Accepted manuscript of the article published in
Testing and Characterisation of Earth-based Building Materials and Elements : State-of-the-Art Report of the RILEM TC 274-TCE,
part of the RILEM State-of-the-Art Reports book series (Volume 35), pp 211-241.
The final publication is available at Springer via https://doi.org/10.1007/978-3-030-83297-1_6

Chapter 6 Durability of earth materials: weathering agents, testing procedures and stabilisation methods

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Abstract

This chapter reviews the potential impact of six environmental agents (water, ice, wind, fire, solar radiation and chemical attack) on the long-term stability of earth buildings together with some of the most common techniques for measuring and improving material durability. Liquid water appears the most detrimental of all environmental agents, not only because it can significantly reduce capillary cohesion inside the material but also because water can penetrate inside buildings through multiple routes, e.g. rainfall, foundation rise, ambient humidity and utilities leakage. Water can also be very damaging when it is present in solid form as the expansion of pore ice may induce cracking of the earth material. The high resistance of earth buildings to wind is instead proven by the good conditions of many historic structures in windy regions. Earth buildings also exhibit good resistance to fire as the exposure to very high temperatures may even improve material durability. Solar radiation has, in general, a beneficial effect on the stability of earth buildings as it promotes water evaporation with a consequent increase of capillary cohesion. Solar radiation may, however, have a detrimental effect if the earth is stabilised by organic binders that are sensitive to photodegradation because, in this case, it may produce material damages ranging from a simple surface discoloration to a much more serious degradation of the intergranular bonds. Unstabilised earth is generally inert and, hence, largely unaffected by chemicals though, in some instances, the precipitation of salt crystals in the pore water can induce material cracking. Chemical degradation can instead be severe in both stabilised earth (due to the dissolution of intergranular bonds) and steel-reinforced earth (due to the corrosion of rebars). No international standard protocol exists to measure the durability of earth materials, which is currently assessed by multiple experimental procedures depending on which environmental agent is considered. Testing standards may, however, be devised in the future by differentiating between weathering protocols, which reproduce the effect of each agent on the earth, and durability protocols, which adopt a fixed experimental procedure to measure the same material property regardless of weathering history.

6.1. Introduction

Raw earth is one of the oldest materials ever used for the construction of human dwellings. The first records of earth buildings date back to the Neolithic period around 8000 BC and have been found in Mesopotamia, a region roughly corresponding to modern Iraq (Wright, 2005). Different civilizations along the southern Mediterranean coast have subsequently embraced the use of earth as a construction material. For example, Egyptians were familiar with adobe construction between 2000 and 1000 BC, as suggested by the Exodus Book of the Old Testament, which mentions that the Pharaoh commanded that Israelites should not be given straw to make bricks.

Earth construction evolved over the years and led to the manufacture of fired earth bricks, which produced a step change in the construction of masonry structures. The first fired earth bricks appeared in Mesopotamia during the Early Bronze period, i.e. around the 3rd millennium BC. However, their use became widespread much later, from the 4th century BC onwards, when the Greeks, and later the Romans, disseminated a viable earth firing technology across Europe and beyond. This led to the construction of masonry structures not too dissimilar from current ones. The oldest standing fired brick building in the world is probably the Theatre of Marcellus in Rome (Italy), which was built between the 13 and the 17 BC, during the last years of the Roman republic. In the 16th century, an extra floor was built on top of the ancient roman structure to host the apartments of the Orsini’s, an influential family of the Italian Renaissance. The durability of the original building is demonstrated by the fact that some of these apartments are still inhabited nowadays.

The oldest standing raw earth buildings are instead found in the Taos Pueblo (USA), which is a complex of ancient adobe dwellings currently inhabited by about 150 people. This complex is much younger than the Theatre of Marcellus as it dates back to about one thousand years ago (Heathcote, 1995). The buildings of the Taos Pueblo have been preserved in their current state thanks to regular maintenance consisting in the application, every year, of a sacrificial earth render on the external surface to protect the underneath structure from weathering.

As suggested by the above examples, many of the oldest standing buildings worldwide are made of fired earth despite the younger age of this material compared to raw earth. This is because of the relatively good durability of fired earth, which is due to the treatment of the material at high temperatures between 900 °C and 1100 °C. This induces the transformation of the clay fraction into metamorphic rock and therefore increases the resilience to weathering (Bruno et al., 2019). Unfortunately, the thermal treatment also increases embodied energy and manufacturing costs while reducing moisture buffering capacity and hygrothermal inertia, which explains why fired brick structures exhibit higher construction and operational costs than raw earth ones. Civil engineering research has therefore been focusing on the development of novel stabilisation methods that improve the durability of raw earth while preserving its advantageous environmental prerogatives and low financial costs.

This chapter reviews the main weathering agents that affect the durability of earth buildings and describes the physical mechanisms through which each of these agents weakens the material. The chapter also discusses some of the laboratory procedures that are currently used to estimate the long-term durability of raw earth exposed to environmental actions. Finally, it examines the main stabilisation techniques that have been employed to increase the weathering resilience of earth materials and, therefore, to enhance their long-term durability.

6.2. Weathering actions

This section describes the main environmental actions that affect the durability of raw earth and presents examples of the impact of these actions on earth buildings across the world.

6.2.1 Water

The strong affinity between soil and water is the main cause of the large hygrothermal inertia of raw earth and explains the high energy efficiency of walls that are made of this material. Unfortunately, the affinity between soil and water is also the cause of the poor durability of earth buildings when exposed to rainfall or capillary rise from the foundation ground. An increase of water content in the earth pores produces a decrease of capillary tension, which in turn reduces both the stiffness and strength of the material (Jaquin et al., 2009; Gerard et al., 2015; Fabbri and Morel, 2016; Bruno et al., 2018). The mechanical deterioration of earth materials at high water contents has been experimentally observed both in the laboratory, at the scale of small samples, and in the field, at the scale of building walls.

In general, as long as the water content stays between 3% and 4%, the strength and durability of unstabilised earth remain relatively large. For example, Quagliarini et al. (2010) found that the compressive strength of adobe walls ranged between 0.8 MPa and 1.2 MPa when the water content was 2.45%, which corresponded to equilibrium conditions under an ambient humidity of 47%. Quagliarini et al. (2010) also observed that this level of strength can ensure a relatively large margin of safety at the base of a two-storey earth building.

Nevertheless, an increase of water content can produce a noticeable reduction of both strength and stiffness. For example, Bui et al. (2014) showed that an increase of water content from 2% to 12% reduces the strength and stiffness of compacted earth by a factor larger than four. The wetting of poorly compacted earth walls can also result in the collapse of buildings, as shown by Scarato and Jeannet (2015), who concluded that the main cause of pathologies in rammed earth buildings was the abnormal increase of pore moisture at the interface between walls and foundations. This increase of pore moisture may be caused, for example, by the accumulation of water in adjacent backfills or by the run-off from nearby slopes, which promote groundwater infiltration and favour capillary rise through the building foundations. Figure 6-1 shows the failure of an earth building in Lyon (France), which was produced by a large increase of water content at the wall base. The wetting-induced collapse of poorly compacted earth can also be explained by means of constitutive models that predict the stress-strain response of unsaturated soils, as proposed by geotechnical engineers over the past decades (e.g. Alonso et al., 1990; Lai et al., 2015; Gallipoli and Bruno, 2017).

Figure 6-1 Collapse of an earth building in Lyon, France, due to the accumulation of humidity at the wall base.

The occurrence of drying-wetting cycles, caused for example by fluctuations of indoor and outdoor humidity, can also induce the periodic shrinkage-swelling of earth materials with a consequent deterioration of mechanical properties (Champiré et al., 2016; Bruno, 2016). Shrinkage-swelling cycles are associated to the progressive reorientation, or reorganization, of earth particles (Basma et al., 1996; Nowamooz and Masrouri, 2008), which may in turn promote cracking and erosion. The impact of shrinkage-swelling cycles on the long-term performance of earth buildings has not yet been accurately quantified, but it depends on both the material type (i.e. mineralogy, grain size distribution) and the construction technique (i.e. compressed earth blocks, rammed earth, adobe, cob).

For centuries, the water durability of raw earth has been enhanced through chemical stabilisation with cement or lime (e.g. Walker, 1995; Parracha et al. 2019a). An example of well-preserved ancient earth structure is Paderne Castle in Algarve (Portugal), which was built in the 12th century by using earth stabilised with air lime (Figure 6-2). Alternative stabilisers, including unusual options such as cow dung (Millogo et al., 2016) or plant aggregates (Laborel-Préneron et al., 2016), have also been employed to reduce environmental impact (Maskell et al., 2014).

Figure 6-2 Paderne Castle in Algarve, Portugal, built in the 12th century by using earth stabilised with air lime.

In general, stabilisation improves water durability but the chemical interaction between the binder and the earth produces a modification of the porous structure. This generates a number of negative side effects including a reduction of moisture buffering capacity (and, hence, hygrothermal inertia), a faster deterioration of mechanical characteristics during fire or freeze-thaw cycles and the impossibility of recycling the earth upon demolition.

6.2.2 Ice

The impact of freeze-thaw cycles on the durability of earth buildings has been scarcely studied in the literature probably because earth buildings are mostly located in temperate regions where frost is unlikely. This means that the suitability of raw earth as a building material in freezing climates remains to be fully ascertained.

Current evidence suggests that the periodic transition between liquid and solid states causes the volumetric variation of pore water and the consequent application of a cyclic pressure on the granular skeleton, which may result in the deformation, spalling and erosion of earth walls. The magnitude of frost damages depends on both the amount of free water present inside the pores and the specific composition of the earth. Damages may range from the appearance of small defects on the wall surface to a deeper alteration of structural integrity (Maniatidis and Walker, 2003). Surface defects comprise cracks, flakes, blistering, peeling, loss of adhesion and boniness while structural defects consist in the occurrence of large settlements that are generally associated to foundation uplift and/or earth bulging at the wall base. In general, higher levels of porosity, especially if associated to the presence of relatively big voids, better accommodate the volumetric variation of pore water during phase change and therefore increase frost durability. This explains why highly porous handmade loam adobes are more resistant to frost than dense extruded clay bricks.

The cohesive strength of unstabilised earth is mainly ensured by the bonding action of capillary water lenses at inter-granular contacts, which is stronger at higher clay contents. Because of this, finer materials tend to be more sensitive to freeze-thaw cycles than coarser ones as discussed by Minke (2006), who suggested that a reduction of clay content below 16% significantly reduces the vulnerability of raw earth to frost erosion. Rammed earth walls tend to exhibit relatively low clay content, which explains why this construction technique appears better suited to cold climates than other ones.

Aubert and Gasc-Barbier (2012) suggested that the loss of cohesion caused by freezing–thaw cycles during the cold season may generate micro-cracks inside the earth, which then grow during the hot season as a consequence of desiccation (Minke, 2006). This progressive opening of cracks augments water adsorption during the subsequent cold seasons and therefore accelerates the degradation of the material. Aubert and Gasc-Barbier (2012) also indicated that freezing–thaw cycles tend to harden the intact earth between cracks and may therefore produce a local reduction of material porosity.

Earth buildings tend to be more vulnerable to frost when the amount of moisture inside the material pores is higher. This is, for example, the case immediately after construction when water content is uniform and generally high across earth walls. Delong (1959) monitored buildings constructed during the winter season, when temperatures were less than zero degrees Celsius, and concluded that freeze-thaw cycles cause a progressive loosening of the granular structure in freshly posed earth. In the same way, earth foundations are not durable in freezing climates because of their high water content which is caused by capillary rise from the underlying ground. The incorporation of thermal insulation inside perimeter walls should also be carefully considered in freezing climates as the presence of a heat barrier lowers the temperature of outermost part of the wall, thus facilitating water condensation and increasing vulnerability to frost.

The effects of freeze-thaw cycles on earth buildings are here demonstrated by the analysis of two cases from the United States. The first case is the Irving House (Figure 6-3), which is located in the region of Geneva, New York. The National Centers for Environmental Information (2018) indicates that, in this region, the average high temperature is 14℃ while the average low temperature is 4℃ with extreme values of 35℃ and -22℃. The Irving House was built in 1846 with unfired earth bricks made of clay, sand, gravel, organic matter and water (with a clay content ranging between 8% and 22%). The blue frame in Figure 6-3 indicates the part of Irving House that is made of adobe bricks. The external wall surface was protected with the typical render used in this region during the 19th century, which included one volume of clay, one volume of sand, one volume of lime, one volume of ash and half volume of beef blood together with fibres such as horsehairs or straw (Ricaud, 2014).

The second case is the Jackson-Einspahr House (Figure 6-4), which is located in Holstein, Nebraska. The National Centers for Environmental Information (2018) indicates that, in this region, the average high temperature is 17℃ while the average low temperature is 4℃ with extreme values of 39℃ and -25℃. The Jackson-Einspahr House was built in 1881 with unfired earth bricks made of clayey soil covered with Prairies grass earth clump, a material locally known as “sod” (“motte de terre” in French), without any mortar (Ricaud, 2014). The original roof was made of wooden boards covered with tarpaper.

The climates of the above two regions are relatively similar and are characterised by the widespread occurrence of frost in the cold season. Yet, comparison of Figure 6-3 and Figure 6-4 indicates that the Irving House is relatively well-preserved, apart from some localised defects on the inner wall surface, while the Jackson-Einspahr House shows extensive signs of weathering. This difference may be due to the regular application of a protective render on the external wall surface of the Irving House, which was not the case for the Jackson-Einspahr House. The application of this protective coating significantly reduced the impact of freeze-thaw cycles on the underlying earth structure. The above observations emphasize the importance of the regular inspection of exposed walls in freezing climates, which is necessary to detect the early signs of cracking or spalling and to ensure the timely remediation of the protective coating (Kinuthia, 2015).

Figure 6-3 a) Irving House built in 1846 in Geneva, New York State, USA (the blue frame indicates the part built in adobe), b) adobe bricks in the attic of Irving House (Ricaud, 2014).

Figure 6-4 Jackson-Einspahr House built in 1881 in Holstein, Nebraska State, USA (Ricaud, 2014).

Earth buildings must comply with standard construction codes, which typically include norms to limit the damage caused by frost. To satisfy these requirements, it is virtually inevitable to stabilise the earth by using a combination of chemical binders such as cement, lime or resins (Guettala et al., 2006; Liu et al., 2010), fibre reinforcement and mechanical densification (Perrot et al., 2018). The use of superplasticisers also allows reducing the amount of water inside earth concretes, which in turn increases the density and strength of the material while reducing frost vulnerability (Ouellet-Plamondon and Habert, 2016).

The durability of chemical stabilisers to freeze-thaw cycles is another important aspect to consider. Guettala et al. (2006) showed that a clayey sand stabilised with 8% cement/resin exhibited a small mass loss of about 1.8% after undergoing twelve freeze-thaw cycles according to the American norm ASTM D560 (2016). On the contrary, the same material stabilised with 8% lime exhibited a more than twofold mass loss of 3.7%. Based on these results, Guettala et al. (2006) recommended that compressed earth bricks should be compacted to a pressure of at least 10 MPa and stabilised with 5% cement to maximise frost resilience. A similar study by Shibi and Kamei (2014) highlighted that a kaolinitic earth stabilised with 5% cement exhibited a 50% reduction of compressive strength after five freeze-thaw cycles. Shibi and Kamei (2014) also observed that the addition of 5% to 20% of basanite, i.e. hemihydrate calcium sulfate $CaSO_4 \cdot 1/2\ H_2O$, and 10% to 20% of coal ash noticeably improved the freeze-thawing resistance of the material. Note that the vulnerability to frost depends on the characteristics of both the earth and the stabiliser, thus it is advisable to test different types of stabilisers with the chosen earth prior to embarking on the construction of a building.

6.2.3 Wind

Wind is another environmental action that undermines the durability of earth structures by causing either immediate or progressive damages (Warren, 1999). Immediate damages are relatively uncommon and are the result of exceptionally strong winds (e.g. hurricanes, cyclones or typhoons), whose turbulence generates high pressure differentials across structural elements and may therefore lead to failure (Khanduri et al., 1998). On the contrary, progressive damages are much more common and are the result of weak to moderate winds, which drive slow erosive processes that endanger the long-term durability of unmaintained buildings (Obonyo et al., 2010). Progressive damages are associated to the formation of small air eddies and vortices that attack the surface of earth buildings by continuously removing loosely bonded particles. The intensity of this erosive process mainly depends on the momentum of the wind impacting the building walls (Warren, 1999).

Progressive erosion occurs according to different mechanisms depending on whether it takes place in arid or wet environments. In arid environments, moisture shortage augments the availability of loose particles that are lifted by the moving air, thus increasing the kinetic energy of the wind (Lian-You et al., 2003). A wind of sufficiently high speed may carry suspended particles from near or distant dry lands such as deserts (Chepil and Woodruff, 1963). The suspended particles hit the building either directly or after bouncing on the ground, thus contributing to the progressive erosion of the wall surface. As erosion progresses, additional particles are detached from the building and become available to be lifted by the wind, thus enhancing the abrasion of the wall surface. Conversely, in wet environments, moisture-laden winds can penetrate the earth walls (Huang and Peng, 2015) and therefore weaken the capillary bonds between grains (Jaquin et al., 2009). A sequence of dry and wet winds can also induce cyclic variations of moisture content inside the exposed earth, which causes the periodic shrinkage-swelling of building walls especially in the presence of expansive clays (Walker, 2004). Swelling is produced by an increase of moisture content inside the earth and may cause the detachment of protective coatings (Warren, 1999) while shrinkage is produced by a decrease of moisture content and may cause cracking. The periodic variation of moisture content can also induce a migration of salts from the core to the surface of the walls, which can lead to the appearance of efflorescences and subflorescences that can cause the detachment of protective coatings (Oliveira et al., 2013).

Progressive damage advances very slowly and it is therefore mostly visible in historical buildings that have been exposed to the action of wind for centuries. Good examples of the progressive damages caused by wind can be observed in some sections of the Great Wall of

China (Lian-You et al., 2003), the Alhambra palace in Spain (Fuentes-García, 2015) and the Paderne Castle in Portugal (Cóias and Costa, 2006). Figure 6-5 shows an example of the progressive erosion caused by the wind at the base of a rammed earth wall of the Paderne Castle. Due to the slow progression of damages, serious consequences can generally be avoided by applying a protective render on the exposed walls and/or by periodically replacing the eroded material (Gomes et al., 2016).

Figure 6-5 Erosion at the base of a rammed earth wall in Paderne Castle, Portugal.

6.2.4 Fire

Fire is an accidental action which can have devastating consequences on the performance of buildings and the life of occupants. During a blaze, the combustion of materials generates toxic smoke and gas, whose inhalation is the main cause of death. Combustible and hazardous materials include textile fabrics, furniture, wall paper and paint, carpeting, insulation and plastic household materials (Jones et al., 1987). Moreover, the combustion of timber beams and columns, which are frequent in the roofs and floors of earth buildings, not only produces harmful smoke and gas, but also reduces the cross section of structural elements and may ultimately lead to the collapse of the building (Buchanan, 2000).

Conventional construction materials, such as concrete (Ali et al., 2004), steel (Laím et al., 2014) and masonry bricks (Russo and Sciarretta, 2013), are non-combustible, though the exposure to high temperatures may eventually produce a degradation of their structural performance. Earth materials with densities higher than 1700 kg/m^3 are also deemed non-combustible according to the German norm DIN 4102 (1998) and are expected to withstand the actions of fire and high temperatures (Minke, 2006; Schroeder, 2016; Siavichay and Narváez, 2010; Bestraten et al., 2011). Instead, earth materials with densities lower than 1700 kg/m^3 often incorporate reinforcing fibres and their resistance to fire therefore depends on the amount of combustible components.

The prolonged exposure to fire can generate different types of damages inside earth materials. Unstabilised clayey earth tends to shrink and crack when exposed to high temperatures while unstabilised coarse earth experiences a loss of cohesion that is the consequence of the evaporation of the inter-granular capillary water lenses that bond particles together (Houben and Guillaud, 2008). In stabilised earth, high temperatures may instead promote chemical reactions that undermine inter-particle cementation and therefore lead to a disaggregation of the material. Finally, spalling can also occur in low porosity earth because of the build-up of pore vapour pressures at high temperatures (Kodur and Phan, 2007).

Unfortunately, very little experimental investigation is available about the response of earth structures to fire. This lack of experimental data, together with the large diversity of earth materials and manufacturing methods, does not allow a simple definition of the mechanisms through which fire affects earth buildings. It may even be possible that the exposure of unstabilised earth to fire improves, rather than degrading, the mechanical performance of the material by transforming the clay fraction of the earth into metamorphic rock. This hypothesis is consistent with the production of fired earth bricks, which rely on the lithification of clay minerals at high temperatures to increase strength and stiffness (Cultrone et al., 2001). However, the chemical, physical and mechanical modifications undergone by the clay fraction during fire depend on the mineralogy of the earth and the modality of exposure to high temperatures (Fernandes et al., 2010; Krakowiak, 2011). At this stage, it is therefore difficult to speculate whether the overall effect of the exposure of an earth building to fire will consist in an improvement or degradation of mechanical properties. Finally, with reference to hygroscopic properties, the mineralogical transformation undergone by the clay at high temperatures entails a reduction of the moisture buffering capacity of unstabilised earth and, hence, a decrease of the hygro-thermal inertia of building walls (Bruno et al., 2019).

6.2.5 Solar radiation

Solar radiation propagates in the atmosphere as electromagnetic waves, which are classified as UV-A, UV-B and UV-C radiations according to their wavelength and photon energy (Table 6-1).

Table 6-1 UV radiations present in sunlight

Solar radiation	**Wavelength (nm)**	**Photon energy (eV)**
UV-A (long-wave)	315 - 400	3.10 - 3.94
UV-B (medium-wave)	280 - 315	3.94 - 4.43
UV-C (short-wave)	100 - 280	4.43 - 12.4

Generally, UV radiation has a beneficial effect on the mechanical characteristics of freshly posed unstabilised earth as it increases the material temperature and therefore promotes the evaporation of excess pore water. This facilitates the development of capillary pore water tensions, which are the main source of inter-particle bonding, thus increasing strength and stiffness (Jaquin et al., 2009; Beckett and Augarde, 2012; Bui et al., 2014; Bruno et al., 2017a). For the same reason, UV radiation may negatively affect the cure of freshly posed stabilised earth, especially in the presence of mineral binders that require either moisture for hydration (e.g. hydraulic limes) or carbon dioxide for carbonation (e.g. air limes).

Exposure to solar radiation can also reduce the durability of "photosensitive" binders that react with the photon energy of UV rays (Andrady et al., 1998). This is, for example, the case of polymeric binders, either synthetic (e.g polyvinyl acetate, acrylic or latex emulsions) or natural (e.g. resins, waxes, oils, fats). These binders are effective in improving the mechanical properties of the earth (e.g. Kebao and Kagi, 2012; Eires et al., 2016) but they contain chromophoric groups, such as carbon-carbon (C=C) and carbonyl (C=O), that absorb the photon energy of UV radiation. The exposure to UV radiations can therefore cause photo-reactions that induce a gradual degradation of the chemical bonds inside the binding phase (e.g. Melo et al., 1999; Azwa et al., 2013; Zakaria and Rosnan, 2015). This degradation starts with a yellow discoloration of the material and then evolves into the chain scission of chromophoric groups, which generates the embrittlement of the binder and the formation of micro-cracks.

The transition from a simple discoloration to mechanical degradation is gradual and is controlled by the exposure time (Azwa et al., 2013). This detrimental effect of UV radiation is even more critical in warmer climates as high temperatures accelerate the deterioration of polymeric binders and produce a faster weakening of the stabilised earth (Tien et al., 2014). Mechanical degradation is also faster in wetter climates as rainwater continuously washes the weathered surface and exposes a fresh undamaged layer of material to UV radiation. Finally, ozone depletion increases the intensity of UV-B radiation and may also accelerate the deterioration of polymeric stabilisers.

6.2.6 Chemical agents

The durability of earth materials may be undermined by chemical agents that are routinely found in the environment (Bui et al., 2009; Grossein, 2009; Mamlouk and Zaniewski, 2011). The impact of these agents is most significant if the earth is stabilised with chemical binders or reinforced with steel (Ciancio and Robinson, 2011; Bui et al., 2019). Steel reinforcement is currently employed in stabilised rammed earth, though it is not recommended in unstabilised earth due to the lack of mechanical anchorage. Rebar schedules are usually selected following the same design codes of reinforced concrete but construction processes are very different as rammed earth is compacted rather than poured in place. A careful compaction of the earth around rebars is crucial to allow a good adhesion of the material to the embedded reinforcement. To ensure this, vertical rebars are installed before the earth is compacted around them while horizontal rebars are periodically placed, during subsequent compaction lifts, making sure that they properly sit on the underlying earth.

High concentrations of chloride ions can cause the corrosion of steel bars and can therefore adversely affect the performance of reinforced earth (Mamlouk and Zaniewski, 2011). Chlorides may be either inherent to the earth or may be artificially introduced by mixing the earth with contaminated water (e.g. salt water). Moisture laden winds can also carry chlorides that penetrate the building surface and then migrate towards the core of the walls (Grossein, 2009). Sulphates are other salts that are also inherent to soils and exist in cement, groundwater, seawater, industrial waste and acid rain. Sulphate hydration products attack the inter-particle bonds of cement stabilised earth and provoke the progressive weakening of the material. For this reason, sulphate-resisting cements should always be used to stabilise earth materials that contain notable amounts of sulphate salts. Note that both chlorides and sulphates are also commonly present in earth materials that are contaminated with animal excrements.

Chlorides and sulphates are highly hygroscopic salts, which are easily dissolved inside pore water. In the presence of a hydraulic gradient, the dissolved salts are then transported to the wall surface where they produce a local increase of concentration. As pore water evaporates, the salts precipitate causing efflorescences on the wall surface or subflorescences behind the wall surface (this is, for example, the case when a vapor barrier is present). Subflorescences are particularly damaging because they are associated to a precipitation of salt crystals inside the material pores, which causes the development of swelling pressures and, hence, the formation of cracks. The above degradation mechanisms may also affect unstabilised earth walls, which are normally classified as resilient to chemical attacks. In reinforced earth, the growth of crystals and the formation of cracks may expose steel elements to weathering, which in turn provokes corrosion.

Carbonation is another chemical process that can undermine the durability of reinforced earth walls. This process consists in the slow reaction of the carbon dioxide from the atmosphere with the calcium hydroxide produced by the hydration of Portland cement in stabilised earth (Mamlouk and Zaniewski, 2011). This reaction produces calcium carbonate, which increases material strength and stiffness but also causes the acidification of the pore water and hence promotes the corrosion of steel reinforcements. Moreover, Portland cement is vulnerable to acids and a decrease of pH inside the pore water can facilitate the dissolution of the binding fraction in stabilised earth. Note that earth acidification can be produced not only by exposure to carbon dioxide but also to sulphur dioxide and other types of industrial waste.

A highly alkaline environment can also undermine the long term durability of earth buildings. High pH levels may transform the silica naturally present in soils into gels, which absorb water and expand in volume, thus causing the formation of cracks inside earth walls. This transformation takes place if alkaline cements, or alkali-reactive aggregates, are present at high moisture contents. Therefore, low alkaline binders, such as blast furnace slag or pulverised fuel ash, should preferably be used for the construction of basements and foundations, which are directly exposed to water due to capillary rise from the underlying ground.

C-S-H hydrates are the principal component of the binding fraction of cement-stabilised earth materials (Mamlouk and Zaniewski, 2011). These hydrates cause the viscoplastic behaviour of the material under load, which is due to the rearrangement of C-S-H particles at nanoscale level. This phenomenon, which may be explained by the free-volume dynamics theory of granular physics (Rossi et al., 2014), is one of the main sources of creep in cement-stabilised earth materials (Bui and Morel, 2015). C-S-H hydrates are instead absent in unstabilised earth where the occurrence of creep is rather the consequence of the propagation of micro-cracks under load (Bui and Morel, 2015). Loaded earth may experience the formation of micro-cracks, which produce a hygric imbalance within the material and the consequent generation of pore water pressure gradients. This further helps the propagation of micro-cracks and the manifestation of creep, which is often associated to a progressive decrease of stiffness at the structural scale.

6.3. Field measurement of durability

Bui et al. (2009) published one of the first long-term experimental study of the durability of full scale earth walls exposed to environmental actions. In this study, unstabilised and lime stabilised rammed earth walls with a thickness of 400 mm were exposed to the wet continental climate of Grenoble (France) for a period of 20 years while surface erosion was measured by stereo-photogrammetry. The final erosion depth was about 2 mm (0.5% of the wall thickness) for the lime stabilised walls and about 6.4 mm (1.6% of the wall thickness) for the unstabilised walls. In a similar study, Faria et al. (2012) investigated the durability of rammed earth walls exposed for a decade to the weather of Serpa (Portugal). Both studies from Bui et al. (2009) and Faria et al. (2012) concluded that lime stabilisation reduces surface degradation and erosion rate, though the durability remained acceptable even for the unstabilised walls.

In 2014, a small earth building was erected in a semi-rural area 3 km from the Atlantic coast of Portugal (Figure 6-6), which is characterised by the prevalence of strong rains and winds from the South. The walls of the building were made of stabilised lightweight cob with reed fibres, lime putty and pozzolan. The walls were manufactured in a sequence of 10 cm cob lifts separated by layers of reeds, which were supported by a concrete foundation and covered by a thermally insulated roof. A detailed description of the wall material and building technology is given in Val et al. (2015) and Carneiro et al. (2016). The North and East walls of the building were left unprotected and directly exposed to the atmosphere, while the South and West walls were lightly protected by a lime wash (Figure 6-6a). The building was continuously monitored since construction and no sign of significant erosion were detected after 5 years, at which time the walls were rendered with an air lime stabilised earth mortar (Figure 6-6b).


(a) (b)

Figure 6-6 Reed-cob experimental cellule: a) shortly after construction with unrendered walls and b) five years after construction during the application of a protective render on the wall surface.

6.4. Laboratory measurement of durability

Field studies provide the most accurate assessment of the durability of earth buildings but they are rare because of the high financial costs and lengthy execution times. Laboratory tests are much more common but it remains uncertain whether they are representative of the actual performance of earth buildings (Walker, 2002). Distinct laboratory tests have been proposed to assess the durability of earth materials exposed to different environmental actions. This has contributed to the proliferation of experimental protocols, which has in turn impeded the formulation of widely accepted standards. In this section some of the existing methods are reviewed and a possible way to simplify and unify current approaches is proposed.

6.4.1 Water

Several laboratory tests have been devised to assess the durability of earthen materials exposed to liquid water. These tests can be grouped in three main families depending on the modality of application of the action and the particular material behaviour under investigation. The first family of tests assesses the resilience of the earth material to the erosion caused by water impact and includes the Accelerated Erosion Test (AET), the Geelong Drip Test and the Swinburne Accelerated Erosion Test (SAET), which are described in the Australian earth building handbook (Walker, 2002). Due to the important role played by the kinetic energy of the impacting water, these tests are better suited to assess the durability of the earth materials under the combined action of water and wind. Instead, the second family of tests has been devised to assess the durability of earth materials when exposed to standing, or slowly flowing, water. It includes the wet-dry appraisal test of the Australian earth building handbook (Walker, 2002), the contact test, the swelling/shrinkage test of the French standard AFNOR XP-P13-901 (2001) and the suction and dip tests of the German standard DIN 18945 (2013). Finally, the third family of tests quantifies the potential mechanical collapse of earth materials subjected to wetting and requires the performance of confined or unconfined compression tests on earth samples at different degrees of saturation.

6.4.2 Ice

Laboratory tests have also been devised to evaluate the durability of earth materials exposed to freeze-thaw cycles. Some of these tests have been adapted from geotechnical standards that are commonly employed to assess the frost durability of road pavements or railway tracks. In many cases, however, these standards tend to be unnecessarily harsh because of the tougher mechanical actions experienced by geotechnical infrastructure compared to earth buildings. For example, some procedures accentuate material weathering by brushing the sample surface after each freeze-thaw cycle (ASTM D560, 2016), which has been criticised by Shihata and Baghdahi (2001) as excessively severe for earth building applications.

Current test protocols generally measure the mass loss experienced by earth samples subjected to a number of freeze-thaw cycles. These procedures mainly differ for the modalities of preparation, curing and equalization of the samples as well as for the imposed temperature cycles (Kinuthia, 2015). Properties such as compressive strength (Simonsen and Isacsson, 2001), tensile strength (Akagawa and Nishisato, 2009) and ultrasound wave velocity (ASTM D2848-08, 2017) can also be measured after each freeze-thaw cycle to infer the durability of the material.

One important mechanism through which freeze-thaw cycles undermine the durability of earth buildings is the development of tensile stresses inside exposed walls, which is caused by the volumetric change of pore water during the transition between liquid and solid states. The reproduction of this mechanism during laboratory experiments is often deliberately amplified by humidifying the samples after each freeze-thaw cycle to compensate for the water lost during the previous test stages. This humidification augments the damages caused by the expansion/contraction of the pore water during the change of phase and has been considered overly severe by some authors (Aubert and Gasc-Barbier, 2012).

6.4.3 Wind

No standard tests exist to quantify the durability of earth materials to the action of wind, though a number of authors have proposed experimental procedures to this effect. The peeling test (Drdácký et al., 2014) is a simple procedure that can be performed both in the laboratory or in-situ to assess the cohesion of the earth surface (Faria et al., 2016). Similarly, the wearing test of the American standard ASTM D559 (2015) quantifies the erosion produced by the stroke of a wire brush on the surface of an earth sample. The Accelerated Erosion Test (AET), the Geelong Drip Test and the Swinburne Accelerated Erosion Test (SAET) (Walker, 2002) are also good options to assess the durability of earth materials under the combined actions of wind and water, as previously discussed.

At a larger scale, Lian-You et al. (2003) and Qu et al. (2007) investigated the erosion of adobe buildings by driven sands inside a laboratory wind tunnel. A relatively large earth sample was placed at the end of the working section of a wind tunnel while the tunnel floor was covered with a bed of sand. During the test, the sand was lifted and carried by the wind, thus enhancing the erosion of the earth sample, which was quantified by measuring the mass loss at the end of the experiment. This is a relatively fast test as the sample is exposed to the wind for a relatively short time, between 10 and 60 minutes depending on the wind speed. Moreover, the speed of the wind and the size of the sample can be varied to account for different in-situ conditions. Han et al. (2014) also proposed the use of portable wind tunnels, with a length of about 13 m, to perform an in-situ evaluation of wind erosion on real buildings.

Past studies have generally highlighted the importance of the abrasive action exerted by wind-driven particles, especially in arid climates. This is an important aspect that will have to be duly considered during the development of future experimental standards.

6.4.4 Solar radiation

In the absence of standard experimental protocols, a realistic approach for assessing the effect of solar radiation ondurability consists in the measurement of the photodegradation experienced by earth samples after in-situ weathering (Marston, 2002). Photodegradation can be measured both at the macroscopic scale, by means of standard laboratory tests, and at the microscopic scale, by Fourier Transform Infrared or X-Ray diffraction tests (Cadena and Acosta, 2014). The latter tests provide information about the changes of structure and mineralogical composition experienced by the material after exposure to UV radiations. Natural in-situ weathering, albeit inexpensive, is however lengthy and may prove inaccurate due to the simultaneous action of multiple environmental agents, which make impossible to isolate the effect of solar radiation. Because of this, a number of laboratory protocols have been devised to reproduce the weathering caused by UV radiations. These protocols have the advantage of being much faster than field weathering, though their representativeness of the actual degradation mechanisms in-situ remains debatable (Beninia et al., 2011). One of these protocols consists in exposing the earth samples to the UV-A or UV-B radiations of electric lamps inside a degradation chamber equipped with a ventilation system to avoid excessive heating (Cadena and Acosta, 2014). This replicates the action of short wavelength radiation by the sun, which is mostly responsible for the photodegradation of stabilised earth (Jones, 2002). Another protocol makes instead use of filtered xenon arc lamps, which have the advantage of producing a radiation that is similar to that of sunlight throughout the UV spectrum, together with the possibility of generating monochromatic radiations (Jones, 2002). This latter feature allows quantifying the material degradation caused by different radiation wavelengths. Generally, both artificial and natural polymeric binders exhibit higher degradation rates when exposed to shorter radiation wavelengths (Andrady et al., 1998).

6.4.5 Fire and chemical agents

Very little research has been undertaken to assess the impact of fire and chemical agents on the durability of earth materials. In the absence of suitable experimental standards, the durability of raw earth exposed to fire or chemical agents can be assessed by means of conventional laboratory tests that are routinely employed to characterise the hydromechanical behaviour of construction materials. These tests may be performed before and after material weathering to compare results and, hence, to assess the durability of the earth. Similar to the case of solar radiation, this approach necessitates the definition of suitable weathering protocols that replicate the actual degradation experienced by the in-situ material during exposure to fire and chemical agents. These weathering protocols may be similar to those already proposed for other construction materials exposed to fire and chemical agents. With reference to fire, a standard code of practice is offered by the recommendations of the RILEM technical committee TC 200-HTC for the characterisation of concrete behaviour at high temperatures (RILEM TC 200-HTC, 2007). Instead, with reference to chemical agents, suitable protocols may be devised following the guidelines of the European Committee for Standardization for evaluating the resistance of concrete structures to severe chemical attacks (EN 13529, 2003) or the recommendations of the RILEM technical committee TC 271- 271-ASC for assessing the durability of construction materials exposed to salt crystallization (Lubelli et al. 2018). Some of these weathering procedures require the direct contact between the earth samples and the water, which is practicable for stabilised earth but requires some degree of adaptation for unstabilised earth.

6.4.6 Standardization of durability tests

The above short review has indicated a large number of experimental procedures to evaluate the durability of earth materials exposed to different environmental actions. Some of these procedures are rather difficult to implement by practitioners in ordinary civil engineering laboratories. The large number and relative complexity of these procedures have so far hindered the formulation of widely adopted testing standards. A significant simplification may, however, be achieved by replacing the present multitude of experimental protocols with a single standard durability test that is valid regardless of the particular environmental action under consideration. The specific impact of each individual environmental action could then be studied by subjecting the earth samples to distinct laboratory weathering protocols, which reproduce the field effect of the chosen action. After weathering, all samples are subjected to the same standard test to assess the durability of the material to the chosen environmental action. In this way, the choice of the durability test becomes independent of the environmental action under consideration.

The standard durability test could be a simple abrasion test, such as that described by Minke (2006) or the ICONTEC NTC 5324 (2004). This test consists in the application of a scrubbing action on the surface of an earth sample for a given period of time by means of a metallic brush or a sandpaper loaded by a fixed weight. The durability of the sample is then directly related to the abrasion resistance, which is measured by the mass lost during scrubbing. Alternatively, the durability could also be evaluated by comparing conventional material properties, such as strength, stiffness and hygrothermal inertia, measured before and after weathering by means of standard tests.

The definition of a single standard test, or a small set of standard tests, would therefore offer the advantage of streamlining experimental procedures, making them accessible to a wide range of academic and industrial organizations.

6.5. Stabilisation methods for enhancing earth durability

The durability of earth materials may be improved by means of different stabilisation methods, whose choice depends on the particular construction technology under consideration (Faria et al., 2012; Bruno et al., 2017b). The choice of the stabilisation method is also affected by the mineralogical characteristics of the clay fraction of the earth and, in particular, by the relative proportions of illite, kaolinite and montmorillonite minerals.

In general, adobes, cob and wattle and daub are often physically stabilised by augmenting the fine fraction of the earth and/or by incorporating natural fibres. Instead, compressed earth blocks and, in some cases, rammed earth are stabilised via the addition of chemical binders such as cement or lime. Cement or lime stabilisation is particularly appropriate in areas where floods are frequent and, in general, when earth walls are not separated from the underlying ground by means of concrete or stone foundations (Alam et al., 2015).

In the following part of this section, the methods of stabilisation are classified as organic or inorganic to facilitate discussion. Organic stabilisation makes use of waterproofing additives and/or reinforcing fibres of organic origin while inorganic stabilisation relies on the addition of chemical binders and/or on the modification of earth grading. Organic additives and inorganic binders can also be combined together to produce a hybrid stabilisation method. This is, for example, the case when quicklime is mixed with animal or vegetal fat to produce an air lime putty that exhibit waterproofing characteristics.

6.5.1 Organic stabilisation

Organic stabilisation makes use of plant aggregates (e.g. corn cob particles, olive pit and cork particles), plant fibres (e.g. straw or husks), animal waste (e.g. cow dung or pigeon droppings) and natural polymers (e.g. starch, vegetal gels from cactus, agave, some roots or leaves, algae, cereal flour, forming natural resins) to improve the mechanical and durability characteristics of earth materials (Laborel-Préneron et al., 2016; Kita et al., 2013).

Plant derivatives have historically been used for improving the strength and durability of earth buildings. Some notable examples include Nopal mucilage (Opuntia sp.), mauve leaves and stems (Sida rhombifolia) and gaucima bark (Guazuma ulmifolia), which have all been employed as earth stabilisers by ancient civilizations in Latin America and the Mediterranean (Kita et al., 2013). Bitumen diluted in vegetal oil has also been used by pre-Columbian civilisations to improve the water resistance of earth buildings in humid tropical areas (Kita et al., 2013; Wendt and Cyphers, 2008). Similar techniques were also adopted by the Babylonians (Barton, 1926). More recently, bitumen water emulsions have been recommended by O´Connor (1973) for earth stabilisation. Kita et al. (2013) also studied the durability of adobe wallets incorporating a protective render made of earth, mucilage and bitumen. They concluded that the presence of mucilage limit drying shrinkage while bitumen reduces rain erosion.

Linseed oil and karité butter are other fat products of vegetable origin that have been used to stabilise earth materials. Lima et al. (2016a) tested an illitic clayey earth mortar stabilised with 1% to 5% of linseed oil observing that the addition of the oil produced an increase of flexural, compressive and tensile strength together with an augmentation of the dry abrasion resistance. The addition of the oil also reduced the vulnerability of the material to water, though this produced a simultaneous decrease of hygroscopicity and, hence, of moisture buffering capacity (Faria and Lima, 2018). In another work by Minke (2007), earth mortars with 6% boiled linseed oil exhibited good resistance to water erosion, though they showed relatively low permeability to water vapour compared to unstabilised earth mortars.

Another organic stabilisation method consists in the addition of polysaccharides biopolymers, which are long-chained, well-structured sugar macromolecules. These biopolymers change the electrostatic charge of clay particles, which facilitates the dispersion of the material and reduces the amount of water that is necessary to achieve good workability. Subsequently, the progressive flocculation of clay particles compacts the material, thus increasing durability (Eires et al., 2017).

Lipids are another family of biopolymers originating from the fat of living organisms, which have been used for the stabilisation of earth materials. The terms oil, butter and cera designate the physical state of lipids, which ranges from liquid to solid depending on temperature (Vissac et al., 2017). Lipids are flexible and insoluble in water, which improves both workability and water resistance but reduces the permeability to water vapour.

Proteins are an additional category of biopolymers that have been used for the stabilisation of earth materials. They are composed of a hydrophobic part, which is absorbed by clay platelets, and a hydrophilic part, which covers the clay surface. They can therefore create a film that prevents water infiltration (Fontaine et al., 2009) while maintaining high vapour permeability (Eires et al., 2017). Proteins can bind clay particles together and hence improve the resistance of the material to water erosion. The most common proteins used for earth stabilisation are caseins and tannins. The latter ones are present in almost all plants and tend to form iron tannate, which is particularly effective in gluing earth particles together (Vissac et al., 2017).

Recent research has also focused on the biomineralisation of earth materials by means of microbes or enzymes. Dhami et al. (2015) tested calcium biomineralised earth blocks achieving a 40% reduction in water absorption, together with a notable decrease of linear expansion, compared to the unstabilised material. Similarly, Mukherjee et al. (2013) tested calcium biomineralised earth blocks achieving a 34% reduction of water content after immersion, together with a 10% increase of wet compressive strength. Ivanov et al. (2014) compared calcium and iron biomineralisation of earth blocks showing that the latter method reduces water permeability at smaller financial costs, though it results in lower levels of compressive strength. Microbially induced iron-oxide precipitation (MIIP) has also been employed to stabilise earth mortars (Velez da Silva, 2017). The stabilised material exhibits lower flexural and compressive strength than the unstabilised one, thus confirming the results of Ivanov et al. (2014).

Organic stabilisation of earth materials has also been achieved via the addition of natural or synthetic fibres. Recycled synthetic fibres from industrial or household waste are generally preferred to reduce environmental impact and embodied energy.

Finally, the utilisation of eco-friendly bio-products has also been recently considered as a possibility for improving the durability of earth plasters during the surface treatment of exposed walls. For example, MIIP has been employed by Parracha et al. (2019b) for the stabilisation of earth plasters resulting in a reduction of both moisture absorption and damage after contact with water (Figure 6-7).

Figure 6-7 Water repellence of an earth mortar stabilized by microbially induced iron-oxide precipitation (MIIP) (Faria and Lima, 2018)

6.5.2 Inorganic stabilisation

Cement and lime are the most common inorganic stabilisers that are used for improving the mechanical and durability characteristics of earth materials. Between the two, cement produces the highest improvement of strength and durability but it also exhibits the highest environmental impact in terms of embodied energy and carbon footprint. Air lime (or simply lime) is older than cement and has been used for centuries to improve the mechanical characteristics of earth buildings. Lime neutralises the free clay cations and promotes the formation of neo-silicates and hydrated calcium aluminates (Guerrero Baca et al., 2010). The advantageous properties of lime are well known to geotechnical engineers, who commonly make use of this binder to enhance the mechanical characteristics of infrastructure embankments or soil subgrades during road construction.

Lime stabilised rammed earth, known as “taipa militar” in Portuguese (Parracha et al., 2019a) or “tapia la real” in Spanish (Bruno, 2005), was used in the Iberian Peninsula during the Muslim period from the 8th to the 15th century to build military structures such as Paderne Castle, Silves Castle or Álcacer do Sal Castle. In these buildings, three different rammed earth techniques can be distinguished corresponding to different levels of durability: a) ordinary unstabilised rammed earth, b) “la real” or “military” rammed earth stabilised with around 10% of lime (Guerrero Baca et al., 2010) and c) “calicostrada” rammed earth where lime mortar is placed on the surface of the formworks before compaction of each lift. This last technique has the purpose of both increasing the durability of the wall to driving rain and enhancing the adhesion of the external render if present.

Eires et al. (2017) studied the behaviour of different kaolinitic earth samples stabilised with 4% of cement or quicklime, 4% of quicklime plus 1% of used soya-bean oil and 4% of quicklime plus 0.1% of commercial sodium hydroxide. The behaviour of these materials was assessed by measuring dry and wet compressive strength, capillary absorption, spraying resistance and vapour permeability. Results show that quicklime stabilisation increases compressive strength in both dry and wet conditions while reducing surface erosion, especially if a small quantity of soya-bean oil or sodium hydroxide is added. All stabilised samples showed lower levels of vapour permeability compared to unstabilised ones.

Gomes et al. (2017) tested a kaolinitic earth mortar stabilised with distinct percentages (i.e. 5%, 10% and 15%) of four different binders, namely air lime, hydraulic lime, Portland cement and natural cement. The study showed a relatively small improvement of mechanical properties with increasing amount of binder. Conversely, the capillarity coefficient, that is the slope of the plot of water absorption per unit area against square root of time (EN 15801, 2009), markedly reduced with growing binder percentage. This was particularly evident for the samples stabilised with Portland cement, which exhibited a very slow drying rate after exposure to water. These results suggest that the application of stabilised mortars on the surface of unstabilised earth walls (as it is often the case during the restoration of archaeological buildings) may augment, rather than reducing, the risk of moisture-related pathologies. In general, protective renderings must be compatible with the underlying earth by ensuring that any moisture reaching the wall surface can easily evaporate to the atmosphere. Moisture transfers through unstabilised earth walls are common (they are due, for example, to capillary rise from the foundation ground) and the application of a protective rendering that does not allow evaporation at the same rate of incoming moisture may compromise the durability of the structure. When hemp fibres were added, the linear and volumetric shrinkage of the mortars decreased, with the only exception of the mortar stabilised with hydraulic lime. The addition of fibres also increased the flexural and compressive strength of the stabilised mortars without, however, achieving the same levels of the unstabilised one. On a negative note, the addition of hemp fibres produced undesirable biological growths inside the earth mortars, with the only exception of the mortar stabilised with air lime (Santos et al., 2017). These biological growths were favoured by a slow drying rate, which means that good ventilation must be ensured during and immediately after construction.

Gypsum is another inorganic stabiliser that exhibits lower embodied energy than lime but it is also more vulnerable to water. Vulnerability to water can be reduced by treating the gypsum at high temperatures, which has however the drawback of increasing the energy and carbon footprint of the material. Lima et al. (2016b) tested an illitic earth mortar stabilised with 5%, 10% and 20% of low fired hemihydrated gypsum. Results from these tests showed that an increase of gypsum content decreased drying shrinkage and increased both strength and surface cohesion with no significant reduction of the moisture sorption/desorption capacity.

Natural or artificial pozzolan is another inorganic stabiliser that hardens when mixed with water and calcium hydroxide, or a material that releases calcium hydroxide such as Portland cement and quicklime. Natural pozzolan is meteorized volcano lava while artificial pozzolan is mainly the by-product of energy production by thermo-electric or biomass plants. Sometimes artificial pozzolans are also sourced from the waste generated by the manufacture of red ceramics or by the demolition of buildings. The thermal treatment of kaolin (Pontes et al., 2013) also leads to the formation of metakaolin that can be used as a pozzolan. Most pozzolans have lower embodied energy than other inorganic stabilisers, which makes them an attractive option for reducing environmental impact. Guerrero Baca and Soria López (2015) investigated the behaviour of earth stabilised with air lime and pozzolan, which was lightly compacted inside formworks. The resulting monolithic walls were lighter, faster to dry and more durable than conventional rammed earth walls. Moreover, samples of this material did not present any sign of deterioration after six months of immersion in water.

Salts, including sodium chloride and sodium hydroxide, have also been used to improve the durability of earth materials. Sodium chloride limits clay flocculation and, hence, improves earth workability (Anger et al., 2009), which in turn reduces the amount of kneading water. The reduction of kneading water produces a decrease of earth porosity and, therefore, enhances the mechanical characteristics of the material. Sodium hydroxide is another salt capable of developing binder reactions that improve the mechanical characteristics of the earth. In particular, sodium hydroxide has been used to induce the geopolymerisation of the aluminosilicates that are inherently present in soils. This leads to the formation of long chains of aluminosilicate minerals, which can bind earth grains together (Eires et al., 2017; Bruno et al., 2017b; Bruno et al., 2018). Note, however, that the long-term durability of earth stabilised by the addition of salts is yet to be evaluated and salt stabilisers must be used with caution. This is particularly true if sodium chloride is used for the stabilisation of earth reinforced with steel rebars, which may then become vulnerable to corrosion.

6.6. Conclusions

The absence of a clear understanding of the mechanisms through which environmental agents affect the durability of earth buildings complicates the engineering assessment of these structures and, hence, the dissemination of raw earth as a routine construction material. To overcome this gap of knowledge, the present chapter has reviewed the effects of water, ice, wind, fire, solar radiation and chemistry on the long-term durability of earth buildings. Current laboratory protocols for characterising the durability of earth exposed to weathering have been discussed in detail, together with the most common stabilisation techniques for improving material resilience.

The most detrimental environmental agent to the durability of earth materials is water, which is very pervasive in the life of buildings due to meteoric precipitation, capillary rise from the foundation ground and ambient humidity. One of the main mechanisms through which water reduces material durability is the increase of moisture content inside the earth pores, which decreases capillary tension and therefore weakens inter-particle bonds.

Earth buildings are also permanently exposed to wind in the same way they are exposed to water but, unlike water, wind produces relatively slow damages, which can be amended by means of regular maintenance of the building envelope.

Ice and fire also have an effect on the durability of earth buildings, though the impact of these two actions is yet to be precisely quantified. The preponderance of earth buildings in areas characterized by temperate climates, where negative temperatures are rare, is one of the reasons why the durability of earth materials in freezing environments has been little investigated. In the case of fire, the exposure to high temperatures may even increase, instead of reducing, the durability of unstabilised earth walls. This is consistent with the improvement of mechanical properties produced by firing during the industrial production of clay bricks. It is also consistent with the existence of ancient earth ruins that have been exposed to fire during their lifetime and have remained reasonably well conserved until present age.

Solar radiation has generally a beneficial effect on the durability of earth buildings as it promotes water evaporation and therefore favours the development of pore capillary tension, which is the main source of inter-particle bonding in unstabilised earth. In the case of organically stabilised earth, however, solar radiation may have an unfavourable effect, especially if photosensitive binders such as synthetic or natural polymers are employed. The photodegradation of these polymeric binders progresses over time from unaesthetic discolorations of the wall surface to the destruction of chemical bonds between earth grains and the consequent weakening of the material.

Unstabilised earth is mostly unaffected by exposure to acid or alkaline environments and is often classified as chemically inert. Nevertheless, the dissolution of salts such as chlorides and sulphates in the pore water can cause the localised precipitation of crystals, which may in turn generate swelling pressures inside the material and the consequent appearance of cracks also in unstabilised earth. In general, salt crystallization can have either an adverse or beneficial effect on the mechanical properties of earth materials depending on factors such as the availability of pore water, the cyclic variation of moisture, the type of salts, the nature of the earth and the chosen building technique. Chemical aggression is even more relevant to stabilised or steel-reinforced earth (which is however rare) and occurs through processes that are not dissimilar from those observed in conventional materials such as fired bricks, concrete or steel.

The most common deterioration process affecting the durability of earth buildings is progressive cracking, which may lead to spalling and erosion. In the majority of cases, cracking is initiated by the cyclic swelling-shrinkage of the earth, which then produces the delamination of the building surface. Earth swelling-shrinkage is often observed in the presence of expansive clay minerals and is caused by the occurrence of wetting-drying cycles. These wetting-drying cycles may be the effect of different causes such as the seasonal variations of climate, the sequence of moist and dry winds and the fluctuation of the water table underneath building foundations. Swelling-shrinkage may also be the consequence of freeze-thaw cycles, which produce a volumetric change of pore water under liquid and solid states. The impact of freeze-thaw cycles is most severe if the material is in a wet state, which is the case immediately after construction. Finally, swelling-shrinkage deformations might also be induced by the growth of crystals inside earth pores, which is caused by a cyclic precipitation-dissolution of salts. If precipitation-dissolution cycles take place on the wall surface, the consequences are relatively minor and are limited to unaesthetic efflorescences that can be easily cleaned. However, if precipitation-dissolution cycles take place inside the earth, for example behind a vapour barrier, the consequences might be more serious as the confined growth of crystals produces stress concentrations that may affect structural integrity.

Few studies have investigated the long-term durability of full scale earth buildings exposed to in-situ weathering. These studies have unsurprisingly shown that stabilised earth structures exhibit lower erosion rates than unstabilised ones. They have, however, also indicated that the cumulative erosion, measured over several years, is in general relatively small and may be deemed acceptable even for unstabilised earth buildings if one takes into consideration the average service life of the structure.

Distinct laboratory tests have been developed to assess the durability of earth materials exposed to different environmental actions, which has led to a multiplication of experimental protocols. Some of these protocols are complicated, time consuming and require equipment that is often unavailable in conventional laboratories. The proliferation of rather complex experimental procedures has impeded the formulation of universally accepted testing standards for characterizing the durability of earth materials. A simplification may, however, be achieved by separating the choice of the test for assessing material durability from the experimental protocols used to weather the material prior to testing. For example, one single normalised test may be used to measure the durability of the weathered material while distinct experimental protocols may be employed to reproduce the weathering effects of different environmental actions. In this way, the choice of the test assessing material durability becomes independent of the environmental action under consideration. A relatively simple durability test may be chosen to maximise accessibility by practitioners and facilitate the formulation of universally accepted laboratory standards.

Stabilisation has been employed since thousands of years to improve the engineering properties of earth materials. Some stabilisation techniques date back to ancient civilizations such as, for example, the Babylonians who employed plant derivatives to enhance the durability of earth buildings exposed to weathering. In general, stabilisation improves mechanical properties but also reduces hygroscopicity and moisture buffering capacity, which in turn produces a decrease of hygrothermal inertia and vapour permeability. The specific physical and mineralogical characteristics of the earth should be considered before selecting a suitable stabilisation method in order to achieve an optimum balance between durability, strength, environmental impact, technological demands and financial costs.

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