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Preservation of Structural Remains at Moenjodaro

By James R. Clifton

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By James R. Clifton

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SUMMARY

Excavated brick walls at Moenjodaro are deteriorating at an unacceptably High rate because of the crystallization and hydration of the mineral thenardite (Sodium sulphate). Its destructive effect is mainly attributed to a volume Increase of 315 per cent resulting when thenardite hydrates to form sodium Sulphate decahydrate. Sub florescence by soluble salts is a much more destruc-
tive process than efflorescence. Soluble salts are being carried into the Brick and to their surfaces by the migration and evaporation of moisture. Possible sources of the moisture in walls are rainfall, drainage and runoff Water groundwater rising by capillary action and condensation of moisture.

To reduce the rate of brick deterioration the following measures are recommended: remove soluble salts from the brick; place damp-proof courses under the top course of walls; seal the bases of walls; and install a drainage System. These and other measures are necessary even if the groundwater table
can be successfully lowered.

possible uses of preservatives and consolidants to conserve brick are

Discussed. Treating brick with preservatives will probably not successfully Protect the and may accelerate the deterioration of brick. Consolidants appear to have one possible application at Moenjodaro, which is to consolidate badly Deteriorated brick, thereby delaying to a future time the need to replace them With new brick. Certain epoxies could be injected into crumbling masses of Brick to improve their structural integrities. Epoxies could also be used in the making of damp-proof courses and membranes.

1.INTRODUCTION

Preservation of the excavated historic structural ruins at Moenjodaro,

Pakistan, is being jointly undertaken by Unesco and the Government of Pakistan,

These structure were constructed some 5000 years ago from burnt brick and mud Morter they were abandoned around 1700 B.C., gradually were covered with soil,

And then were partially excavated .in the 1920's. Well over one-half of the

Original Structure are still unexcavated and a large portion of them are below

The present groundwater table.

At the time of excavation the standing brick wall were found to be relatively well preserved. Soon afterwards, however, development of white salt efflorescence on the walls was observed (1). Since then the brick has been rapidly deteriorating because of salt crystallization and hydration, which has resulted in exfoliation and disintegration of the brick. Most of this salt damage has been attributed to the destructive effects of the sodium sulphate mineral thenardite (2). Major sources of the salts are considered to be groundwater laden with soluble salts, which rise by capillary action; debris and soil adjacent to the walls; and airborne particles. In addition, the bricks and mud mortar themselves may have been prepared from materials having high salt contents or they possibly absorbed significant quantities of salt while buried.

Flooding and erosion of the Moenjodaro site by flood waters of the Indus River pose another threat to the preservation of the ruins. The river is at

2 km from the site and earth dikes have been, constructed to protect the from flood waters.

In developing the plans for the preservation of Moenjodaro four major tasks for been identified

(1) diversion of the Indus River away from the site,
(2) lowering of the groundwater table below the site by tube wails,
(3) preservation and stabilization or the structural remains, and
(4) removal of salts from the site by growing and harvesting salt-absorbing plant.

The structure was requested by Unesco to specifically address the preservation of the structure remains, including recommending methods for protecting the bricks from further damage, methods for removing salts from the brick, and to identify materials which possibly could be used to consolidate deteriorated brick.

2. OBSERVATION

The writer visited the Moenjodaro site during the period 28-30 October

1979. a few days earlier the site had been exposed to rainfall and ponding water was observed in several locations both inside and outside the structural remains,

salt efflorescence was visible on brick walls which were as much as 19 m above the level of the surrounding plain, almost to the base of the Stupa. Salt effloresce:

noticed on top of some brick wails while little efflorescence was found on

their sides Apparently the bricks on the top course of some walls are of recent production and contained substantial amounts of soluble salts when manufactured.

The effects of the soluble salts were manifested by the exfoliation and in some severe cases, disintegration of brick. Usually the most serious deterioration took place in the brick located near the base of the walls. To mitigate the destructive effects .of the salts the following measures have been implemented.

Salt efflorescences are being brushea from the surface of bricks, collected, and diposited away from the site. Damp-proof courses, consisting of 70mm thick concrete slabs coated with a bituminous material, are being inserted into the walls several courses above the base of the walls (Figure 1). In addition, coated concrete slabs are being placed against the sides walls which have not been excavated. The tops of some walls have been recently capped with brick bonded by portland cement mortar. These measures appear to have successfully protected those portions of the walls which are above the damp-proof course from further salt deterioration. The bricks below the damp-proof courses, however, are still rapidly deter-orating.

The feasibility of creating a damp-proof course by the injection of silicone

Was previously explored. An international firm specializing in such work carried Out of the experiment. A brick wall was isolated from joining walls, holes drilled Into brick at a spacing of 150 mm, and a diluted silicone solution injected under Pressure. Unfortunately this simple treatment was not successful as the movement of moisture and salt through the silicone-treated region has not been significantly impeted.

In the past, a temporary capping of adobe (mud) brick was placed on the

Wall. Gradually these adobe bricks were eroded by rainfall and the eroded mud Coated the side of the walls. This mud coating absorbed salts from the brick Walls, thereby retarding further salt damage. When the salt-laden mud coating was removed, however, a mud film adhered to the brick which discoloured the walls.

This discolouration is readily 'apparent and is felt to be aesthetically un-

Acceptable some evidence was observed of rainwater flowing down the faces of walls eroding both brick and mud mortar. For example, channels in some wall surfaces were probably created by flowing water. Also runoff and drain water has cut through the bottom courses of some walls.

4. DETERIORATION PROCESSES

3.1 Salt action

The major processes responsible for brick deterioration of Moenjodaro have been attributed to the crystallization and hydration of soluble salts (2). The

White efflorescence appearing on the brick is caused by the crystallization of Soluble salt at surface openings of pores as moisture evaporates. Efflorescence in Itself not harmful but does indicate that internal salt and moisture Migration is taking place. Closely related to efflorescence but much more Harmful is florescence, in which the salts crystallize underneath the surface Of weathered brick or stone. Subflorescence causes the surface to continually Peel and, therefore, it can be very damaging (3). Desert climates are favorable

enviroment for subflorescence.

Some soluble salts readily hydrate and dehydrate in response to temperature

and relative humidity changes. The predominant salt at Moenjodaro is the sodium sulphate mineral thenardite (Na_2S0_4), with lesser amounts of aphthitalite

[($K,Na)_3Na(S0_4)_2$] and burkeite [$Na_6\ (CO_3)\ (S0_4)$] being present (2). Then ardite is a specially destructive salt. Its destructive effect is mainly attributed to a volume increase of 315 per cent accompanying the hydration reaction

$$Na_2SO_4 + 10\ H_20 \quad NaS_2O\ 10\ H_2O.$$

Under the conditions of a saturated solution and standard pressure (1 atmosphere),the equilibrium temperature for the reaction is 32.4 C (i.e. below 32.4 C, Na_2S0_4 is formed). This equilibrium temperature is slightly lowered when certain other salts are present (4). Hydration of Na_2SO_4, is rapid and the hydration and dehydration processes can be repeated several times in a single day (2). For example, the dehydration of $Na_2SO_4.10\ H_20$ can take place within 20 minutes at 39 C (5). Weather records taken at a site near Moenjodaro (6) indicate that 32.4 C is bracketed by the daily average minimum and maximum temperatures from early March to late October. Therefore, conditions are favorable at Moenjodaro for the repeated hydration of Na_2SO_4 and dehydration of $Na_2SO_4 .\ 10H_2O$.

Disruption of brick may also be caused by a considerable difference in the thermal expansion of salts in the pores of brick compared to the expansion of the brick itself. This process is important in areas where a large daily temperature variation occurs, often found in desert regions.

The salts at Moenjodaro have been attributed to a variety of sources including recent flooding by the Indus River, groundwater carrying salts to the surface by capillary action, windstorms carrying along salt particles, and it is thought that salts were in the brick at the time of preparation. The main sources of the salts, however, have not been unequivocally identified.

3.2 Effects and sources of moisture

The destructive effects of salts are usually only realized if moisture is available to dissolve, transport and to deposit them within the pores of porous materials. In addition, moisture can degrade stone and brick by dissolving slightly soluble cementitious materials. Main sources of moisture in the wails of Moenjodaro are probably rainwater, drainage ana runoff water, and groundwater. In addition, during periods of high relative humidities, some moisture may be condensing from the atmosphere within the walls. As with the main sources of salts, the main sources of the moisture in the walls have not been unequivocally identified.

3.2.1 Rainwater

The amount of rainwater entering the walls has not been measured. However,

driving rains usually do not easily enter walls made from burnt brick and mud mortar. Most rainwater probably penetrates the walls through their top surfaces rather than through their sides. This is because rainwater striking the top surfaces can rapidly erode the mud mortar producing deep cavities in which water can accumulate and enter the walls. Therefore, it is important to provia some type of damp-proof membrane near the top course of the walls.

3.2.2 Drainage and runoff water

While relatively small amounts of precipitation occur at Moenjodaro (around 64 mm), most of it occurs during a few intense rainstorms. Such rainfalls do not readily penetrate the fine particle soils which are apparently present at Moenjodaro. Therefore, a large amount of drainage and runoff water probably accompanies each rainstorm. Evidence of poor drainage was observed during the inspection e.g. ponding of water in low areas, water trapped behind walls, as well as signs of water erosion. A drainage system capable of adequately handling the drainage and runoff water clearly should be constructed.

3.2.3 Groundwater and capillary rise

Groundwater can rise from the groundwater level up into masonry walls by capillary rise, carrying soluble salts into walls. Usually such processes are slow but eventually a large amount of salts can be drawn into masonry walls.

Drainage and runoff water also can rise up walls by capillary action. The height that moisture can rise in a soil and wall is controlled by the capillary pressure (dependent on the sizes of the capillaries), the evaporation rate, and the permeability of the soil or wall. Considering only the effects of pore size, the height of capillary rise increases as the pore radius decreases. Water can also travel in a horizontal direction by capillary action. Furthermore, it travels twice as far in a horizontal direction as vertically.

A major and expensive task which has been planned at Moenjodaro is to lower the water table to the level it was (about 7 m below the plain level) before large-scale irrigation was started. At present the water table is between 4 m (in winter) to 2 m (in summer) below the plain level. The main reason for lowering the 'water table is to prevent groundwater from rising into trie brick walls by capillary action. However, several investigators have suggested (2,7,8) that the height of capillary rise above the water cable at Moenjodaro and at similar areas will be only around 3 m or less. If the capillary rise is r.o more than 3 m, then lowering the water table may not significantly reduce the amount of salts accumulating in the bricks. Certainly, lowering the water table will not prevent drainage and runoff water, and rainwater from entering the walls. Therefore, the writer recommends that, before construction of the tubewall system is started, the capillary rise patterns of the groundwater be determined over several seasons.

A relatively easy method to make this determination is to measure the electrical resistivity of the soil. Soil resistivity measurements are routinely performed by engineering firms dealing with soils.

3.2.4 Condensation of moisture

Condensation of moisture at high relative humidities in brick walls can occur if the dew point is reached within the walls. Condensation of water in capillaries also can occur, especially if the atmospheric relative humidity is 90 per cent or above (3). Soluble salts entrapped in brick, however, are responsible for che largest amounts of hygroscopic (condensed) moisture accumulating in bricks, the amount being several times that condensing in salt-free bricks.

Therefore, removing the soluble salts from the bricks at Moenjodaro should significantly reduce the possibility of large amounts of moisture condensing within the walls.

5. RECOMMENDED PRESERVATION MEASURES

Both short-term and long-term preservation needs exist at Moenjodaro.

First, the condition of the walls must be stabilized, i.e. their deterioration rate reduced to an acceptable level. Then long-term maintenance practices must be implemented. It would be erroneous to assume that carrying out the preservation methods contained in the Master Plan (9) would eliminate the need for continuous maintenance. All too often stabilization work is thought to be a permanent solution and maintenance neglected, which can result in irreparable damage. As long as Moenjodaro exists, brick and mortar will undoubtedly deteriorate and need replacement. The following recommendations are aimed at slowing down die deterioration rate of the structural ruins.

4.1 Protecting walls from moisture

4.1.1 Damp-proofing methods

The methods which are currently being used to protect walls from moisture (Figure 1) appear to be generally effective, with the following exception: portions of walls beneath the damp-proof course are still deteriorating at an unacceptably righ rate. In addition, portland cement mortar binding together the-brick of the top courses is rapidly deteriorating. Several changes in the present practices are recommended. A damp-proof course should be placed immediately below the top course (Figure 2) to stop rainwater from entering the walls through their top

surfaces. The vertical damp-proof membranes on the unexcavated sides of walls only extends down to the level of trie horizontal damp-proof course, whereas it should extend down to the same depth as the ground level of the excavated side of the wail.

Concrete slabs coated with a bituminous material are being used in construction of the damp-proof courses and damp-proof membranes. Concrete itself if a porous material, ineffective as an impervious membrane, and is only serving as a substrate for the bituminous impervious coating. It is recommended that a different type of impervious membrane be installed. For example, bituminous coated fiber-felt sheets which are lead-cored, or equivalent, could be used.

The brick below the lower damp-proof course should be treated with a coal-tar epoxy, or equivalent, to seal the base against moisture penetration. Sides of all brick, except the visible sides, should be given a relatively heavy coating. Surface cricks will undoubtedly still deteriorate but at a much reduced rate. Their deterioration rate can be further reduced by using a type of brick having a high resistance to salt damage.

Damp-proof courses and membranes should be installed, and bases of walls Sealed, even if the water table is successfully lowered. Lowering the water table say not be as effective in impeding capillary action as anticipated. Furthermore, other sources of moisture will still be present.

4.1.2 Installation of a drainage system

A drainage system should be installed to reduce problems caused by drainage and runoff water. Further, drainage behind excavated walls should be provided

even if damp-proof membranes are installed. A recommended system is illustrated in Figure 2. The perforated drain pipe should be covered with gravel 12 mm in diameter or larger. The gravel should be periodically cleaned or replaced to remove fine particles that tend to clog it. This system also could be installed next to the base of walls to prevent the accumulation of water. Floors should be properly sloped so that water will quickly enter the drainage system and not pond between walls.

4.2 Salt removal

The salts must be removed from the bricks to reduce their deterioration rate to a manageable level. Regardless of the measures taken to prevent moisture from penetrating the walls, some moisture will find a passage into tr\e walls, Transformation cf the soluble salts into less soluble salts will not have the desired results. Soluble sulphate salts can be precipitated as insoluble barium salts, by creatine the orick w-th an aqueous solution of a soluble barium salt. such a process was developed over IOC years ago by Church (10, 11). Unfortunately, barium sulphates precipitate almost immediately when the barium solution interacts with sulphate anions, and will form a hard dense surface crust on the brick.

Further, while barium sulphate is forming a new soluble salt will be produced which will crystallize beneath the barium sulphate crust (12).

The writer recommends that the salts be removed from the bricks by using some type of poultice. First the walls should be lightly dampened with salt-free water to dissolve the salts antthen the poultice attached. They are removed after becoming lader with sales. The poultice treatment will probably need to be repeated several times. Thereafter, residual salts can be brushed off as they gradually appear on the surfaces of bricks. Poultices are usually orepared from observing clays, and they can.be reinforced with paper or wood libers. Paper poultices have been used previously at Moenjodaro. Insufficient documented information is available, to judge the effectiveness of the paper poultices compared to clay poultices.

Salt removal should only start after the walls are protected as recommends in. Section 4.1. Otherwise, as previously found at Moenjodaro, salt removal will only draw more salt into the walls.

4. 3 Selection of materials

Sodium sulphate cqin cause the deterioration of concrete and the corrosion Of metals. Therefore, materials used in preserving the structural ruins and in. constructing the tube well-drainage canal system, should be carefully selected.

If portland cement mortar or concrete is used, a sulphate-resistant cement should be selected. A portland cement meeting the ASTM requirements for Type V Portland Cement '13), or the requirements of an equivalent standard, is desirable. Anchors, Novels, or reinforcing bars used for wall repairs should not be made from normal steel or cast iron. Certain ferrous metals are susceptible to corrosion which can lead to the cracking and spelling of brickwork. Therefore, non-corroding materials should be elected, e.g. epoxy-coated steel (14), certain types of stainless steel (15), or non-corroding non-ferrous alloys (16).

New brick used to replace deteriorated brick should be relatively free from soluble salts. Some of the new brick being used appears to be heavily contaminated with salt. A large amount of usable original brick is still in the debris piles around the site. This brick should be collected, soluble salt removed from them- and the cleaned brick stacked upon wooden platforms above ground level until used.

5. CONSERVATION MATERIALS

The writer was requested by Unesco to explore the feasibility of using consolidants and preservatives to conserve deteriorated brick. Consolidants are deep-penetrating materials which have the ability to re-establish the cohesion between particles of deteriorated inorganic building materials such as stone, brick and concrete whereas materials whose chief functions are to prevent the ingress of moisture into stone and brick, i.e. water repellents, are classified as preservative.

5.1 Preservatives

Various preservatives have been applied to stone and brick for more than one hundred years with little success. In fact, treatments with preservatives have frequently accelerated stone and brick decay through two major processes.

First, moisture will usually collect behind the treated brick and upon evaporation of the moisture any salts in solution will be deposited and crystallize beneath the treated surface, resulting in spalling of the treated surface. In the second process, because of differences in thermal expansive properties of the treated and untreated brick or stone, shear stresses may be generated that eventually results in interfaciai delamination. Recently over 50 stone and brick preservatives were tested at the National Bureau of Standards, none of which gave satisfactory performance (17). Therefore, the writer and others (18) are opposed to the indiscriminate use of preservatives on important historic structures.

5.2 Consolidants

Compared to stone consolidation, relatively little work has been carried our on consolidating brick. The writer recently made a critical literature review of stone consolidants (19). Based or. this review, stone consolidants which could be considered for consolidating brick are briefly discussed.

5.2.1 Types of consolidants

Consolidating materials can be divided into four main groups according to their chemistry. These groups are: inorganic materials, alkoxysilanes, synthetic organic polymers and waxes. Most inorganic consolidants produce a white insoluble phase within the matrix of porous materials by the precipitation of insoluble salts. Little success has been achieved in consolidating stone with inorganic materials, and in some cases their use has greatly accelerated stone decay. The same results can be expected if they ore used to consolidate brick. Some of the reasons given for the poor performance of inorganic consolidants, are their tendencies to produce shallow and hard crusts, the formation of soluble salts as reaction by-products, and the questionable ability of some of them to bind inorganic particles together.

Waxes have been found to be effective and durable consolidating materials.
However, major problems are encountered in using waxes in areas with nigh temperature such as Moenjodaro,. because of the tendency of waxes to soften and to entrap dust and grime. If a wax was used to consolidate brick at Moenjodaro, the brick would undoubtedly badly discolor.

The remaining two groups of consolidants, alkoxysilanes and synthetic organ polymers, are the most promising materials for treating deteriorated brick

5.2.2 Alkoxysilanes

Alkoxysilanes, often termed silanes, are regarded as being among the most, promising consolidating materials for stone. The main reasons why alkoxysilanes are being highly regarded are firstly, because of their ability to deeply penetrate porous matrices and, secondly, because their polymerization can be delayed until deep penetration has been achieved. Strength improvements of around 20 per cent have been found when sandstone specimens were impregnated with alkoxysilanes. Their ability to consolidate deteriorated materials in the field, however, has not been equivocally demonstrated.

Bee use alkoxysilanes can deeply penetrate porous materials they should not form brittle surface crusts. They also seem to be unaffected by exposure to strong sunlight,Alkoxysilanes appear to be a promising type of material for consolidating porous brick. Their performance, however, seems to be somewhat dependent on the specific substrate being consolidated. As with any consolidant, the compatibility of silanes with specific substrates must be experimentally tested before they are lised on an important historic structure.

Unfortunately, alkoxysilanes are expensive, costing around $30 per liter for commercially available materials. In addition, their performances are so much affected by the skill of the applicator that a reliable experienced firm should be given the responsibility for their application.

5.2.3 Synthetic organic polymers

Of the numerous types of organic polymers commercially available, only are being used extensively to consolidate stone. They are acrylic polymers and epoxies.

Methylmethacrylate has been extensively used to consolidate stone and concrete. It is applied solvent-free to porous solids and polymerized in situ. Methylmethacrylate can be polymerized into poly (methylmethacrylate) by heating or by gamma radiation.

If deep or complete impregnation and complete polymerization can be achieved, zethylmethacrylate can substantially improve the mechanical properties and durability of deteriorated porous materials. Incomplete impregnation, however, say result in the formation of a distinct interface between treated and untreated brick. As with alkoxysilanes, a reliable firm should be contracted for applying and polymerizing Methylmethacrylate.

Acrylic copolymers, dissolved in organic solvents, also can be applied to brick. However, their depth of penetration may not be sufficient to adequately consolidate deteriorated brick.

An epoxy consists of an epoxy resin and a curing or polymerizing agent.

Epoxies are excellent adhesives and useful for making structural repairs. An epoxy could be injected into crumbing masses of brick at Moenjodaro to improve their structural integrity. Epoxies could also be used for re-adhering large brick fragments to wails. A coal-tar epoxy could make a durable impervious membrane when applied to brick or sheets of fibre-felt.

Most epoxies are too viscous to penetrate very deeply into brick. Epoxies can be diluted with organic solvents to improve their penetration. Nevertheless, the writer does not recommend the use of epoxies to consolidate brick for several reasons: epoxies have a tendency to chalk when exposed to sunlight, brittle composites will probably be formed between brick and epoxies; and great Skill would be required to treat brick properly with epoxies.

5.2.4 Possible uses of consolidants

Consolidants appear to', have only one possible application at Moenjodaro, which is to consolidate badly deteriorated brick, thereby delaying to a future time the need to replace it with new brick. Conceivably, the life of a deteriorate brick could be extended by as much as 20 years if treated with a suitable con- solidant. The compatibility of a consolidant with the brick should be determined with brick test specimens before applying the consolidant to brick in original walls.

Several important factors should be considered before any consolidant is used. Consolidants are expensive and to give anticipated performances they should be applied by experienced and reliable firms. Improperly applied, consolidants can do more harm to brick than natural weathering processes. Lastly, we are not yet able to predict the durability of consolidated stone (probably true of consolidate brick) for even 20 to 30 years. Therefore, consolidants should not be applied to brick which is in reasonable condition.

The writer suggests that if the consolidation of badly deteriorated brick Is considered, tests be carried out to evaluate the performances of consolidated brick. Consolidants which appear to be candidates for testing include methyl- methacrylate, butylmethacrylate, acrylic copolymers, alkoxysilances, and low viscosity epoxies.

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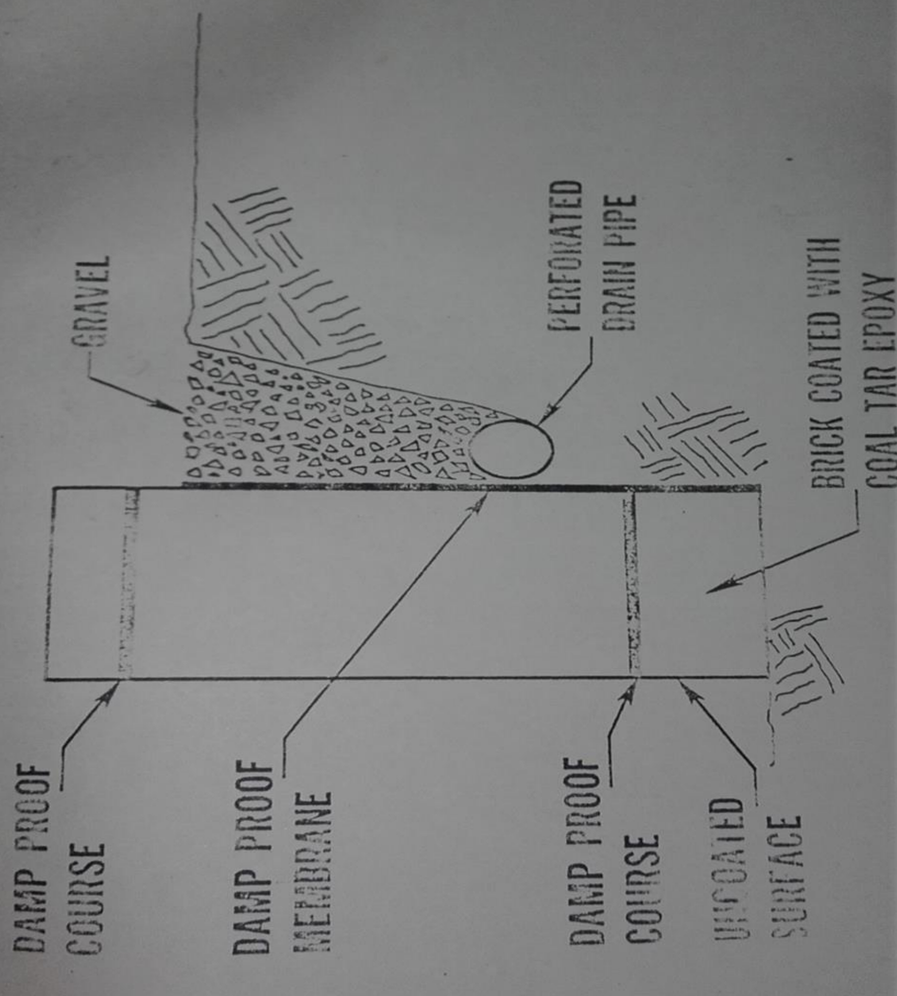
DAMP PROOF COURSE
DAMP PROOF MEMBRANE
DAMP PROOF COURSE
UNCOATED SURFACE
GRAVEL
PERFORATED DRAIN PIPE
BRICK COATED WITH COAL TAR EPOXY

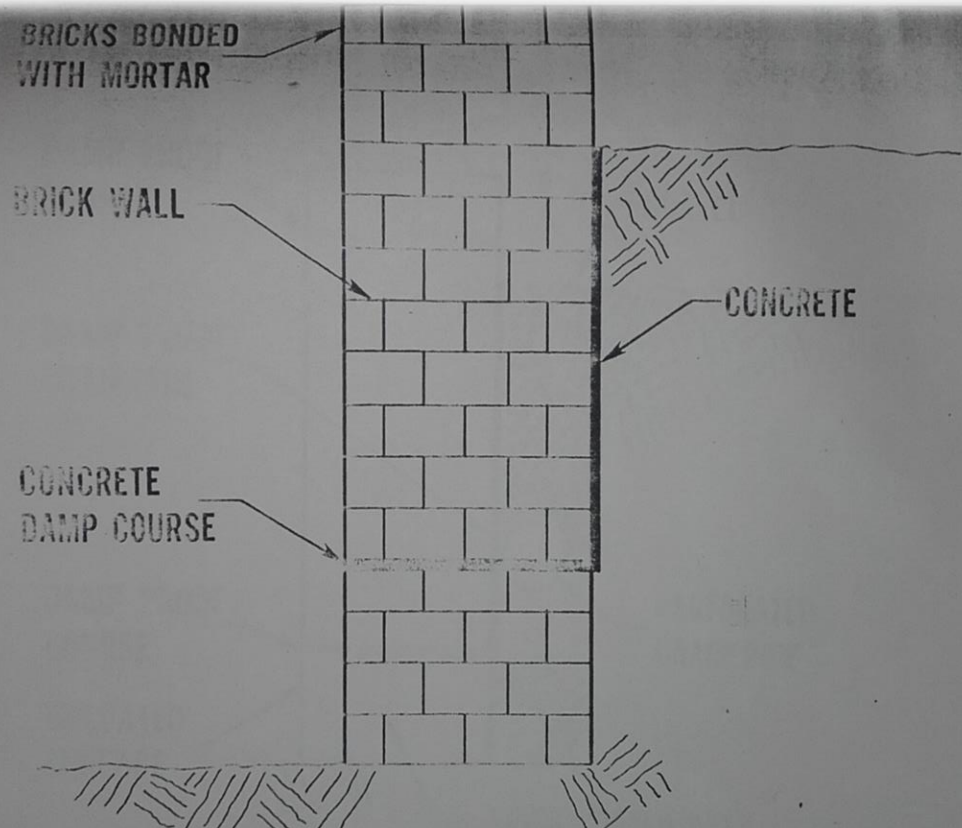

Figure 1. Measures currently used to protect walls. Concrete slabs are coated with a bituminous material.