**Zeitschrift:** IABSE reports = Rapports AIPC = IVBH Berichte

**Band:** 57/1/57/2 (1989)

**Artikel:** Fair-face concrete durability in tropical environments

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**DOI:** https://doi.org/10.5169/seals-44261

# Fair-Face Concrete Durability in Tropical Environments

Durabilité de surfaces en béton dans un environnement tropical

Dauerhaftigkeit von Betonoberflächen in tropischer Umgebung

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## SUMMARY

A description of two case studies concerning the ageing of exposed fair-face reinforced concrete structures at the University of Dar es Salaam in Tanzania and at the University of Malawi at Zomba. The paper outlines the investigation of "thermal distress" as part of the mechanism of deterioration and places it in the context of other environmental factors involved, the characteristics of constituent materials and the workmanship applied to them.

## RÉSUMÉ

Deux études de cas d'altération de surfaces de béton exposées aux Universités de Dar-es-Salaam (Tanzanie) et Zomba (Malawi) sont décrits. L'article présente l'analyse des sollicitations thermiques avec la prise en compte des autres facteurs extérieurs, des matériaux utilisés et de la qualité de l'exécution comme éléments du mécanisme de détérioration.

## ZUSAMMENFASSUNG

Zwei Fallstudien zur Alterung exponierter Betonflächen bei den Universitäten Dar-es-Salaam (Tanzania) und Zomba (Malawi) werden erläutert. Der Beitrag beschreibt die Untersuchung der thermischen Beanspruchungszustände im Umfeld der übrigen Umwelteinflüsse, der verwendeten Baustoffe und der Ausführungsqualität als Teile des Zerfallsmechanismus.

## 1. Introduction

It is a commonplace assumption that concrete is a permanent material which ages slowly and requires no maintenance. It is taken for granted that concrete can survive casual disregard for good-practice guidance embodied in national codes and standards. Nothing could be further from the truth. Durable concrete is not easily produced and experience shows that, in a tropical environment, durability calls for higher standards of care and control than in temperate zones; yet it is to the latter that most established works of reference relate.

## 2. Factors causing deterioration

Close examination of a 30 year heritage of fair-faced reinforced concrete structures at two universities in Africa leads us to believe that "thermal distress" of exposed elements is an important and under-rated component of deterioration. Chemical contamination of constituent materials and of a completed structure is frequently discerned. The adverse effects of elevated temperatures and swift evaporation on the mixing and placing of fresh concrete are usually apparent and inadequate attention to the curing regime is always a crucial factor. These important aspects are rendered the more damaging when diurnal fluctuations in surface temperature propagate a fracture system, thereby increasing moisture penetration to liberate and transport aggressive substances, and promoting the advance of the carbonation front. Unless all reinforcement has been provided with consistently adequate concrete cover, corrosion inevitably proceeds on its destructive course.

## 3. Effect of surface temperature variations

Our studies indicate that surface temperatures attained under the influence of solar radiation can be extremely high on exposed concrete, particularly where conductance or re-emission of radiation are impeded by insulation. Thermal shock induced by the passage of clouds and wind or sudden rainfall swiftly extends any crack pattern initiated by imperfections in casting or curing techniques. Restraint of the member will set up stresses and deformations which, by repeated fluctuation and reversal, will induce fatigue fracture patterns and impose them upon the existing stress regime.

## 4. Surface temperatures at Zomba

At Zomba, in a tropical upland zone 15 degrees 23' South and 964 metres above sea level a maximum air-shade temperature of 37 degrees can be accompanied by a conservatively calculated roof surface temperature of about 84 degrees. The incident angle upon walls and other units has an ameliorating effect; northwest and northeast facing concrete louvres were found to attain 68 degrees C and 70 degrees C respectively whilst adjacent wall surfaces were 10 degrees C less. Accompanying ambient night-time temperatures were in the region of 20 degrees C, though a minimum of 7 degrees C has been registered during cooler seasons of the year.

## 5. Temperature propagation in concrete

Marked changes in temperature can provoke stress cracking, particularly where high temperatures are swiftly quenched. Prolonged exposure causes heating to a considerable depth. Assessment of the velocity of propagation during a 24 hour period through homogeneous concrete has been made and 35 mm per hour was taken as a reasonable average.

## 6. Calculation of "sol-air" temperature equivalent

For assessment purposes the heating effects of incident solar radiation and convective warm air immediately adjacent to the surface can be combined by employing the "sol-air" temperature concept. This involves the establishment of a temperature (Te) that would create the same thermal effect as the incident radiation in question, which value can then be added to the shade-air temperature (To). The composite figure (Ts) is not strictly accurate, for the radiant portion is more complex in composition than this simple relationship would suggest and a physicist would be dissatisfied with the precision of the result. Nevertheless, it is our experience that application of the solar-excess temperature by this means corresponds with on-site measurement with sufficient accuracy to be accepted as valid for the inexact science of building.

Thus Ts = To + Te
where Ts = "sol-air" temperature equivalent, in degrees C,
To = outside shade-air (dry-bulb) temperature, in degrees C,
Te = solar excess temperature,in degrees C,
= Q.a/fo
where Q = intensity of radiation heat flow, in W/sq.m
W = Watt = Joule/second
a = absorptivity of the surface; a dimensionless proportion which with reflectance r equals unity
= 0.65 for normal grey concrete (0.35 reflectance)
and fo = outside surface (film) conductance, increased by air movement across the surface,
= 12 W/sq.m degrees C for dense concrete in still air.

## 7. Assessment of radiation intensity

To establish the solar flux (Q) it is necessary first to obtain, for the latitude required, a solar chart with the stereographic projection of months and daylight hours on it. By superimposing upon the chart an appropriately graduated solar radiation overlay to the same azimuth scale (one each for horizontal, normal and vertical surfaces, plotted to the orientation of the building in question) it is possible to plot a sunrise to sunset maximum flux diagram for any particularly vulnerable portion of the structure. A day which corresponds with the period of maximum shade-air temperature as recorded by a local meteorological station should be selected. Drawing counterpart graphs for concurrent solar-excess and shade-air temperature throughout that day make it possible to establish a likely maximum combination.

## 8. Temperature gradient profiles

Simple calculator routines enable linear and non-linear temperature gradient profiles for regular intervals through the day to be constructed. Variations in shade-air temperature are slow enough for normal propagation through the structure to smooth out differentials. However, solar-excess temperature builds up rapidly on the sunlit face, propagating through the structure to emit from the shaded face by re-radiation and convection many hours later. Re-emission from the sunlit face reaches a significant level only when solar radiation wanes. The thermal "wave" causes a marked oscillation of bending and stressing, particularly if the element is firmly restrained by the structure.

## 9. Deformation and stresses derived

By employing well-documented standard relationships it is possible to assess likely unrestrained deformation or restrained stresses in each element. The vulnerability of exposed restrained portions of a continuous structure then becomes apparent. Tensile stresses develop which are well in excess of maxima recommended in established codes for concrete, particularly in cyclic flexure. When the cyclic nature of the diurnal thermal regime is considered certain aspects of fatigue failure come into play. One of the earliest findings of research into fatigue in concrete was that tensile cracking occurs at lower levels of cyclic or repeated load than under sustained static load. Extending consideration to the behaviour of a complex building structure becomes difficult. Observed distress in brickwork walls supporting long buildings has been explained by investigating longitudinal and transverse displacements of brickwork and concrete.

## 10. Recommendations for thermal durability

Our findings lead us to the following general recommendations. Movement joints designed to accommodate the extreme range of seasonal ambient shade-air temperature are sufficient to cater for the likely overall thermal response of the structure but additional attention should be given to providing more closely spaced thermal stress-relieving joints in cladding elements exposed to solar-gain. All joints should be simple and open with bearings able to accommodate countless reversals of movement. "Strong points" should be centrally located or isolated by joints. Reinforcing bars should be evenly distributed in each direction on all faces and not widely spaced. Cover should be adequate but not over-generous.

## 11. Other hazards determined.

Good quality, dense and durable concrete, when sensibly detailed, will withstand thermal effects without distress. However, at both universities cyclic thermal stressing can be seen to have increased deterioration originating from other causes. Zomba exemplifies an inland tropical climate of moderate altitude and humidity, notable for clear skies and drying winds. Here the main hazards are rapid water loss from the fresh mix and inadequate curing. Aggregates are derived from quarried quartz granulite and lake-shore sand. They are of reasonable quality though angular and harsh. Dar es Salaam, by contrast, lies within sight of the sea and barely 100 metres above it, both temperature and humidity are usually high. Here the main hazards are the high and irregular water demand of crushed coralline limestone aggregates and the presence of chlorides, both "historic" from within the coral and as an aerosol from the Indian Ocean monsoon winds. Sand supplies are derived from seasonal river beds, frequently silty and contaminated.

## 12. Hot weather concreting precautions

In both nations, as so frequently elsewhere in the tropics, many hot-weather concreting precautions are overlooked:

- testing the water supply for chloride and sulphate content,
- cooling mixing water; shading stockpiles,
- damping down shutters well in advance and erecting wind-breaks around them,
- assuming an adequate supply and consistent origin for cement and sand,
- incorporating a water-reducing additive to restrain the water-cement ratio and enhance workability, painting mixers, bins and barrows a light colour,

- mixing, transporting, placing and compacting the concrete in one swift operation during early morning or evening hours,
- covering the concrete immediately it is finished,
- curing it for a sufficient period with more than a single dribbling hose during working hours only.

Getting these right is the exception rather than the rule, yet it is these precautions that produce durable concrete with an inherent resistance to the attrition of tropical conditions.

13. Carbonation and sulphation

Research during recent years has established that a world-wide increase in atmospheric carbon dioxide above its normal 0.03 percent is taking place. It is postulated that deforestation and desertification bear as much responsibility as industrialisation. If that postulation is true, tropical Africa is affected equally with other parts of the globe. The university buildings of the Malawi and Tanzania testify to the action of this natural "pollutant" causing carbonation of concrete and the neutralization of its high alkaline passivation of reinforcement to a degree similar to that of structures in the United Kingdom. Natural carbonization of rainwater leads to "acid rain" and natural biological and bacterial action in surface moulds promote the production of sulphates and catalyse carbon, further neutralizing the alkalinity of concrete and leading to surface cracking. The higher ambient temperatures of the tropics tend to promote these chemical reactions.

14. The visual ageing of concrete

The main symptoms of ageing are colour change (including dirt collection), organic growths (algae, lichens), inorganic growth (efflorescence, lime deposits), stains from interactions with other materials, crazing, spalling and crumbling. Most of these symptoms are purely visual but the latter three can swiftly jeopardize the structural performance of the member.

15. Repair of cracking

Before embarking upon any specific treatment it is important to be aware of why the cracks have occurred, otherwise an inappropriate and ineffective, even damaging, repair method might be selected. Remedial work is normally undertaken only when one or more of the following points adversely affect the performance of the structure;
- the structural safety, loadbearing capacity or stability,
- the durability; wide cracks allow access of air and moisture to the reinforcement,
- the appearance; of importance on aesthetic grounds only.

16. Types of crack

Cracks can be divided into three categories and it is important to be sure which category applies before repairs are undertaken;
- dead cracks, caused by a past event not expected to recur. These can be filled with a rigid repair material,
- live cracks, which do not remain constant in width but open and close as the structure sustains load or temperature change. These should only be filled with a flexible repair unless the movement can be eliminated or accommodated elsewhere.
- growing crack, which increase in width because of a continuing defect, for instance, corrosion of reinforcement. These should only be repaired when the cause has been eliminated.

## 17. Choices of crack repair method

The location and environment of the cracks affect the choice of repair material and method. Techniques which rely upon gravity to introduce material into the crack may be used successfully on horizontal surfaces but are rarely effective elsewhere. The presence of moisture, liquid water or contaminants must be taken into consideration. In our experience, the skill of available operatives is an important consideration; elegant "hi-tech" systems call for specialist expertise.

## 18. Normal range of choice of repair material

Repair methods available can be summarised as follows;

- resin injection, epoxy and polyester resins are commonly used for crack injection, they exhibit high strength (usually excessive) and can be formulated to resist all commonly encountered conditions except very high temperatures. They are relatively rigid (particularly so the epoxies) and thus not suitable for live cracks. Resin injection calls for the presence of a specialist contractor.
- vacuum impregnation, involves encapsulating the structure, creating a vacuum within it and employing natural air pressure to force resin into the cracks. Though effective the method is difficult to apply and, as before, calls for the presence of a specialist contractor.
- polymer emulsions, applied as suspensions of polymer in water and appropriate to gravity applications only. Less robust than epoxies and polyesters but with more strain tolerance. Some are susceptible to damp conditions. They are more appropriate for application by unskilled labour and can penetrate fractures as fine as 0.1 mm.
- cement based materials, are suitable for the wider "dead" cracks, and when an appropriate polymer bonding agent is incorporated they can be applied by semi-skilled labour to a large proportion of repairs by trowel. By adjusting the formulation it is possible to apply them by gravity or injection.

## 19. Surface coatings

A wide range of surface coatings can be applied to concrete, from thin purely cosmetic emulsions to thick membranes. If cracking has become stable then a coating can usually be applied but our experiences have not been entirely satisfactory. Vapour permissivity is an important characteristic to avoid detachment yet, when it is achieved, liquid water, oxygen and carbon dioxide seem ready to pass through also. Recent advances in molecular organic chemistry have resulted in a wide range of reactive siliconates which utilize residual alkaline components of the concrete to form "permanent" bonds. They do not line the pores but become unified with the pore structure. Unfortunately they all employ volatile alcohol bases and are therefore sensitive to high application temperatures; a serious impediment to the reaction process and almost unavoidable in the tropics. New siloxanes appear to be solving the problems we have experienced and may offer a practical treatment for the future.