Grouting as a repair/strengthening solution for earth constructions

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1. Introduction

Earth, as a building material, has been used since ancient times, and is still being used with that purpose. Actually, one third of the world population lives in earthen houses /1/. In fact, earth constructions can be found all over the world, showing special presence in developing countries, where other building materials are still limited and building traditions were maintained. Earth was used for building shelters, houses, temples and even military constructions, like fortresses. This shows its versatility that allied with its great abundance in Nature contributed for the success of this material over the times.
As a consequence of earth's intensive use during many centuries, currently, there is a great architectural heritage stock. Proved by the 10% of places and monuments entirely or partially built in earth classified as World Heritage /2/. Nevertheless, earthen materials are very sensitive when compared with modern materials, since they are more vulnerable to external aggressive agents, revealing most of the times a faster degradation rate /3/. For its poor behaviour also contributes the fact that earthen materials present a very low tensile strength, a low compressive strength and a fragile behaviour, making the earthen structures, for example, strongly vulnerable to earthquakes /4/.
In part, this explains why 16% of the places and monuments classified as World Heritage that are in the list of heritage at risk are entirely or partially built with earth /2/. Moreover, these numbers reveal the urgency of intervention measures in order to preserve these places and monuments, and preventing their definitive loss.
The structural damage in this kind of structures manifests, in general, in the form of cracks or voids, caused by drying shrinkage, thermal movements, foundations settlements, plant growth and earthquakes, this last one having devastating consequences. Repairing those cracks is fundamental in order to obtain an improved structural behaviour, especially if the earth construction was built in a seismic zone.
During the last years, grout injection has revealed to be an economic and reliable solution for repairing and consolidating ancient masonry. However, the specificities of this technique and the specificities of ancient masonry required that fundamental studies had

to be carried out. This obliged to the development of mineral grouts capable of granting the materials compatibility and the durability of the solution, and at the same time granting the required mechanical and rheological properties /5/. Thus, these studies showed the necessity of a careful selection of the grouts raw materials and composition, leading, for example, to the limitation in the use of certain raw materials, such as the Portland cement, and to the promotion of others, such as the hydrated lime and pozzolanas, i.e., materials similar to the ancient ones.
Grout injection can also be used for repairing cracks of earth constructions and work as a complement in mixed strengthening solutions. However, specific grouts for earth constructions still have to be developed. These need to grant compatibility and durability requirements as well. In general, these requirements are fulfilled by using similar materials to the ones used in the original construction, which means, using the own earth to be part of the grout (mud grouts). Moreover, the design has to obey to strict requirements in order to allow a successful intervention. Among these requirements, the rheological behaviour of the grout in the fresh state has an important role. Since it dictates the capability of the grout to penetrate through the cracks or voids structure. Furthermore, it also has influence on other properties of the grouts, which are important to control in order to achieve a proper grout design.
Therefore, in this paper, the methodology that should be established for the design of mud grouts suitable for earth constructions will be discussed. This results from an ongoing PhD research that still is in an initial phase, that aims, precisely, the development of grouts specifically to be applied in earth constructions.

2. Earth as a building material

Earth (or loam as it is scientifically referred to) is the product of erosion from rock in the earth's crust, promoted by erosion agents like movement of glaciers, water, wind, thermal expansion and contraction, expansion of freezing water in the rock pores, organic acids of plants and organic matter decomposition attacks, and chemical reactions due to water and oxygen /1/. This results in a material constituted by particles of several sizes and shapes. These particles can be classified, according with their size, as clay, silt, sand and gravel. Depending of the country and utilization given to the earth, the classification ranges may vary. Although, the particles size ranges presented in Table 1 are commonly accepted by the people dealing with earth constructions.
All particles fractions have their role in the behavior of earthen materials. However clay has major importance. It acts as a binder by surrounding and attaching the silt, sand and gravel particles, giving cohesion to the material, while the other particles behave as the filler of that matrix. Thereby, the higher is the earth clay content the higher will be the strength of the resulting earthen materials. On the other hand, clay particles are reactive to water. Swelling on its presence and shrinking on drying. If the clay content is excessive, this behavior leads to undesired cracking of the earthen materials that harden

upon drying. Therefore, a compromise in the clay content has to be established in order to avoid excessive cracking or lack of cohesion caused by insufficient clay content.

Table 1: Earth's particles classification commonly accepted for earth construction

Particle classification	Size range
Clay	0-0.002 mm
Silt	0.002-0.060 mm
Sand	0.060-2 mm
Gravel	>2 mm

The clay portion of earth is the portion with the finest particle size and it is composed by a mixture of different clay minerals. The most common are kaolinites, illites and montmorillonites /1,3/. The structure of these minerals is crystalline and therefore regular, being each particle a combination of small sheets in a multi-layered plate structure /3/. The basic crystalline structure of clay minerals consists of two main structural units. The first unit are layers of $(Si,Al)O_4^-$ tetraeders which are bonded over oxygen atoms in one plain; the second structural element consists of octaeders in which the central ion (mostly aluminium but also Fe^{3+}, Fe^{2+} or Mg^{2+}) is surrounded by OH^- ions. The clay crystal lattice is then formed by layers of these structural units strongly bonded, presenting most frequently two types of arrangements /6/: two-layered (1:1 clay mineral) and three-layered (2:1 clay mineral). Kaolinite clay minerals are included in the former arrangement and illites and montmorillonites are included in the last (see Figure 1).

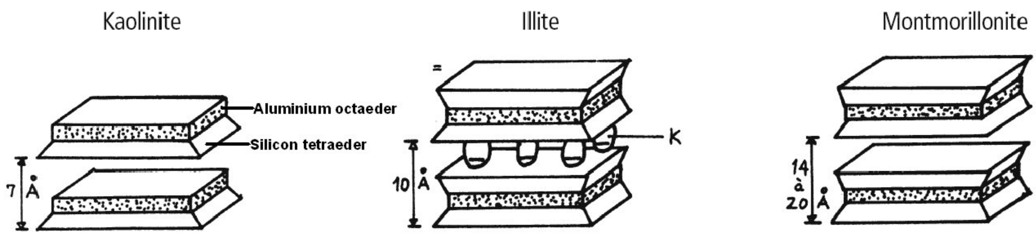

Figure 1: Commonly found clay minerals /7/.

Water molecules and other ions can be easily absorbed within the interstitial space between the layers, which makes the interstitial space expand, increasing the particles volume. The volume increase depends on the bond existent between the layers as well on the specific surface of the particle, which by their turn are dependent of the type of clay mineral. This phenomenon causes the swelling behaviour observed in earthen materials under direct contact with water. Therefore, the swelling of earthen materials depends upon the clay mineral types and on their percentage within the clay fraction.

Kaolinites are the least expansive clay minerals and montmorillonites the most expansive, while Illites exhibit an intermediate behaviour.

On clay drying, the water absorbed into the layers interspaces is able to get out, leading to a volume decrease of the clay particles. This makes the earthen materials shrink and crack if the developed stresses are not supported. The shrinkage of earthen materials depends on the clay minerals and clay content, as well. Kaolinite clays may present a linear shrinkage from 3% to 10%, Illites from 4% to 11%, and montmorillonites from 12% to 23% /8/. By cracking, the strength of earthen materials is reduced and points of vulnerability to other decay agents, such as water infiltrations, are created.

The cohesion of earthen materials conferred by the clay fraction is in significant part due to electrostatic forces. These forces result on the fact that clay particles are not electrically neutral. Substitution of the Si and Al atoms by atoms of lower valence, or unfilled valences of the structural units results in negative charges in the basal planes (faces) of plate clay particles /8/. Low positive charges usually occur in the particles edges due to their breakage and consequent interruption of the crystal structure /9/. Electrical edge-face bonds are then established between the particles. Edge-edge and face-face association also can occur by flocculation, which requires the presence of ions in the water involving the clay particles.

Therefore the binding provided by the clay fraction depends on its quantity as well as on the clay minerals present. Montmorillonites have greater binding properties while Kaolinites present a much lower binding capacity. This is directly reflected in the strength of the earthen material.

The clay content of an earth used for earth construction must, therefore, result of the balance between the acceptable shrinkage, and the required strength and cohesion of the material. These factors depend on the construction typology and on the building process. However, Warren /3/ suggests that the clay content should be between 1/10 and 1/5 of the overall weight. These limits are not consensual among the recommendations and standards for earth constructions, since they result from the self experience of each country or research group.

Like as for the clay content, also the silt, sand and gravel contents are not consensual. Nevertheless, according to Warren /3/ an appropriate earth for construction should have a silt content of 1/4, and a sand and gravel content between 1/3 and 2/3, by weight.

Silt, sand and gravel almost hardly produce shrinkage when compared to the shrinkage provided by clay. These particles fractions have a particular role in the strength of the material. For example, a well graded earth normally leads to a higher strength earthen material, since it allows to mitigate the shrinkage and to increase the contact between particles in the material’s microstructure.

Earth may also contain other compounds in their composition, like organic matter. Organic matter can be added or can exist naturally in the earth used for produce the earthen materials. If added it has as intention to improve earth properties, for example, by adding straw or animal’s dung in order to improve the tensile strength and the workability, respectively. However, organic matter can be also source of undesired salts and other substances through its decomposition, which can also be a source of voids within the material.

3. Earth stabilization

When building with earth, most of the times, the earth available in the neighborhoods is used. This raw earth may be unsuitable for building in that particular case, if the resultant earth materials do not hold the required properties. Stabilization is then required to improve, or eventually provide, those properties if no better earth is available nearby. The best known and most practical stabilization methods of earthen materials are increasing the density by compaction, reinforcing with fibres, or adding cement, lime, and bitumen /8/. Besides these last three, many other products can be used for stabilization, such as sodium waterglass, synthetic resins, paraffin, synthetic waxes, synthetic latex, ethyl-silicate, etc. It is also known that during centuries some natural products were also used as stabilizers, such as blood, urine, manure, casein, animal glue and plant juices /1/. Although, most of products do not have the benefit of an adequate research effort, like cement, lime and bitumen had /8/.
In general, stabilization aims the improvement of the mechanical properties, achieve better cohesion, limit the shrinkage/swelling effects and achieve better resistance to wind and water harmful effects. Stabilization can be mechanical, physical or chemical. Mechanical stabilization consists in the compaction of the earth resulting in changes in its density, mechanical strength, compressability, permeability and porosity. Physical stabilization consists in acting in the earth's physical properties, as for example, by changing its texture, or by using elctro-osmosis for draining water. Chemical stabilization involves the addition of other materials capable of reacting physically/chemically with the earth grains, modifying then the earthen material.
Although the advantages of earth's stabilization, it should only be used if necessary and no as systematic disproportionate application, since it can increase the production cost significantly and spoil original characteristics of the earth /8/.

4. Earth construction techniques

There are several ways to build in earth, which differ around the world, influenced by several factors among which are the climate, the local earth characteristics and the social factors. Although, the most worldwide known and spread earth building techniques are the adobe and the rammed earth.
Adobe bricks/blocks (also usually called simply adobes) or mud bricks/blocks are earth unburned bricks/blocks, normally made by filling or throwing moist lumps of earth into a formwork (Figure 2a), being the surface smoothed either by hand or by a timber piece, a trowel or a wire, afterwards /1/. Very frequently straw or lime is added to the earth, during the adobes production, to improve their characteristics. After being unmolded, adobes are dried in open-air conditions. This is the critical phase in the production, since then shrinkage occurs. In order to minimize the shrinkage effects (mainly cracking) special

care should be taken, like avoiding direct exposure to the sun in hot climates by covering the adobes with straw or turning them over regularly. The adobes are then used for building masonry walls (Figure 2b) or more complex elements like arches, vaults or domes.
Building in rammed earth consists in compacting moist earth layers of 10 to 15 cm by ramming them within a formwork (Figure 3a), for building a wall /1/. In general, the formwork is constituted by two parallel panels connected with each other. The earth layers can be compacted manually, or using modern equipment, like electrical, pneumatic or vibrating rams (Figure 3b). The construction of a rammed earth wall is made by blocks, as if it was a regular masonry wall but with units of exaggerated dimensions. After each rammed earth block being built, the formwork is immediately removed and it is reused for making the subsequent block. Traditionally, each rammed earth block has a height from 50 to 80 cm /1/. The construction of a rammed earth wall is usually performed layer by layer and by making the blocks intercalated (Figure 3c). Typically, the blocks of the following layer are simply laid on the previous one, constituting a horizontal dry joint. However, due to the drying of the previously constructed layer, they present different shrinkage levels, which may result in cracking of the most recent built blocks. A solution often adopted to prevent this, consist in making a lime/earth mortar joint /1/. This joint, by having a delayed hardening and a plastic behavior, allows the movements between the blocks without cracking. Moreover, the selection of the earth to be used in the construction of a rammed earth wall requires to be carefully evaluated, since the shrinkage has to be limited. Most of the times it is required to adjust the earth texture by adding coarse particles, like sand or gravel. Using stabilizers, such as cement and lime is also possible. The shrinkage has to be limited in order to safeguard the monolithic behavior of the structure by avoiding the formation of uncontrolled major vertical cracks. The water content also has to be careful evaluated in order minimize the shrinkage and enhance the construction process by reducing the labor required for compaction. The strength of this kind of material is mainly attributed to the particles interlocking provided by the compaction, instead of the binding provided by the clay.

(a) (b)

Figure 2: Adobe typology: (a) worker producing adobes;(b) wall of an adobe house.

In North Europe cob houses are often found, mainly in United Kingdom, where there was a common construction technique used between the fifteenth an nineteenth centuries /1/. This is a variation from the piled earth technique, which consists in making balls with wet earth reinforced with fibres, which are then thrown up on to the wall head and beaten into place /10/.
Another earth building technique well spread in the world is the wattle-and-daub. In this technique, earth only works as an infill material and not as a structural material. The earth infill, normally, covers a network of vertical and horizontal wooden elements that supports all the deadweight /1/.

(a) (b) (c)

Figure 3: Rammed earth as an earth construction typology: (a) rammed earth formwork /7/;(b) rams for earth compaction /7/; (c) rammed earth house /11/.

5. Earth construction decay mechanisms

Earthen materials, like other building materials, are also subjected to different types of degradation. However, the degradation rate is generally faster in earthen materials /3/.
In general, the earth constructions decay may be attributed to: (i) material deficiencies; (ii) foundation problems; (iii) structural defects; (iv) thermal movements; (v) water; (vi) biological activity; (vii) wind; (viii) natural disasters.
Material deficiencies are normally related with the earth's composition and texture. As previously mentioned, if an earthen material lacks on clay content and presents excessive content of stones and gravel, it will lack of compressive strength and lack of resistance to excess moisture effects. On the other hand, if the earth contains a very high clay content, excessive cracking due to shrinkage may occur, as well as swelling problems /3/. Materials like straw, added to earth have beneficial effects in its tensile strength at short-term, but at long-term they will decompose and disappear, leaving undesired substances, for example salts. These substances might induce cryptoflorescence and efflorescence problems.
Like for other structures, foundation problems may have terrible consequences to the structural integrity, which may result in collapse or in severe crack formation. Normally, these problems are related with differential settlements and with seasonal variations of the water table.

Structural defects may also result into severe damage to earth constructions inclusively collapse. This kind of deficiencies results, in general, from bad or inexistent design or due to construction errors. The horizontal thrust transmitted by roofs (with A-frame trusses) to the walls is a major, and often found, example of damage caused by structural defects, since earth walls cannot absorb it without resulting into severe cracking and into movements of the walls /10/.

Thermal movements are, as a decay agent, often ignored, since normally it is assumed that the inherent softness and pliability of earthen structures might render them immune to such problems, but in general this is not true /3/. These movements normally result in vertical cracks, found through the walls length and spaced in regular intervals, and in walls junctions, which diminish the earthen structures monolithic behaviour and stiffness.

Water may be considered one of the worst enemies of earth constructions. Problems with water start immediately after construction (rammed earth) or materials production (adobe), due to shrinkage, which typically results in cracking to the material, reducing its strength and exposing it to other decay agents. The shrinkage behaviour of earth is enhanced by its water content, i.e. the higher is the water content the higher is the shrinkage. Although, the volume decrease only occurs until the moisture content reaches the shrinkage limit /1,3/.

On the other hand, if an earthen material gets in contact with water, it will tend to swell and its strength will decrease, since it will start losing its solid state, according with the Atterberg limits. The expansiveness of earth may create internal stresses and may damage other elements, like the renderings. When the earthen material starts to dry it will shrink, resulting consequently in more cracking. This is why an earth construction should be protected against the direct influence of rain after being built. Additionally, the impact of rain may also have others prejudicial effects. If a wall is submitted to direct rain exposure, the impact results in erosion. Thereby, these walls must be protected by a roof overhang, which may prevent or delay this kind of degradation. Another way to protect earth walls against direct rain impact, is by applying a rendering, which works as an erosive layer and anti-penetration water barrier that must be renewed regularly. Even if the direct impact of rain is avoided, erosion may continue to happen, due to the “splash-back” of heavy rain falling on hard surfaces adjacent to earth walls with low or even inexistent masonry plinths /10/. Plinths have also an important role in preventing ground water rising by capillarity, which besides the water direct contact problems previously mentioned, may be a source of efflorescence and cryptoflorescence problems. Earth constructions covers have to be efficient and need to be subject to maintenance very regularly in order to avoid infiltrations. In cold climates, the water contained within the earth pores may freeze. The volume expansion of water turned into ice results in internal tensile stresses, exceeding the material strength and leading it to crack. Nowadays, the huge quantity of humidity produced inside houses, may be incompatible with earth constructions if a very low permeable to moisture rendering (like a cement mortar one) is applied in the outside face of the walls. This kind of renderings limits the dry out of the absorbed moisture, which accumulates inside the walls. In fact, this is judged to be the underlying cause of some recent earth constructions collapses /10/.

The high moisture content in an earth construction, may also lead to the growth of plants. The development and penetration of plant roots results in cracking, due to the tensile stress caused by their expansion. The tunnels provided by death plant roots attract animals searching for food or shelter, extending even more the damage, by drilling new tunnels and feed from the organic matter composing the earth /3/. Small animals, like insects, are more damaging than the larger, since huge colonies may develop, feeding from the organic matter (for example straw used to reduce the shrinkage effects of the earthen materials), and so the extension of the provoked damage is normally greater. Additionally, less visible evidence of their presence is available, which hinders on time intervention. Physical impact of domestic animals or farming machinery is other source of decay for earth constructions, mainly in buildings for agriculture purposes, such as barns.
Wind has mainly an erosive action over earth constructions. However, it can also affect other decay agents, like shrinkage or rain water impact.
Natural disasters, such as earthquakes, floods and storms, can inflict severe damage and even lead to the collapse of an earth construction. Nevertheless, earthquakes are the natural disasters with the highest catastrophic effects (Figure 4), thus being of special interest among researchers dealing with this kind of constructions. The seismic behavior of earth constructions is very deficient when compared with other contemporary structures, due to their low strength and high deadweight. The deficient constructive dispositions also greatly contribute for the poor seismic behavior of earth constructions. Such deficiencies are typically related with the lack of connection between the elements composing the earthen structures. Therefore, a strong earthquake may lead them to collapse or may inflict severe structural damage, by originating harsh cracks and reducing the overall structural stiffness /12/.

Figure 4: Partial collapse of a house at Rancho Camulos in California, USA, after the 1994 Northridge earthquake /13/.

6. Grouting as a consolidation technique

A grout can be defined as a fluid mortar employed for the filling, homogeneization, imperviousness, consolidation and/or upgrading of the mechanical properties of systems presenting pores, voids, cracks, loss of cohesion or of cohesionless systems /5/. In general, grouts are composed by fillers and binders. The materials that can be used with this last purpose are numerous. However, two major groups can be distinguished: the organic and the inorganic (or mineral) binders. The main materials of organic binders are polymer systems, which can be applied in pure form, pigmented or filled with filling materials /5/. The inorganic binders include air-hardening binders, such as hydrated lime, and hydraulic ones, such as hydraulic lime, Portland cement and all kind of modern cements, lime-pozzolan mixtures and any combination of the previous /5/.

During the last years, grouting has revealed as a reliable and economic solution for repair and consolidation of historical masonry. This technique has been mainly used in ancient three-leaf masonry walls. In this kind of masonry, injection aims to reduce the weakness of the internal core by filling the existing voids and cracks with the hardened grout, and to improve bond with the external leaves. Several studies have shown the potentiality of this technique in promoting an overall enhanced behavior of this kind of walls /5,14-16/. With this technique, the repair of deep and thin cracks lying in the external leaves or in single leaf walls is also possible. Nevertheless it requires grouts with high penetrability and thus fluidity.

Despite of the grout Injection recognized advantages it is a non reversible technique, which can induce durability and compatibility problems with the injected system, if non suitable materials are chosen to compose the grout. Thereby, nowadays the trend is the use of binary (mixes of cement and hydrated lime, natural or artificial pozzolans, silica fume, etc.) or ternary (cement, hydrated lime and natural or artificial pozzolans) grouts with low cement content /5, 17/.

Though, the application of grouting to ancient masonry required fundamental studies on material compatibility and solution durability to be carried out. During many years the aim of grout injection in ancient masonry was to improve the mechanical properties of the injected masonry, often neglecting the durability and compatibility concerns. In fact, recent studies have shown that the grout compressive strength is not a fundamental parameter for the grout design /5/, which encouraged the use of binders others than cement, and led to the development of the binary and ternary grouts. Furthermore, this kind of grouts, due to its low content in cement and due to the incorporation of materials similar to the original ones of the masonry, allows avoiding compatibility problems, leading to solutions with enhanced durability /17/.

In a rational grout design methodology for a specific intervention, the requirements for the grout materials shall be defined in first place. This approach should consider the structure, rather than the material, as the starting point. Therefore, the grout design requirements can be defined in two main categories /5/: requirements regarding the mechanical behaviour and the requirements regarding the durability of the injected structure. The improvement of the mechanical behaviour of a structure requires the design of a grout with very good injectability and bonding properties, in order to allow the injection of small cracks and voids, and to assure continuity to the masonry. The desired mechanical properties of the grout depend of the structural level of damage and of its structural improvement requirements. It also depends on the time span within which the required mechanical properties must be achieved, since the strength development rate is a controlling factor. For slowly hydration or carbonation hardening binders it is impossible to achieve acceptable levels of strength within a reasonably short time dictated by structural necessities. This is why, in binary and ternary grouts, a small percentage of cement with low salt content is normally adopted, which allows to surpass this limitation with its fast hardening. The Table 2, adapted from /5/, shows a brief description of the grout design requirements concerning the mechanical behaviour of the injected structure.

On the other hand, durability requires the development of a microstructure as close as possible to the microstructure of the existing materials. This can be achieved partly with the use of raw materials similar to the existing ones. However, the expected mechanical properties may be insufficient. A compromise is possible within the use of a limited Portland cement content, as it is used in the binary and ternary grouts /5/. The bonding is also a key factor for the durability requirement, since it limits the intrusion of detrimental agents and the subsequent undesirable chemical reactions /5/. A brief description of the durability requirements is presented in Table 3.

Table 2: Requirements of grouts related to the mechanical behaviour of the injected structure (adapted from /5/).

Requirement	Description
Injectability	- low yield value and viscosity - penetrability: in voids with diameter smaller than 0.3 mm - stability: no substantial density gradients along the height of the stored grout - low bleeding: lower than 5% after 120 min rest
Bonding with existing materials	- relatively low shrinkage (although autogeneous shrinkage is unavoidable) - minimal heat of hydration - setting and hardening in dry as well as in wet environment
Sufficient mechanical properties within a defined span	- development of the required mechanical properties in 90 days - compressive and flexural strength dictated from the structural analysis

In a grout design for historical masonry consolidation, subsequently to the selection of the raw materials composing the grout, according the defined requirements, the grout is tested in a trial zone, in order to validate the design on site. Only after the full approval, the gout is used for further consolidation.

Table 3: Requirements of grouts related to the durability of the injected structure (adapted from /5/).

Requirement	Description
Compatible microstructure	- compatible porosity and pore size distribution: they depend on the porosity of the existing materials as well as on the required strength of the new materials - type of the hydration products: similar (though not necessarily identical) to the existing
Bonding with the existing materials	- limitation of diffusion of SO_2, chlorides etc. - resistance against deterioration due to environmental factors
Properties of the raw materials	- minimal content in gypsum and soluble salts (especially in releasable alkali)

7. Grouting as a repair solution for earth constructions

Typically the degradation of earth constructions results in the formation of cracks, loss of material, loss of cohesion, loss of strength or even collapse of the construction. However the formation of cracks is often the visible part of the structural damage. Repairing these cracks is fundamental in order to obtain an improved structural behavior or to re-establish the structural integrity. This is particularly important if the earth construction was built in a seismic zone, in order to recover the monolithic behavior that the construction had before. Crack repair also prevents further decay caused by other agents, like water infiltration and plant growth. The traditional techniques for repairing cracks in earth constructions require the removal of parts of the original walls, in order to create a key pattern around the crack and in some cases it requires the enlargement of the crack, which may destabilize the construction. The removed material is then replaced by new material, which have to assure the bond between the two faces of the crack /10/. These techniques are very disturbing and intrusive, which makes the grout injection a more practical and less intrusive solution.

Grouting can also be used to fill voids and gaps in the earth construction caused by biological activity, such as the penetration of plant roots or tunnels excavated by animals. Moreover, it also can be used to complement other strengthening/repairing techniques, such as the application of ties for strengthening the connection between walls.

Thus, grout injection seems to be a promising solution for repairing earth constructions. However, an overall design methodology for grout injection of earth constructions is not available yet. The methodology used for masonry can be adopted. Although, the grout design requirements have to be redefined specifically for earth constructions. Still, different types of grouts, incorporating different materials, have to be developed.

Few attempts and studies for injecting adobe constructions were already done /3, 18-21/. The grouts used or studied had in common the incorporation of earth on its composition, and therefore they were designated as mud grouts. By using earth as a component or as all part of the grout almost solves the problems of compatibility and prevents possible additional durability problems /3/. Besides earth, the blends used in these previous works also incorporated stabilizers, such as bentonite, hydrated lime, hydraulic lime, fly ash, “mercula” clay, Portland cement and gypsum. The results obtained showed that grouting adobe constructions is a promising technique. Although, great problems and limitations were noticed, such as the high shrinkage, lack of fluidity and deficient penetration capacity of the grout.

The design methodology basis for the design of mud grouts is in many ways similar to the one used for design of grouts for ancient masonry. Both durability and mechanical behavior of the material should be kept in mind (Figure 5).

A good mud grout design requires that enough bond develops between the hardened grout and the original materials. To get the two sides of a crack become well attached is crucial, both for durability and structural reasons. That is why the grout shrinkage shall be limited, which due to the swelling/shrinkage behavior of the earthen materials makes it a complex task. It demands the reduction of the water content, which may compromise the injectability and penetrability of the grout and therefore the efficiency of the injection. Thereby, all the factors influencing the rheology, such as the texture (particle size distribution and particles shape), the interaction between particles, the quantity of solids in the grout, the mixing procedure and the action of superplasticizers or dispersants, should be carefully accounted for in the design of the mud grouts. Resourcing to stabilizers and correcting the particles size distribution are also possibilities to reduce the grout shrinkage. If very fine mud grouts are required the earth composing the grout has to be sieved, which increases the grout clay content and thus the shrinkage. Therefore it is necessary to proceed to the correction of the particle size distribution by adding “inert” fine materials. Materials such as quartz powder, silica fume, fly ash and calcium carbonate powder can be used for this purpose.

Also stability during the grout fresh state is required, i. e, it shall present limited bleeding, no segregation and adequate water retention. Limited bleeding and no shrinkage allow assuring that the material remains homogenous, while the water retention allows that the grout maintains its fluidity and penetrability during the injection, since the earthen materials behave as sponge absorbing the water in the grout. Using an earth with large particles to compose the grout can constitute a major drawback since they easily tend to settle and the water retention capacity is less than the one from the small particles.

A mud grout also needs to present chemical stability. The salts content has to be limited in order to avoid efflorescence and crypto efflorescence problems. Moreover, the grout should present resistance to aggressive compounds present in the original materials of the construction. For example if a possible grout contains Portland cement there is a possibility of formation of expansive products, such as ettringite, since the presence of sulphates is very common in earthen materials.

The design of mud grouts depends on many variables and requires a “non-linear system” to be solved, since all variable depends on each other (Figure 5). For instance, a higher strength grout requires the addition of stabilizers, such as Portland cement. By adding high amounts of cement, this results in a lower porosity of the hardened grout compromising the durability of the solution. This means that changing the grout composition to adjust one specific requirement, has consequences towards the other requirements.

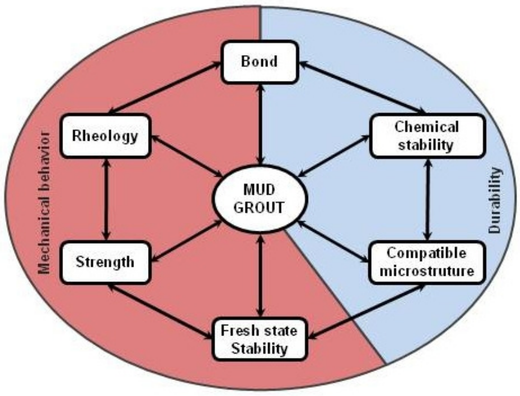

Figure 5: Design requirements of a mud grout.

The interaction between a mud grout and the earth construction to be injected has also great importance in the decision of a grouting intervention. The shrinkage/swelling behavior of earthen materials may constitute a major drawback, since the bond between the repair and the original material may be compromised by the water introduced. During the injection, the original earthen materials interact with grout by absorbing its water. This can have two types of effects on the original materials. By being absorbed, the water makes the earthen materials swell and at the same time makes the grout shrink, as soon it dries. Cracks may occur in the interface turning the grouting in to a failed intervention. The grout water absorption may also result in a reduction of the original earthen materials strength. This can constitute a major problem if high amounts of grout are required to be injected, because the structural integrity may be compromised.

8. Conclusions

Grouting has many advantages as a repair technique for earth constructions. This was proved by the previous researches demonstrating promising results with mud grouts. Although, the knowledge about mud grouts is still very limited. Therefore deep studies on the mud grouts rheology still have to be carried out. The design methodology also needs to be refined, requiring also an extensive experimental research testing several possibilities to improve the mud grouts properties and evaluating their effect in secondary properties.

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