

# Strengthening of masonry and earthen structures by means of grouting – design of grouts

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**ABSTRACT:** Grout injection is a technique commonly used in the repair and strengthening of masonry, due to the simplicity in its execution. However, to design a suitable grout, a proper methodology must be followed. The grout must accomplish requirements that depend mainly on mechanical behaviour and durability features of the structures. Grouting can be also applied to earthen structures, for repairing cracks and filling voids. The same methodology can be used to design grouts, but the requirements must be adapted. Therefore, this paper presents a discussion concerning the repair and strengthening of masonry and earth constructions through grout injection. To emphasize the differences in the requirements, first a short characterization of earth as a building material is given. Subsequently, the main decay phenomena are identified. Finally, attention goes to the effect of shrinkage and swelling behaviour of earth and the design of an appropriate grout for injection.

## 1 INTRODUCTION

The preservation of the architectural heritage is nowadays considered a key issue in the cultural life of modern societies. In the last years, large investments were done in this field, which led to important developments in the areas of inspection, non-destructive testing techniques, monitoring and structural analysis of monuments. However, the understanding, analysis and repair of historical constructions still remain as one of the most significant research challenges.

An important part of European historic constructions were built in masonry walls, typically composed by two external leaves of brickwork or stonework and by an inner leaf. These walls are characterized by a significant presence of voids in the internal leaf, by the weak strength of the materials and by a weak, or even inexistent, connection between the different leaves, leading to fragile collapse mechanisms under compressive and shear-compression loading (Anzani et al. 2004 & Valluzzi et al. 2004)

Among the popular strengthening techniques for solving this kind of debilitation and for masonry repairing, one of the most used is the grout injection. The concept of strengthening or repair masonry by applying this technique is quite simple. It consists in the filling of voids, gaps and cracks, by a fluid new material, which after some time gets into a hardened state, improving the bond between the different

leaves and the overall mechanical characteristics. However, the definition of its rheological and mechanical properties, as well the study of its interaction with the masonry, both at the micro-level, meso-level and macro-level, makes the design of grouts a very complex task. These questions are fundamental to achieve to the requirements and criteria established for intervention in ancient masonry. Nevertheless, the last years developments came to demystify some of the aforementioned questions and to allow a proper, despite of in part being empirical, grout design methodology for masonry (Toumbakari 2002).

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 earth houses (Minke 2003). As a result of its intensive use over the past centuries, there is currently a great architectural heritage stock, mainly in the developing countries, which needs to be preserved. In fact, from the places and monuments classified as World Heritage, 10% are entirely or partially built in earth, and 16% of the ones that are in the list of heritage at risk are also built in earth (ICOMOS 2001). These numbers reflect the level of degradation that these constructions may have undertaken and the complexity associated to their proper preservation.

Typically, earth is characterized, from the structural point of view, as a fragile material with a very low tensile strength and also with a low compressive strength (Chaudhry 2007). Taking into account that usually earthen structures are heavy, these character-

istics make this kind of constructions to present a poor seismic performance (Chaudhry 2007). Besides that, earth specific characteristics make it vulnerable to other agents, like water, wind, animal and plant aggressions. All these factors may be a source of cracking or voids in earthen structures, which must be repaired adequately in order to regain the structures original strength and to prevent further decay.

One possible solution to solve the aforementioned problems is the injection of grouts, as it is for masonry. In order to apply grout injection to earth constructions, a design methodology must be developed and followed to achieve to appropriate interventions. A starting point might be the use and further improvement of the grout design methodology established for masonry. Nevertheless, the specificity of earth as a construction material must be taken into account in the requirements to be established.

This paper presents a discussion on the development of a grout design methodology for earthen structures, based on the methodologies developed for masonry in the last years.

## 2 EARTH CONSTRUCTIONS

### 2.1 *Earth as a building material*

Earth as a building material, or loam as it is scientifically referred to, is a mixture of clay, silt, sand, and sometimes larger aggregates like gravel or stones (Minke 2003). Loam is a 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 (Minke 2003). All these factors, besides the rocks composition, are different from region to region. This is reflected in the differences found in the earth composition and particle size distribution of each region, which on its turn is reflected in the region earth construction typology.

In earth, clay acts as a binder and silt, sand and gravel as a filler. The clay is also responsible for the shrinkage/swelling behaviour. The higher is the clay content the higher is its drying shrinkage and swelling, but the binding provided is also greater. Shrinkage also depends on the water content in a similar way. The higher is the water content, the higher the shrinkage will be.

Clay is the portion of earth with the finest particle size (particles with a size less than  $2\ \mu\text{m}$ ) and it is composed of a mixture of different clay minerals. The most common are kaolinite, illite and montmorillonite (Warren 1999 & Minke 2003). The structure of these minerals is crystalline and therefore regular, being each particle a combination of small sheets in a multi-layered plate structure (Warren

1999). Water molecules can be easily absorbed within the interstitial space between the layers increasing the particles volume. This absorption capacity causes the swelling behaviour under direct contact with water, which is different according to the clay mineral types and their percentage within the clay fraction. Kaolinite is the less expansive clay mineral and montmorillonite the most expansive one, while Illite exhibits an intermediate behaviour in that perspective.

On clay drying, the water absorbed into the layers interspaces is able to get out, leading to a volume decrease. Therefore, shrinkage will be also influenced by the clay minerals types and their percentage. Kaolinite clays may have a shrinkage rate of 3% to 10%, Illites 4% to 11%, and montmorillonites 12% to 23% (Chaudhry 2007). Shrinkage produces cracking, which reduces the material strength and creates weak points susceptible for other decay mechanisms such as water penetration. Typically, in an earth suitable for construction the clay content should be between 1/10 and 1/5 of the overall weight, in order to avoid insufficient binding or shrinkage problems (Warren 1999).

Silt and sand almost hardly produce shrinkage when compared to the shrinkage provided by clay (Warren 1999). These two particle size portions, mainly their size distribution, have a particular role in the compressive strength of the material. A well graded earth normally leads to a higher compressive strength. 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 (Warren 1999).

Earth may also contain other materials in their composition, like organic matter and stabilizers. Organic matter can be added with the intention to improve earth properties and it can be found, for example, in the form of straw or animal's dung in order to improve the tensile strength and the workability, respectively. However, it can be also source of undesired salts and other substances, through its decomposition.

Stabilizers are normally added to earth in order to improve its water erosion resistance. Therefore, substances, like lime, cement, bitumen, sodium waterglass, synthetic resins, paraffin, synthetic waxes and synthetic latex can be found. Other substances that have been used through centuries like blood, urine, manure, casein, animal glue and plant juices can be also added with the same purpose (Minke 2003). Some of these substances may also have an improvement effect in other properties of earth, like binding force, compressive and tensile strength, shrinkage, water permeability, etc.

## 2.2 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 world wide known and spread methods are adobe and rammed earth.

Adobes are earth unburned bricks, normally made by filling or throwing moist lumps of earth into a formwork, being the surface smoothed either by hand or by a timber piece, a trowel or a wire, afterwards (Minke 2003). It is also very frequent adding straw or lime to earth during adobes production, to improve their characteristics. After being unmolded adobes are dried in open-air conditions. This is the critical phase in adobes production, since it is when 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 or regular turning over the adobes.

Building in rammed earth consists in compacting moist earth layers of 10 to 15 cm by ramming, within a formwork (Minke 2003). In general, the formwork is constituted by two parallel panels connected with each other by spacers. The ramming of the earth can be performed manually, or relying on modern equipment, like electrical, pneumatic or vibrating rams. During the construction, the formwork can be reused by removing and then re-erecting it for the subsequent layer. Traditionally, each wall layer has from 50 to 80 cm height. Usually, between these layers a lime/earth mortar is placed, in order to avoid cracking, due to the different water content resulting from the drying of the previously constructed layer. Compared with other earth construction techniques, specially wet techniques, the shrinkage ratio is much less and strength is much higher (Minke 2003). The earth normally used has a low clay content, which explains the low shrinkage, since the strength of the material is mainly due to the particles interlocking, provided by compaction, instead of the binding provided by the clay.

In North Europe cob houses are often found, mainly in United Kingdom, where there was a common construction technique used between the fifteenth and nineteenth centuries (Minke 2003). 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 (Keefe 2005).

Another earth building technique well spread over North Europe, mainly in Germany, is the wattle-and-daub. In this technique, earth only works as an infill material and not as the structural one. The earth infill, normally, covers a network of vertical and horizontal wooden elements that supports all the deadweight (Minke 2003).

## 2.3 Earth constructions decay mechanisms

The decay mechanisms of other kind of construction materials also affect earth constructions. The degradation rate is, however, generally faster (Warren 1999).

In general, the earth constructions decay may be attributed to: (i) material problems; (ii) foundation problems; (iii) structural defects; (iv) thermal movements; (v) water; (vi) plant growth and animal attack; (vii) wind; (viii) earthquakes.

Material problems are normally related with the earth composition and particle size distribution. If, for example, earth for construction contains insufficient clay and presents excessive content of stones and gravel, it will lack of compressive strength and lack of resistance to excess moisture effects. On other hand, if the earth contains a very high clay content, excessive cracking due to shrinkage may occur, as well swelling problems (Warren 1999). 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 water seasonal variations of water table.

Structural defects may also result into severe decay to earth constructions. The horizontal thrust transmitted by roofs (with A-frame trusses) to the walls is a major example of damage caused by structural defects, since earth walls cannot absorb it without resulting into severe cracking (Keefe 2005).

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 (Warren 1999). 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, 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 (Warren 1999 & Minke 2003).

On the other hand, if earth 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 earth starts to dry it will shrink, which consequently results in more cracking. That is why an earth construction should be protected against the direct influence of rain immediately 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. Normally, these walls are protected by a roof overhang, which may prevent or delay this kind of degradation. Another way to protect earth walls against direct rain, is 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 (Keefe 2005). Plinths have also an important role in preventing ground water rising by capillarity, which besides the water direct contact problems, may be a source of efflorescence and cryptoflorescence problems. In cold climates, the water contained within the earth pores may freeze. The volume expansion results in internal tensile stresses, exceeding the material strength and leading it to crack. Nowadays, the huge quantity of steam 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 the underlying cause of some recent earth constructions collapses (Keefe 2005).

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 (Warren 1999). Small animals, like insects, are more damaging than the larger, since huge colonies may develop, feeding from the organic matter, 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 for buildings for agriculture purposes, such as barns.

Wind has mainly an erosive action over earth constructions. However, it can affect other decay agents, like shrinkage or rain water impact.

The seismic behaviour of earth constructions is very deficient when compared with other contemporary structures, due to their low strength and high deadweight. A strong earthquake may lead earthen structures to collapse or to severe damage, originating harsh cracks and reducing the structures overall stiffness (Tolles et al. 2002).

### 3 GROUTING AS A STRENGTHENING TECHNIQUE FOR MASONRY

#### 3.1 *Grouting objectives*

One of the most common masonry consolidation and strengthening techniques is the grout injection. This technique is 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 showed the potentiality of this technique (Vintezileou & Tassios 1995, Toumbakari 2002, Valluzzi et al. 2004) to promote an overall enhanced behaviour. It is also possible, repair deep and thin cracks lying in the external leaves or in single leaf walls, which requires grouts with high penetrability and thus fluidity. However, this 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.

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 (Toumbakari 2002). 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 binders. The main materials of organic binders are polymer systems, which can be applied in pure form, pigmented or filled with filling materials (Toumbakari 2002). The inorganic binders include air-hardening binders, like 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 (Toumbakari 2002). However, 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 content of cement (Toumbakari 2002, Vintzileou & Miltiadou 2008).

### 3.2 Grout design methodology

During many years the aim of grout injection in ancient masonry was to improve the mechanical properties of the injected system, often neglecting the durability and compatibility concerns. In fact, recent studies have showed that the grout compressive strength is not a fundamental parameter for design (Toumbakari 2002), 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 composition with materials similar to the original ones of the masonry, allows avoiding compatibility problems, leading to solutions with enhanced durability (Vintzileou & Miltiadou 2008).

Therefore, in a rational grout design methodology for a specific intervention, the requirements for the grout materials should 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 (Toumbakari 2002): requirements regarding the mechanical behaviour and 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 structure 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 binders it is impossible to achieve acceptable levels of strength within a reasonably short time dictated by structural necessities. Table 1, adapted from Toumbakari (2002), 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 compro-

mise is possible within the use of a limited Portland cement content, as it is used in the binary and ternary grouts (Toumbakari 2002). 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 (Toumbakari 2002). A brief description of the durability requirements is presented in Table 2. Subsequently, according the defined requirements, the raw materials composing the grout are selected, and before being fully applied to masonry, the grout is tested in a reference zone, in order to validate the design on site.

## 4 GROUTING AS A STRENGTHENING TECHNIQUE FOR EARTHEN STRUCTURES

In an earth construction the grout injection aims at the repair and improvement of the mechanical behaviour. This technique can be used to fill the existing voids in these constructions, caused by animals and insects attacks. It can also be used to repair cracks, resulting from shrinkage, thermal movements, foundations settlements, plant growth and earthquakes. Repairing cracks is fundamental in order to obtain an improved structural behaviour, especially if the earth construction was built in a seismic zone. Crack repair also prevents further decay caused by other agents, like water penetration and plant growth. There are other traditionally used techniques to repair cracks in earth constructions. However, when compared with grout injection, these techniques are very disturbing and intrusive, since they require the removal of parts of the original walls, in order to create a key pattern around the crack and in some cases to enlarge the crack, which may destabilize the construction. The removed material is then replaced with a new one, which have to assure the bond between the two faces of the crack (Keefe 2005). Therefore, injection becomes more practical to be applied. Still, 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 requirements have to be redefined. Nevertheless, the knowledge about the mechanical behaviour of earth construc-

Table 1. Requirements of grouts related to the mechanical behaviour of the injected structure (adapted from Toumbakari 2002).

Requirement	Description
Injectability	<ul style="list-style-type: none"> <li>- low yield value and viscosity</li> <li>- penetrability: in voids with diameter smaller than 0.3 mm</li> <li>- stability: no substantial density gradients along the height of the stored grout</li> <li>- low bleeding: lower than 5% after 120 min rest</li> </ul>
Bonding with existing materials	<ul style="list-style-type: none"> <li>- relatively low shrinkage (although autogeneous shrinkage is unavoidable)</li> <li>- minimal heat of hydration</li> <li>- setting and hardening in dry as well as in wet environment</li> </ul>
Sufficient mechanical properties within a defined span	<ul style="list-style-type: none"> <li>- development of the required mechanical properties in 90 days</li> <li>- compressive and flexural strength dictated from the structural analysis</li> </ul>

Table 2. Requirements of grouts related to the durability of the injected structure (adapted from Toumbakari 2002).

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 <sub>2</sub> , 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)

tions and materials properties is still limited, which makes the definition of requirements for the grouts a very difficult task. Almost all materials used for grouting of masonry can be used in this case. Additionally, modified or unmodified mud grouts also can be used. The low strength of earth constructions and the similarity with the composition turns mud grouts into a compatible grout composition, preventing possible additional durability problems (Warren 1999). Due to the shrinkage/swelling behaviour of earth constructions, discussed previously, grouting with inorganic grouts may constitute a major drawback, since the bond between the repair and the original materials may be compromised by the water introduced. When the injection is performed in a crack, the water contained within the grout can be absorbed, making the earth swell and at the same time making the grout shrink. As soon as the earth around the grout starts to dry, it will shrink. Cracks may occur in the interface turning the grouting in to a failed intervention. In order to prevent this dangerous phenomenon, expansive grouts can be used, by addition of gypsum. In addition, if large quantities of grout are introduced in an earth wall, for example to fill voids caused by rodents, the added water may reduce the material strength, putting the structure safety at risk. Therefore, the susceptibility of the original material to swelling and shrinkage must be carefully evaluated before any kind of intervention.

## 5 CONCLUSIONS

The grout design methodology used for masonry structures can be a good starting point for the establishment of an extended methodology for earth constructions. Although, the specificity within the materials used and the construction typology needs to be incorporated. The limited availability of scientific material characteristics for this type of constructions requires further research, in order to allow an appropriate grout design.

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