene blue required to cover the total area of the particles constituting the earth.

CONSERVATION PROBLEMS OF EARTHEN ARCHITECTURE

Earth architecture is particularly subject to decay processes. For this reason it requires *constant maintenance* not only from the point of view of conservation, but to guarantee its real functionality, a prerequisite to make sure that this architecture continues to be inhabited and built (Figg. 2, 3). In particular, the factors of decay are *internal factors*, due to structural defects and *external factors*, such as the action of water and the type of use (Fratini, 2014).

The earth material is particularly sensitive to the action of water because water tends to make earth plastic again with consequent loss of the mechanical characteristics of resistance and rigidity. The water acts both as an erosive agent (rain) and as capillary rising damp with consequent disaggregation phenomena (Fig. 4). The decay phenomena can be grouped into the following categories:

- superficial decay of physical and biological nature;
- humidity patches; fracturing, swelling and exfoliation of plasters; biological patinas;
- loss of material due to erosion and fall of elements.

This last phenomenon develops in areas that have lost cohesion due to the action of water. They can influence the stability of the structures in case the loss of material affects important building elements. These phenomena are mainly located at the base of the walls (due to bad drainage that determines capillary rise and disintegration of the masonry) and at the corners (exposure to rain and wind).

Fig. 2 Syrian corbelled dome house, well maintained

Fig. 3 Syrian corbelled dome house, lack of maintenance

Fig. 4 Rain erosion of an adobe masonry in Piedmont (Italy) due to lack of maintenance of the roof

PREVENTIVE CONSERVATION OF EARTHEN ARCHITECTURE

The above mentioned factors of decay are usually related. Therefore, in order to develop an adequate intervention, non-damaging and preventive with regard to the possible establishment of new decay phenomena, it is important to understand which is the actual cause of the processes and not just intervening on the single phenomenology. It has been said that the factors of decay are essentially due to action of water and structural problems. Therefore, a preventive conservation will have to act in these two directions.

With regard to water, all the solutions designed to protect buildings from the rain, to avoid capillary rise and infiltrations must be taken through the following interventions:

- more resistant plaster coatings, possibly stabilized with suitable products (e.g. lime) and reinforced with non-rigid vegetable fibres that prevent shrinkage cracking (Figg. 5, 6). Furthermore, whitewashing would be desirable (normally limited only to the lower part of the constructions) to make them a little more resistant to the washing action of the rain (Fig. 7);
- improvement of the run-off water drainage system, in order to avoid stagnation and concentrated flow on the walls (Figg. 8, 9);
- improvement of the drainage system on the ground in order to avoid erosion at the base of the walls and to avoid capillary rise.

With regard to structural problems, it is necessary to implement strategies that limit the consequences of the poor connection among the walls and with the roof and foundations (Fratini, 2012).

Fig. 5 Accurate maintenance of houses in the village of Ait Ben Haddou (Morocco)

Fig. 6 Earthen plaster added with vegetable fibers to avoid shrinkage fractures (Morocco)

Fig. 7 Whitewashing in a Syrian corbelled dome village

Fig. 8 Improvement of the water run-off to avoid concentrated flow on the walls in a Syrian corbelled dome house

Fig. 9 Protection of the ridge of the walls to avoid water infiltration (Morocco)

TRADITIONAL/INNOVATIVE TECHNIQUES OF CONSERVATION

Earthen plasters for the protection of surfaces

The term plaster generally indicates the superficial layer that covers the masonries in order to protect them, ensuring adequate waterproofing and a regular finishing (Figg 10, 11). Specifically, with regard to earthen plasters, their use has been documented since ancient times; in the Neolithic period, to give greater resistance over time to the artefacts, a layer of mud was applied on a wooden trellis forming the wall of the huts (similar to the present building technique called wattle and doub). Later, other and more refined types of plaster, such as mixes of clay, sand and gypsum, evolved from the Minoan era, until reaching, at the beginning of the Roman Empire, the highest expression. In the Middle Ages there was a stop in the progress of the technique while in the Renaissance, thanks to the flourishing of the treatises, the knowledge and techniques of earth use were rediscovered. Afterwards, during the XIX century, with the increasing use of the modern hydraulic binders, new types and applications of plaster were developed causing the progressive abandon of the earthen plasters. Today, however, the new bio-architecture currents are trying to recover these artefacts. The properties of an earthen plaster, suitably stabilized applied on earthen masonries have many positive aspects with respect to those made of lime or cement:

- mechanical and chemical compatibility with the earthen support;
- good permeability to water vapour;
- increasing the thermal and acoustic insulation.

In addition the earthen plasters are reversible, recyclable, non-toxic, easily removable, non-polluting, easily available and without energy consumption.

The additives/stabilizers used to improve the durability of the earthen plasters and in general the earthen masonries are distinguished in inorganic and organic (natural or synthetic), sometimes mixed. Among the inorganic additives, there are lime, gypsum, Portland Cement, or other pozzolanic materials (rice husk ash, ground granulated blast furnace slag) (Eires, 2015; Choobbasti, 2010; Rescic, 2021).

The stabilizing action of cement (improvement of compressive strength, resistance to erosion, to rain and abrasion) develops through the formation of hydraulic compounds (CSH, CAH). These cement compounds do not bind with all of the earth particles, but help to form a stable matrix throughout. Lime is one of the oldest and most widely used stabilizers. Several authors have studied the interaction between lime and earth and it has been determined that the addition of lime improves strength, stiffness, plasticity/workability of raw earth. The lime-earth reaction can be described by three phenomena: 1) cation exchange; 2) pozzolanic reaction with formation of hydraulic compounds; 3) carbonation (Ciancio, 2014). The lime offers the advantage of carrying out its action by maintaining the peculiar characteristics of the pure earthen plaster (breathability in the first place) (Mattone, 2016; Falchi, 2016). Gypsum is an additive widely used for the stabilization of the earthen plasters thanks to its compatibility, breathability, elasticity and for its economic convenience and eco-sustainability (Mattone, 2017). Gypsum is easily available and low energy consumption is needed for its production process. Furthermore, during the setting phase, it increases in volume contrasting shrinkage during the drying phase thus preventing the formation of cracks. Chemical stabilization (alkaline activation or geopolymerisation) was recently introduced for the in situ consolidation of the Alhambra earthen walls (Elert, 2008). The process of geopolymerization can be simplified in two main phases which interact with each other during the process: 1) the alkaline solution attacks the crystal lattice of the clay minerals with weaker structure (the expandable lattice clay minerals such as smectite and illite-smectite) with subsequent release of silicon and aluminium in solution; 2) polymerization by condensation of the species released and formation of silico-aluminates compounds similar to those of cement (Hardjito, 2010; Mubarak, 2011). The results of this process are time dependent, therefore a long curing time is essential for a complete reaction and compounds formation.

Organic compounds (e.g. bitumen, fibres, mucilage, gums, resin, oils and fats, tannins, etc.) (Van Damme 2017; Kita, 2013; Vissac, 2017; Gomes, 2012; Laborel-Préneron, 2016) traditionally used to improve the performances of mortars and blocks are numerous and are often mixed with the inorganic materials (e.g. lime) (Rodriguez-Navarro, 2017). Bitumen is added in the form of an emulsion and forms a thin film which coats the clay particles during drying. The main effect of adding bitumen is to improve cohesion and water resistance. Fibres are widely used in earthen building (Fig. 6). The fibres act to increase the tensile strength, reduce density, accelerate drying and reduce cracking by dispersing stresses. The most common fibres used include straw, for example from wheat, rice or barley. The chaffs or husks of these crops can also be used. Other suitable vegetable fibres include hay, hemp, millet, sisal, filao needles, and elephant grass. The influence of biopolymers addition (i.e mucilages, gums, resin, oils and fats, tannins, etc.) in earth materials result in rheological effects developed in clay particles of soil. The main effect verified is related to the change of the electrostatic charge of the clay particles. This causes dispersion and after attraction. The use of oils or fats has been the most used waterproof process in earthen buildings. In fact if oils or fats are added in basic environments (earth based plasters with lime) their triacylglycerol's content, when hydrated, results in insoluble calcium salts of fatty acids. These salts are hydrophobic and connect well with the calcium of lime and provide water repellency (Čechová, 2009). In some Latin American territories and, in particular, in Mexico, earthen mixtures stabilization was traditionally made through the addition of vegetable fibres such as straw and mucilage of succulent plants. The use of the mucilage of Nopal (Opuntia Ficus Indica) is particularly widespread. This product was commonly used since the pre-Hispanic era in earthen buildings and, according to scientific studies conducted so far, it would offer a solution to the problem deriving from the scarce availability of water, necessary for the realization of architectural artefacts, in many Central American territories.

More recently, synthetic compounds like PVC, polyvinyl acetate, acrylics, sodium silicate and many others have also been introduced in various amounts to stabilize earth-based materials.

Fig. 10 Ongoing works to protect with an earthen plaster the walls of a village in Morocco

Fig. 11 The earthen plastered city walls of Marrakech

Products for on site treatments

Particularly valuable earthen masonries in which the application of an earthen plaster is not admissible for aesthetic reasons, requires consolidation/protection of the earth material itself with appropriate products.

The first experimentations were concentrated in the identification of consolidants and water-repellent products, based on silicates and epoxy resins. However, the application of these products gave rise to many problems; the interventions were completely irreversible, the cost was high, some products were polluting/toxic and in general they did not lead to definitive and effective solutions. Therefore, over the years, the use of these products has decreased. Research focused first on other products like sodium silicate, colourless silicon-based paints or polyurethane-based inorganic products. Nevertheless also these products showed to be ineffective or with disadvantages, such as the lack of vapour permeability.

At present the researches are concentrated around substances of natural origin obtained mainly from plants such as banana leaves, coconut oil, carob, prickly pear sap, aloe vera, cactus mucilage, etc. (Mattone, 2010). Only some of these materials are tested in the laboratory and only occasionally, on the private initiative of a few scholars, are thoroughly investigated and scientifically verified.

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