OLD MATERIALS AND TECHNIQUES TO IMPROVE THE DURABILITY OF EARTH BUILDINGS

AIRES CAMÕES[1], RUTE EIRES[2] & SAID JALALI[3]
University of Minho
Campus de Azurém, 4800-056 Guimarães, Portugal
[1] aires@civil.uminho.pt; [2] rute@civil.uminho.pt; and [3] said@civil.uminho.pt

Abstract

Quite a big part of the world's heritage is still made by earth constructions. The durability of the existent heritage, as well as the new earth buildings is particularly conditioned by erosion caused by water action, especially in countries with high rainfall index. With this research one intends to value the ancient knowledge in order to allow higher durability.

Analysing the old building techniques to protect the earth material from the water action it is possible to understand how earth buildings were preserved, during several centuries, resisting to harsh weather conditions. Among these techniques, one can observe the incorporation of biopolymers (such as oils or fats of animal or vegetable origin), the addition of some minerals and the stabilization with lime. However, this ancient knowledge seems to have been forgotten, probably due to the existing prejudice concerning earth building which is often associated with a poor construction.

This research aims, also, the study of new methods of soil stabilization, with lime and biopolymers, adapting the ancient knowledge to improve the durability related to the water action. This way, alternative solutions were obtained in order to improve the performance of earth buildings in terms of resistance, especially when in contact with water, reducing the water permeability and keeping the vapour permeability of the material, one of the main advantages of earth construction.

Key words: Old materials; durability and water resistance.

1. Introduction

This paper result from the research work carried out by the author Rute Eires during her PhD thesis (Eires 2012). One part of this research deals about techniques of protection against water action for earth construction and is present here, as well as a synthesis of the experimental work, making reference to the main tests and results obtained. The motivation for this research was the lack of knowledge about methods to improve the durability of earth material and the necessity of more scientific research about soil stabilization specifically to get a better performance against water action. This way, the main objective was to achieve soil stabilization mixtures to be possible build with compressed earth (rammed earth or compressed earth blocks, CEB) without additional coating, obtaining a good durability against water without compromise the aesthetic potential of the earth material (Eires 2012).

2. Old techniques and materials to protect the earth from the water action

In ancient times, to protect the earth buildings from the action of rains and water absorption, different construction techniques, as well as the stabilization of the earth material itself, were used. Thereafter, the main techniques and materials used for this purpose in earth construction will be presented.

2.1. Techniques - Architecture detail and building system

The main old techniques used in earth construction to protect from water susceptible critical points will be mentioned below, referring architectural details and building construction systems used in earth buildings.

2.1.1. Foundations and plinths

The soil humidity is one of the major problems of water infiltration in buildings, so in earth construction this point deserves special attention in construction details and selection of materials to be used. The detailing and the materials selection for the foundations depend, above all, on permeability to water present in the foundation ground. This way, it is important to avoid little permeable lands and places at risk of flooding. The most used materials for foundations were the cyclopean concrete and stone or ceramic brick masonry to avoid the water rise in the building through capillary suction. As detail, it is favourable the raising of the foundations to a height higher than the ground quota as a way to make difficult the rise of water in the walls.

The main function of plinths is to protect the facade of splashing water that falls from the eaves. Like this, the plinth height is also related to the advance of the eaves, being advised a height between 30 and 60 cm (Teixeira et al 1998). The most frequently used techniques were also the stone or ceramic brick masonry or a single protective coating, as a plaster or other covering materials.

2.1.2. Walls and corners

The reinforcement of the walls and corners is important because it improves the mechanical resistances of construction material and it avoids the cracks appearance and posterior water infiltration or even the disintegration of the material exposed to the weather conditions.

In traditional Portuguese construction with rammed earth or adobe, where the soil used was very sandy and did not allow good cohesion, it were introduced other materials in the mixture like pieces of ceramic materials (tiles or bricks) or even organic materials such as acorns or small branches. In addition reinforcement through horizontal layers was also used, using lime mortar often with these mentioned materials involved in the mortar to achieve a better reinforcement (Correia et al 2003 and Teixeira et al 1998).

2.1.3. Facades coating

When the building site have considerable indices of precipitation it is pertinent to protect earth walls, above all if the used soil is not resistant by itself. For such, the earth walls have been protected through:

- Plasters or paints that need to be periodically renovated, acting as sacrifice layers;
- Coating with other building materials as tiles and wood or stone boards; or
- Using a double wall system, joining other material to be exposed to the outside from building, e. g. stone or brick masonry.

Related to the sacrifice layers, these have been used since ancient times, in any kind of building, including the construction in stone, as wall in the earth buildings. The coatings were performed by vertical layers that protect the walls from the weather. These were cyclically eroded and remade, with or without removing the old layer. The common used coating to protect the earth buildings was earth or clay plaster based. The mixture of these plasters vary according to region, using different amounts of stabilizer, mainly lime, and fibres and/or sand to avoid cracking. The clay, itself, is water resistant, once the constituent clay particles expand on contact with water forming a barrier. However this does not prevent entirely the water passage just makes more difficult the water go through the wall (Guelberth et al 2005). The application of two layers is common, using a mortar in the first layer with sand or a fibre material as straw, to avoid cracking, especially if the plaster has high clay content. The second layer can be more clayey, but it is applied in a fine thickness. It is mentioned about the fibres utilization in earth material that these lead to a dispersion of water by successive layers along the exposed surface, reducing the impact of the erosion by water action, as well as reduces the amount of water that goes through the wall (Crocker 2000).

There were also lime based plasters for finishing and decoration that were applied as protection to the interior or exterior of walls. These fine finishing layers were made with lime and mineral additives, being often pigmented and polished. This polishing promotes greater water repellence and consequently a better weather protection. In this way, this technique was also used in earth construction. There is the example of similar ancient techniques, such as the Tadelakt from Morocco and the Qudad of Yemen. Carole Crews refers also the existence of a polishing technique in India and New Mexico, giving the example of an old building in a basement in Anasazi in the ruins of Tsankawi (Crews 2010).

The paints have also the function of protection against water action. In earth construction it was common the use of natural paints, as lime based ones, often with oils, fats or casein. It is mentioned that the casein or oil paints were more waterproof and also maintained the vapour permeability (Houben et al 2008 and Crews 2010).

2.1.4. Frames of doors and windows

It is also necessary to correctly detail the reinforcement of doors and windows' frames in earth buildings to avoid cracking that is an open way to the water passage.

This way, the coating of the frames is very important, once these are more exposed to the rain action. In this case, the use of various materials, such as wood, stone or burned bricks was common.

2.1.5. Roofs and eaves

In areas of high rainfall, the top of the walls may be one of the critical points that can suffer greater erosion by water if not properly protected. As such, the use of sloping roofs is common and convenient. These sloping roofs were made with other construction material such as wood and with advancement beyond the exterior walls protecting these from the direct action of water. However, in drier climates it is common the use of flat roofs or vaults. These roofs are coated also with earth or clay for protection. These are renewed periodically and sometimes even overlapped without removing the previous layer.

2.1.6. Connection between different materials

The use of different building materials can cause the appearance of cracks by its distinctive retraction. To solve this problem, in Portuguese rammed earth construction it was checked the use of clay as an element of protection between different materials. This was found in the involvement of woods to avoid its deterioration in contact with earth in the presence of moisture, e. g. in the support of wood beams on the top of walls (Correia et al 2003).

2.1.7. Moist areas in buildings

The protection against water should also be taken into account in the inside of buildings, predicting the use of adequate coatings in moist areas, as bathrooms and kitchens, particularly near to the washbasins. It should be also especially care with water tubes. This happens because the earth material, if it is not stabilized with materials to reduce its water absorption, can suffer deterioration in contact with water. So, it is important to stabilize the soil and coat it with waterproof materials in these specific areas and, if it is possible, to apply these tubes in the outside of the walls.

2.2. Materials

The soils stabilization is also a way to raise the durability of earth buildings by the increasing of their mechanical strength and resistance against water action.
Like that, since ancient times, it has been added to earth material different stabilizers and additives. Next, one will present three common materials that can be used for this purpose individually or combined with each other.

2.2.1. Stabilization with lime and pozzolans

Pozzolan is a high fineness material that, when added to lime, becomes cementitious in the presence of water. This property can be beneficial in soil stabilization and in mortars or plasters with lime to coat the earth walls. There is a millennial example of lime-pozzolana utilization in earth constructions and mortars, the "*sarooj*". This material has origin in Iran and it has been used to protect earth buildings from water action. The "*sarooj"* is a binding durable material and it consists in a pozzolanic mixture based on clayey soil (sand and clay), lime, ashes and other additives. This mixture results in a material similar to hydraulic portland cement. It was applied for water thanks typical from Iran, called "*āb anbār",* as in ice Iranian reservoirs called "*Yakhchal"* (Hutton 2010 and Malekzadeh 2007).

2.2.2. Stabilization with biopolymers

Polymers can be from natural or artificial origin, from biological (vegetable or animal) or mineral origin. At the present research study the mentioned biopolymers are organic polymers from natural and biological origin, without laboratorial synthesizing.

The incorporation of biopolymers on earth construction was carried out for a long time and they were used in particular in order to improve the behaviour against water. There are numerous examples of biopolymers that have been added as stabilizers in earth construction, some from vegetable origin, such as flours, starches, gums, cactus, oils, waxes or resins of plants and those from animal origin, such as animal fats, whey, casein, egg whites, blood, excrement and urine (Eires et al 2010). The use of oils or fats has been the most used waterproof process in earth buildings. These materials were incorporated in the quicklime hydration and there were two different methods in their preparation. It could be by simple hydration, joining oils or fats to the lime with the adequate amount of water and after adding this mixture to the soil or it could be used a process called "hot hydration", mixing simultaneous the soil or clayey sand with oils and fats with the respectively necessary water.

In historical terms, the lime hydration with oils was already cited by Vitruvius, that mentioned about earthen tubes for water, the following "*The joints are then to be coated with a mixture of quick lime and oil*" (Vitruvius, I century b.C.). At century XVI, it was used as hydrophobic additive a reuse of whale oil that was first used in illumination. This oil with lime formed a material called "*gala-gala*", commonly used in Açores and Brasil (Veiga 2008). In Portugal, the quick-lime hot hydrated with oils was also used to stabilize earth walls. This kind of use was mentioned for traditional buildings with wood and rammed earth construction in Lisbon.

The influence of biopolymers addition in earth construction result of rheological effects developed in clay particles of soil. The main effect verified is related with the biopolymers capability to change the electrostatic charge of the clay particles. This causes dispersion and posterior attraction, that change the particles from a state of *face to face* (Fig. 1 - a) to a state of *face to edge* (Fig. 1 - b).

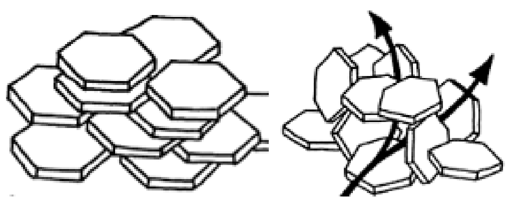

Fig. 1 – Clay boards: a - face to face and b - face to edge (Hamer et al 1975)

In basic surrounding environments, e.g., in earth based plasters with lime or in soil stabilized with lime, if oils or fats are added their triacylglycerols content when hydrated result in insoluble calcium salts of fatty acids. These salts are hydrophobic and connect well with the calcium of lime and provide water repellence (Čechová 2009). The oils and fats usually have a good performance in the capillary absorption, but in other properties such as mechanical strength can cause a decrease in the resistances. In addition, the mechanisms that take place in the microstructure are not clearly known (Čechová 2009). This reduction in the resistance is justified by the peculiarity of the oil or fat to encapsulate the calcium hydroxide particles and avoid the carbonation process (Santiago et al, 1992, in Čechová 2009). However, the use of an adequate oil percentage can conduce to superior resistances due to a reduction of porosity in the hardened state (Rovnaníková, 2002, in Čechová 2009).

All over the world ancient techniques with biopolymers addiction were found, whether in soil stabilization or in mortars or paints preparation for protection of earth construction. At table 1 are some examples.

Table 1 - Biopolymers at ancient earth construction

Local/Reference	Biopolymer (s)	Techniques/ Materials/ Obtained properties
India BASIN et al 2002	**Cow dung or urine**	*"Gohber"* – plaster technique, used mainly to fill up surface cracks. Mixture: 1 part of cow dung and 5 parts of earth (in mass). "*Cow dung improves the cohesion and plasticity of soils of low clay content*". *"Another practice is the addition of horse urine, which acts as a hardener and improves impermeability and impact resistance".*
North of Gana Beas 1991	**Dung and carob tree pods**	Paint – waterproof effect and hardener of walls and floors in laterite.
Egypt and Sudan Hassan Fathy 1969	**Straw and dung with fermentation**	Adobes and plasters - hydrophobic properties and enhanced resistance.
México and pre-Columbian people CPNT - *Consejo de Promocion de Nopal y Tuna* 2009	***Nopal –*** catus *Nopalea coccinellifera* or *Cactus cochenilliferus* or *figueira-da-índia* catus	Used in manufacture of lime based paints. The *nopal* is still used as waterproof materials for protection against rain, to allowed the addition of other decorations materials in earth walls.
México and EUA southwest Beas 1991	***Agave –*** catus *Leuchtenbergia principis*, *Lophanta, Caeruslens* or *Lechuguilla*	Used in mortars – the gum is boiled and the extract is kept for two or three weeks before to mix in the clay mortar.
South America, specially Peru Beas 1991	***Tuna*** – catus *Opuntia Ficus Indica*	Soil stabilizer for walls and plasters. Acts as consolidative. More water resistant combined with the surface polish technique.
South America and Africa Beas 1991	**Látex -** natural resin *Hevea Euphorbiacex*	Paints – Waterproof effect.
South America and Africa Beas 1991	**Banana** – stems and leaves	Utilization of these components boiled for mortars and paints (only leaves). Waterproof effect. The fibres avoid the cracks.
Malaya, Indonesia and India Este Beas 1991	**Dammar –** natural resin *Diopterocarpaceae* family	Mortars – Waterproof effect.
"Asia minor" Winkler, 1956, in Beas 1991	**Animal blood**	Technique that fell into disuse, which was used as stabilizer for soil or mortars with or without lime. Improve the water resistance and the compressive strength. But present a high risk of fungi growth.
"Babylonia" (century V b.C.) Maniatidis et al 2003	**Natural bitumen –** resultant from natural decomposition of vegetable or animals	Soil stabilizer. More effective in soils with little clay. It produces a waterproofing film that prevents the ingress of water.

2.2.3. Stabilization with mineral additives

In addition to the known stabilizers such as lime, cement, pozzolans or gypsum, others mineral additives have been used to improve the soil characteristics, mainly its durability. Between these additives are some salts and mineral compounds. The most used ones in earth construction are sodium chloride and sodium hydroxide (Houben et al 1989 and Anger et al 2009).

The known effect of sodium chloride is the viscosity control of clay and its consolidation by flocculation of clay particles, binding them again by attraction, depending on the amount of salt contained or added to the soil. This viscosity control is important, once that has influence on the mechanical properties. Consequently, one can reduce the water content and soil porosity, obtaining a more resistant soil mixture (Anger et al 2009).

The sodium hydroxide, as well as other additives soda based, is known as increasing soil reactivity, developing cementation reactions. This can complement the soil stabilization, improving its resistances (Houben et al 1989).

3. Experimental research

In the experimental research work one was tested different biopolymers and additives for soil stabilization, as well the addition of the common stabilizers lime and cement. The mentioned processes of lime hydration with oils were also studied. Here one will present the results obtained with the cited ancient technique of hot lime hydration with oils.

3.1. Methodology and tests

The present research work results from a sequential study of different mixtures. At the first stage were tested different biopolymers and additives to mix in a soil prepared in laboratory. This mix was prepared with selected sand and clay to avoid interferences of organic matter or other constituents contained in natural soils. At the second stage one was tested the biopolymer and additive with better behaviour against water action adding lime as soil stabilizer. The selected additives used were oil and sodium hydroxide and one was tested the two mentioned process of lime hydration with oils. The better behaviour was obtained using the hot process. At the last stage the performance of these selected materials and hydration process in a natural soil was verified (Eires 2012). In this paper, one has focus is this final stage, more representative of this study.

In order to perform the laboratorial tests, it was prepared compressed specimens to simulate CEB or rammed earth. Three different specimens were performed; cylinders of Ø5 cm/6 cm of height (made with 2MPa of pressure that is representative of a CEB manual machine); cylinders of Ø15 cm/3 cm of height and cubes of 20x20x20 cm^3 (compacted with a pneumatic hammer in order to simulate rammed earth technique).

The main tests that were performed in this research work are presented here to show the most important results of the studied mixtures concerning its performance against water action. These tests were: compressive strength in dry and saturated specimens; water absorption by capillarity; and water vapour permeability test.

The compressive strength test was performed in a simple uniaxial test with a displacement velocity of 1 mm/min according to ASTM D1633.

To obtain the water absorption by capillarity it was used an adaption from a method from LNEC (Gomes e Folque 1953), that consist in placing the specimens in a layer of wet sand. In this test one was used also a fabric between the sand and the specimens to keep the surface clean and flat.

To the water vapour permeability test one was performed based on EN 1015 19:2000 (permeability test for hardener plasters), using specimens in contact with two different relative humidity environments by the use of a saline solution of potassium nitrate. The permeability is measured by the mass difference occurred in the specimens caused by the water vapour passage through the specimens.

Figure 2 shows one specimen during the compressive strength test (Fig.2 – a) and 4 specimens used during the water vapour permeability test (Fig. 2 – b).

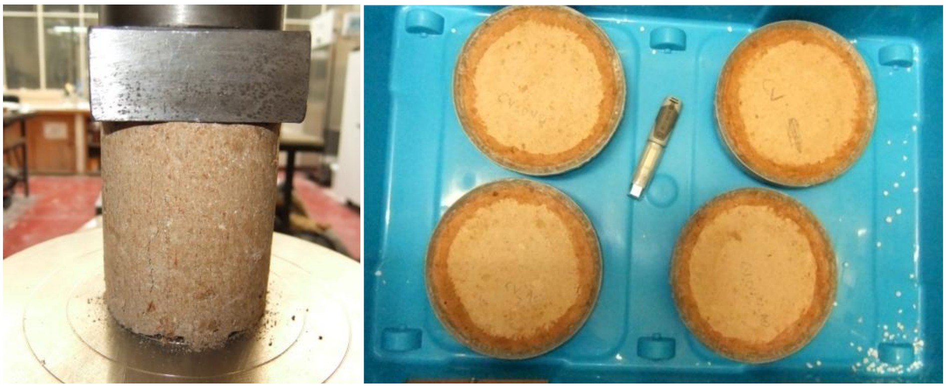

Fig. 2 – Specimens during the compressive strength (a) and permeability tests (b)

3.2. Selected materials

One was used a soil with a little amount of clay, more representative of a poor soil that need a stabilizer to improve its resistances. The soil contains, in mass, 85 % of sand, 6 % of silt and 9 % of clay. Concerning the clay type, it was observed that the soil contain a bigger amount of kaolinite and less illite and montmorillonite.

Among the biopolymers tested in the first stage of the research work carried out (amid, flour, sugar, casein, glycerol, water with cellulose, linseed oil and used cooking oil) the used cooking oil one was selected by its better performance at the final stage of the research, which main results are presented here. As well, between the additives tested (sodium hydroxide, sodium chloride, sodium silicate, alum, calcium chloride and sodium borate) the sodium hydroxide was selected by its better overall performance.

The used stabilizers were quicklime as the main one, as well hydrated lime and cement to in order to compare the obtained results. Portuguese limes were used, the quicklime (QL) containing in its composition 99% of CaO and the hydrated lime (HL) containing 90 % of CaO. The selected cement (C) was the most common used in Portugal – CEM II/B-L 32.5N.

3.3. Tested mixtures

The following mixtures, using the soil as base material, were tested: soil without stabilizers or additives; soil with cement; soil with hydrated lime; soil with quicklime; soil with quicklime and additives (sodium hydroxide and/or used cooking oil). In table 2 one can observe the tested mixtures compositions expressed in percentage of mass of soil.

Table 2 – Tested mixtures

Mixture	Stabilizer	Additive	Biopolymers
REF	-	-	-
C	Cement 4 %		
HL	Hydrated lime 4 %		
QL	Quicklime 4%	-	-
QL_NaOH		NaOH 0.1 %	-
QL_Oil		-	Oil 1 %
QL_Oil_NaOH		NaOH 0.1 %	Oil 1 %

3.4. Obtained results

3.4.1. Compressive strength

Figure 3 shows the results (kPa) obtained in the performed tests, considering dry and saturated probes (cylinders of Ø5 cm/6 cm of height), showing also the coefficient of variation (in percentage).

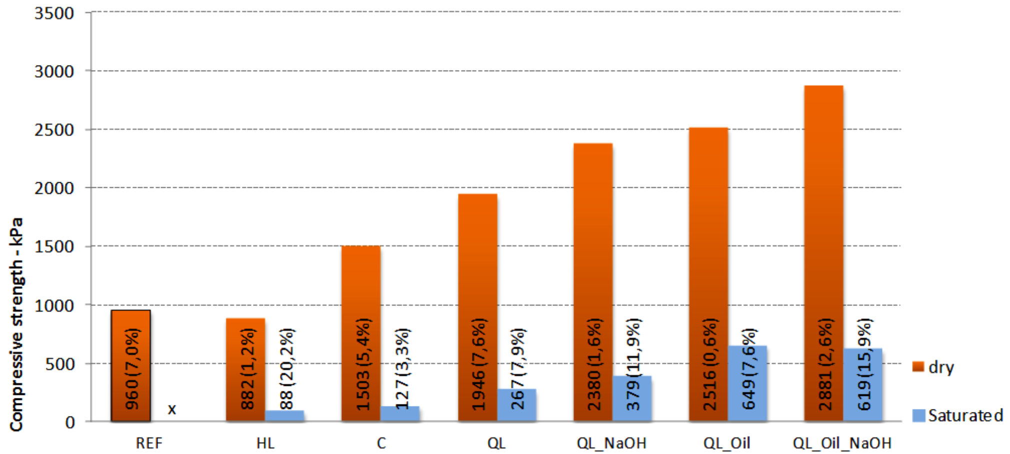

Fig. 3 – Compressive strength tests (dry and saturated probes)

As one can observe through Figure 3, in this soil, quicklime (QL) provide better resistances than the other stabilizers (HL and C). With HL one can see a little decrease than that obtained in reference mixture (REF). The results show also advantage of sodium hydroxide or used oil addition, individually or simultaneous (QL_ NaOH, QL_Oil and QL_Oil _NaOH) once these mixtures presented higher compressive strength values. In saturated specimens, in general, one can see a very significant compressive strength decrease but in correspondence with the ones obtained with dry specimens. However, the mixtures QL_Oil and QL_Oil _NaOH present similar resistances.

3.4.2. Water absorption by capillarity

Figure 4 shows the coefficient of absorption obtained in the studied mixtures and the coefficient of common material used in construction, concrete and hollow brick (values of Minke 2006), for comparison purposes.

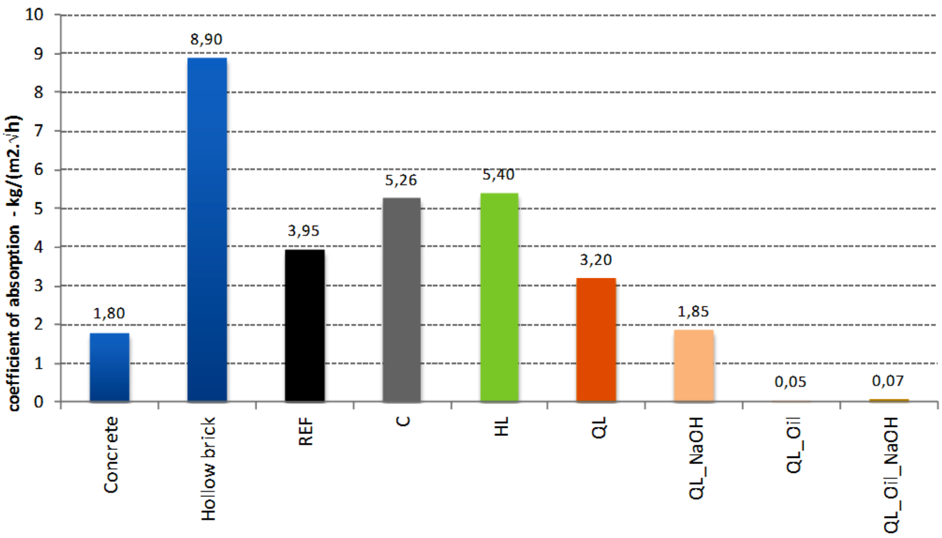

Fig. 4 – Coefficient of water absorption by capillarity of soil mixtures studied and common materials

Among the studied soil mixtures, one can observe that the addition of cement or lime do not reduce the water absorption. Moreover the results showed even a slightly increasing with HL and C addition. The use of quicklime reduces the absorption, above all with addition of sodium hydroxide or oil. Comparing with other materials, it is observed that soil mixtures have bigger absorption than concrete but smaller than hollow brick. The soil with quicklime and sodium hydroxide has absorption close to the concrete and the oil mixtures have the lowest values of absorption.

At figure 5 one can see the differences between the heights of water absorbed by capillary in the specimens. The oil mixtures showed a reduce height of water and the more saturated specimens was the ones of made with cement or hydrated lime (C or HL).

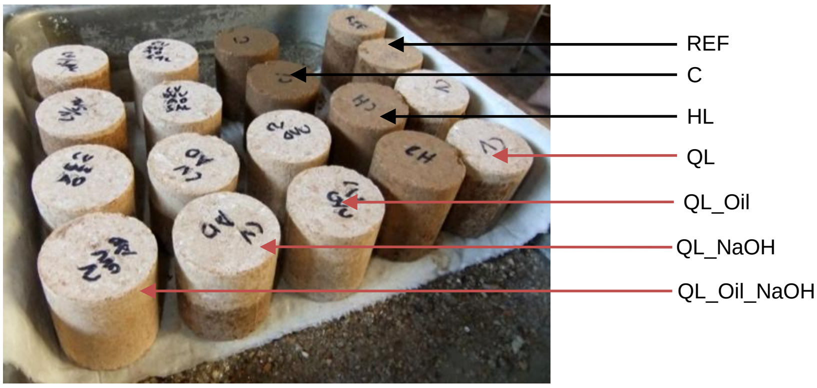

Fig. 5– Specimens during the water absorption test

3.4.3. Water vapour permeability

Figure 5 shows a comparative analysis of values obtained in the performed permeability test (with cylinders of Ø15 cm/3 cm of height) and values of other common materials (Pinto 2002).

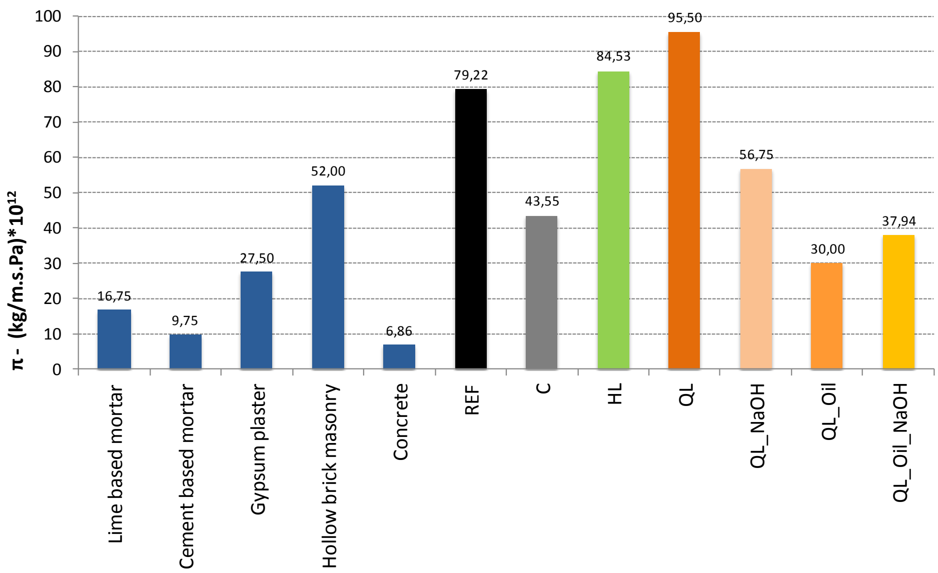

Fig. 5 – Water vapour permeability of soil mixtures studied and common materials

The results demonstrate that the earth material has higher permeability than other common construction materials, but the introduction of stabilizers can change this behaviour. The mixtures C, QL_NaOH, QL_Oil and QL_Oil_ NaOH reduce substantially the permeability, but these values are higher than concrete or even the common used mortars. This way it is expectable that the addition of oil or sodium hydroxide will not compromise the necessary vapour permeability of a building for a good interior environment.

4. Conclusion

The use of quicklime with the mentioned hot process present in this soil a good performance, with better mechanical resistance (in dry or saturated conditions), reduced water absorption by capillarity and reduced erosion, without compromise the water vapour permeability.

The addition of oil or sodium hydroxide can improve even more this performance of quicklime. Above all, the best performance related to compressive strength was achieved adding oil with sodium hydroxide and concerning water absorption was the addition of oil.

This way, one can conclude that these additions will be beneficial for earth construction in order to improve its durability against water action, being possible to build walls without coating it guarantying a good performance.

References

1. Anger, R., Fontaine, L. and Houben, H., 2009. Influence de la teneur en sel et du ph sur la plasticite du materiau terre. In: Cagliari Architecture Department, *International Conference MEDITERRA 2009, 1st Mediterranean Conference on Earth Architecture*, Cagliari, Sardinia, Italy, 13 - 16 March 2009. Edicom Edizioni.
2. ASTM, D 1633 – 00, 2000. *Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders*, ASTM, West Conshohocken, PA 19428-2959, United States.
3. BASIN & Pratical Action, 1999. Mud plasters and renders, *BASIN - Building Advisory Service and Information Network*. Original test - Appropriate Technology Magazine Volume 26/Number 1th June of 1999, AT Brief N.28, Edited by Practical Action Publishing, The Schumacher Centre for Technology & Development, 2002.
4. Beas, M., 1991. *Traditional architectural renders on earthen surfaces*, Master Dissertation, University of Pennsylvania.
5. Čechová, Eva, 2009. *The effect of linseed oil on the properties of lime-based restoration mortars*, Ph. D., University of Bologna.
6. Correia, M. and Merten, J., 2003. A taipa alentejana: sistemas tradicionais de protecção (The traditional rammed earth of Alentejo: protection systems). In: PROTERRA/CYTED, Centro de investigación de Arquitectura Tradicional (CIAT), *II SIACOT, Ibero-American Seminary of Earth construction*. Madrid, Spain, 2003.
7. CPNT - Consejo de Promocion de Nopal y Tuna, 2009. *Usos y Aplicaciones del Nopal*, [online] Available at: <http://www.cpnt.org.mx> [accessed 2009].
8. Crews, C., 2010. *Earth Plasters and Aliz*, in The Art of Natural Building, NetWorks' Productions, [online] Available at:< www.networkearth.org> [accessed 2010].
9. Crocker, E., 2000. Earthen architecture and seismic codes; Lessons from de field. In: UNESCO, ICOMOS and Turkish Ministry of Culture, *International Conference on the Seismic Performance of Traditional Buildings*, Istanbul, Turkey, 16 -18 November 2000. [online] Available at: <http://www.crockerltd.net/articles.htm>.
10. Eires, R., Camões, A. and Jalali S., 2010. Optimização do desempenho de construção em terra com recurso a bio-polímeros. In: CEAUCP, UC, ESG, FCO, Cdt and Rede Ibero-Americana PROTERRA, *Seminário de Arquitetura de Terra*

em Portugal, 6ºATP/Seminário Ibero-americano de Construção e Arquitetura com Terra - 9ºSiacot, Coimbra, 20 a 23 Fevereiro, 2010. Ed Argumentum.
11. Eires, R., 2012. *Construção em Terra: Desempenho melhorado com incorporação de biopolímeros (Building with earth: improved performance with biopolymers incorporation)*, Ph. D. University of Minho, Portugal.
12. Fathy, Hassan, 1969. *Arquitetura para os pobres – Uma experiência no Egipto rural (Architecture for the poor),* original text from Cairo 1969 with the title “Gourna, a Tale of two Villages”, Edited in Portugal for Argumentum and Dinalivro, 2009.
13. Gomes, R. and Folque, J., 1953. *O uso da terra com material de construção (The use of earth as construction material)*, Technical document - C.I.T Nº9, series D-4, LNEC.
14. Guelberth, C. and Chiras, D., 2005. *The natural plasterbook – earh lime and gypsum plasters for natural homes*, New Society Publichers.
15. Houben, H. and Guillaud, H., 1989. *Earth Construction – A comprehensive guide*, original Published with the title “Traite de construcion en terre de CRATerre” Editions Parenthèse, 1989. English edition CRATerre-EAG, Practical Action Publiching, The Schumacher Centre for Technology & Development, 2008.
16. Hutton, S., 2010. *Answers to questions about Oman - Making sarooj*, [online] Available at: <www.newsbriefsoman.info> [accessed 2010].
17. IM, Instituto Meteorológico, 2005. *Perfil Climático - Portugal Continental - Clima 1961-1990 (Climate Profile – Continental Portugal – climate 1961-1990)*, Ed. Instituto Meteorológico, I.P., Lisbon.
18. IPQ, NP EN 1015-19:2000, *Métodos de ensaio de argamassas para alvenaria, Parte 19: Determinação da permeabilidade ao vapor de água de argamassas de reboco endurecidas (Test methods for masonry mortars, Part 19: determination of permeability to water vapour of hardened plaster)*, Instituto português da qualidade, IPQ, 2000.
19. Malekzadeh M.J., 2007. Dams of the Ancient City of Istakhr. In: IRNCID and ICID, *International History Seminar on Irrigation and Drainage*, pg.121, Tehran, Iran, Maio, 2007.
20. Maniatidis, V. and Walker, P., 2003. *A Review of Rammed Earth Construction*, DTi Partners in Innovation Project ‘Developing Rammed Earth for UK Housing’, Maio, 2003.
21. Middleton, G., 1987. Reviewed by Schneider, L., *Bulletin 5 - Earth-Wall Construction, CSIRO-2*, and 4sth edition, National Building Technology Centre, Commonwealth of Australia, Department of Industry, Technology and Commerce.
22. Minke, G., 2006. *Building with Earth - Design and Technology of a Sustainable Architecture*, Birkhäuser – Publishers for Architecture.
23. Pinto, P., 2002. *Caraterização de Barreiras Pára-Vapor e sua Aplicação (Characterization of Vapour-Barriers and its application)*, Master Dissertation, University of Porto.
24. Teixeira, G. and Belém, M., 1998. *Diálogos de edificação: técnicas tradicionais de restauro (Building dialogues: traditional techniques of restoration)*, Publication, Porto: Centro Regional de Artes Tradicionais, CRAT.
25. Veiga, E., 2008. Arquitetura luso brasileira e suas relações com a toponímia (Brazilian Portuguese architecture and its relations with the toponymy), *Colóquio*

260 anos de herança açoriana. In: NEA, Universidade Federal de Santa Catarina, Florianopolis – Santa Catarina, Brasil, 15 -17 Setembro, 2008.

26. Vitruvius P., 2011. *De architectura – Book VIII*, in Vitruvius: On Architecture, original text written by the author at I century b.C., [online] Available at: <http://penelope.uchicago.edu/Thayer/E/Roman/Texts/Vitruvius>, accessed 2011.
27. Walker, P. and Standards Australia, 2002. HB 195-2002, *The australian earth building handbook*, Standards Australia International.
28. Hamer, F. and Hamer, J., 1975. *The Potter's Dictionary of Materials and Techniques*, Pr. (1st Ed. 1975) 4sth Ed. 2004. Univ. of Pennsylvania.