Construction in Earths

If earth structures have a common characteristic it is in their mass and their modelling. No other form of building exhibits in the same way the soft contours and curving shapes that go intrinsically with earth construction. Massive earth walls are a consequence of relatively low strengths and the material, although cheap, is suitable only for low rise construction. Where there are apparent exceptions to this rule, as in the tower houses of the Hadraumut in the Yemen it will be found that the lower construction is of stone, although possibly set in earth mortars. Although used for vaulting the construction of roofs and upper floors in earth alone is very secondary and what is significant in earth construction could generally be regarded as being confined to low rise walling. Nevertheless earth has been used to raise immense mass-structures, such as city walls, the highest reputedly about 30 m (100′), with a roadway on top — The Round City of Baghdad (eighth century C.E.) — and great artificial hills such as Silbury, England (neolithic). The bulk of the material of the Great Wall of China is earth though much of it is unrecognisable as such due to its stone facing. The mouldability and sinuosity of earth construction make it distinctive when used alone, but many buildings of more conventional profile and faced with more durable materials conceal earth cores.

In the simplest form of construction, which is rammed earth, the building may rise direct out of the native soil. This is a typical technique in the plains of Northern China where immense areas are covered with deep deposits of wind-blown alluvium — loess. In cutting away to provide the material for their work the builders have used the nearest available source, excavating from the future surroundings and interior of their buildings the material to be used for the walls. As the soil is cut, wetted, mixed and placed on the walls so the earth beneath the wall stands clear as the lowest course of the structure. The result is a homogenous, thermally insulating, durable and massive structure which is integral with its site, perhaps to be lined with plaster internally and smoothed over with a mud render on the outside.

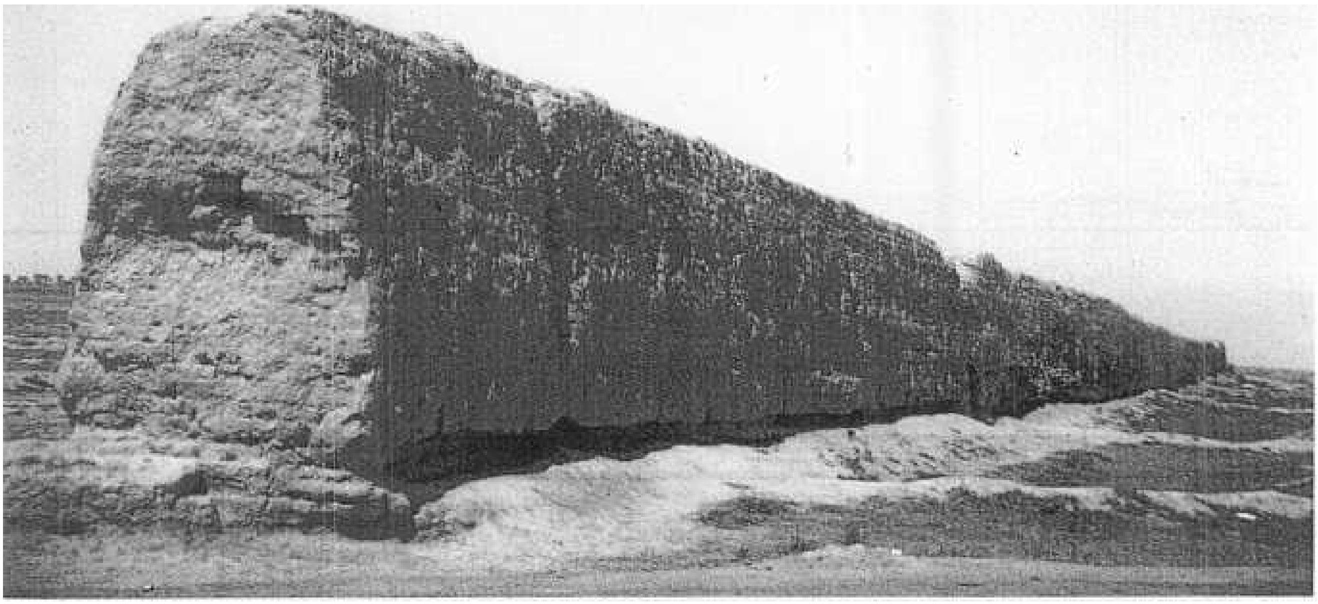
Variants on the method of application of the wetted earths to a wall structure give rise to differing nomenclature. Clay lump is generally accepted as being a method by which relatively stiff lumps of damp earths are placed in position to be made coherent by trampling or similar compression, the inevitably ragged external surface being cut to the desired shape with a form of adze, draw knife, hoe or similar tool. An advantage in placing the mixture in a semi-dry but still plastic condition is that a minimum of moisture reduces the amount of shrinkage. This technique — 'the lump' or clay lump building (Arabic — al Dub, ex Coptic 'Dub') gave rise to the term Adobe, (Spanish via the Mahgrib) which has become the general term for building with mud brick. In the United States and Mexico a dried earth block is an ADOBE. Semi-wet placement of earths can be improved by ramming. This work is generally known as pisé (French) and kehsht (Persian).

Soils are porous, their porosity relating to their density which in turn is a factor resulting from compression and water content on placing. Improved densities can be obtained by ramming or pounding the material rather than simply trampling it into place. To be effective this technique requires shuttering or containment within boards on either side of the wall, such shutters being removable after the initial drying has taken place. A minimum of water is used to achieve workability. The expulsion of air and the increase in density gives very considerably improved load-bearing properties and cohesion. This is a technque which demands and relies upon a well-organised and part-mechanised building operation and consequently tends to produce structures much closer to the rectilinear forms of conventional architecture. In both methods of construction work proceeds layer by layer with typical lifts of about half a metre, this being a depth at which the material is adequately stable in the condition in which it is placed.

These methods of wet placement contrast with construction in dried (mud) brick in which the mud will have been cut to shape or modelled in a plastic condition and allowed to dry before being placed in the wall. In mud bricks shrinkage takes place prior to the earth being placed and although a wet mud mortar may be used water absorption is not sufficient to cause damaging expansion in the brick. The mortar is laid thinly to minimise its shrinkage.

The size of bricks is limited by handlability and the size beyond which shrinkage cracks become significantly prevalent during the drying out period in manufacture. Many modern adobe bricks are blocks compressed during manufacture.* Typically historic mud-bricks are near-square, flat slabs up to 500 mm and edge dimension is between 50 and 100 mm thick.

The cohesive qualities of earths increase with the proportion of clays contained in them. The builder and brickmaker, being essentially pragmatic, will adjust their mixes of sand, silt and clay to the point where a conveniently sized brick will dry without pulling itself apart by cracking as it shrinks. A proportion of as little as 10% of clays is typically satisfactory and clay content above 25% is unnecessary. Above 30% it is excessive. If greater cohesion or internal tensile strength is required fibrous material may be added. Chopped straw is the most common



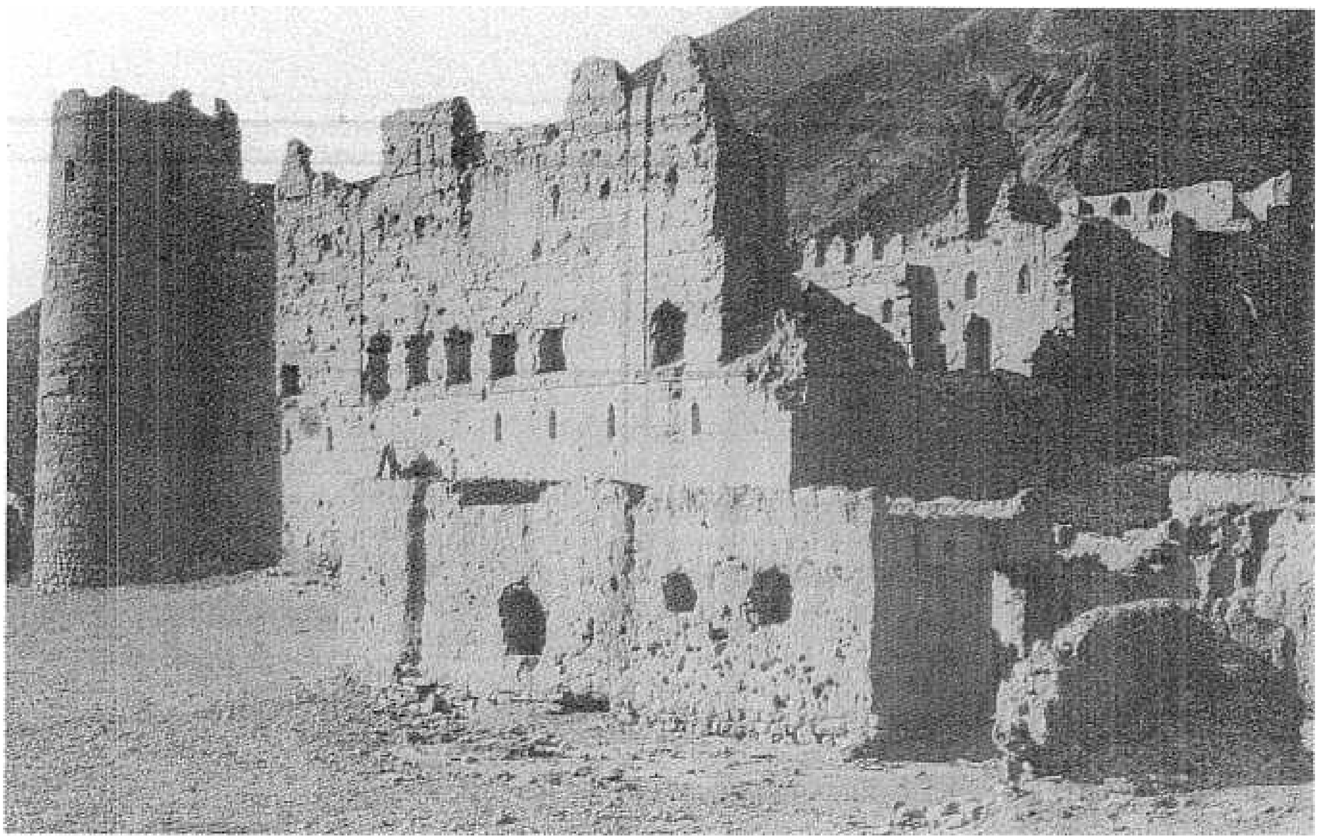
Groundwater erosion on the Great Wall. (Sinkiang, China).

but many other fibrous forms have been used. Coherent blocks have often tended to be formed as flat slabs rather than more approximately rectangular bricks and are usually substantially larger than burned bricks, normally being laid in thin beds of fine mud mortar with broken bond. An even admixture of particle sizes across the silt-sand range is ideal, and soils lacking in any part of the range can be tempered to adjust the inequality.

The suction of the blocks quickly causes the mortar to move from the state of being slurry to being a semi-rigid paste and the work proceeds quite fast, there being very little settlement in the newly laid work. This rapid strengthening effect is sufficient to allow large slabs to be placed in arches and barrel vaults for which the technique of ring arch construction has long been established. The slabs are laid with their broad faces vertical but transversely across the vault and each arch is built slightly inclining backwards. The suction effect provides sufficient adhesion to allow successive rings to be built up, their weight being carried on the ring previously constructed. Rings are generally carried forward in segments several rings being advanced simultaneously in increasing sequence. By this means long tunnel vaults can be constructed without centring and much ancient construction in the Middle East was carried out on this method. Vaults in burned brick were constructed similarly.

Fibrous block or slab construction of a related type is the product of vernacular building in wetter climates where turves or compressed long dead vegetation in the form of peat are cut into rectangular elements, dried sufficiently to be readily handled and built conventionally into thick walls. Such a structure is inevitably compressible — a difficulty sometimes overcome by the incorporation of a significant quantity of additional earth or of rock.

Modern technology offers the opportunity to increase compression mechanically. Hydraulic or mechanical leverage presses are readily transportable and can be operated on the building site in the vicinity of the earth deposits. A large industry has grown up in the manufacture and sale of such earth (adobe) blocks in South Western U.S.A. and in Northern Mexico. Very little historic construction has been carried out in such materials but the availability of



Damage due to physical impact by bombardment. (Birket Muz, Oman).

higher density blocks will have some significance for the conservator needing to introduce additional material into an earth structure.

It is commonly supposed that earth structures are sufficiently soft and tolerant of movement to be free of the formation of cracking due to thermal stress. This is not the case. Long walls of earth construction exhibit vertical fractures at regular intervals — sometimes as much as thirty to forty metres which are an indication of failure due to the effect of a combination of thermal and moisture changes on an annual rather than a diurnal cycle. Such cracks are readily opened up by rain and become immediate sources of weakness and decay. Water collecting in them can be sufficient to achieve rapid run off which accelerates the process concentrating the maximum erosion at the lowest point of the crack and opening it further. This is to some extent compensated for by falls of material which fill the lower section eventually choking the erosion. Similar protection can be given to lower sections of wall by the accummulation of debris at the foot of a wall, forming a minor glacis or scree.

The process of water impact and discharge from earth structures is more complex than might be imagined. Water rejection can be effective and earths can be surprisingly weatherproof. Some buildings rely simply on earth for their watertightness. Many historic buildings have depended for the exclusion of water over many centuries, on nothing more than a layer of tamped clay-rich soil on the roof. In a climate where the rate of drying or evaporation substantially exceeds the absorption of rain the waterproofing can be continued indefinitely provided that the structure is regularly maintained. In this there is an apparent conundrum because soil is inherently porous and unstable when it has absorbed substantial amounts of water.

When the surface of a dry earth structure is wetted by rain, water is absorbed by the outer skin and swelling immediately occurs. Provided that the outer surface is, in its dry state, sufficiently dense the effect of the swelling is to close the pores and reduce the rate of absorption effectively providing a water resistant layer. The surface thereby gains a certain rigidity and further water is discharged. Slow continual penetration takes place due to capillary action, softening the surface layer by layer.

If the rate of fall is high and if the impacts are substantial the softened soil will erode and the outer particles will be carried away but in most circumstances the wetted but not dissolved outer skin will prove a barrier to the passage of most moisture and on drying a hard, almost brittle shell-like surface can result. Beneath this surface there will be a layer of soil much reduced in density having expanded but not having shrunk commensurately on the discharge of moisture. On the next occasion of wetting this more friable surface is very much more vulnerable and water penetration is likely to be much more severe. Hence it follows that the traditional practice is to smooth down the outer surfaces of mud roofs and susceptible rendered areas at frequent intervals while wet.

In many parts of the world devices such as small stone rollers are kept available for the purpose. Inevitably some material is lost on each of the wetting cycles. Continual renewal of the outer layer at regular intervals using clay rich earths is part of a regular system of maintenance of this type.

Only in the driest of climates can the earth structure effectively survive without a coping or waterproof capping to the walls and vulnerable upstands. Since, however, much earth building is found in arid or semi-desert areas a great many earth structures are simply rendered across the tops of walls and battlements with the same mud render that coats the vertical surfaces generally. While this render will generally be of the same basic material as the core of the walls the aim of the builders will be to achieve a higher density in the surface and it is, therefore, trowelled and sometimes burnished to improve the surface density. Tensile strength is often improved by the inclusion of fibrous material, straw being the normal component. The use of animal dung can provide both straw and an albuminous content which is essentially a surfactant. This allows easier movement between the particles of clays. By providing lubrication improved densities can be obtained under hand pressure and organic additives are, therefore, employed with real advantage.

Just as the process of rolling, tamping or smoothing a roof is an esential part of weather protection so is the protective coating of walls, and regular maintenance is essential if the earth structure is to be maintained. This is, of course, generally a labour intensive operation and where the ratio of cost between labour and materials changes as living standards improve so the cost of maintaining the building becomes demonstrably and often rapidly higher. While these remarks are generally applicable to buildings in arid climates, temperate and even maritime climates have a great heritage of earth building which is much less well-known and often concealed by more durable coatings than simply mud. Significant numbers of historic earth buildings exist in the northern states of the U.S.A., Britain and Northern Europe.

Where rainfall is other than infrequent or moderate the tops of walls must be secured under roofs of tile, slate, stone or thatch and their bases will commonly be built on stone foundations. The rise of moisture is sometimes inhibited by mortarless (dry wall) construction. Sometimes burned brick is used as a wall base and brick or stone will be built in as cills, lintels and quoins. Protective coatings to the walls may be as rudimentary as limewash following the softly modelled curves of a cottage wall. Sometimes the rigidity of a hard cement render completes the disguise. The strength of a combination of rigid materials and a structural mass or core which is relatively soft is not calculable in engineering terms and demands great sensitivity of judgement based on extensive experience on the part of the conservator.

These combinations of the relatively soft and rigid materials used in conjunction can immediately be grouped into two types — the first in which the earth structure is the load-

Skin formed on mud-rendered surface by heavy rains. (Langzhou, China).

bearing element and the second in which it is not. Where an earth structure is load-bearing the critical strength is that of the earth. Elements set into it or bearing upon it will tend to be stronger and to move in a different manner as moisture and temperature change, and their reaction to stress will be accommodated by strains in the softer matrix of the earth. In some instances a rigid material will fail in consequence. A heavy coat of a cement render may well be stable and virtually load-bearing locked into plinth, cornice, window surrounds and rigid quoins but as the distribution of loads alters it may be unable to accommodate the more subtle changes taking place in the core of the structure and, taking increasing loads, will bow or shatter leaving the conservator with the problem of a replacement which will accommodate further movements without similar failures. The fault lies with the combination of a soft core and rigid skin and demands reconsideration of the loadings. Failure may occur rapidly with the collapse of complete sections. In the converse case a rigid frame which carries earthen elements will be able to accommodate movements if the main structure itself can move while retaining flexibility. Framed structures with earth infilling provide this option.

Timber framed housing has been used in North America, throughout Europe and across much of Asia and in many instances the infill panels have been of mud carried on timber frameworks or armatures. Mud and stud, wattle and daub and mud plaster have been the material used by vernacular builders throughout history. They have proved durable and flexible. Settlements in timber frames cause panels to warp and force walls out of plumb but the structure remains complete. Aided, perhaps, by continual repair the panels adapt to the new condition and remain weathertight. Only in the cases of the most extreme dereliction are these panels taken apart and the frame renewed. The principle of minimum intervention will usually allow careful repair of the structual members and retention of the deformed but still viable building.

In deciding on methods of handling and treatment the conservator needs a balanced understanding of the empirical behaviour of earth structures and analytical knowledge of the character and behaviour of the particles. Simple field tests provide a guide to the nature of the earths under consideration which are essential to the understanding of the basic historic fabric, and hence to matching it.

Density may be determined to within useful limits by weighing a carefully-cut, volumetrically-measured sample of dried material, and porosity may be determined by weighing the sample again in a fully saturated condition. The sample will have been cut or cored so that its volume can be measured precisely in a dry condition. The weight of water taken up by the sample contained in an exactly-fitting envelope provides a measure of porosity. An irregular sample may be plastic sheathed and cast into a mould. Three measurements are required; dry weight, saturated weight and weight of the mould filled with water alone. A

Rigid cement rendering applied final finish mud brick wall. (Oaxacha, Mexico).

greased mould of Plaster of Paris will serve.

The nature of the constituents falls in gradation across a range in which the smallest group of particles is likely to be below one ten thousandth part of the largest in size. Sand particles may be regarded as being in a range below 3 mm in maximum dimension down to about 0.1 mm. For the description of particle sizes below 0.1 mm the unit of measurement is the micron = (1/1000 of a mm). Silts fall into the range between 2 μ and below 200μ. Clays lie in the range below 2μ. There is no precise delineation between sands and clays. It is a boundary of convenience and some authorities prefer a delineation of 0.5 mm (500).

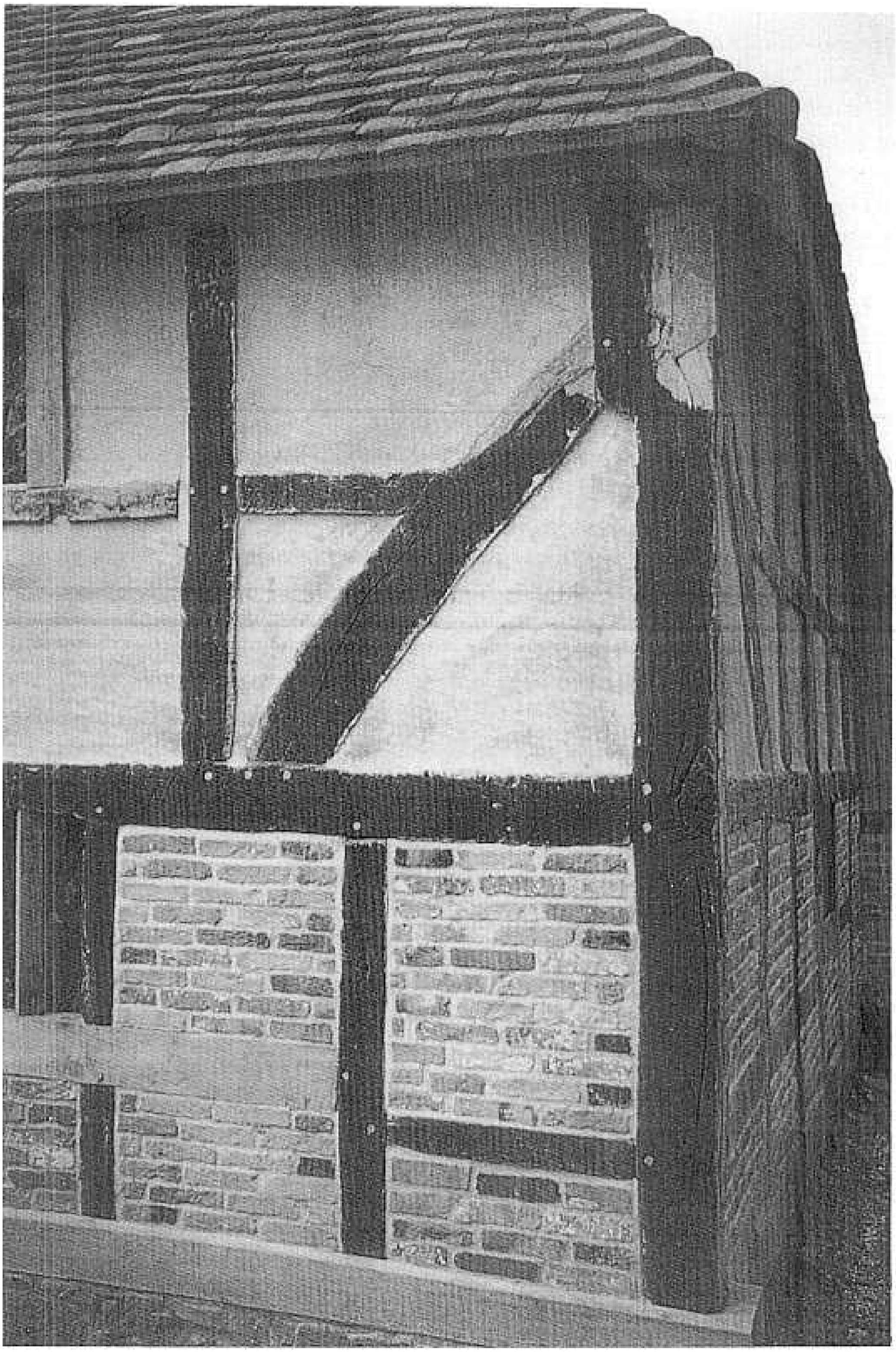
While the characteristics and behaviour of sands and silts does not vary greatly from each other clays are very different from both. They are a special group both physically and chemically.

Clays are characteristically assemblies of stable compounds of oxygen with the mid-range metal and semi-metal elements — aluminium, sodium, calcium, boron, magnesium, potassium and silicon, which form large (in molecular terms) natural assemblies of regularly-shaped molecules of pure material.

Effectively these are lattice structures not dependent upon water for crystallisation. Their forms vary, but they always tend towards a regular arrangement. Typically they form flat plates of polyhedral shape — such as minute hexagonal discs. These discs, however, do not subsist in isolation. Their surface attractions cause them to assemble in stacks in a regular pattern sometimes incorporating two or more different compounds alternately in one stack. As a consequence of these regular arrangements each type of clay has its own distinct characteristics. The interspaces between the discs are of molecular dimensions, and the total structure of each assembly may approach 2μ being an assembly of hundreds of discs.

Clays are rarely pure. Not only are the individual compounds often mixed in themselves to form any one clay — the various clays rarely occur alone and, because they move easily through interstices in the silts and are readily transported by wind, they are readily diffused and consequently widespread. A clay-rich soil may contain as little as 25% by weight of clays and few soils will have less than 5%.

The arrangement of particles as stacks of discs produces special characteristics. Water molecules moving into the very small voids between the discs take up a relationship in which surface attractions exert powerful forces, while other metallic elements such as iron can obtain a firm lodgement and so change the characteristics of the clay. The strong forces holding the plates together resist rupture across their plane but have little resistance to transverse movement. In other words the stack can be broken easily by sliding the plates apart but it will resist being pulled apart on its alignment. As the piles of discs have a regular shape they tend to align themselves similarly, and in consequence an applied force will cause them to move as a body. This characteristic accounts both for the slip-



Brick and wattle panels daubed with mud set in a timber frame. (Chichester, England).

periness and the coherence of wetted clays. The capacity of the spaces between the discs to accept and draw in water accounts for their swelling as water is absorbed.

Clays break down and degrade passing through sequential phases. Some types, such as laterite, represent older and, therefore, more decayed forms. Initially many clays are the direct product of the decomposition of major rock formations. Kaolin for instance is the result of the weathering of an igneous rock, granite, and is one of the few clays consistently found in near pure form. Other common forms are Illite and Montmorillonite. These also are in the less degraded range.

Because of the limitation in size in the formation of the plates clays are always composed of particles well below the limits of resolution of the naked eye and, below the limits of distinction by touch. They always feel greasy, therefore rather than gritty. Their small size makes them susceptible to molecular agitation or bombardment and in consequence they approach the limits of suspension in water. However they do settle slowly out of suspension but can form lyophobic colloidal solutions in which they remain remotely linked in solution and, therefore, sustain a very diffuse suspension. Their behaviour is also critically dependent upon the mineral characteristics of the water itself.

Earth building is essentially practical and empirical and most of the field techniques derive from skilled judgement and experience. Increasingly, however, the disciplines of science are becoming applicable in specialist areas of conservation. Their correct application is dependent upon laboratory techniques of analysis, research and sometimes of sophisticated equipment in their application. There is already a great gulf between those types of conservation which derive from and depend upon traditional methods and those which are based on scientific theory. Even in analysis there is — perhaps more than elsewhere — a yawning gulf between field operations by traditional methods and the laboratory. The reasons for the specific behaviour of clays can only be understood by controlled study and high resolution microscopy. Clay chemistry demands sophisticated analysis to determine behaviour and composition and the introduction of materials usable as consolidants and their carriers. A number of techniques of conservation have been evolved in which sophisticated chemistry faces the test of long-term proving in field conditions. One of the more promising early developments has involved the deposition of silicates in earths requiring stabilisation by the decay of organic radicals carrying silicate ions. Such compounds break down to leave the inorganic components deposited as a consolidant in the soil. With the large range of materials available as carriers consolidants act sometimes as catalysts or dispersants. The possible variations, like the soils themselves cover a very wide spectrum and produce a baffling complexity of conditons and results, none of which can be relied upon until widespread extensive long term testing has been achieved.

The science of the use of synthetic compounds for the consolidation of earth structures is, then, in its infancy; but it is a healthy infant, showing promise of robust development.

By direct contrast traditional techniques have an immense history of trial and error and the knowledge born of long experience. Both scientific and traditional knowledge are important to the conservator whose work may involve a preponderance of one or the other method or perhaps a combination of both. An understanding of the techniques of analysis and a knowledge of the proportions to be sought in suitable mixes may with advantage be backed up by traditional practices in application and mixing.

The contrast between methods is apparent in the ways of testing the nature of earths and clays. Local traditions will often be a quite sufficient guide to a suitable earth, indigenous people knowing the qualities of the material to be obtained from particular places. This knowledge, while entirely satisfactory for practical, traditional purposes will not extend to an understanding of particle size or proportions of materials and the local builder will be unaware that a soil with less than 5% and more than 25% of clays by dry weight is unlikely to be suitable for his purposes or that the remainder of the content of a satisfactory soil is likely to be sands and silts in approximately equal proportion with not more than 10% of organic matter as fibre and possibly an albuminous material to provide workability. He will think in terms of texture, workability, feel, shrinkage and plastic qualities. The conservator, having analysed the original material will know however that the raw earths require tempering to produce the ideal balance of mix. For the mixing process he will take note of traditional practice.

Inevitably there have been many variations on the basic formulae. In areas where limes and gypsums have been readily available there are many instances in which a deliberate addition of calcitic or gypsum-based materials have been made in order to achieve a permanent set. Some of these have been successful to the point of producing a material whose hardness has caused it to be thought of as an artificial stone.

A specific instance is the Qubbat as Sulaibiya, built in the 9th century close to the Tigris near Samarra. Although there is plenty of rock in the vicinity this very early, (if not the earliest) domed tomb in Islam was built of a compacted and hardened earth which has set off with the strength and coherence of a hard plaster. A combination of compaction, the minimum addition of water to minimise shrinkage and the formation of a crystalline structure in the material is sufficient to give it virtually permanent durability by contrast with the less well-built soil structures nearby whose ruins now cover tens of square kilometres in ungainly heaps.

Another common additive has been ash sometimes coupled with oil or blood in mixtures applied particularly to floors to improve wearing characteristics. Mixtures of bitumen and earths have been used as mortar and for the obvious purpose of improving waterproofing in the bases of walls and on roofs. These are long lasting and easy to detect as well as being easily simulated. This last material stands virtually alone in the vocabulary of naturally available earth binders in being totally water resistant. All other variations of earth structures are sensitive to water conditions and susceptible to failure as a result of the expansion and ultimate loss of bond caused by increasing volumes of water.

The stability of dry earth depends on the friction between particles within it. Theoretically a well compacted earth structure in a perpetually dry condition should last indefinitely unless destroyed by impact or eroded physically. In practice dry conditions do not occur. Water is always associated with inhabited structures causing cyclic expansion followed less certainly by contraction, allowing the transfer and deposition of salts and sustaining plant growth. Frost action, physical erosion and slump may all be a consequence. Water may be introduced as rising damp, as ground level flooding, as rain, snow or hail or as vapour condensing from the air. A neglected cause of entry is the leakage of pipes. The first step in modernisation of property is often the introduction of piped water. This is not always accompanied by systems for the removal of water and the previous methods may be inadequate, resulting in a build-up of waste or leaking water in the structure.

While the mechanisms of decay are fundamentally the same as those affecting burned brick their operations can sometimes be dramatically different. One reason is simply that the progressive wetting of earths terminates in a total slump of the material. The initial effect is to cause expansion. A typical compressed earth taking up water will expand in volume by upwards of 10% and will be capable of absorbing up to its own weight in water while broadly retaining its compressive strength. It does, however, become increasingly plastic and its increase in volume is, therefore, accompanied by deformation in response to physical constraints or loadings.

Thus an earth block, freestanding but carrying a load will continue to support that load on taking up water but will expand laterally by deformation rather than by raising the load. On loss of water the block shrinks within the profile of its newly adopted form and the load can move downwards. This process can be repeated indefinitely and the loading will change. The load bearing characteristic of the structure therefore can change due to plasticity. It can change even more dramatically by the sudden loss of coherence when the material becomes totally saturated. At this point adhesion between the particles which has been enhanced or maintained by the effects of surface tension within the pores is completely lost. In a saturated condition the pores vanish, there is no surface and, therefore, no surface tension and the particles are free to move into suspension. Immediately prior to this condition the material loses all strength and slumps. This dramatic loss of strength is not paralleled in burned brickwork.

Earth structures are more attractive to plant life than brick or stone and in many cases they are the natural medium for its sustenance.

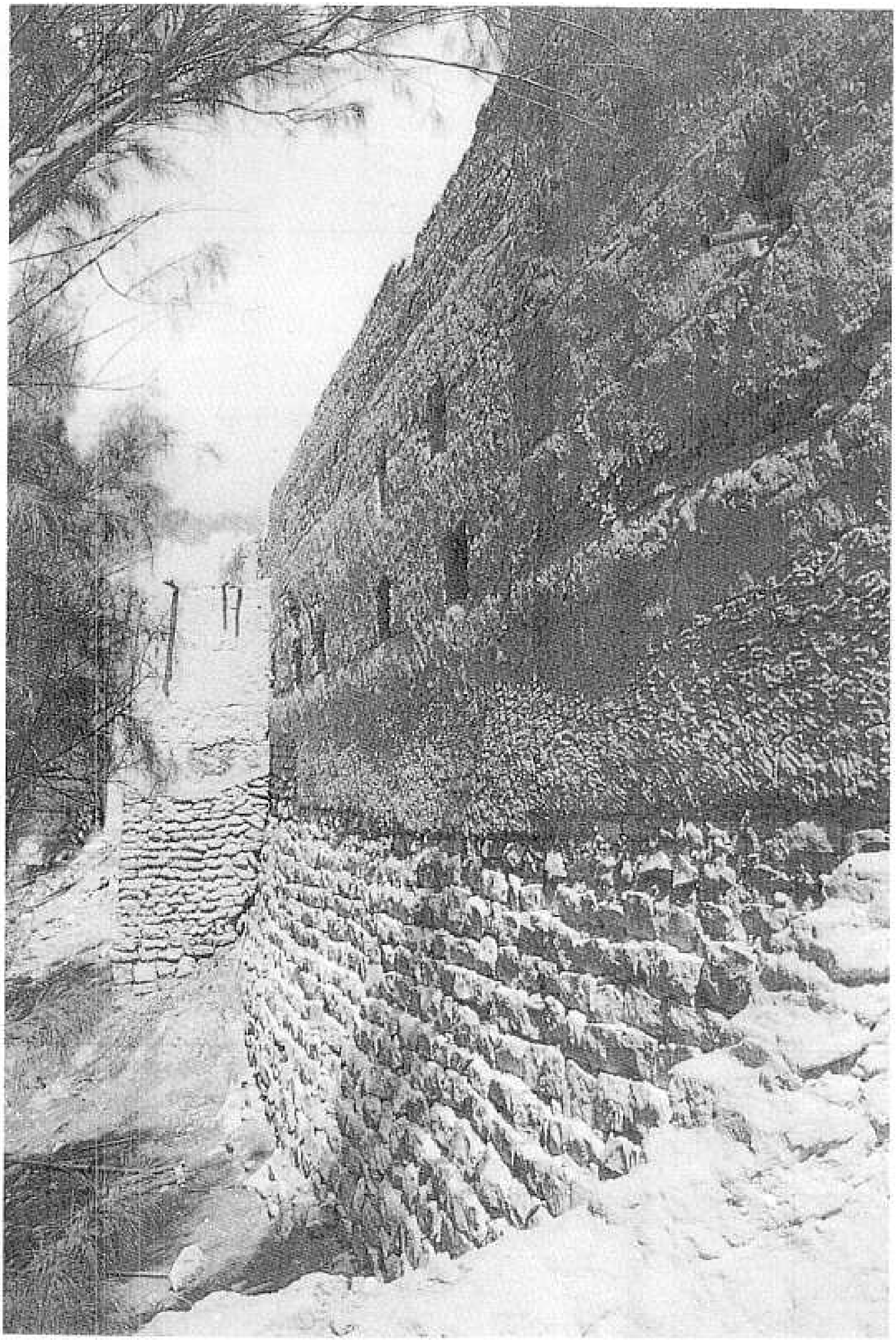
Invasive root damage can, therefore, be a more significant problem than in other structures and the consequences of tree growth and fall can be totally destructive. On the other hand earth structures designed with the protection of plant growth in mind can be retained and protected. Hill forts, embankments and dams may rely on a turf covering for protection and weathering. A turf-covered dam can be stable and permanent, but if trees are allowed to grow and fall the dam can be weakened to the point of failure simply by the removal of the root ball and its earth.

The protection afforded by mud or clay renders and coatings must be restored continually as every successive wetting causes an expansion of the dense surface layer which is not recovered at the evaporation stage. The density of the surface layer is an essential protection against water penetration and the swelling which occurs on the initial wetting improves the density temporarily.

Even greater surface softness is caused by the deposition of salt crystals on or immediately below the surface of an earth structure. Slightly saline water drawn up into an earth wall evaporates leaving behind it crystals whose swelling is caused by the powerful forces resulting from the acceptance of molecules into a crystal lattice in its growing phase. As the crystal grows the clay, silt and sand particles are forced apart and the surface bonding or friction forces become ineffective. In a loose or powdery condition the particles are then free to move and disturbances such as vibration, wind action, impact from wind-blown sands and even insect activity are sufficient to dislodge them. Most dangerously this dislodgement occurs at or close to ground level undercutting the building and precipitating collapse.

In earth structures the behaviour of material is very much more a product of the nature of its constituent particles than it is in burned brick. By virtue of the fusing of the brick the material becomes coherent and the individual particles are locked into a rigid structure which is physically if not chemically inert. In earth structures each particle retains its identity and the behaviour of the mass is determined by the individual behaviour of the many types of particle.

Earths generally are built up of four grades of material — organic, (which may take any size and is generally fibrous or of microscopic life form), and sands, silts and clays, all of which are mineral. In the presence of moisture the organic material will decay very much faster than the inorganic minerals, ultimately washing out and leaving little residue.



Mud-brick wall protected by being built up on a stone plinth. (ad Dariyeh, Saudi Arabia).