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The effects of flooding upon buildings in developing countries

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The general effects of flooding on buildings and structural materials in developing countries are comprehensively reviewed. The aim of the paper is to stimulate further field based research as to how and what type of building improvements can be introduced, given the prevailing economic and cultural constraints of many communities, and to examine the appropriateness of floodproofing measures in developing countries where there are often few floodplain management or large scale flood prevention schemes. Proposals are suggested as to the method and type of information which is required for detailed studies prior to developing new and more effective building designs.

Key words: Flooding; building materials; material decay; building repair; floodproofing; flood prevention schemes; damage assessment.

INTRODUCTION

There are very few publications which systematically analyze the effects of flooding on buildings and building materials in developing countries. For example, the assumption that flood damage is random lends support to the argument that little field work has been carried out. Without such field and analytical data it is difficult to have faith in the accuracy of estimates of damage costs, the need for temporary/long-term shelter, or the suitability of rebuilding-rehabilitation programmes. Further, it is impossible to assess whether the effect of flooding upon the building industry should be categorized as disruptive or destructive (Cuny, 1978).

Indeed, very often imported and inappropriate high technology/high cost schemes (as defined by the inhabitants and not the local administration and relief agencies) may be used to the detriment of other relief measures. Alternatively, inexperienced architects, administrators and casual relief workers naively reinvent traditional vernacular building types that may be no better than the originals. As has been pointed out, the guidelines proposed by the U.K. Building Research Establishment in *Model Regulations for Small Buildings in Tropical Countries* state that soil (used in various ways), thatch, grasses and unsquared timber *should not be used.* This is a somewhat naive directive which would be impossible to implement in any developing country (Davis, 1978).

The only way to completely avoid the effects of flooding is to live well away from the areas that can be inundated. Coastal plains, flood plains, valley bottoms and the banks of stream channels are unsafe and may be described as areas where surface water is the prime land eroding and forming agent. Living in these areas, for whatever reason, implies a compromise which has a concomitant increase in risk and hence vulnerability to this type of natural hazard.

In developing countries this risk is accepted as the vulnerable locations are absolutely essential for, for example, agriculture, communications and building materials. To avoid large fertile flood plains would be impossible. Hence in Bangladesh 30% or more of the land is subject to regular seasonal flooding.

Following a flood incident it is appropriate to focus on the disastrous effects by asking a series of pertinent questions concerning the interaction of the structures and building materials with the water. There must also be a detailed appreciation of the prevailing social and economic conditions (Table 1). This set of questions was used during the collection of factual information for this paper and given the paucity of answers, the 'state of the art' is still in an elementary stage of development.

BUILDINGS IN DEVELOPING COUNTRIES

Before assessing the effects of flooding on buildings it is essential to accept and work with the principle that with any natural or man-made environment and for any type of building (mud hut, brick cottage, multistorey, concrete framed apartment) there is an enormous difference between the best and worst that can be built at the same cost. This includes a house's construction quality, ability to fulfil its intended function, normal behaviour and resistance to catastrophic events. While codes of practice and building regulations can impose certain standards, the design and performance of a building is very dependent upon the whims of the owner. The prevailing socioeconomic conditions are also important considerations and for example help to determine the degree of seasonal maintenance.

In developing countries, safe buildings are often low down in lists of survival priorities. Hence, to take an existing structure and convert it from one of poor normal performance to one of good normal performance can only be done if it involves either no expense to the occupant, for example, when time, labour and a design is freely available, or a little expense if the inhabitants desire an enhanced status, or it outgrows it present requirements.

The dependence of a building's performance upon its owners or occupants is illustrated in Fig. 1; this shows decay characteristics of materials. With time all materials decay, it is only the rate that varies. For example, stone decays slowly and soil quickly. It is of fundamental importance to realize that decay, and hence the building, follows an exponential path to the point of total collapse. Figure 1 is also important in showing that decay, repair costs and performance are inter-related. For the purposes of this paper the lesson is simple. A building that has major defects of is allowed to decay does not perform as well in a flood as the one that is well maintained.

Table 1.

1. What actually happens in a flood, from a victim or community's own account? How did the flooding occur at their particular settlement?
2. What are the failure mechanisms causing damage to the buildings?
3. How precisely do the buildings behave structurally and materially?
4. What is meant by a destroyed building? Are the materials also destroyed?
5. What actually happens to the damaged buildings, for example how many are simply washed away? How many end up as a pile of rubbish on the site? Is there a difference in the damaging effects between 'pukka' and low cost housing?
6. How are dwellings rebuilt? Who builds them? With what materials and at what cost? How important is the recovery of damaged materials.
7. What part is played by the importation of materials from nearby markets and further afield?
8. Does the flood provide an opportunity to improve building technology? If so how effective are the improvements?
9. How does the flood affect the price of materials? Do price rises suggest that preflood maintenance/improvement measures be taken? What local building materials become scarce?
10. Is there enough information to be sure that minor and major pieces of engineering works do not increase the effects of the flood or shift waters elsewhere on the flood plain?
11. How do people behave during a flood, for example, do they repair the roof or abandon it in the belief that it would imminently collapse? Do they move their possessions onto the roof or first floor?
12. Does a preflood warning lesson the damage to buildings, particularly low cost houses? Are there community responses to protecting buildings?
13. Do people lower down the river system gain (financially) from the flood by being able to recover lost materials that can be reused?
14. What are the effects of structural damage upon death, injury and health?
15. What local responses have been successful in reducing flooding problems near buildings?
16. Are floodproofing/waterproofing measures economically justifiable? Do they work for anything except pukka housing?

In developing countries experience has shown that once a house is constructed with low cost material and simple techniques it does not necessarily increase its monetary value. It therefore usually deteriorates unchecked to the point where the action of a flood is 'the last straw.' In places of increasing flood inundation such as the Ganges flood plain there is an increasing vulnerability particularly as the present housing stock is slowly disintegrating, unchecked by any form of maintenance.

FACTORS RESPONSIBLE FOR DAMAGE TO BUILDINGS

The mechanical and hydrological parameters defining the effects of water upon buildings have been described for many decades and very few additions or alternatives have been made by successive authors (White, 1939). The mechanisms were and are described in relation to 'high quality' building types such as houses in the U.S.A. or the U.K. and they need radical modification when considering buildings in developing countries.

Depth. Building performance is very sensitive to the depth of flood water and hence is used by many researchers as the main criteria for damage/cost assessment (White, 1964; Parker and Penning Rowsell, 1972; Penning Rowsell and Chatterton, 1977). Since local variations in flood depth are significant for certain types of buildings, the flood depth should not be calculated at the main channel. For contouring flood depths even bumps and hollows of a few centimetres can be of significance, particularly for soil walls. Here, if there is a continuous supply, a 10 mm depth of water will cause the wall to be totally undermined. Even with a more substantial wall, the actual height of a wall affected can be more than 3 m above the flood depth.

Hydrostatic loads. The hydrostatic loads are directly proportional to the flood depth, and act upon both vertical and horizontal surfaces. Maximum damage occurs where the applied forces are unbalanced between the outside and inside of a waterproofed house.

The effects are to cause general collapse, displacement and overturning. In the best housing, where fired bricks are bonded with soil mortar, 'piping' and 'jetting' can take place through the joints. Shallow water (0.3 m) even with low velocity flow can result in pressures sufficient to dislodge sheds, push doors inwards, break glass windows and scour out shallow foundations.

The flood is also responsible for uplift forces and these are related to depth, density of material and displacement characteristics of the structure. A wooden building floats upright because the centre of buoyancy is above the centre of gravity. The weight of concrete below water is reduced by half, with the result that concrete strip foundations are more easily displaced. Pockets of trapped air can cause

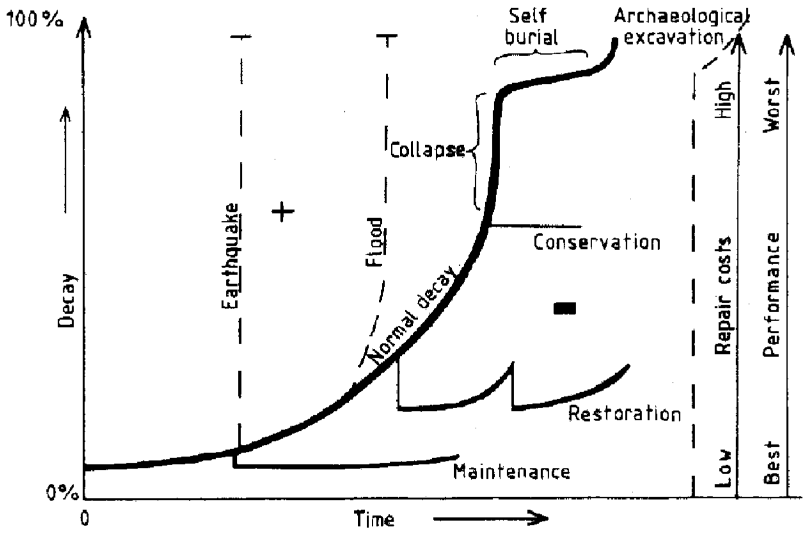

Fig. 1. + The decay speeded up from the normal caused by changing external influences such as increased rainfall and humidity. — The decay slowed down from the normal as a result of the action of man or change of climatic conditions. Here *normal* refers to the building when it is allowed to decay without the influence of man or catastrophic natural events.

explosions of well sealed cavity walls, cavities and flat concrete roofs (having spaces immediately beneath) and items such a pottery storage jars. All of these can burst with devastating effect also damaging the adjacent structure.

In Western countries the level of flood and waterproofing is defined by the history of previous flood depth together with predicted levels. Normally 3 m above ground level is the economic level for such measures, but no cost-benefit figures for developing countries were found during the research for this paper. Where, traditionally, the building materials have been freely won and the cost of the house is mainly in the labour input, it is difficult to envisage waterproofing measures that are financially justifiable. Here structural floodproofing measures to whole areas and communities may be more appropriate.

Velocity. The velocity of flood waters varies considerably within small distances due to many factors including: stream shape, land gradients, local topography, trees, position of buildings, field patterns and engineering works.

On the large flood plain the velocity is normally under 1.5 m/s but can reach up to 3 m/s. This is usually less than half that in the main stream. It is not uncommon for the inhabitants to be able to swim with possessions to places of safety. In flash floods, sea surges, where temporary dams of trapped material fail (here the higher the velocity the greater is the possibility of getting trapped material) or where flood protection works break, the velocity of water often exceeds 10 m/s.

The velocity tends to decrease with depth, though non-uniformly due to drag and turbulence. The damaging effects of the velocity are due to the resultant dynamic forces and particularly since they are usually unbalanced with pressure on one side and suction on the other. The impact pressures are often lessened by aeration of the water where fast flowing water crosses over obstructions. The suction effect of water at high velocities flowing through structures can lift flagstones, swollen/distorted timbers, tiles and drain covers.

High surface velocities tend to produce overturning action, thereby redistributing the 'dead' and 'active' forces within the walls. Where soils, soil mortar, rubble and bricks are used (i.e. walls with low tensile strengths) shearing and crushing may take place near the foot of the wall.

Wave action. On the flood plains wave action usually results from water flowing over or around obstructions, though occasionally claims have been made concerning the creation of waves by rescue boats. Coastal waves, due to wind, air pressure, currents, sea bed topography or the fetch are a bigger problem. Wave action is a local increase of depth and velocity, and along the coast it considerably increases the impact forces and only occasionally the hydrostatic loads. Waves created on inland flood plains cause nominal zones of erosion just above and below the water level and keep the wall fabric above it in repeated cycles of wetting and drying.

Sediment and debris. The velocity of the flood water, related to volume are the main factors responsible for the transport of all sediment and debris. Floating loads include trees, crops, houses, animals, boats and objects such as boxes, tanks and furniture. Where the velocity is low and there is a shallow depth, eddy currents and obstructions often result in the washed material ending up in a not too distant place. Materials such as wood, cloth, corrugated sheet steel, tins and ropes washed down from higher up the catchment can provide immediate post flood aid. When not too saturated with water these typical materials usually form the basic elements for 'instant housing.' The suspended loads are mainly silts and sands that flow throughout the water mass at the same velocity. The bottom loads are gravel, boulders, concrete and bricks which normally bounce along the floor of the main channels.

All the materials mentioned above frequently block drainage channels and are often deposited in or against buildings. Muddy silts are the main deposits within a building and effect the ability of the structure to dry out. The fine material is able to penetrate the whole building including cavities, appliances and drains.

The greatest problem caused by large transported items such as trees, logs, carts, is their impact on buildings. The typical soil and timber huts clearly stand little chance of resisting such collisions.

Flood duration. The duration of a flood is normally calculated from the time the river overflows through the maximum development, to the time when the water is back within its banks.

For houses and fields it is more realistic to accept that flooding continues on while there is still visible water lying around. Generally, floods caused by hurricanes are short and sharp, as indeed are flash floods and floods near the headwaters of a catchment. Here the period of river overflow can be measured in terms of hours. Seasonal floods on low lying land and extra tropical storms last for long periods, often three or more weeks. In all cases the receding of the flood waters takes much longer than the flooding event.

Despite the general assumption that the influence on the structure as a whole is minimal, the duration of the flood has a major detrimental influence upon the behaviour and decay of materials in general. The duration must also be considered proportional to the rate of absorption and the length of the drying out process. For example 1 m^2 of single thickness brick wall can hold 55 l. of water and take 2 months to dry out. Unfired inorganic materials such as soils and soft limestone and the organic materials especially paper, softwood and leather all swell, soften and deform. Ferrous metals rust and if wet for any length of time tin containers and pipes will often corrode through. The behaviour of materials after wetting is described in greater detail below.

It is possible to modify the local duration by careful site selection, and the introduction of drainage during the flood withdrawal and maintenance. Buildings should be positioned in 'open' systems or 'positive closed' systems. The first allows the water to freely drain out of a local catchment while the latter allows that water to drain off a local high point. Buildings should not be placed in a negative closed system such as a depression. This, plus similar features including depressions worn by animals and protection bunds, allows trapped water to stand for a considerable time.

Rates of change in water levels. The rate of rise and fall of the flood water can have an influence on the building damage. A rapid rise of water affects the ability of people to protect their buildings and repair engineering works. The tendency is for hydrodynamic loads to dramatically build up. A rapid draw down can leave slopes such as are found in embankments with positive pore pressures which often results in slope failure.

Frequency. Where frequent flooding occurs there is a marked speed up of decay processes. The materials seldom have the chance to reach a state of moisture equilibrium in that they are either drying out or are wet and saturated by the time of the next event. Salt efflorescence on stone and soil brick and wet/dry rot fungii in wood are particular problems.

Seasonal floods often do not allow sufficient time for people to make structural repairs or introduce improvements. On the other hand the inhabitants in such places have learnt to cope with the events and here it may be imprecise to term flooding a disaster. Where flooding is infrequent, the flood hazard is often forgotten or seen as being of little significance. In such cases water/flood proofing schemes are not implemented and the vulnerability is proportionately increased.

The season. The seasonality of flooding has no direct significance upon the damage to buildings. However, it has been inferred that a summer soil moisture deficit can result in a greater rate of ground heave. Newly stored agricultural products can significantly increase the loading on walls. Where saturated materials freeze, cracking can result.

THE EFFECTS OF URBAN DEVELOPMENT UPON FLOODING

In the expanding urban areas the assumption that while run off is increasing, the dissipation of surface water is progressively improving, is questionable. The author's research indicates a general increase in frequency of urban flooding in developing countries. Indeed, newer town areas tend to be on previously unused marginal land that is more susceptible to water inundation. The historic urban centres located on the least vulnerable land at the time of original occupation are being made more susceptible.

It is commonly found that sewer systems and storm drains in the older centres are undersized with inadequate gradients for the drainage requirements. Since they are frequently partially blocked for normal drainage loads, they are totally inadequate for coping with the ingress of large volumes of flood water. Likewise, in the suburbs and generally low lying lands, drainage ditches and larger canal systems are seldom designed to cope with exceptional events. This is often exacerbated by the blocking in channels of vegetation, rubbish and even new buildings. The latter commonly includes squatter settlements, although they are frequently professionally engineered commercial developments.

Surface drainage is often impaired by modification of the land surface, for example, by roads/railways on embankments, borrow pits, waste mounds, depressions associated with houses and animal pens, terraced housing, property walls, bridges and even by the odd collapsed house. While most of these features will only form temporary blockages to flood waters, where they form a closed negative topographic feature water may become permanently trapped until drained by pumps or relief channels. Also topographic modifications can redirect water flow away from preferential drainage routes. Concentrating water into artificial and unexpected routes can lead to unpredicted erosion, large dynamic loading and long durations for standing water. Due to the complexity of these urban man-made catchments, drainage is often difficult. The water cannot simply be drained into a neighbouring area with the hope that it will eventually flow away. This may simply transfer the flood elsewhere.

THE EFFECTS OF FLOODING UPON THE STRUCTURE AND MATERIALS OF PUKKA HOUSES AND VERNACULAR HOUSES

'Pukka' is a word that means the 'best.' It is a term applied in developing countries to houses that have been architect designed and engineered. Hence they are expensive structures that can only be afforded by the wealthy. Often such houses are made to immitate those found in western countries (having been first introduced by expatriates) and are built with high technology materials and imported products. Pukka houses represent a status symbol despite often being inappropriate to the culture and environment. Less wealthy people copy such houses in less expensive products and quite often the structural performance is poor — the result of overstressing the materials on an inadequate design.

Vernacular houses are the traditional structures of an area. They are built either by the occupiers or the local craftsman according to long established customs, with materials found to hand. In terms of local incomes they may be expensive or cheap structures to build and maintain. Variations in form and ornamentation gradually develop to meet new environmental conditions and social dictates. With time, each structure tends to become distinctive. Patching, repairs, alterations, additions and rebuilding often in different materials with a different style makes vernacular houses structurally complex. On the other hand, smaller huts and temporary shelters may simply stay the same over many generations. These are replaced as the materials decay, the structure deforms or as a result of external influences such as floods.

The impact of floods upon all types of house structures is very complex, highly variable and poorly understood. In general the effects of water and flooding on the structural elements and building materials are listed below.

1. Foundations

1.1. Pukka. Where walls are bonded onto strip footings or where they are founded well below ground level into stiff/dense soils or weak rocks they do not usually suffer from sliding, the result of hydrostatic and hydrodynamic loads.

However, where the wall simply sits on the ground or on the strip footings at ground level, sliding and rotation often takes place. This is dependent on such factors as frictional resistance and water dynamic forces.

When cohesive soils such as silts and clays and organic soils become saturated, groundheave normally takes place with the inevitable distortion of the superstructure. During the drying out period cohesive soils will then shrink and cause differential foundation movement.

The degree of swelling is complexly related to factors such as the type of clay, the permeability and length of saturation Maximum heave is normally delayed from the time of maximum wetting and can effect the soil 3—5 m below ground level.

Granular soils such as sand and gravel do not swell as a response to wetting but where they are loose or weakly cemented, foundation loads can cause consolidation and settlement. Löess and other fine silty soils often have a grain structure that can collapse upon wetting or when subject to increased loading.

Buildings where the structural element is a series of columns attached to pad foundations normally perform well in floods. This is because the static and dynamic loads simply tend to collapse in the infill panels. Here structural failure results from the impact of floating debris, inadequate diagonal bracing and insufficient embedding of the columns into the ground. Pad footings where concrete is poured behave better than placed concrete and brick blocks.

Foundation walls that retain simple basements perform adequately if the basement is allowed to fill up slowly with water. It is often appropriate to purposely fill up the basement with fresh water thus lessening the problem of pollution and silt accumulation. Here the main problem occurs if the superstructure is watertight and a surcharge is applied by the water upon the ground around the basement, so forcing the walls to collapse inwards. 'Sealed' basements can explode upwards.

Where the water velocity is high, for example on the outside of the main stream channel, where protection banks have failed, or where water flows down steep inclines, scouring can considerably undermine foundations. Further, where the foundations are very shallow, seepage, piping then scouring may take place through into the inside of the structure.

1.2. Vernacular. Traditional one or two storey houses usually have low wall loadings so the strength of the soils at ground level is sufficient without the need for deep or substantial foundations. In a flood the failure of the superstructure is normally too rapid for the integrity of the foundations to be of significance. Where foundation failure occurs, it is due to a sliding action. That is water going underneath, or structural poles being pulled out of the ground.

Ground heave or consolidation may affect the structure. The low shear strength of soil walls or poor quality brick work may result in cracking and displacement. Timber framed structures can normally cope with these differential ground movements.

2. Walls

2.1. Pukka. Concrete, reinforced concrete and steel framed buildings and buildings raised on stilts are resistant to flooding and the normal design factors are usually sufficient for the structure to cope with flood-induced deflections.

However, infill panels are very susceptible to displacement. Their bonding into the frame is often nominal and is usually engineered to be no more than for weather proofing and rapid replacement. Hence glass, aluminium sheets and various fibre boards are rapidly torn out or imploded. Where the walls are built with precast or cast *in situ* concrete panels, or are single/double thickness brick, they are damaged to varying degrees depending on the hydrostatic, dynamic and impact loads.

Such walls usually fail by implosion or fall over when the centre of gravity lies outside the load bearing base. Where the mass of the wall increases and also when the load passed down through the wall increases, the ability of the wall to resist the flood forces progressively improves.

Wall claddings and renders are severely damaged by impact and suction effects of flood waters. Since they are not normally watertight, static pressures do not cause implosions. Walls that make use of soil mortar to bond the brickwork almost always deform rapidly. Firstly, the soil has low shear strength and secondly the soil softens to a mud and squashes out. 'Piping' may also occur through the wall thickness, often dislodging areas of brickwork.

2.2. Vernacular. The materials and techniques used for wall construction are normally too simple to have been waterproofed. Thus the insides fill up at the same rate as the rise outside and no static loading results., Walls built with inorganic materials, such as stone rubble, soft brick and soil brick, have low shear strength. Dynamic and impact loads quickly fail them. Where the wall is soil they disintegrate catastrophically.

Where walls are built with organic materials they are relatively lightweight and damage very easily. If there is no diagonal bracing and if the joints are tied together with rope, the buildings tend to collapse easily. These are washed away as bits of structural elements and wall panels. Where the building is well constructed, the house may be buoyed up and pulled out of the ground. In this case the structure may stop nearby, caught on an obstacle or may break up in some distant rapid.

3. Roofs

3.1. Pukka. The timber frames of pitched roofs are normally poorly anchored onto the wall plate and therefore tend to slide off. If they have trapped air they often turn upside down and sink due to their shape. When the roof is covered with tiles these inevitably become detached and the roof timbers float away as a distorted mass. Where the roof is not braced or trussed it is often pushed inwards.

Flat concrete or reinforced concrete roofs normally perform well in floods and their collapse usually results from the structural movements of the supporting walls. Where the flat roof sags (particularly noticeable with bitumen covered roofs) or has parapet walls, drainage is often poor. Accumulation of water during heavy rain can sufficiently overload the roof to the point of collapse.

3.2. Vernacular. A roof constructed with a series of beams supporting a soil covering is very heavy, as is a thatched roof of a timber framed hut. In floods these sorts of roofs absorb water, dramatically increasing their weight, are very unstable, and usually destroy the structure beneath. The timber beams and joists normally rest upon the walls without a wall plate so when submerged, float off.

Where a system of clay or slate tiles is used these simply stay in position by gravity and hence in a flood are quickly dislodged. Pitched roofs with bracing are often the best constructed part of the house and in such cases they remain as a unit and may only float away when the flooding is deep.

4. Building materials

4.1. Brick. Bricks are the most important building material for pukka houses. In Third World countries bricks are normally made from the easily won 'normally consolidated' flood plain silty clays and clayey silts. Since they are hand-moulded with a high moisture content they have a low density.

In addition, bricks are made in simple kilns, often no more than a 'clamp,' the bricks are fired in highly variable conditions. Often the temperatures do not pass the critical 700 °C and the kiln atmosphere may be oxidizing or reducing. Such bricks are normally very soft and occasionally vitrified and distorted. The other common defect is the inclusion of a high soluble salt content occasionally above 2%. Once made, bricks are used immediately. Only occasionally are they left in the kiln or in stacks for many years. In the first case, defective bricks are not easily recognized. In the latter case and very typically of the Ganges flood plain the bricks are badly decayed before use.

In a flood, bricks behave very variably. Well made, well fired bricks have withstood the effects of floods for many centuries, as witnessed by a wealth of historic monuments. However, in domestic architecture the main problems are softening of the poorly fired bricks, cracking/disintegration in places of differential movements and extra stress, and efflorescence causing rapid spalling during the drying out process. Where the bricks are very porous and have absorbed large quantities of water, the extra wall weight may crush the normally decaying brickwork near ground level.

4.2. Concrete. Mass concrete, precast concrete and reinforced concrete are not adversely affected by water inundation if the engineering design and site works were competent. On site it is essential in developing countries that the concrete formulation and mixing is controlled and that the construction works are supervised. The finished product must also be maintained properly so that the safety factors of the original design are not reduced.

Typical defects that enable water to accelerate decay include: