Conservation and New Construction Solutions in Rammed Earth

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Abstract The conservation and rehabilitation of several sites of cultural heritage and of the large housing stock built from rammed earth requires adopting intervention techniques that aim at their repair or strengthening. The present work discusses the main causes of the decay of rammed earth constructions. The intervention techniques used to repair cracks and lost volumes of material are also discussed. Regarding the strengthening of rammed earth walls, the discussion is focused on the techniques that improve the out-of-plane behaviour. Special attention is given to the injection of mud grouts for crack repair in rammed earth walls, including the presentation of the most recent developments on the topic, namely

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regarding their fresh-state rheology, hardened-state strength and adhesion. Finally, the use of the rammed earth is discussed as a modern building solution. In addition, several typical techniques for improving rammed earth constructions are discussed, aiming at adequate those to modern demands. In addition, the alkaline activation of fly ash is presented and discussed as a novel improvement technique.

Keywords Rammed earth • Damage • Repair • Conservation • Strengthening • Grout injection • Alkaline activation • Fly ash

1 Introduction

Nowadays, building with earth is still considered to be one of the most popular solutions for shelter and housing. In fact, thirty per cent of the World's population, i.e. nearly 1500 million people live in a house built with raw earth [1]. In general, earth constructions have great presence in developing countries, where economical and technical limitations often make this type of construction the only feasible alternative. On the other hand, in developed countries the practice of building with raw earth has fallen into disuse over the past century, as a consequence of the technological development and extensive use of modern building materials (mainly concrete sand steel). Despite that, there is a large housing stock built from earth, widely distributed around the world comprising many monuments and buildings of acknowledged historic, cultural and architectural value [2, 3].

The earth construction concept includes several building techniques that have different constructive features [1], which depend mostly on local limitations related to the properties of the available soil and other resources, and thus this type of constructions is often associated with vernacular architecture. From all the traditional earth construction techniques, rammed earth, adobe masonry, wattle-and-daub are the most commonly found around the World, while CEB (compressed earth blocks) masonry is the most common from the modern techniques [4].

Rammed earth, also known as *"taipa"*, *"taipa de pilão"*, *"tapial"*, *"pise de terre"*, *"pisé"* or *"stampflehm"*, consists in compacting layers of moist earth inside a removable formwork, therefore building monolithic walls (Fig. 1). In fact, the formwork constitutes a key feature, which differentiates this technique from the others. The conception and design of the formwork have been an evolving process, which resulted in several configurations. In order to grant the quality of the rammed earth wall, this element must present adequate strength and stability to support the dynamic loads of the compaction process, and adequate stiffness to mitigate the consequent deformations [4].

Another important feature that requires tight control is the weight of the formwork, which must be sufficiently low in order to make it easily handled by the workers (in the assembling and disassembling operations). Typically, the formwork is supported directly on the wall and is dislocated as the rammed earth blocks that form the wall are built, and whereby this is called crawling formwork [5].

Fig. 1 Construction of a new rammed earth house in Odemira, Portugal

The construction is carried out by courses (like masonry), in which the formwork runs horizontally around the entire building perimeter and then is moved vertically to build the next course. Alternatively, a formwork externally supported can also be used to perform rammed earth, thus implying the assembly of a scaffolding structure (see Fig. 2a). In Spain, there are some pre-Muslim rammed earth sites reported, where this type of formwork was used, which is identified by the absence of putlogs holes (which usually result from the removal or deterioration of timber elements used to support a crawling formwork, and get embedded in the wall when the block is compacted) [5].

The elements of traditional formworks are made of timber, but not exclusively, as ropes and tying needles, for example, can be used for holding the shutters in place (Fig. 2b). Nowadays, the trend is to use the same metallic shutters used in concrete technology to constitute the formwork; a crawling formwork is composed by two metallic shutters or a self-supporting formwork is constituted by assembling the shutters in such way that they cover the entire wall.
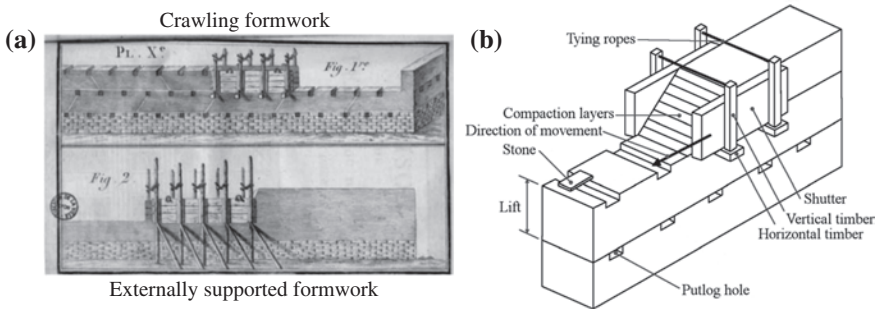
Fig. 2 Rammed earth formworks: **a** Crawling and externally supported formwork [6]; **b** elements of a traditional crawling formwork

The compaction of rammed earth blocks is traditionally carried out by manual means, resorting to rammers that in general are made of timber (Fig. 3a). Nowadays, the compaction process has been simplified by the introduction of mechanical apparatus such as pneumatic (Fig. 3b) and vibratory rammers, which comparatively reduce substantially the labour and time consumed in the construction. The dimensions of the rammed earth blocks are very variable from country to country, from region to region or even within the same region; for example in Alentejo (Portugal) the length of rammed earth blocks from typical dwellings may vary from 1.4 to 2.5 m, the height from 0.4 to 0.6 m and the thickness from 0.4 to 0.6 m [7].

The conservation of rammed earth constructions according to modern standards and principles requires the development of repair, consolidation and strengthening solutions that are compatible, but at the same time effective. For example, cement based materials have good mechanical properties, but their use as a repair material should be avoided, since their properties are rather different from those of rammed earth. In extreme situations, such differences can result in severe damage to the construction. Currently, the trend is to use earth based materials that grant the requirements of the construction demanding repair measures. Some of these repair solutions will be further discussed in detail, as well as solutions for structural strengthening.

Nowadays, rammed earth construction is regarded as a sustainable building solution for housing, but in most countries rammed earth is considered as a non-standard building material, which can be an obstacle to its utilization. On the other hand, there are some countries that have developed documents to regulate rammed

Fig. 3 Rammers used to compact rammed earth: **a** manual rammer; **b** pneumatic rammer (courtesy of Bly Windstorm from Earthdwell)

earth construction [2], but the demanded properties often limit the use of local soils. In most cases, this is surpassed by chemical stabilization of the soil, using binders such as cement and lime, which results in solutions less attractive from economical and sustainable points of view.

2 Rammed Earth in the World

From the history of all earth construction techniques, rammed earth is relatively recent [8], but its origin is not consensual. According to Houben and Guillaud [1] this technique was first developed in its "true" form in China during the Three Kingdoms period (221–581 AD). On the other hand, Jaquin et al. [3] argue that the technique had two independent origin focuses: in China and around the Mediterranean basin. It first appeared in China, where Jest et al. [9] claim that remnants of rammed earth walls and houses found in Qinghai, Tsaidam (between Tibet and Central Asia), date from the Muomhong period (2000–500 BC). The Phoenicians used rammed earth in their settlements in Iberian Peninsula and in northern Africa from around 800 BC, and a type of rammed earth vernacular construction has existed in Iberian Peninsula since that time [3]. Rammed earth technique also developed in northern Africa, particularly as a military building material. The spread of Islam from northern Africa to Iberian Peninsula from 711 AD brought rammed earth as a quick construction technique. As a consequence, the rammed earth technique is documented in several Arabic documents from the 8th century AD in military constructions of settlements and in alcazabas such as that of Badajoz [8].

In the sixteenth century AD, the rammed earth technique was used in South America by the Portuguese and Spanish settlers and later on (eighteenth and nineteenth centuries) in North America and Australia by European settlers. It was also used in the construction of many European settlements in South America, such as Sao Paulo, where there is a rich earth construction heritage. The publication of construction manuals by Cointeraux in 1791 [6] marked and stimulated rammed earth construction in Europe, which was re-introduced as a fireproof alternative solution to the typical timber constructions of that period. Then, with the invention of Portland cement in the nineteenth century, rammed earth construction waned. However, this technique helped solving the housing problem in Germany generated after the end of World War II [8]. More recently, there has been a growing interest on earth construction (including rammed earth) which led, for example, to the creation of the CRATerre group by University of Grenoble, one of the most important international centres concerning earth construction. Most recently, rammed earth has been championed in Australia, New Zealand and North America, where recommendations and standards to regulate earth construction have been developed. Rammed earth is still used as a vernacular construction technique in parts of Nepal and Bhutan, and is being developed in many other parts of the world.

This short overview on the history of rammed earth shows that this technique is worldwide spread. Figure 4 shows that earth construction (where rammed earth is
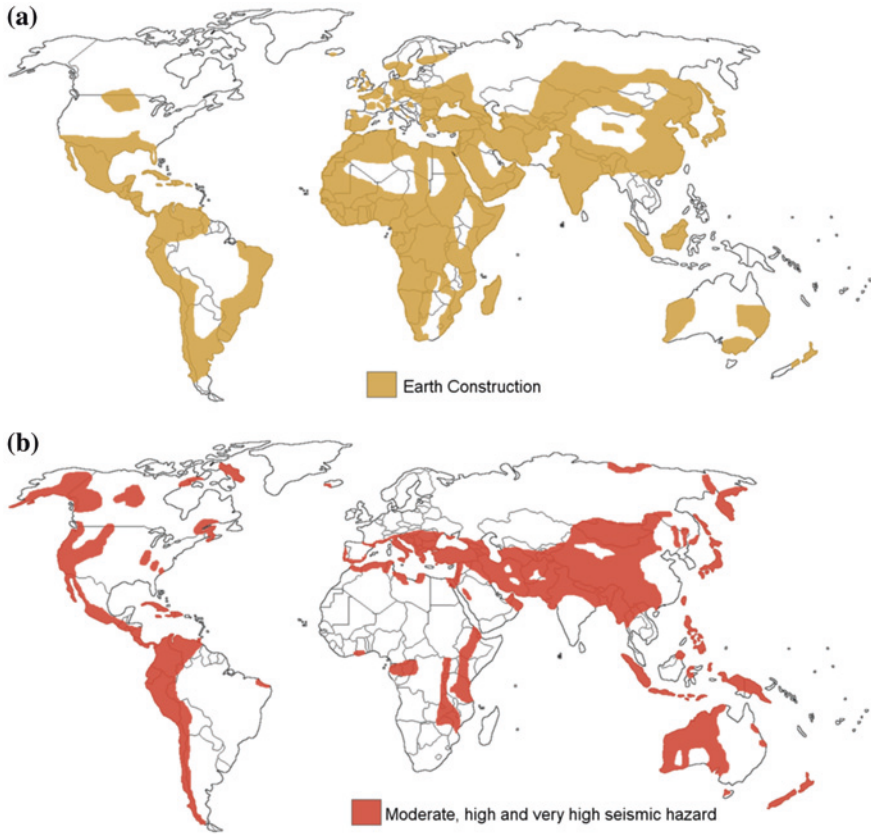
Fig. 4 World's geographical distribution: **a** earth construction (source: CRATerre-ENSAG); **b** zones of moderate to very high seismic hazard (based on De Sensi [10])

included) is present in all five inhabited continents. Moreover, it is shown that the geographical distribution of earth construction is almost coincident with zones of moderate to very high seismic hazard.

3 Damage and Rehabilitation

3.1 Damaging Agents and Pathologies

Like other building materials, rammed earth is also subjected to different types of degradation, but in this case the degradation rate is in general faster, especially if compared to modern materials [11]. 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 to the texture of the soil used in the construction or to the composition of the earth mixture. If the soil has low clay content and presents excessive percentage of stones and gravel, it may result in rammed earth walls with low compressive strength and water resistance. On the other hand, if the clay content of the soil is excessive, it may result into excessive cracking due to shrinkage [11]. The addition of natural materials, such as straw and manure, to the earth mixture is a common procedure in earth construction. Straw has beneficial effects in terms of tensile strength, but at long-term and if adverse conditions are observed, it will decompose, leaving undesired voids that have negative impact on the mechanical properties.

Commonly to other types of structures, foundation deficiencies may result in terrible consequences to the structural integrity, such as severe cracking or even collapse (Fig. 5a). These problems are related to the capacity of the foundation soil to bear the loads transmitted by the massive rammed earth walls. Moreover, the poor tensile strength of rammed earth walls does not allow them to absorb differential settlements caused by seasonal variations of the water table or by the presence of different foundation soils along the length of the wall.

Structural defects may also result into severe damage to rammed earth construction. These may be caused by incorrect or inexistent design or due to construction errors. For example, timber A-frame trusses are often used as support structure of the roof of rammed earth constructions, but if they are incorrectly designed they may transmit horizontal thrust that cannot be absorbed by the walls, resulting into leaning and cracking of the walls [12].

Thermal movements are often ignored as decay agent, since it is assumed that the inherent softness and pliability of earthen structures may render them immune to such problems, but in general this is not true [11]. These movements
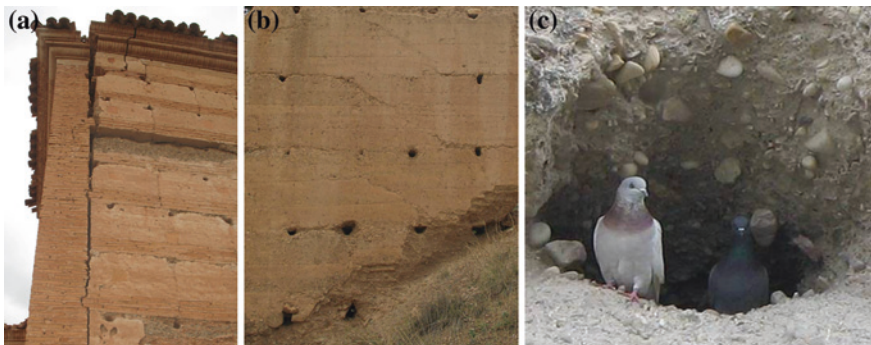
Fig. 5 Damage in rammed earth constructions: **a** corner crack caused by settlements of the foundations or by horizontal thrust of the roof; **b** basal erosion caused by rainfall; **c** damage caused by nesting pigeons

normally result in vertical cracks, found through the walls length (spaced at regular intervals) and at walls junctions, which debilitate the monolithic behaviour and stiffness.

Water is considered to be one of the worst enemies of rammed earth constructions. The water-related problems start immediately after finishing the construction, due to the inherent drying shrinkage, which typically results in cracking of the material, reducing its strength and exposing it to other decay agents. The shrinkage behaviour of earthen materials is function of the water content of the earth mixture upon compaction, i.e. the higher the water content, the higher the shrinkage. However, there is a maximum limit to this volume decrease, set at the shrinkage limit of the soil [4, 12].

On the other hand, the strength of rammed earth walls is strongly affected by its moisture content; the higher the moisture content, the lower the strength. Therefore rammed earth walls must be protected against the direct influence of rainwater after being built. Additionally, the direct impact of rainwater may also have other prejudicial long-term effects, such as the occurrence of basal erosion that reduces the bearing section of the wall (Fig. 5b). These problems are usually mitigated by protecting walls with roof overhangs, external renderings and masonry plinths [12]. This last element serves also to avoid the direct contact of rammed earth with the ground to prevent the occurrence of rising damp. It should be noted that renderings with low water vapour permeability (e.g.: from cement mortar) are harmful for rammed earth constructions, since the interior moisture accumulates inside the walls. In fact, this is judged to be the underlying cause of some recent earth constructions collapses [12].

The high moisture content in an earth construction, may also lead to the appearance of biological activity. The development and penetration of plant roots results in cracking, due to the tensile stress caused by their expansion. The voids, resulting from shrinkage cracks or from decomposition of the straw, attract animals searching for food or shelter (Fig. 5c), extending even more the damage, by drilling tunnels and feed from the incorporated organic matter (e.g. straw) [11]. Small animals, like insects, are more damaging than the larger (e.g. rodents), since huge colonies may develop extending the damage to larger areas.

Wind has mainly an erosive action over earth constructions. However, it can also contribute to other decay agents, like shrinkage or rainwater impact.

Natural disasters, such as earthquakes and floods, can inflict severe damage and even lead to the collapse of rammed earth constructions. Nevertheless, earthquakes are the natural disasters with the highest catastrophic effects, thus being of special interest among researchers dealing with this kind of constructions. In general, the seismic performance of earth constructions is very deficient when compared with contemporary structures, due to their low strength and high deadweight. Deficient constructive details also greatly contribute to the poor seismic behaviour of earth constructions. Such deficiencies are typically related to 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 [13].

3.2 Structural Intervention Techniques

The rammed earth building stock is large, worldwide spread and includes both ordinary and monumental buildings. The conservation of this stock requires the adoption of intervention measures that must follow specific principles, but this is a topic almost absent from technical documents on conservation of historical buildings. However, it is generally accepted that the intervention measures must allow the structure to function in a soft mode, and that excessive stiffening of a structure can lead to further damage. This was the result of a technical meeting after the TERRA 2000 conference, where it was accepted that not only guidelines for clear identification of structural and seismic cracks are necessary, but also that improved methods for the repair of such cracks are required [14].

The purpose of a structural intervention on a rammed earth construction can be at repairing or/and at improving its structural capacity. In the first case the intention is to recover the original structural behaviour partially or totally, which is in agreement with the principles referred to previously. The second case intends to improve the structural behaviour significantly, and thus such interventions are not so prone to follow these principles.

There is little documentation reporting and describing structural interventions specifically for rammed earth constructions. Generally, such documents propose intervention solutions that are adapted from other earth construction techniques, similar to rammed earth (e.g. cob), which result from an extensive practical experience on such constructions. In the following paragraphs the most significant intervention techniques on rammed earth will be discussed, including a novel technique based on the injection of mud grouts.

3.2.1 Refill Lost Volumes

A repair intervention on rammed earth walls can have two main goals: to refill lost volumes of material and to connect cracked parts. The absence of great volumes of material is a common pathology of rammed earth constructions, which can be attributed to several factors such as: partial collapse caused by an earthquake or another external factor, presence of biological activity, basal erosion caused by rising damp and erosion caused by rainwater impact. The obvious repair solution for this problem is to replace the missing material with new material, and for that there are some techniques that serve this purpose.

A common technique used to repair basal erosion consists in using a mix of soil (previously studied) similar to that of the rammed earth construction, which is compacted in place (Fig. 6a). First, the missing section is regularized and the loose material is removed. Then, a single-sided formwork partially covering the damaged section is assembled, and the earth mixture is compacted from the uncovered zone in horizontal layers. One of the main problems with this technique is associated to the difficulty in compacting adequately the last layers due to the limited
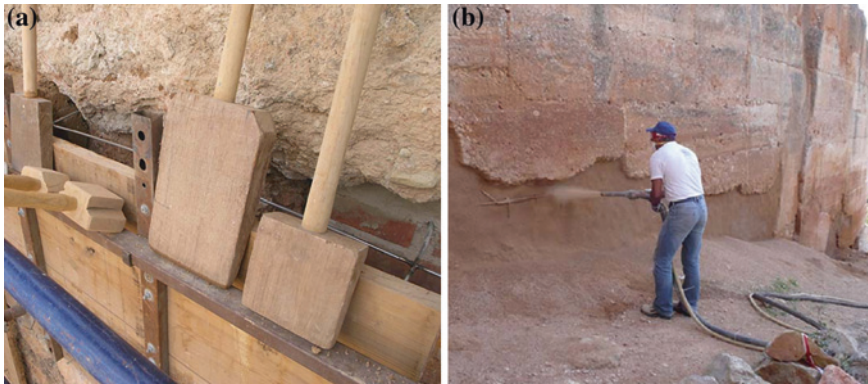
Fig. 6 Repair of the basal erosion of Paderne's Castle [16]: **a** by compacting new rammed earth material in place; **b** by projecting earth at high speed

vertical space within the formwork. This situation is normally overcome by leaning the last layers, which allows compacting them from outside the wall surface. Another problem comes from the shrinkage of the new rammed earth material upon drying, which is responsible for difficulties in bonding the repair material to the original rammed earth. Therefore, steel reinforcements and plastics meshes are often included. An alternative to this procedure, which also mitigates the shrinkage problem, consists in prefabricate rammed earth blocks that are put in place and then bonded with earth mortar. Researchers also reported cases where bricks, adobes and even concrete were used as replacing materials [11, 15].

Projected earth (Fig. 6b) is a recent intervention technique used to repair basal erosion, which was applied successfully in the conservation of Paderne's Castle (Algarve, Portugal) [17] and in the Alhambra of Granada (Spain) [18]. This technique consists in projecting a mixture of moist earth at high speed against the damaged area, whereas the impact energy is supposed to grant a similar compaction to that of the original rammed earth. This technique has some aesthetical limitation, since the rammed earth layers are not recreated, and instead a much more homogenous surface texture is obtained. The shrinkage is another problem of this technique, since the projection of the earth is only adequately executed by the wet method [18], which requires high moisture content of the earth mixture in order to provide adequate flowability for the projection apparatus. It should be noted that this technique is recent and thus further investigation must be carried out.

3.2.2 Reconnect Cracked Parts

The presence of structural cracks is a common pathology of rammed earth, and whose cause is often attributed to settlements of the foundation, to concentrated

loads, to horizontal thrusts applied by the roofs or to earthquakes. The repair of such cracks is essential to recover the original monolithic behaviour of the rammed earth walls. Moreover, cracks are weak points for water infiltration, which are prone to cause further decay to the construction. Several techniques are used to repair these cracks, but whose efficiency greatly varies from case to case. The most basic method used to repair structural cracks consists in simply filling it with earth mortar. The mortar, with a composition similar to that of the rammed earth, is introduced from the faces, and wherever the crack is extremely thinner the wall needs to be cut back. In terms of re-establishing the connection of the crack, this method is inefficient, but if the problem is strictly the water infiltration then it constitutes an adequate solution. The filling of the crack by grout injection is a good alternative to this method as it will be further discussed.

Stitching the crack is another solution to reconnect cracked parts, and consists in creating a mechanical connection between the two sides of the crack ("stapling" the crack), see Fig. 7. According to Keefe [12], this is carried out by cutting horizontal chases in the wall with a determined spacing along the crack, which are then filled with mud bricks and earth mortar prepared with a soil similar to that of the original rammed earth.

Fig. 7 Repair of cracks by stitching [5]
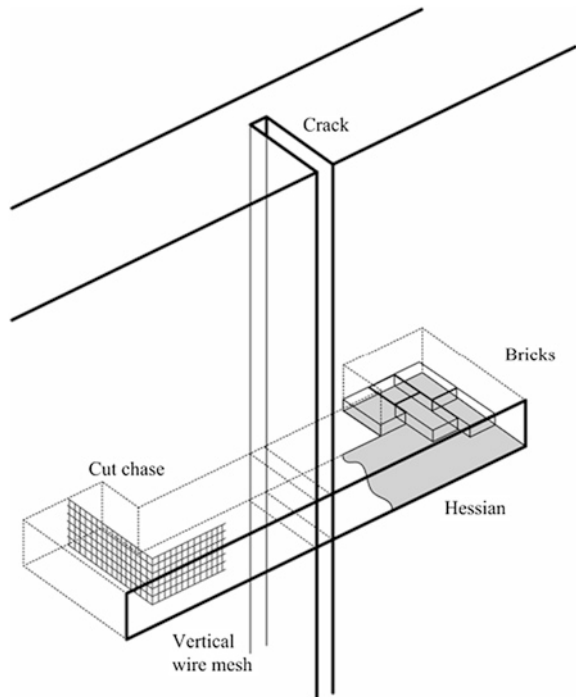
3.2.3 Strengthening

The introduction of stone masonry buttresses (see Fig. 8a) is probably one of the most basic and ancient solutions for out-of-plane strengthening of rammed earth walls. This solution serves both as amendment for the seismic performance and as solution to solve the problem of leaning walls caused by horizontal thrusts transmitted by traditional timber roofs. The introduction of steel tie bars to connect opposed facades is another method to improve the out-of-plane behaviour of rammed earth walls, see Fig. 8b. The placement of external beams tied by wires on opposed walls is an alternative to the previous technique. This constitutes a more global strengthening, as the forces from the beams are transmitted along the walls. On the other hand, the forces in the tie bars are transmitted to the walls in localized points by anchorage plates [19], whose dimensions are designed accordingly.

The connection of perpendicular walls is generally weak, since very often cracks are observed at this type of connection, which debilitate the structural behaviour, specially its seismic performance. The placement of grouted anchors connecting perpendicular walls is a valid technique for solving this problem, but Pearson [21] argues that their use in earth walls is limited because of the low shear strength of earthen materials, and they should not be relied upon to stitch major structural cracks.

As it is generally accepted, the tensile strength of earthen materials is very low and constitutes a key factor contributing to the high seismic vulnerability of earth constructions. The improving of the tensile strength of rammed earth is possible through the fixing of timber elements on the facades of the building, which is then rendered with a compatible earth mortar. As alternative to timber elements, metallic meshes or geo-meshes can be used, see Fig. 9. From an aesthetical point of view, this solution should only be used where the rammed earth facades are covered by a rendering.

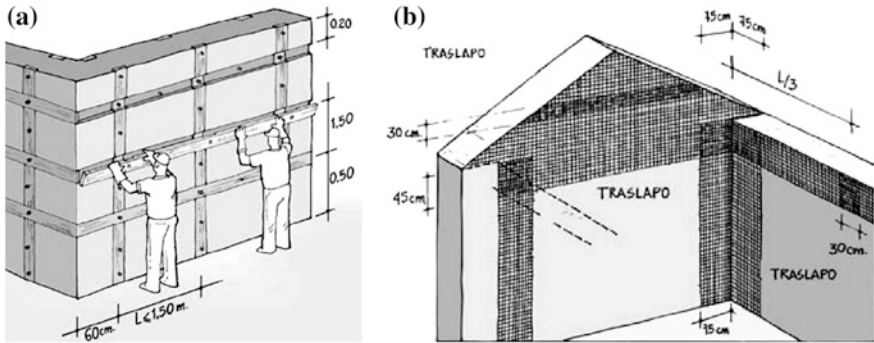**Fig. 8** Strengthening of rammed earth walls by means of: **a** buttressing [20]; **b** tie bars [5]

Fig. 9 Strengthening by fixation: **a** timber elements [22]; **b** metallic meshes [23]

4 Repair by Injection of Mud-grouts

4.1 Mud Grouts Background

The repair of structural cracks is essential for re-establishing the structural integrity of an earth construction. However, in rehabilitation interventions on earth constructions, cracks are often not truly repaired. Most of the times, they are "cosmetically" hidden by covering with a plaster or by filling them with mortar. These procedures do not grant an appropriate continuity to earth constructions, and in some situations they cause more problems than they solve [12]. Grout injection may constitute a more feasible, efficient and economic repair solution. Nevertheless, grouts compatible with earthen materials must be employed, which are not similar to those used for consolidating historic masonry (based on fired brick or stone units), including the recently developed binary and ternary grouts [24]. The obvious trend is to adopt grouts incorporating earth, also called mud grouts [11], but the knowledge on these grouts is still limited.

Currently, there are several published works on grouts for the consolidation of historical masonry. However, there are only a few cases where mud grouts are studied or applied for repairing earth constructions [25]. Roselund [26] describes a grouting solution applied to the restoration and strengthening of the Pio Pico mansion in Whittier, California, which is built in adobe. The damage to this mansion was mainly in the form of cracks in the adobe walls, as a consequence of the 1987 California earthquake. The cracks were repaired by injecting a modified mud grout, whose composition consisted of earth, silica sand, fly ash and hydrated lime. The design of this mud grout (whose hardening relies not only on clay but also on another binder) was mainly focused on obtaining a material with adequate consistency, acceptable shrinkage, and with hardness, strength and abrasion resistance similar to those of the original adobes. The results of the preliminary study of the intervention project showed that the tested unmodified mud grouts presented excessive shrinkage, while the modified ones presented low shrinkage, justifying

the preference for the latter type of grout. After this intervention, the Pio Pico mansion was struck by the 1994 Northridge earthquake. The resulting minor to moderate damage, when compared to the damage in other buildings in a similar condition, showed that grout injection in combination with other consolidation/strengthening measures is effective in preventing serious additional damage [27].

Jäger and Fuchs [28] also used grout injection for consolidating the remaining adobe walls of the Sistani House at Bam Citadel in Iran, severely damaged during the 2003 Bam earthquake. A modified mud grout composed of clay powder, lime and wallpaper paste was employed for this purpose. The decision on the grout composition was preceded by a composition study that included testing the addition of other materials (such as cement and water glass). The shrinkage and the mechanical properties, namely the compressive, flexural and splitting tensile strengths, were the properties tested in this study.

On the other hand, Vargas et al. [29] defend the employment of unmodified mud grouts (mud grout whose hardening relies only on the clay fraction when it dries out) rather than modified ones. This point of view is supported by an extended set of splitting tests carried out on specimens consisting of adobe sandwiches bonded by a layer of mud grout. Several compositions were tested, including unmodified and mud grouts modified by the addition of different percentages of cement, lime or gypsum. Their results showed that, in general, the unmodified mud grouts have better adhesion capacity. In addition, the results of diagonal compression tests performed on adobe masonry wallets repaired by injection of an unmodified mud grout showed that it is possible to recover the initial strength of the damaged walls. Furthermore, the addition of binders, such as cement or hydraulic lime, greatly increases the Young's modulus of a mud grout, which may be from one to two orders of magnitude higher than that of earthen materials [30, 31]. Despite the advantages of modified mud grouts regarding shrinkage and resistance to water, its employment must be carefully evaluated, since excessive stiffness constitutes an important drawback with respect to satisfying mechanical compatibility with earthen materials.

The role of the construction and its interaction with hardened grout is another key point that is highlighted by Vargas et al. [29], while other documents mainly focused on the material properties of the grout.

4.2 Grout Injection Approach in Earth Construction

As pointed out by Silva et al. [32], the design of a mud grout is a complex process. For instance, it must consider the construction demands, namely recovering the structural behaviour and granting durability, see Fig. 10, in a similar approach to that used in the conservation of historical masonry [24]. Then, the composition is defined such that the properties of the mud grout meet the demands. The complexity of the design lies in the interdependence between each of the grout properties, which becomes evident when the composition is adjusted. Therefore, it is essential

Fig. 10 Design methodology of a mud grout [32]
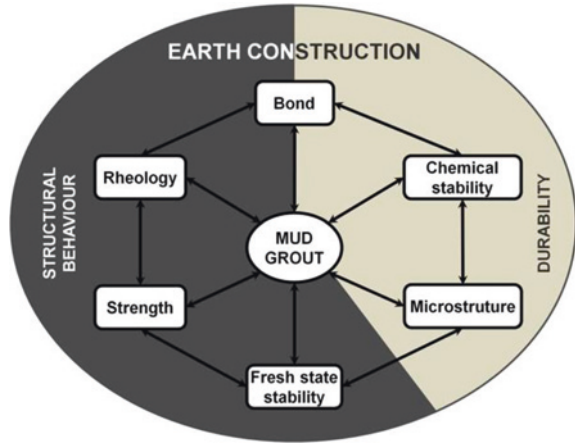
to understand how the composition of a mud grout affects its properties in order to design it effectively. In the subsequent paragraphs, the different material properties and their interdependencies are outlined in detail, namely rheology, strength, bond, chemical stability, stability against sedimentation of the fresh mix and the microstructure compatibility.

4.2.1 Rheology

The mud grout must hold a rheological behaviour that allows it to enable complete filling of cracks or voids laying in the earth constructions. This is essential to assure the continuity of the repaired earthen walls and to re-establish the monolithic behaviour of the earthen structure. Thereby, all the factors influencing the rheology, such as the texture (particles size, distribution and shape), the interaction between particles (dispersion or flocculation), the quantity of solids in the grout, the mixing procedure and the action of super-plasticizers or dispersants, must be carefully accounted for during the design of the mud grout. Moreover, the capacity of the dry earthen materials in quickly absorbing high amounts of water requires that the grout presents a great water retention capacity during its injection. This is essential in order to maintain adequate fluidity and penetrability during the full injection process.

4.2.2 Strength

The grout strength should correspond to the level demanded by the structure and be compatible with the original material. The use of grouts much stronger than the original earthen material should be avoided. Also, stiff grouts can cause problems of mechanical compatibility, since the hardened grout is hardly able to follow the

displacements occurring in the earth construction, resulting in damage to the intervention. Therefore, the addition of stabilizers has to be carefully considered, since these increase greatly the Young's modulus of the earthen materials. For example, the Young's modulus of unstabilized adobe from an old construction can range between 80 and 500 N/mm^2 [33], while a mud grout prepared with 40 % binder (50 % of hydraulic lime and 50 % of cement) and 60 % earth (mixture of 30 % of kaolin clay with 70 % of sand) can present a Young's modulus ranging between 10340 and 10590 N/mm^2 [30]. Also, not using a binder in a mud grout composition means that its hardening relies exclusively in the drying of the material. The drying of the mud grout is processed essentially through the water absorption by the original earthen material. The incorporation of hydraulic binders gives the mud grout a more independent behaviour, when regarding its hardening.

4.2.3 Bond

An efficient mud grout design requires that enough bonding develops between the hardened grout and the original earthen material. This is essential for granting continuity throughout the earthen structure, both for structural and durability reasons. The swelling/shrinkage nature of earth constitutes a major drawback. During the drying of a mud grout, its shrinkage can lead to cracking and consequently the required bond cannot be established. This is a problem that can also be found in reparation works using earthen materials [12]. In order to overcome the shrinkage problem of mud grouts, several options can be considered. The first one consists in adopting selected clays with low shrinkage ratio in the composition of the grout, such as kaolinite clays. The texture of the mud grout is another parameter which can be intervened, by decreasing the clay content of the grout and by correcting the particles size distribution with addition of "unshrinkable" fine material (such as fly ash, silica fume, calcium carbonate powder, quartz powder, among others). Another possibility consists in decreasing the water content. However, this solution has significant consequences over the rheology, which can only be counteracted by using dispersants. Using stabilizers is also an alternative to solve the shrinkage problem, but other problems can arise from this decision, namely those concerning the compatibility between materials.

4.2.4 Chemical Stability

A mud grout also needs to present chemical stability over time. The salts content has to be limited in order to avoid efflorescence and crypto-efflorescence problems. Moreover, the grout must have adequate resistance against aggressive compounds existing in the original earthen materials. For example, if a mud grout contains Portland cement, there is a possibility that the formation of expansive products will occur, since the presence of sulphates is very common in earthen materials.

4.2.5 Stability Against Sedimentation of the Fresh-State

While the mud grout is in its fresh-state, the solid particles in suspension must not suffer sedimentation. For that, it needs to present limited bleeding, no segregation and adequate water retention. These technical aspects are essential in order to assure that the mud grout maintains its fluidity and penetrability during the injection and remains homogeneous after hardening. For example, using a soil with large dimension particles in the composition of the mud grout is an obvious solution to help solving the shrinkage problem, but such option can constitute a major drawback since these larger and heavier particles are prone to sedimentation.

4.2.6 Microstructure Compatibility

Obtaining a hardened mud grout microstructure compatible with that of the original earthen materials is essential for fulfilling the durability requirement. The water vapour transport occurring within the original material should not be disrupted by the hardened mud grout. For example, the injection of a grout with low porosity (possible case of mud grouts modified by cement addition) can constitute a barrier that condensates the water vapour at its interface with the earthen material. This may be harmful for the construction, depending on the level of the intervention. The condensed water can leech the material around the grout disturbing the already created bond, and damage the intervention. In those cases where a big grout barrier is created, the condensed water can lead to the weakening of the earthen materials, that can be responsible for a possible collapse at long-term. Therefore, the incorporation of materials such as cement has to be carefully evaluated, since it reduces the porosity of the mud grout. The thermal properties of the hardened grout must also be closer to the ones of the original earth materials. This is even more important in monolithic earth constructions (for example rammed earth), where the grout has to be able to follow the thermal displacements of the earthen material.

4.3 New Developments on Unmodified Mud Grouts

Regarding the development of unmodified mud grouts, the authors have been researching the topic and present here an overview of the research findings validated by an extensive laboratorial investigation.

A mud grout composition study has been carried out, which assessed the influence of the mud grout composition on its fresh and hardened properties, namely rheological behaviour, strength and adhesion. By reproducibility reasons, the solid phase of the tested mixes was composed by commercial materials with controlled production quality, namely kaolin powder (Wienerberger, Kaolin RR40) and limestone powder (Carmeuse, Calcitec 2001 S). The kaolin represents the clay fraction
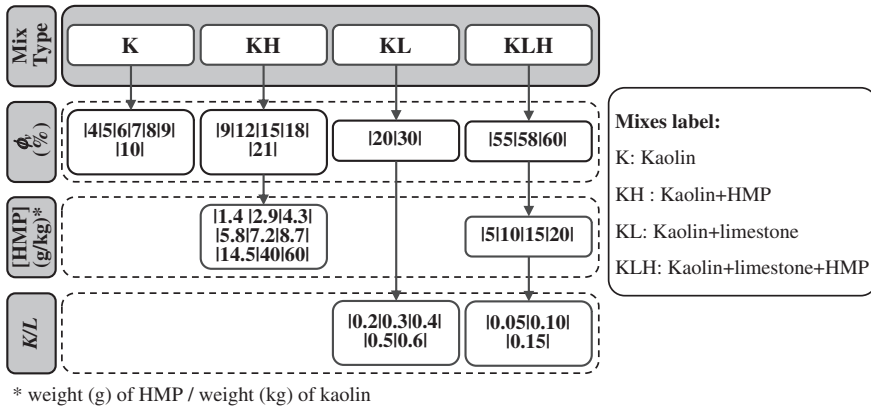
* weight (g) of HMP / weight (kg) of kaolin

Fig. 11 Matrix of the tested mixes

of the mud grout, while the limestone powder represents the silt fraction. Sodium hexametaphosphate (HMP) was also used as admixture for fluidity improvement.

Several mixes with different proportions of kaolin, limestone powder and HMP were tested. The variables of the study were the volumetric solid fraction (ϕ_v), the amount of HMP added as function of the kaolin content ([HMP]) and the ratio between the weight of kaolin and limestone powder (*K/L*). These variables are combined in the matrix given in Fig. 11, where the mixes are grouped according to the composition: kaolin (K); kaolin and HMP (KH); kaolin and limestone powder (KL); and kaolin, limestone powder and HMP (KLH). The same mixing procedure was followed for all mixes, see [34] for details. The fresh-state rheological behaviour of the mixes was assessed by means of Marsh funnel test (ASTM C 939 [35]) and by determining their flow curves using a Viskomat PC mixer-type rheometer [34].

The strength of the hardened KLH mixes was assessed through flexural and compression tests, according to EN 1015-11 [36]. The specimens were tested after achieving the equilibrium moisture content (constant mass of the specimens) at room temperature of 20 °C and relative humidity of 65 %.

The adhesion developed between earthen materials and three selected mixes (Table 1) was tested on 18 earthen beams with dimensions $160 \times 40 \times 40$ mm³, see Fig. 12a, prepared with three types of soil typically used in the construction of rammed earth houses in Alentejo (Portugal). The soils were sieved to remove

**Table 1** Composition of the mud grouts used for assessing the adhesion

Mud grout	[HMP] (g/kg)	*K/L*	ϕ_v (%)	W/S (wt.)	% Clay	% Silt	% Sand
MG_55	20	0.15	55	0.30	16	58	26
MG_58	20	0.15	58	0.27	16	58	26
MG_60	20	0.15	60	0.25	16	58	26

Table 2 Properties of the soils used in the bond test after being sieved

Soil	% Clay	% Silt	% Sand	PL	LL
S1	19	47	34	28	44
S2	15	37	48	17	32
S3	18	29	53	20	35

Clay < 0.002 mm/*silt* ≥ 0.002 mm and < 0.060 mm/*sand* ≥ 0.060 mm and < 2.0 mm (fractions usually defined for earth construction)
PL Atterberg's plastic limit/*LL* Atterberg's liquid limit
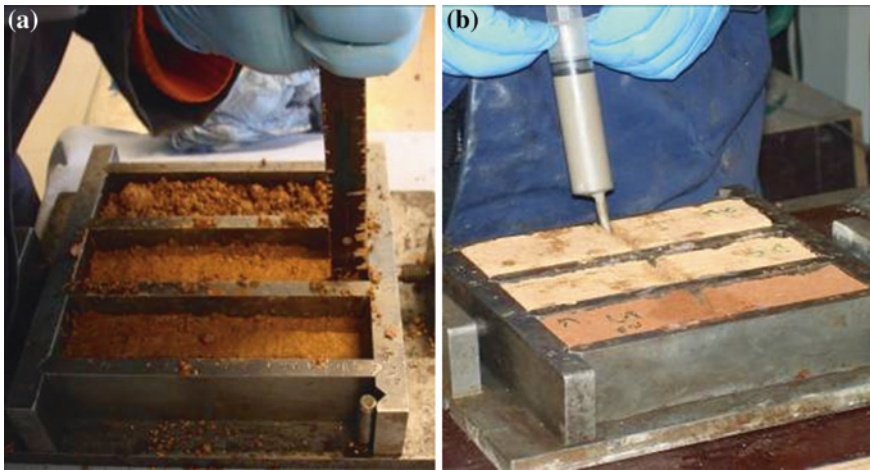
Fig. 12 Preparation of the earthen beams: **a** for adhesion tests; **b** injection of the broken earthen beams after 3-point bending tests

particles larger than 2 mm, which resulted in the properties given in Table 2. The beams were tested under bending, being repaired afterwards by injecting selected KLH mixes (2 beams of each soil per mix) into the crack between the two parts of each beam, see Fig. 12b. After 15 days, the repaired beams were tested again under bending.

4.3.1 Fresh-state Rheology

The results of the flow time tests of the K mixes (Fig. 13a) showed that the higher the ϕ_v, the higher the measured flow time. Moreover, the flow through the Marsh's funnel is not possible after a critical solid fraction (ϕ_{vcr}) is reached, which is approximately 9 to 10 %. Higher solid percentages are not adequate to prepare a mud grout. This behaviour is a consequence of the colloidal behaviour of the kaolinite particles in suspension, which interact with each other under Brownian
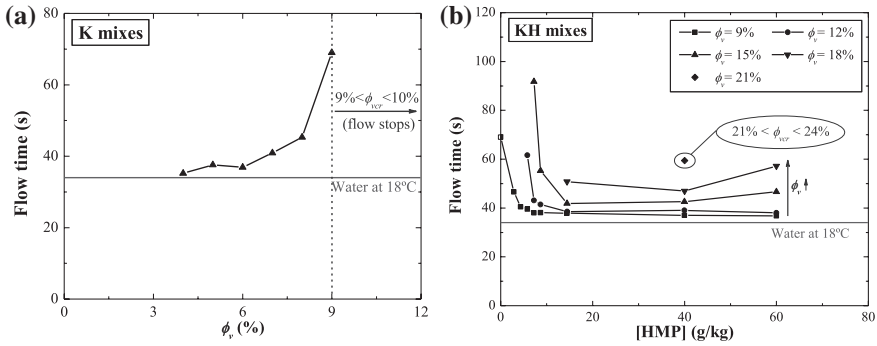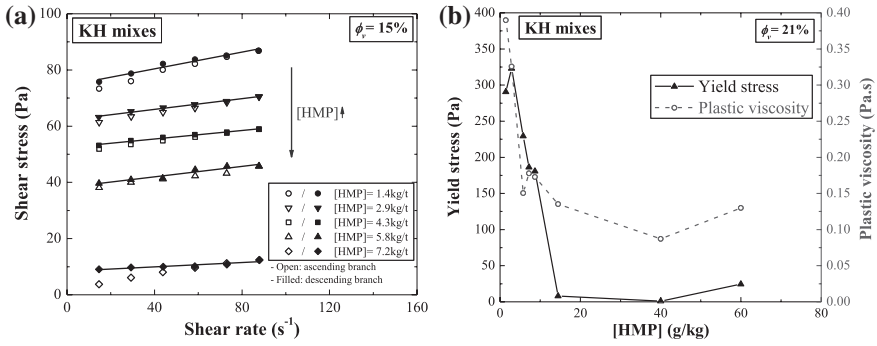
Fig. 13 Flow time measurements: **a** K mixes; **b** KH mixes

and/or hydrodynamic motion, generating two possible particle states: deflocculated or flocculated [37]. The interaction between kaolinite particles is governed by Derjaguin-Landau-Verwey-Overbeek (DLVO) forces, namely electrostatic forces (repulsion between like electric double layers and attraction between unlike charged surfaces) and van der Waals attractive forces. If the attractive forces are favoured, the clay particles tend to flocculate, forming an internal structure (house-of-cards or scaffold structure) that opposes the flow.

The aforementioned internal structure is disturbed by the addition of HMP in the KH mixes, where it is responsible for the following deflocculating mechanisms: (i) increase in the overall negative surface charge by the adsorption of anionic HMP polymeric chains onto the kaolinite surface, especially at the edges of the kaolinite particles [38, 39]; (ii) stabilisation caused by the steric hindrance effect of the adsorbed HMP chains [40]; (iii) complexing of the dissolved alkaline-earth cations and replacing them by lower valence Na^+ cations, which increases the thickness of the electric double layers [38]. These mechanisms allow further increase in ϕ_{vcr} (between 21 and 24 %), where the higher the [HMP], the higher the fluidity (Fig. 13b). However, at high [HMP] the fluidity decreases due to a concentration of linear polyphosphate chains that is above a critical value and promotes the association of kaolinite particles instead of their repulsion [40].

Figure 14 shows that the shear stress required to shear the KH mixes decreases with increasing [HMP]. The addition of increasing amounts of HMP reduces substantially both Bingham's parameters of the KH mixes (parameters obtained by linear fitting of the descending branch of the flow curves). However, the yield stress seems to have the greatest contribution to the flowing resistance, and furthermore this parameter is the main responsible for the failure registered with some Marsh funnel tests.

The results of the Marsh's funnel tests for the KL mixes (Fig. 15a) show that the increase in clay content (increase in *K/L*) increases the flow time. Moreover, it is shown that substituting the clay content with a silt size material (limestone powder), significantly increases ϕ_{vcr} when comparing to the K and KH mixes.

Fig. 14 Flow curves: **a** KH mixes with $\phi_v = 15$ % (with Bingham's model fitted to the descending branch); **b** Bingham's parameters of KH mixes with $\phi_v = 21$ %
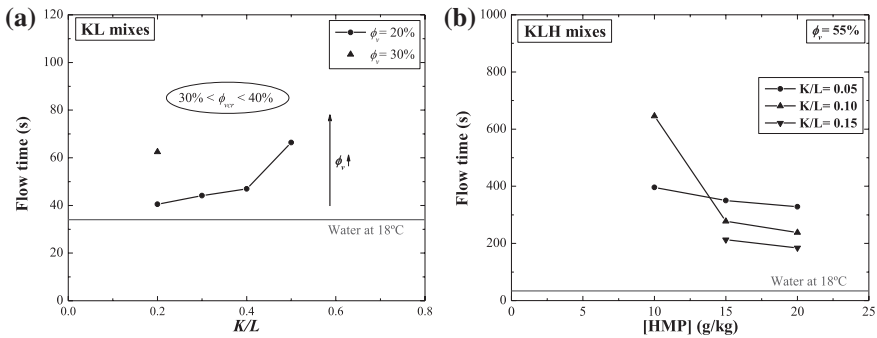
Fig. 15 Flow time measurements: **a** KL mixes; **b** KLH mixes with $\phi_v = 55$

The KLH mixes showed the combined effect of the addition of HMP and the incorporation of limestone powder (Fig. 15b) by further increasing ϕ_{vcr}, since flowing suspensions with ϕ_v between 55 and 60 % were obtained. However, the flow times increased substantially when compared with those of the K, KH and KL mixes. The addition of increasing amounts of HMP results in the reduction of the flow resistance of the KLH mixes (Fig. 16a), but it seems to have greater impact on the reduction of the yield stress than it has on the plastic viscosity (Fig. 16b). In fact, the addition of high quantities of HMP brings the yield stress to values close to zero, which is an important finding regarding the success of a grouting intervention [41]. This importance relies in the fact that if the injection pressure of a mud grout inside a crack is not sufficient to keep the shear stress at the head higher than the yield stress, the flow stops, which does not allow the complete filling of the crack by the grout.
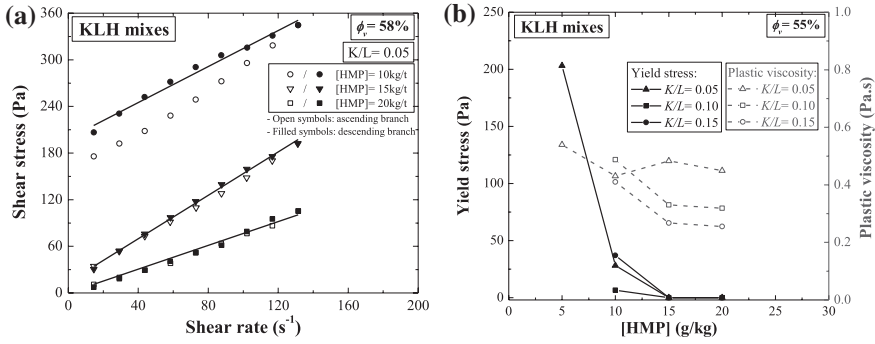
Fig. 16 Flow curves: **a** KLH mixes with $\phi_v = 55$ % and K/L $= 0.05$; **b** Bingham's parameters of KLH mixes with $\phi_v = 55$ %
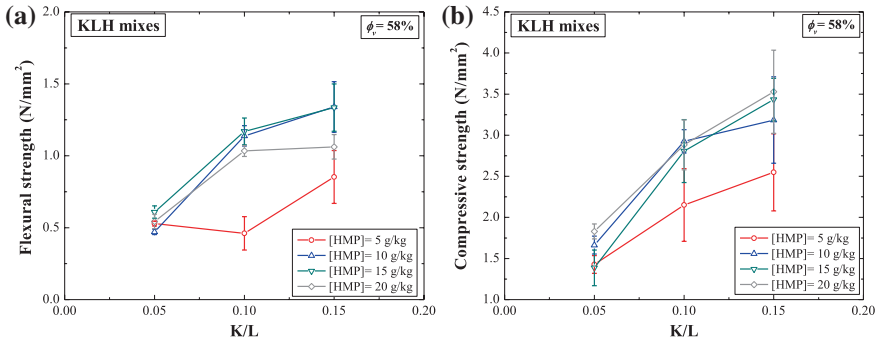
4.3.2 Strength

The flexural strength of the KLH mixes with a *K/L* ratio of 0.15 is presented as function of ϕ_v in Fig. 17a. It appears that there is no relation between these parameters, with the exception of the mixes with an [HMP] of 20 g/kg. On the other hand, the compressive strength of the mixes seems to be favoured by an increasing ϕ_v, see Fig. 17b. In regard to the effect of clay content, increasing *K/L* promoted positive development of both strength parameters (Fig. 18). Moreover, the mixes with a low *K/L* developed flexural and compressive strengths that are quite satisfactory when compared with those of earthen materials [34].
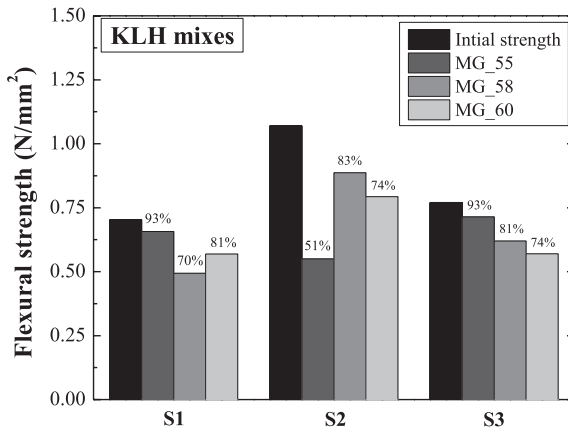
4.3.3 Adhesion

The results of the three-point bending tests performed on the repaired earthen beams, as well as the repair efficiency of the selected mud grouts, are presented
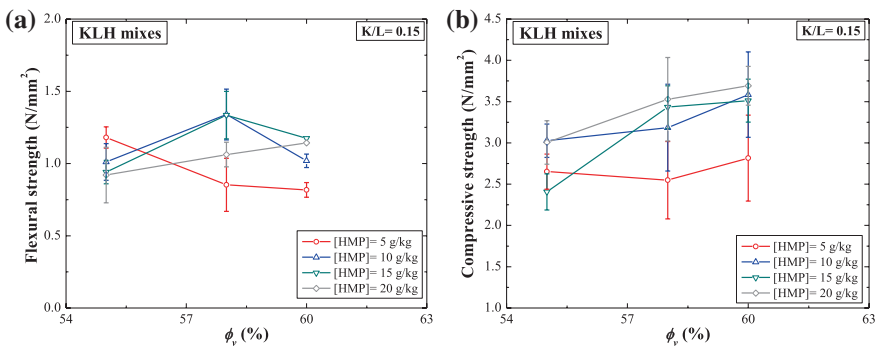
Fig. 17 Strength of the KLH mixes with *K/L* $= 0.15$ (both average values and scatter are outlined): **a** flexural strength; **b** compressive strength

Fig. 18 Strength of the KLH mixes with $\phi_v = 58$ % (both average values and scatter are outlined): **a** flexural strength; **b** compressive strength

Fig. 19 Adhesion capacity of the selected mud grouts for the three soil types

in Fig. 19. The grouts failed at re-establishing completely the original strength of the earthen beams. However, the repaired beams developed a flexural strength of at least 0.5 N/mm^2, which is above the minimum flexural strength for adobes required by the New Mexico [42] and New Zealand [43] standards (0.35 and 0.25 N/mm^2, respectively). The volumetric solid fraction ϕ_v of the selected grouts does not seem to interfere significantly with the repair efficiency, which probably means that the water content of the mud grout may be further increased in order to favour its injectability properties, but accounting for the possible occurrence of excessive drying shrinkage.

5 New Horizons for Rammed Earth

5.1 Rammed Earth as a Modern Building Solution

Rammed earth is in general considered to be a non-standard material, since its use in the construction industry does not follow any industrialized processes [44]; rammed earth walls are entirely built on site, which makes their properties extremely dependent on the characteristics of the available soil and workmanship. In addition, there are only a few countries that have codes/standards for earth construction (e.g. [43, 45, 46]), which together with the limited knowledge on the technique and resulting material, discourage the option for this building solution, especially in countries where those documents are absent. However, the recent environmental concerns in the building industry have been recalling rammed earth construction as a modern building solution, mostly due to its recognized sustainability and interior comfort benefits [4, 47].

On the other hand, the mechanical and durability requirements for rammed earth demand the use of soil with adequate properties [48]. Such requirements, within the framework of modern building codes, can be excessively severe to the traditional unstabilized rammed earth, especially in what concerns to local hazards such as earthquakes. Therefore, finding a soil at the construction site with adequate properties to meet these modern requirements is hardly possible. However, this limitation can be overcome by transporting an adequate soil to the construction site, by improving the local soil or by improving the construction process.

Chemical stabilization by addition of binders, such as bitumen, lime and cement is a recurrent solution used to improve the properties of the soil. The stabilization by addition of bitumen aims at improving mainly the durability of rammed earth, namely in what concerns to the resistance against water (erosion and swelling). The bitumen is added in an aqueous emulsion and mixed with earth. Upon drying, the bitumen forms a thin strong film that holds together the particles of the soil, which also improves the cohesion of the material and thus its strength. This stabilization technique is particularly indicated for sandy or sandy-gravel soils [1].

Lime stabilization is historically related to rammed earth construction, since millenary fortresses from the Iberian Peninsula still exist nowadays due to the durability and mechanical strength promoted by this stabilization technique. The cementitious compounds resulting from pozzolanic reactions between the lime and the clay fraction in the soil are the main responsible for this improvement. Thus, this technique is indicated for clayey soils.

The addition of cement is currently the preferred stabilization technique for new rammed earth constructions, since it significantly improves the strength of almost all soil types. The stabilization effect is provided by the formation of a cementious matrix that binds the particles of the soil. This matrix results from the hydration reactions of the cement and from the pozzolanic reactions with the clay fraction.

Rammed earth constructions are considered to have a high seismic vulnerability, like most earth construction techniques, and the main reason is the poor

out-of-plane and in-plane behaviour of the walls. As a consequence, there are several proposed solutions/techniques that aim at improving the behaviour of rammed earth walls through the building process. The most basic solution consists in building walls thicker than usual, but this result in a significantly higher cost.

The walls from rammed earth constructions can be seen as masonry made of macro-blocks, which are defined by horizontal and vertical joints existing between them. These joints result from the building process and have an important role in shrinkage control. However, the bond (shear-bond and adhesion) between blocks is debilitated by cracking resulting from this phenomenon, which has negative consequences on the in-plane shear behaviour of the walls. However, the building process can be adapted to mitigate this problem. The "*pisé*" technique is a French variation of rammed earth, where a layer of lime mortar between the blocks is included. The lime mortar cures for several weeks, during which it remains plastic and allows shrinkage movement between blocks without cracking [4].

The inclusion of hard materials, such as stones, bricks and tiles, in the horizontal joints is frequently observed in traditional rammed earth dwelling from the Iberian Peninsula (Fig. 20a). This is thought to improve the shear-bond behaviour between blocks and thus it can be adapted for new constructions. In a set of surveys carried out in Columbia, Lacouture et al. [22] found several cases of reinforcement of the vertical joints. These reinforcements consisted of timber elements that were embedded in the rammed earth to connect two contiguous blocks (Fig. 20b). The same principle can be applied in new rammed earth constructions to improve their structural behaviour.

The introduction of vertical reinforcements during the compaction of the walls, such as bamboo canes, can also result in the improvement of their shear and out-of-plane behaviours [49]. However, the presence of the reinforcements renders difficult the compaction process by making it more time consuming and by compromising the density of the material around the reinforcements.
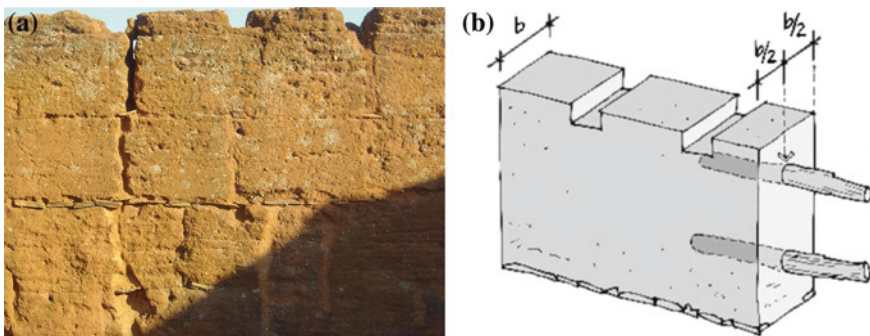
Fig. 20 Strengthening of rammed earth joints: **a** inclusion of schist stones in the horizontal joints (abandoned dwelling); **b** reinforcement of the vertical joint by timber elements (based on [22])

Providing reinforced concrete frames for the rammed earth [50] is currently a usual solution used in southern Portugal to obtain a construction with improved seismic behaviour. The concrete frames assume the structural function of the building, while the rammed earth serves as infill. The uncertainties about the non-standard feature of rammed earth and about the respective design are thus eliminated, and the reinforced concrete structure is designed according to the current codes.

As it was shown, there are several solutions to improve the structural behaviour of rammed earth constructions. Nevertheless, a promising future for rammed earth construction in the global building industry requires the development of knowledge on this building technique and the consequent development and establishment of specific design codes. For example, the recent publishing of the book Rammed Earth: Design and Construction Guidelines [51] led to an increase in rammed earth construction in the UK.

There have been recent advances in the modelling of unstabilised rammed earth samples, by using theories borrowed from unsaturated soil mechanics. These suggest that in an unstabilised soil, the soil particles are held together by small bridges of water acting across the pores between the particles. These bridges are held in place by surface tension and the capillary action due to the relative humidity of the pore air. There are thousands of such bridges holding all the particles together, and these act to provide additional strength and stiffness to an unsaturated soil when compared to a completely saturated or dry soil [52]. Using such a model helps to explain the behaviour of unstabilised rammed earth in the presence of water, why the strength reduces at increasing water contents, and why collapse eventually occurs when a section of rammed earth becomes saturated [53].

The relationship between stabilised rammed earth and water is much more complex, with initially free water being used in the hydration of the cementing products, and further water acting across pores as for an unstabilised sample. In this case, it is difficult to directly infer the behaviour of the rammed earth because of the complex interactions between the water and the cement. There are many aspects of this research are still being investigated, such as the nature of the pore network in rammed earth, and the development of the micro-structure of stabilised rammed earth.

5.2 Stabilization Using Alkaline Activativated Fly Ash

As referred previously, soil stabilisation by addition of cement is often used to improve the properties of rammed earth. According to Reddy and Kumar [54], the cement content has the most important contribution for the embodied energy of cement stabilized rammed earth, which increases almost linearly with increasing cement content. Lax [55] demonstrated that for a specific case, the embodied energy of 8 % cement stabilized rammed earth and that of unstabilized rammed earth is 1.84 times higher. The difference can be even higher if traditional

compaction methods are used instead of those mechanical and if no transportation of soil is required, as was assumed in that case. It appears that the impact of cement stabilization on the performance of rammed earth construction is substantial; however, this procedure has a negative impact in the sustainability of this building technique.

Soil stabilization is often required for safety and durability reasons. However, preserving the sustainability of rammed earth requires adopting solutions that include materials with low embodied energy. Adding natural materials, such as cow-dung, sawdust and straw, is a possibility, but the problem lies on their low effectiveness and reliability when compared with addition of cement or lime.

A possibility for reducing the impact of the stabilization process on sustainability of rammed earth consists in using industrial wastes, such as fly ash. Fly ashes result from the combustion of coal in power stations. This thermal treatment makes it a material prone to be used in a technique termed alkaline activation. The alkaline activation of raw materials such as fly ash enables the formation of what is called a geopolymeric binder. This binder can then be mixed with the soil and upon hardening it forms a matrix that involves and binds the particles, forming a soil-binder interface that usually delivers strength levels higher than the soil alone. In general terms, alkaline activation consists in a reaction between alumina-silicate materials and alkali or alkali earth substances, namely: ROH, R(OH)$_2$, R_2CO$_3$, R_2S, Na$_2$SO$_4$, CaSO$_4$·2H$_2$O, R_2·(n)SiO$_2$, in which R represents an alkaline ion like sodium (Na$^+$) or potassium (K$^+$), or an alkaline earth ion like calcium (Ca^{2+}). It can be described as a polycondensation process, in which the silica (SiO$_2$) and alumina (AlO$_4$) tetrahedra interconnect and share the oxygen ions. The resulting polymeric structure of Al–O–Si bonds is the main structure of the hardened geopolymer matrix, which is very similar at a molecular level to natural rocks, sharing their stiffness, durability and strength.

The authors have been doing some research on the stabilization of granitic residual soils using alkaline activated fly ash. These soils, typically found in northern Portugal, are formed from the weathering of granite rock. They are characterized by a well graded grain size distribution and very low plasticity indexes, which usually classifies them as silty sands (SM) and clayey sands (SC). In fact, the clay content of these soils is typically very low, making them unsuitable for unstabilized rammed earth construction, or even for stabilization with lime. Escobar [56] tested three granitic residual soils from northern Portugal, and verified that the dry compressive strength of rammed earth specimens (compacted with the standard Proctor test density) barely exceeded 0.4 N/mm^2. This is a very low value for unstabilized rammed earth construction, and thus building with these soils is only feasible if they are chemically stabilized.

Following the work of Escobar [56], one of the assessed soils (soil S1) was stabilized using alkaline activation of fly ash, using a broad set of compositions, and the unconfined compressive strength as the control parameter (see [57] for details). The activator was composed by sodium silicate and sodium hydroxide and the fly ash was class F (contains less than 20 % CaO and has pozzolanic properties). The effect of several variables was analysed, such as: soil maximum particle size,

liquid:solid ratio, activator concentration and Na$_2$O:ash ratio. A further analysis was performed in order to quantify the effects of additives like hydrated lime, sodium chloride and concrete super-plasticisers.

The main findings of this composition study were that the compressive strength is greatly increased by the geopolymer binder, even in the case of the lowest fly ash content (about 15 % in wt.); the compressive strength varies between 3 and 23 N/mm^2, for curing periods between 1 and 7 days at 60 °C. The application of this technique to the construction of rammed earth walls shows significant potential. Nevertheless, further research is required for optimizing the mixture composition in accordance with the technical and sustainability requirements of rammed earth. This will result possibly in lower binder quantities, since the strength values obtained were higher than needed for this type of structure. Authors are currently assessing the eco-efficiency of this stabilization technique and comparing it with that from soil–cement stabilization.

6 Conclusion and Final Remarks

The rammed earth building stock is large and includes several heritage places and monumental architecture, which are of great interest to preserve. There are several factors contributing to the decay of rammed earth construction; however, the most common pathologies found are cracking and loss of material. Repairing such damage is crucial in order to preserve these constructions. It should be required that the repairing materials should be similar to the original material as much as possible, which requires using earthen materials in such interventions. To refill lost volumes of material, there are several techniques that can be used, such as reconstruction by ramming earth in the damaged area or by projecting it. On the other hand, cracks can be repaired by filling or stitching.

The strengthening of rammed earth constructions is another form of preservation. The majority of the intervention techniques discussed here aim at improving the out-of-plane behaviour of rammed earth walls, which include buttressing, tie rods, grouted anchors and rendering meshes. Finally, the approach of injection of mud grouts for repairing cracks in rammed earth walls was discussed in detail.

It was shown that the clay fraction has great influence on the rheological behaviour of an unmodified mud grout. The clay particles present in the mud grout tend to flocculate to form an internal house-of-cards or scaffold structure, which opposes the flow. The addition of a deflocculant promotes the repulsion between clay particles and promotes their dispersion in the liquid phase, which weakens and disrupts the aforementioned structure. This improves the fluidity of the grouts and allows increasing the solid fraction without compromising this last property. Moreover, adding increasing amounts of silt size materials (such as limestone powder), for decreasing the clay content of the mix, also allows a further increase of the solid fraction. Thus, designing a mud grout with adequate ϕ_v (to avoid excessive drying shrinkage) demands accounting for the previous two effects.

Regarding the strength of unmodified mud grouts, it was shown that the higher the clay content, the higher the flexural and compressive strength. Nevertheless, the maximum clay content of a mud grout must be limited, since excessive clay content has a negative impact on its rheological behaviour. A compromise should be found between these properties.

The adhesion capacity of selected mud grouts was also assessed. The mud grouts recovered a reasonable part of the initial strength of the specimens (between 51 and 93 %), but not completely. However, in practical terms, this shows the great potential of the injection of mud grouts in the conservation of the rammed earth heritage.

Despite the recognized sustainability of rammed earth construction, its future in the building industry requires adopting improvement measures in order to adequate it to modern demands. Both the material and the building process can be improved for this purpose, which includes solutions such as chemical stabilization, reinforcement of the joints between blocks, introduction of vertical reinforcements (bamboo canes) and embedment of reinforced concrete structure.

Finally, it was presented and discussed an alternative chemical stabilization technique, which consists in using alkaline activated fly ash. This is a technique in development, but preliminary results on granitic residual soils showed its great capacity in improving the compressive strength. Further developments are required to optimize the mixture composition in accordance with technical and sustainability requirements.

References

1. Houben, H., Guillaud, H.: Earth Construction: A Comprehensive Guide. CRATerre—EAG. Intermediate Technology Publication, London (2008)
2. Delgado, M., Guerrero, I.: The selection of soils for unstabilised earth building: A normative review. Constr. Build. Mater. **21**(2), 237–351 (2007)
3. Jaquin, P.A., Augarde, C.E., Gerrard, C.M.: Chronological description of the spatial development of rammed earth techniques. Int. J. Architect. Herit. **2**(4), 377–400 (2008)
4. Minke, G.: Building with Earth: Design and Technology of a Sustainable Architecture. Birkhäuser, Basel (2006)
5. Jaquin, P.A.: Analysis of historic rammed earth construction. Ph.D. thesis, Durham University, Durham, United Kingdom (2008)
6. Cointeraux, F.: Traite dês Constructions Rurales et e Leur Disposition. Paris, France (1791)
7. Correia, M.: Rammed Earth in Alentejo. Argumentum, Lisbon (2007)
8. Fernandes, M.: A Taipa no Mundo. Seminário de Construção e Recuperação de Edifícios em Taipa, Almodôvar (2008)
9. Jest, C., Chayet, A., Sanday, J.: Earth used for building in the Himalayas, the Karakoram and Central Asia—Recent Research and Future trends. 6th International Conference on the Conservation of Earthen Architecture, Las Cruces, New Mexico, Getty Conservation Institute, Los Angeles (1990)
10. De Sensi, B.: Terracruda, La Diffusione Dell'architettura Di Terra—Soil, Dissemination of Earth Architecture (2003)
11. Warren, J.: Conservation of Earth Structures. Butterworth Heinemann, Bath (1999)
12. Keefe, L.: Earth Building: Methods and Materials, Repair and Conservation. Taylor & Francis, London (2005)

13. Tolles, E., Kimbro, E., Ginell, W.: Planning and Engineering Guidelines for the Seismic Retrofitting of Historic Adobe Structures. The Getty Conservation Institute, Los Angeles (2002)

14. Houben, H., Avrami, E.: Summary report, Project Terra research meeting. Plymouth University, Torquay, England (2000)

15. Costa, J.P., Cóias, V., Pifano, A.: Avantages de l aterre projetée dans la conservation structurelle du patrimoine en terre. In: Séminare: Le Patrimoine Architectural d'Origine Portugaise au Maroc: Apports à sa Conservation, Rabat, Marrocos (2008)

16. Mileto, C., Vegas, F., López, J.M.: Criteria and intervention techniques in rammed earth structures. The restoration of Bofilla tower at Bétera. Informes de la Construcción **63**, 81–96 (2011)

17. Cóias, V., Costa, J.P.: Terra Projectada: Um Novo Método de Reabilitação de Construções em Taipa. In: Achenza, M., Correia, M., Cadinu, M., Serra, A. (eds.) Houses and Cities Built with Earth: Conservation, Significance and Urban Quality, pp. 59–61. Argumentum, Lisboa (2006)

18. García, R.M.: Construcciones de Tierra. El Tapial. Nuevo Sistema para Construcción y Restauración Mediante la Técnica de "Tierra Proyectada". Ph.D. thesis, University of Granada, Granada, Spain (2010)

19. Parreira, D.J.: Análise Sísmica de uma Construção em Taipa. Tese de Mestrado. Instituto Superior Técnico, Lisboa (2007)

20. Ashurst, J., Ashurst, N.: Practical Building Conservation. Brick, Terracotta and Earth. Gower Press, Aldershot (1988)

21. Pearson, G.T.: Conservation of Clay and Chalk Buildings. Donhead Publishing Ltd, Shaftsbury (1997)

22. Lacouture, L., Bernal, C., Ortiz, J., Valencia, D.: Estudios de vulnerabilidad sísmica, rehabilitación y refuerzo de casas en adobe y tapia pisada. Apuntes **20**(2), 286–303 (2007)

23. Pérez, C., Valencia, D., Barbosa, S., Saavedra, P., Escamilla, J., Díaz, E.: Rehabilitación sísmica de muros de adobe de edificaciones monumentales mediante tensores de acero. Apuntes **20**(2), 369–383 (2007)

24. Toumbakari, E.: Lime-Pozzolan-cement grouts and their structural effects on composite masonry walls. Ph.D. Thesis, Katholieke Universiteit Leuven, Leuven, Belgium (2002)

25. Oliver, A.: Conservations of nondecorated earthen materials, In: Avrami, E., Guillaud, H., Hardy, M. (eds.) Terra Literature Review: An Overview of Research in Earthen Architecture Conservation, pp. 108–123. The Getty Conservation Institute, Los Angeles (2008)

26. Roselund, N.: Repair of cracked walls by injection of modified mud. In: Proceedings of the 6th International Conference on the Conservation of Earthen Architecture: Adobe 90 Preprints, pp. 336–341 Las Cruces, New Mexico (1990)

27. Tolles, E.L., Webster, F.A., Crosby, A., Kimbro, E.E.: Survey of Damage to Historic Adobe Buildings after the January 1994 Northridge Earthquake. The Getty Conservation Institute Scientific Program Report, Los Angeles (1996)

28. Jäger, W., Fuchs, C.: Reconstruction of the Sistani house at Bam Citadel after the collapse due to the earthquake 2003. In: D'Ayala, D., Fodde, E. (eds.) Preserving Safety and Significance, Proceedings of the VI International Conference on Structural Analysis of Historic Constructions, vol. 2, pp. 1181–1187. Bath, UK (2008)

29. Vargas, J., Blondet, M., Cancino, C., Ginocchio, F., Iwaki, C., Morales, K.: Experimental results on the use of mud-based grouts to repair seismic cracks on adobe walls. In: D'Ayala D., Fodde E. (eds.) Preserving Safety and Significance, Proceedings of the VI International Conference on Structural Analysis of Historic Constructions, pp. 1095–1099. Bath, UK (2008)

30. On Yee, L.: Study of earth-grout mixtures for rehabilitation. MSc thesis, University of Minho, Guimarães, Portugal (2009)

31. Silva, R.A., Schueremans, L., Oliveira, D.V.:(2010) Repair of earth masonry by means of grouting: importance of clay in the rheology of a mud grout. In: Proceedings of the 8th International Masonry Conference, pp. 403–412. Dresden, Germany

32. Silva, R.A., Schueremans, L., Oliveira, D.V.: Grouting as a repair/strengthening solution for earth constructions. In: Proceedings of the 1st WTA International Ph.D. Symposium, pp. 517–535. WTA publications, Leuven (2009)
33. Silva, R.A.: Caracterização experimental de alvenaria antiga: reforço e efeitos diferido. MSc. Thesis, Guimarães: University of Minho (2008)
34. Silva, R.A., Schueremans, L., Oliveira, D.V., Dekoning, K., Gyssels, T.: On the development of unmodified mud grouts for repairing earth constructions: rheology, strength and adhesion. Mater. Struct. **45**(10), 1497–1512 (2012)
35. ASTM C 939-94 : Standard test method for flow of grout for preplaced-aggregate concrete (flow cone method, American Society for Testing and Materials. West Conshohocken, PA (1994)
36. CEN. EN 1015-11 : Methods of test for mortar for masonry—Part 11: Determination of flexural and compressive strength of hardened mortar. European Committee for Standardization, Brussels (1999)
37. Van Olphen, H.: Clay Colloid Chemistry: for Clay Technologists, Geologists, and Soil Scientists, 2nd edn. Wiley-Interscience, New York (1977)
38. Andreola, F., Castellini, E., Ferreira, J.M.F., Olhero, S., Romagnoli, M.: Effect of sodium hexametaphosphate and ageing on the rheological behaviour of kaolin dispersions. Appl. Clay Sci. **31**, 56–64 (2006)
39. Legaly, G.: Colloid clay science. In: Bergaya, F., Theng, B.K.G., Lagaly, G. (eds.) Developments in Clay Science: Handbook of Clay Science, pp. 141–245. Elsevier, The Netherlands (2006)
40. Papo, A., Piani, L., Riceceri, R.: Sodium tripolyphosphate and polyphosphate as dispersing agents for kaolin suspensions: rheological characterization. Colloids. Surf. A Physicochem. Eng. Asp. **201**, 219–230 (2002)
41. Brás, A., Henriques, F.M.A.: Natural hydraulic lime based grouts—The selection of grout injection parameters for masonry consolidation. Constr. Build. Mater. **26**, 135–144 (2012)
42. NMAC.: NMAC 14.7.4: Housing and Construction: Building Codes General: New Mexico Earthen Building Materials Code, New Mexico Regulation and Licensing Department, Santa Fe, New Mexico (2006)
43. SNZ.: New Zealand Standard 4298:1998, Materials and workmanship for earth buildings, Standards New Zealand, Wellington (1998)
44. Bui, Q.B., Morel, J.C., Hans, S., Meunier, N.: Compression behaviour of non-industrial materials in civil engineering by three scale experiments: the case of rammed earth. Mater. Struct. **42**(8), 1101–1116 (2008)
45. SNZ.: New Zealand Standard 4297:1998, Engineering design of earth buildings. Wellington: Standards New Zealand, Wellington (1998)
46. SNZ.: New Zealand Standard 4299:1998. Earth buildings not requiring specific design. Wellington: Standards New Zealand, Wellington (1998)
47. Pacheco-Torgal, F., Jalali, S.: Earth construction: lessons from the past for future eco-efficient construction. Constr. Build. Mater. **29**, 512–519 (2012)
48. Maniatidis, V., Walker, P.: A review of rammed earth construction. Natural Building Technology Group, Department of Architecture & Civil Engineering, University of Bath (2003)
49. Minke, G.: Construction Manual for Earthquake-Resistant Houses Built of Earth. Gate—BASIM (Building Advisory Service and Information Network). Eschborn, Germany (2001)
50. Gomes, M.I., Lopes, M., Brito, J.: Seismic resistance of earth construction in Portugal. Eng. Struct. **33**(3), 932–941 (2011)
51. Walker, P., Keable, R., Martin, J., Maniatidis, V.: Rammed earth: design and construction guidelines. BRE Bookshop, Watford (2005)
52. Jaquin, P.A., Augarde, C.E., Gallipoli, D., Toll, D.G.: The strength of unstabilised rammed earth materials. Géotechnique **59**(5), 487–490 (2009)
53. Jaquin, P.A., Augarde, C.E.: Earth Building: History Science and Conservation. Bre Press, Bracknell (2012)

54. Reddy, B.V.V., Kumar, P.P.: Embodied energy in cement stabilised rammed earth walls. Energy and Buildings **42**, 380–385 (2010)
55. Lax, C.: Life cycle assessment of rammed earth. MSc. thesis, University of Bath, United Kingdom (2010)
56. Escobar, M.C.: Rammed earth: feasibility of a global concept applied locally. MSc. thesis, University of Minho, Portugal (2011)
57. Cristelo, N., Glendinning, S., Miranda, T., Oliveira, D.V., Silva, R.A.: Soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction. Constr. Build. Mater. **36**, 727–735 (2012)