KURDISTAN ENGINEERS UNION

"PROTECTION OF HISTORIC AND OLD BUILDINGS AGAINST GROUND MOISTURE"

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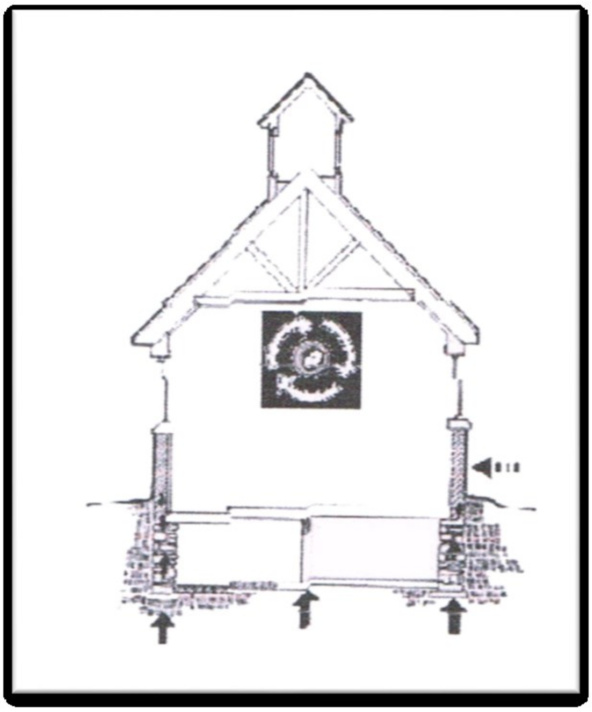
١. Introduction:

The saturated moisture in the ground as a result of surface run-off and naturally occurring water tables, Ground moisture can penetrate through cracks and holes in foundation walls or can migrates up from moisture under the foundation base. The aimed purpose is how to protect historic or old buildings against such a moisture by more practical way.

٢. Transport or Movement of Moisture:

Knowing the five most common sources of moisture that cause damage to building materials is the first step in diagnosing moisture problems. But it is also important to understand the basic mechanisms that affect moisture movement in buildings. moisture transport, or movement, occurs in two states: liquid and vapor. It is directly related to pressure differentials. For example, water in a gaseous or vapor state, as warm moist air, will move from its high pressure area to a lower pressure area where the air is cooler and drier. Liquid water will move as a result of differences in hydrostatic pressure or wind pressure. It is the pressure differentials that drive the rate of moisture migration in either state. Because the building materials themselves resist this moisture movement, the rate of movement will depend on two factors: the permeability of the materials when affected by vapor and the absorption rates of materials in contact with liquid.



The dynamic forces that move air and moisture through a building are important to understand, particularly when selecting a treatment to correct a moisture problem. This drawing shows how moisture can invade "inward" from the exterior; "upward" from the ground; and be generated from "within" the interior. All have damaging effects.

The mechanics, or physics, of moisture movement is complex, but if the driving force is difference in pressure, then an approach to reducing moisture movement and its damage is to reduce the difference in pressure, not to increase it. That is why the treatments discussed in this Brief will look at managing moisture by draining bulk moisture and ventilating vapor moisture before setting up new barriers with impermeable coatings or over-pressurized new climate control systems that threaten aging building materials and archaic construction systems.

Three forms of moisture transport are particularly important to understand in regards to historic buildings-infiltration, capillary action, and vapor diffusion-remembering, at the same time, that the subject is infinitely complex and, thus, one of continuing scientific study. Buildings were traditionally designed to deal with the movement of air. For example, cupolas and roof lanterns allowed hot air to rise and provided a natural draft to pull air through buildings. Cavity walls in both frame and masonry buildings were constructed to allow moisture to dissipate in the air space between external and internal walls. Radiators were placed in front of windows to keep cold surfaces warm, thereby reducing condensation on these surfaces. Many of these features, however, have been altered over time in an effort to modernize appearances, improve energy efficiency, or accommodate changes in use. The change in use will also affect moisture movement, particularly in commercial and industrial buildings with modern mechanical systems.

Therefore, the way a building handles air and moisture today may be different from that intended by the original builder or architect, and poorly conceived changes may be partially responsible for chronic moisture conditions. Moisture moves into and through materials as both a visible liquid (capillary action) and as a gaseous vapor (infiltration and vapor diffusion).

Moisture from leaks, saturation, rising damp, and condensation can lead to the deterioration of materials and cause an unhealthy environment. Moisture in its solid form, ice, can also cause damage from frozen, cracked water pipes, or split gutter seams or split masonry from freeze-thaw action. Moisture from melting ice dams, leaks, and condensation often can travel great distances down walls and along construction surfaces, pipes, or conduits. The amount of moisture and how it deteriorates materials is dependent upon complex forces and variables that must be considered for each situation.

Determining the way moisture is handled by the building is further complicated because each building and site is unique. Water damage from blocked gutters and downspouts can saturate materials on the outside, and high levels of interior moisture can saturate interior materials. Difficult cases may call for technical evaluation by consultants specializing in moisture monitoring and diagnostic evaluation. In other words, it may take a team to effectively evaluate a situation and determine a proper approach to controlling moisture damage in old buildings.

٢.١ Infiltration is created by wind, temperature:

Gradients (hot air rising), ventilation fan action, and the stack or chimney effect that draws air up into tall vertical spaces. Infiltration as a dynamic force does not actually move liquid water, but is the vehicle by which dampness, as a component of air, finds its way into building materials. Older buildings have a natural air exchange, generally from ١ to ٤ changes per hour, which, in turn, may help control moisture by diluting moisture within a building. The tighter the building construction, however, the lower will be the infiltration rate and the natural circulation of air. In the process of infiltration, however, moisture that has entered the building and saturated materials can be drawn in and out of materials, thereby adding to the dampness in the air. Inadequate air circulation where there is excessive moisture (i.e., in a damp basement), accelerates the deterioration of historic materials. To reduce the unwanted moisture that accompanies infiltration, it is best to incorporate maintenance and repair treatments to close joints and weather strip windows, while providing controlled air exchanges elsewhere. The worst approach is to seal the building so completely, while limiting fresh air intake, that the building cannot breathe.

٢.٢ Capillary action:

Capillary action occurs when moisture in saturated porous building materials, such as masonry, wicks up or travels vertically as it evaporates to the surface. In capillary attraction, liquid in the material is attracted to the solid surface of the pore structure causing it to rise vertically; thus, it is often called "rising damp," particularly when found in conjunction with ground moisture. It should not, however, be confused with moisture that laterally penetrates a foundation wall through cracks and settles in the basement. Not easily controlled, most rising damp comes from high water tables or a constant source under the footing. In cases of damp masonry walls with capillary action, there is usually a whitish stain or horizontal tide mark of efflorescence that seasonally fluctuates about ١-٣ feet above grade where the excess moisture evaporates from the wall. This tide mark is full of salt crystals, that have been drawn from the ground and building materials along with the water, making the masonry even more sensitive to additional moisture absorption from the surrounding air. Capillary migration of moisture may occur in any material with a pore structure where there is a constant or recurring source of moisture. The best approach for dealing with capillary rise in building materials is to reduce the amount of water in contact with historic materials. If that is not possible due to chronically high water tables, it may be necessary to introduce a horizontal damp-proof barrier, such as slate course or a lead or plastic sheet, to stop the vertical rise of moisture. Moisture should not be sealed into the wall with a waterproof coating, such as cement parging or vinyl wall coverings, applied to the inside of damp walls. This will only increase the pressure differential as a vertical barrier and force the capillary action, and its destruction of materials, higher up the wall.

٢.٣ Vapor diffusion:

Vapor diffusion is the natural movement of Pressurized moisture vapor through porous materials. It is most readily apparent as humidified interior air moves out through walls to a cooler exterior. In a hot and humid climate, the reverse will happen as moist hot air moves into cooler, dryer, air-conditioned, interiors. The movement of the moisture vapor is not a serious problem until the dew point temperature is reached and the vapor changes into liquid moisture known as condensation. This can occur within a wall or on interior surfaces. Vapor diffusion will be more of a problem for a frame structure with several layers of infill materials within the frame cavity than a dense masonry structure.

Condensation as a result of vapor migration usually takes place on a surface or film, such as paint, where there is a change in permeability. The installation of climate control systems in historic buildings (mostly museums) that have not been properly designed or regulated and that force pressurized damp air to diffuse into perimeter walls is an ongoing concern. These newer systems take constant monitoring and back-up warning systems to avoid moisture damage.

Long-term and undetected condensation or high moisture content can cause serious structural damage as well as an unhealthy environment, heavy with mold and mildew spores. Reducing the interior/exterior pressure differential and the difference between interior and exterior temperature and relative humidity helps control unwanted vapor diffusion. This can sometimes be achieved by reducing interior relative humidity. In some instances, using vapor barriers, such as heavy plastic sheeting laid over damp crawl spaces, can have remarkable success in stopping vapor diffusion from damp ground into buildings. Yet, knowledgeable experts in the field differ regarding the appropriateness of vapor barriers and when and where to use them, as well as the best way to handle natural diffusion in insulated walls.

Adding insulation to historic buildings, particularly in walls of wooden frame structures, has been a standard modern weatherization treatment, but it can have a disastrous effect on historic buildings. The process of installing the insulation destroys historic siding or plaster, and it is very difficult to establish a tight vapor barrier. While insulation has the benefit of increasing the efficiency of heating and cooling by containing temperature controlled air, it does not eliminate surfaces on which damaging moisture can condense. For insulated residential frame structures, the most obvious sign of a moisture diffusion problem is peeling paint on wooden siding, even after careful surface preparation and repainting. Vapor impermeable barriers such as plastic sheeting, or more accurately, vapor retarders, in cold and moderate climates generally help slow vapor diffusion where it is not wanted.

In regions where humidified climate control systems are installed into insulated frame buildings, it is important to stop interstitial, or in-wall, dew point condensation. This is very difficult because humidified air can penetrate breaches in the vapor barrier, particularly around electrical outlets. Improperly or incompletely installed retrofit vapor barriers will cause extensive damage to the building, just in the installation process, and will allow trapped condensation to wet the insulation and sheathing boards, corrode metal elements such as wiring cables and metal anchors, and blister paint finishes. Providing a tight wall vapor barrier, as well as a ventilated cavity behind wooden clapboards or siding appears to help insulated frame walls, if the interior relative humidity can be adjusted or monitored to avoid condensation. Correct placement of vapor retarders within building construction will vary by region, building construction, and type of climate control system.

٣. Drainage systems for ground water:

Ground water is rainwater infiltrated into the ground. This water flows down through the ground until it finds a waterproof layers on top of which aquifers will be formed. Buildings are often constructed with basements or underground floors, usually used for car parking. This option, justified by the rationalization of the available space, requires that possible, if not almost certain, presence of groundwater is taken into account. Perhaps because construction of underground structures was not so common Y years ago, there are no regulations in Portugal ensuring the quality of groundwater drainage systems and, as a consequence, there are many buildings in which such systems are totally absent. Ground water drainage systems are designed to collect and conduct infiltrated waters to a pumping chamber. As these waters are often conducted to the rainwater drainage public network, the pumping chamber can actually be shared by rainwater and groundwater drainage systems in the building.

٣.١ System components:

The components of ground water drainage systems in buildings depend on the specificities of each situation. The most common components are listed in Table ١-٣.

Table ٣.١

Components of groundwater drainage systems in buildings

Element	Description
Gutters	Are usually used to remedy situations in buildings constructed without the necessary protections and are placed between internal and external walls, where collected groundwater is conducted to the pumping chamber.
Drains	Plumbing designed to collect underground water through open joints, orifices or permeable surfaces.
Inspection chambers	Are spread throughout the drainage system in order to ease maintenance operations.
Waterproofing layers	Screens, often in asphalt, although other material can be used, which are designed to protect pavements and walls against humidity
Draining curtains	Membranes usually sold in rolls, which are riddled with granular nodules of high-density polyethylene (HDPE) and applied to buried walls to drain underground water.
Elevatory installation	Installation designed to elevate groundwater to the public network level.

٣.٢ Designing:

Similarly to rainwater drainage systems, assessment of the flow rate to drain is the first step of any calculation. These estimates are difficult due to the number of uncertainties involved.

According to Duerholt Error! Reference source not found. The basis for calculating the flow rate should be precipitation. Assuming that ٥٠ % of rainwater infiltrates in the soil and that drainage time is about ١ hour per each ٥ minutes of precipitation, the groundwater flow rate of about ١ l/s per each ١٠٠٠ m٢ of infiltration basin. Generally, the drainage flow rate needs to be well estimated, considering, for example, that in urbanized terrain the basin's area will be much smaller than in less built-up terrain. Her authors, such as Torres Error! Reference source not found. Admit a range of values between ٠.٨٠ and ١.٢ l/s per ١٠٠٠ m٢ of contributing basin.

٣.٣ Materials:

Selection of materials for rain and groundwater drainage systems in buildings is mainly driven by economy and durability. There are no concerns about the quality of the water and therefore the chemical behavior of piping materials is not as important as it is in water distribution systems. The same type of materials are used both for rainwater and groundwater systems, although normally metal pipes are not use in groundwater systems. The most common materials are:

- Metal: galvanized steel, cast iron, cast aluminum;
- Thermoplastic: Polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP);
- Vitrified clay;
- Concrete

٤. Clay barriers for protecting old buildings:

Conservators and architects working with built heritage at risk from ground moisture intrusion face a difficult choice. Leaving the building unprotected can lead to moisture related deterioration; installing vertical and/or horizontal barriers using standard materials requires chemical or mechanical intervention with the historic fabric. The use of compacted clay to form a barrier is commonplace in some areas of environmental engineering, and can be applied to built heritage conservation. Naturally occurring or slightly modified soils were traditionally used for protecting buildings in a number of vernacular techniques. Knowledge of what types of soils are suitable for use could provide certain regions with a low-cost, low-impact alternative for protecting historic buildings. Three commercially available products previously shown to have low hydraulic conductivity were analyzed in order to identify waterproofing mechanisms; these included two specialized betonies-sand mixtures and a Saxonian glacial till.

The till relies on a high proportion of densely agglomerated fine grains to achieve a low permeability when consolidated, possibly assisted by the presence of calcite. The specialized mixtures rely on an engineered grain size distribution; with practically no silt sized grains, and a fraction of sodium betonies capable of forming colloidal suspension when compacted. All materials showed a low risk of shrinkage when compacted at optimum moisture content.

Different mechanisms appear to account for the low hydraulic conductivities found in clay barrier material. The implication is that a range of soil material may be suitable for protecting built heritage from ground moisture intrusion and its associated decay mechanisms. The suitability of glacial till may present large areas of Northern Europe with locally available barrier material.

Retroactive damp-proofing generally requires chemical and mechanical intervention with the historic fabric; the irreversible nature of such techniques makes them unsuitable for contemporary heritage management.

Whilst a commonplace vernacular roofing material across semiarid climates, verified early evidence of clay used to protect against ground moisture is limited to a few farmsteads in Saxony. These date mostly to the eighteenth and nineteenth centuries. The clay was compressed into a barrier between Y cm and P. cm thick at the foot of external masonry. There are indications that a similar technique was traditionally used to combat rising damp in the Jinggangshan region of China. Whilst further as yet undiscovered vernacular examples in regions with suitable soils are probable, proliferation of such techniques is likely to have been inhibited by a general tolerance of damp cellars. Evidence of lime and clay rich soils or mixtures used as flooring in important civic buildings dates back to the late Neolithic.

Use of earthen barriers persisted in hydraulic engineering. An early industrial application was the use of puddled clay to seal British canals, reservoirs and dams from the late eighteenth century. This technique was gradually superseded by rolling out mats of pre-tamped clay, and in turn by the development of geotextile linings in the mid twentieth century. These encapsulate a thin layer of high swelling betonies clay in panels or between membranes. Use of clay barriers has also become widespread in sealing landfill and waste repositories. Whilst specialized betonies-sand mixtures or geotextiles are commonly selected, naturally occurring soils have been tested for suitability and used as alternatives.

Several commercial producers of clay barrier material now also market specialized mixtures for building works. These optimized betonies-sand mixtures are designed to be compacted against external foundations to form vertical or horizontal damp-proof

Courses without the need for any further fixing. Beyond these, a number of recent conservation projects in Saxony and Brandenburg have utilized local till as barriers. Besides being reversible, naturally occurring clays have the additional benefit of providing nearby areas with a local source of material. This can further reduce the embodied energy of the technique in comparison to the use of specialized mixtures, which rely on geographically limited betonies and may involve long distance transportation of finished products. A comparison of material used in conservation projects in Saxony to the specialized products can identify and distinguish properties for achieving low hydraulic conductivity, in turn facilitating the location of other suitable naturally occurring clays.

This paper presents an analysis of three commercially available products that have been repeatedly used as clay barriers in building engineering. Two are industrially produced betonies-sand mixtures and one is an unmodified Saxonian glacial till. The objective is to examine the mechanisms by which they achieve a low hydraulic conductivity. The aim is to facilitate the selection and modification of naturally occurring, local soils for use in retroactive damp-proofing of built heritage.

٤.١ Theory of waterproofing with clay:

Clay is a very fine-grained soil material, typically particles less than um in diameter. The clay fraction is made up mainly of clay minerals, laminates of electro-chemically bound phyllosilicates. Due to a negative charge across their sheet structures, certain clay minerals have the ability to adsorb and exchange cations such as sodium or calcium. These can in turn bind large amounts of water within the interlaminate zone and thus cause the mineral structure to approximately double in volume, as a polymolecular film forms and progressively forces the laminates apart. This is known as crystalline swelling. The most expansive clay mineral is montmorillonite, the main component of bentonite. Sodium montmorillonite can also undergo a secondary, more gradual yet far greater form of swelling. This is known as osmotic swelling. It occurs when diffuse clouds of positively charged ions overlapping the clay minerals cause the mineral structures to entirely delaminate and peptise to form a colloidal suspension. Compaction of sodium betonies will increase the overlap of diffuse clouds and the effect of osmotic swelling. Drying out leads to shrinkage, which can form cracks within the soil as a whole. If the clay fraction makes up a significant percentage of the total grain-size distribution in a soil, then that soil is referred to as clay. Loam is a soil with a medium clay fraction. A clay or loam may contain numerous types of clay minerals as well as other grain factions such as silt and sand, and other mineral components or additives.

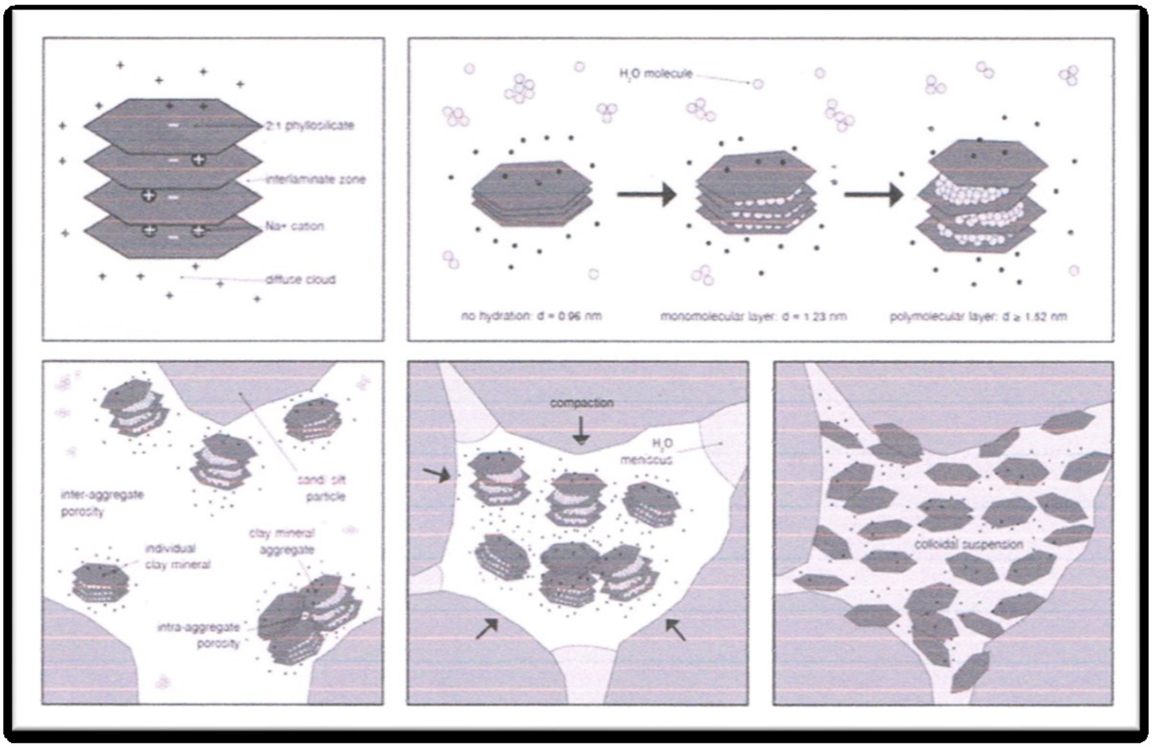


Fig. ١

Sodium montmorillonite activity. Top left clay mineral with layer charges; top rightcrystalline swelling; bottom osmotic swelling after compaction "Diagram not to scale"

Density should be monitored at regular intervals. Care must be taken to prevent water penetration occurring between the barrier and the masonry. Settling, shear forces and dimensional expansion due to clay mineral activity must be resisted. High moisture loads may require drainage at the foot of the barrier. Horizontal barriers running underneath foundations have been installed; in existing buildings this will clearly necessitate excavation of the existing floor.

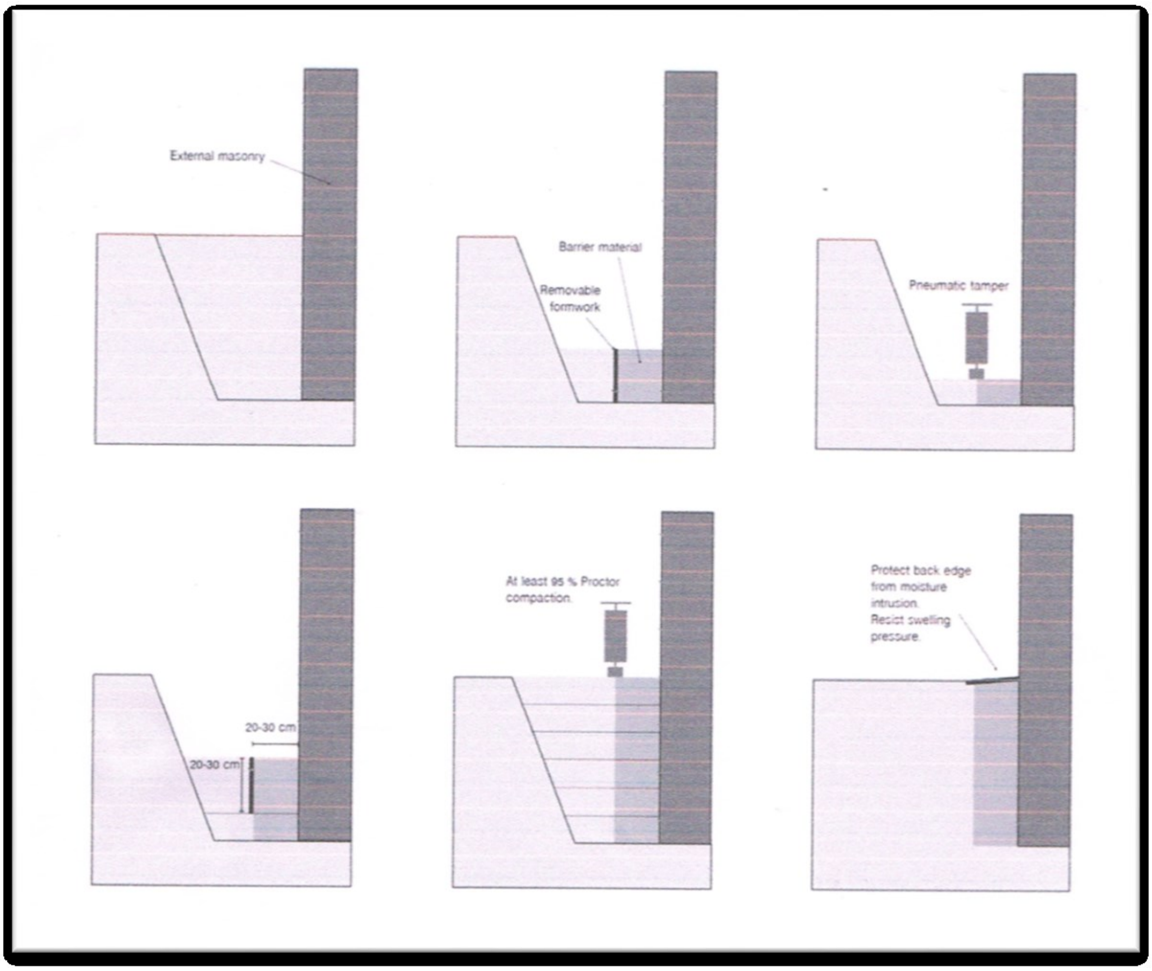


Fig.٢
Installation of vertical clay barriers

٤.٢ Methods:

Two specialized clay mixtures and a naturally occurring soil were selected for analysis. The natural soil (hereafter referred to as till) is excavated from a terminal moraine in southern Saxony; the specialized mixtures (hereafter referred to as mixture A and mixture B) are manufactured in a factory environment by two separate producers.

Table ٤-٢

Key properties of tested materials in comparison to products suitable for use as landfill barriers

	Mixture A	*Mixture B*	*Saxonian till*	*Bentonite sand mix* [42]	*Volcanic soil, Chile* [12]	*Ankara clay* [13]
Clay fraction ($d <$ ٠.٠٠٢ mm)	٩٪	٧٪	١٤٪	١٠٪	٣-٥٪	٥١.٥-٦٤.٢٪
Coarse fraction ($d >$ ٠.٠٦ mm)	٨٨٪	٩١٪	٥٤٪	٩٠٪	٤٣-٥٣٪	١٠.٥-١٩.٨٪
Calculated conductivity (m/s)	١$E^{-٥}$	١.٥$E^{-٤}$	٨.٥$E^{-٩}$			
Measured conductivity (m/s)^a	٨.٥$E^{-١١}$	٥$E^{-١٠}$	٨.٥$E^{-١١}$	١٠$E^{-٩}$	٥.٢ − ٦.٥$E^{-٩}$	٠.٩ − ٣$E^{-١١}$
Water adsorption (% *of initial mass*)	١٤٨٪	٢٢٦٪	٤٣٪			
Particle density ($g/cm^٣$)	٢.٦٢	٢.٦	٢.٦	٢.٥٨	٢.٤٥ − ٢.٦٦	(٢.٦)
Proctor compaction [a] ($g/cm^٣$)	٢.٠٩	١.٧٦	٢.٠	١.٧	١.١٢ − ١.١٥	١.٢٨ − ١.٥٠

Opt. moisture [a] ($\% \ of \ total \ mass$)	٨.٥٪	١٧٪	٩٪	١٧٪	٤١ – ٤٢٪	١٦ – ٢٦٪
Bulk density ($^{g}/_{cm^{٣}}$)	١.٩٢	١.٥	١.٨٤	١.٤٥	٠.٧٩ – ٠.٨٢	١.٠٢ – ١.٢٩
Porosity ($\% \ of \ total \ volume$)	٢٧٪	٤٢٪	٢٩٪	٤٥٪	٦٩٪	٦٠٪
Degree of saturation ($\% \ of \ hydrated \ porosity$)	٨٥٪	٢١٪	٦٩٪	٢٠٪	٣٪	٧٪
Opt. moisture ($\% \ of \ total \ mass;$ $d < ٠.٠٤ \ mm$)	٢٤٪	٤٧٪	١١٪			
٩٧٪ $dry \ moisture$ ($\% \ of \ total \ mass;$ $d < ٠.٠٤ \ mm$	٢٠٪	٢٧٪				
Shrinkage limit ($\% \ of \ total \ mass;$ $d < ٠.٠٤ \ mm$)	٢٥٪	٣٧٪	١٥٪			

٤.٣ Grain Size distribution:

Grain size distribution was determined according to DIN ١٨١٢٣ in order to evaluate various aggregate content and classify soil type. Samples of approximately ٢٥٠g were oven dried before being sieved through progressively decreasing mesh sizes down to ٠.٠٦٣mm. The aggregate caught in each mesh was weighed. Remaining aggregate with a diameter smaller than ٠.٠٦٣mm was then poured into a hydrometer and the specific gravity of the water-soil mix was recorded at intervals as smaller particles progressively settled to the bottom. The results were plotted on a grain size distribution curve (Fig.٣).

Grain size distribution chart

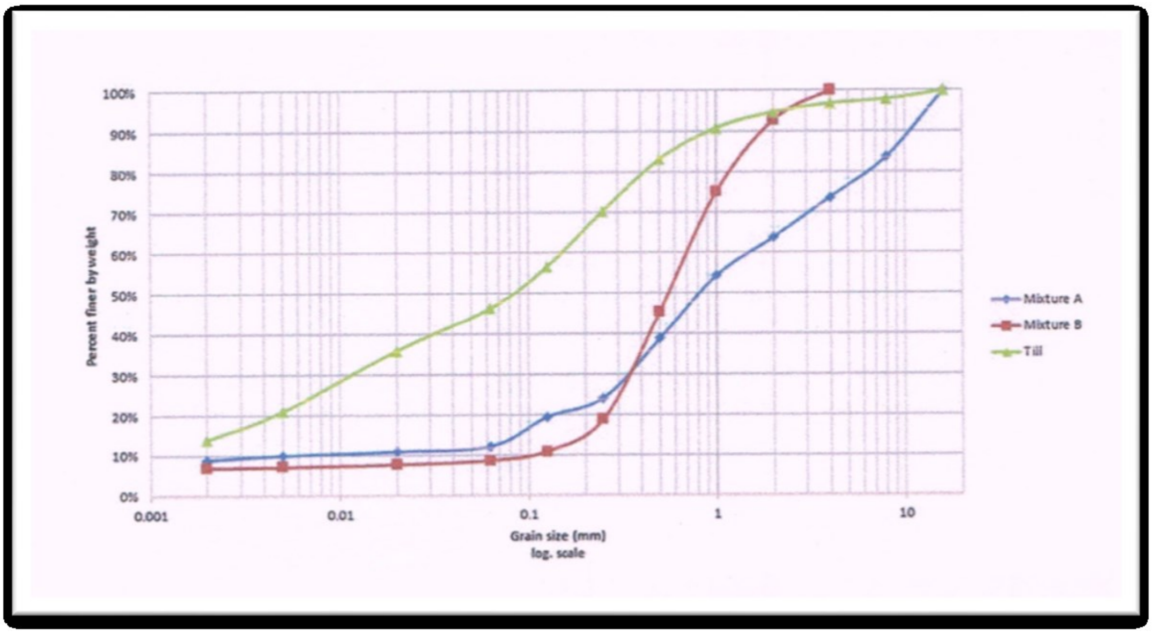


Fig.٣

Shown to reduce permeability of clayey soils at certain threshold quantities. Cement and fly-ash additives have also been shown to reduce hydraulic conductivity in certain clays.

٤.٤ Hygroscopicity:

The water mass absorptivity test enables a classification of the finer aggregate, in order to give an indication of the presence of clay minerals and their likely plasticity. The very high absorptivity of the specialized mixtures falls in the region of≥ ١٣٠٪, confirming the presence of highly plastic clays or bentonites. The water mass absorptivity of the natural clay falls into the region of٤٠ *to* ٦٠, indicative of moderately plastic silts and clays.

٤.٥ Porosity:

Measured particle densities are similar to those of other clay barrier materials and fall within the expected range of ٢.٦ – ٢.٧ $g/_{cm^٣}$ for sandy soil types. The total porosities of Proctor compacted mixture A and the till are noticeably lower than similar barrier materials, including that of compacted mixture B, in which almost half the volume is made up of pore space. This is reflected in the degree of saturation: despite the higher moisture content, only ٢٠٪ of the pore space in mixture B will be saturated following Proctor compaction, whereas ٧٠٪of the till and ٨٥٪ of mixture A will be saturated.

Studies have shown clay structures to exhibit dual-porosity, an intra-aggregate region at the nanometer scale, which contributes little to the effective porosity in which conductivity is possible, and an inter-aggregate region at the micron scale, which decreases with increasing dry density and saturation. The relatively high Proctor densities and saturation of mixture A and the till suggest they are dominated by intra-aggregate porosity. If sodium montmorillonite is present compaction can induce osmotic swelling and result in a colloidal suspension, further reducing effective porosity. A possible explanation for the relatively low bulk density of mixture B could be an optimized pore space closure in order to limit outward expansion and swelling pressure of the compacted mass.

٤.٦ Stability:

The shrinkage limit enables an assessment of shrinkage risk. To do this it is necessary to calculate the moisture content of the examined aggregate according to the formula $wf = (WPR - We * dch/dfwf = (WPR - We * dc)/df$ whereby $wfwf$ is the moisture content of the examined fine aggregate, $wPRwPR$ the optimum moisture content of the total aggregate and wcwc the moisture content of the removed coarse aggregate as a percentage of mass, dede the diameter of the smallest coarse aggregate, and $dfdf$ the diameter of the largest fine aggregate in mm. Values of ١٪ were set for wcwc.

The optimum moisture content of the till and mixture A are at or below the shrinkage limit. This indicates only minimal volumetric change can occur with any further loss of moisture. Whilst mixture B lies slightly above the shrinkage limit at optimum moisture content, reducing to ٩٧% dry Proctor compaction brings it well below the limit. This suggests the mixtures should be compacted slightly to the dry side of optimum moisture to avoid any risk of shrinkage; it should be noted that mixture B is supplied with a moisture content that enables this.

The presence of calcium carbonate is likely to further reduce hydraulic conductivity in the till. With sufficient humidity, cation exchange can replace metallic ions in swelling clays with the calcium ions of calcareous minerals. This forms agglomerations of fine particles which enable a more densely compacted, stabilized grain matrix. The stabilizing effect of lime additives in clayey soils has been investigated with respect to calcium oxide, calcium hydroxide and calcium carbonate, however it is not entirely understood to what degree cation exchange and to what degree other stabilization processes are responsible. A stabilizing effect of calcite found in nature is the cementation of calcareous loess following gradual moisture redistribution in deposits .The cementation generally associated with quicklime (Cao) has been shown to reduce permeability of clayey soils at certain threshold quantities. Cement and fly-ash additives have also been shown to reduce hydraulic conductivity in certain clays.

٤.٧ Swelling:

The objective of this experiment was to determine the predominant swelling mechanism by plotting deformation over time. Measured deformation itself is to be viewed with caution given the limited sample sizes used.

Swelling deformation measured over time produces a very different curvature in the till compared to the mixtures, the total heave of the two mixtures is noticeably different in itself. The till swelled by approximately ٠.٨٠٪ within the first ٠.٥٠h, and leveled out at ١٪ after ٥٠h. Mixture B reached a similar overall deformation of ٠.٧٥٪, however only after nearly ٣٠٠h of gradual swelling. Mixture A also swelled gradually, however achieved a total deformation of almost ٦٪ after ٣٠٠h. The rapid heave of the till is likely to be a result of its overall higher clay content, indicating the final stages of crystalline swelling as the sample fully saturates. The steady heave of the two mixtures is highly indicative of the gradual onset of osmotic swelling, indicating a significant proportion of sodium-montmorillonite.

The lower overall deformation of mixture B is likely to be a result of its higher porosity, which allows more room within the matrix for the delaminating clay minerals to expand into.

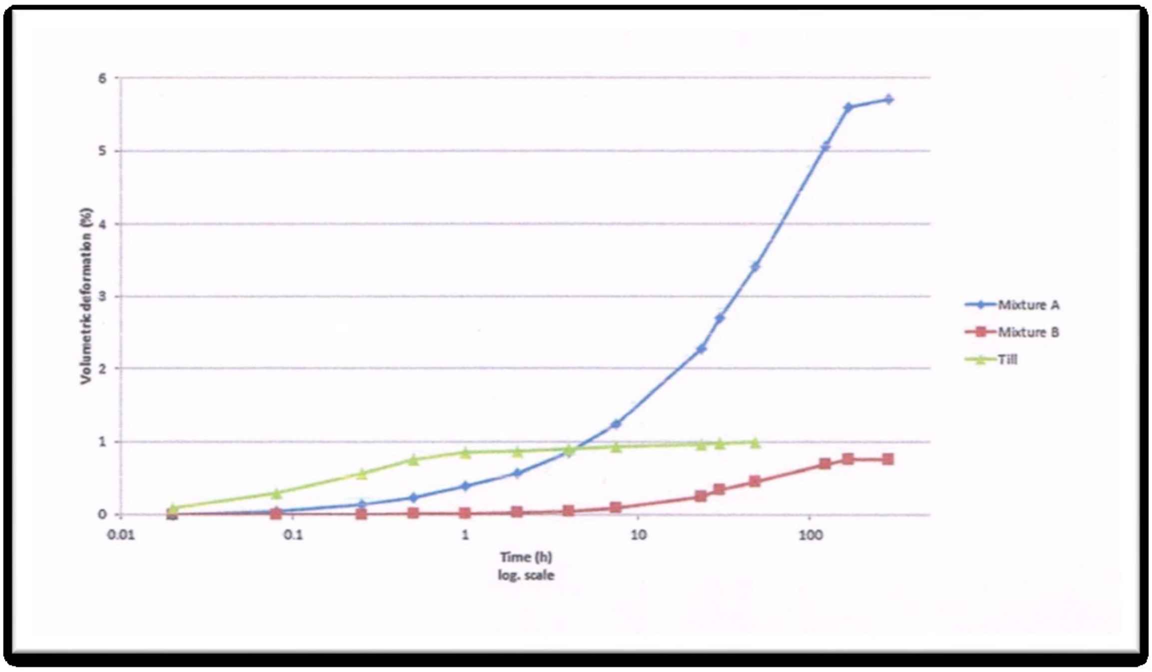


Fig. ٤

Swelling deformation plotted over time. Note gradual (osmotic) swelling onset of specialized mixtures, that the specialized mixtures rely on osmotic swelling to achieve low hydraulic conductivity is significant for the

Future design of sand-bentonite mixtures suitable for protecting historic buildings. Mishra et al. found sodium-bentonite content to be a controlling factor in the hydraulic conductivity of sand-bentonite mixtures. Calcium bentonite is also widely used in landfill and repository engineering, but undergoes far less swelling and its primary role may be in filtering leachates via ion exchange. The implication is that the limited natural occurrence of sodium bentonites will restrict use in sustainable conservation strategies to certain regions. Furthermore, groundwater chemistry has been shown to have an effect on the longterm stability of betonies, and a gradual exchange of sodium to calcium has been observed in bentonite panels. Highly saline ground moisture loads may preclude the use of sand-bentonite mixtures.

That any deformation was measured in the till is significant in that it confirms the presence of swelling clays, which are capable of cation exchange. This can result in the formation of agglomerations with calcite minerals that could potentially contribute to the low measured hydraulic conductivity.

٥. Outlook and Conclusion For protection by Clay barriers:

Comparing the products with some of the many soil types and mixtures used in landfill and repository engineering can help direct future research into potential barrier material. The specialized mixtures fall within the broad range of sand-bentonite mixtures used in landfill and repository engineering, with the proviso of containing predominantly sodium-montmorillonite. Whilst effective in retarding moisture flow, the highly localized provenance of sodium-bentonite will limit its use in sustainable conservation strategies to certain areas. Where it is available, sodium-bentonite powder should be mixed with sand or gravely Sand; high silt content is likely to increase the risk of shrinkage. Calcareous additives should be avoided to prevent cation exchange.

The aim was to facilitate the selection and modification of naturally occurring clays that may be locally available to heritage sites. Each of the tested materials exhibited different properties in order to achieve low hydraulic conductivity:

- Mixture A has an even grain size distribution and forms a dense matrix. A small fraction of sodium bentonites further reduces conductivity by peptizing when the mixture is compacted.

- Mixture B also has a small fraction of sodium bentonites; these appear to be optimized to close an otherwise porous, sandy matrix following compaction, resulting in minimal heave and swelling pressure.

- The glacial till has a high proportion of fine aggregate, giving its consolidated matrix a low effective porosity. This includes a relatively large clay fraction, with some swelling clay minerals present. The calcium carbonate content may further reduce conductivity, by cementing pore space through dissolution, or increasing the density and stability of the matrix due to cation exchange.

- A resistance to shrinkage is notable in all products, in that their optimum or supplied moisture content is at or below the shrinkage limit. This will reduce the risk of shrinkage during dehydration.

٦. References:

١. Clay barriers for protecting historical buildings from ground moisture intrusion, Martin Michette, Rudiger Lorenz, Christof Ziegert, ٢٠١٧

٢. Controlling unwanted moisture in historic buildings, Sharon C. Park, ١٩٩٦

٣. Rain and ground water drainage system for buildings, Eduardo Joao Vindeirinho Rino, ٢٠١١