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WATERTIGHTNESS OF CONCRETE
TUNNEL STRUCTURES
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WATERTIGHTNESS OF CONCRETE TUNNEL STRUCTURES

Paper by prof.ir. A. Glerum for the meeting of the working group "Research" of the International Tunnelling Association in Brighton, June 1982

1. INTRODUCTION

The Netherlands are situated in the delta of the rivers Rhine, Meuse and Scheldt. Therefore the ground mainly consists of sediments, such as sand, clay and silt. In certain regions peat layers of varying thickness are found.

The high permeability of some of these materials and the fact that the groundwater table is generally only 1 m below ground level, make an adequate watertightness one of the main features of tunnel engineering in the Netherlands.

Tunnels in Holland are both of the immersed and cut-and-cover type. The first one being mainly used for river crossings, the second for on land built tunnels. A mixture of both types is the so-called caisson tunnel, where units of about 40 m length are built on ground level and then lowered to their final depth by excavating the ground below the floor slab under pneumatic pressure.

Although there are marked differences in these construction types, the watertightness problems are more or less the same.

2. TO WHAT EXTENT SHOULD A TUNNEL BE WATERTIGHT?

Before going into detail the question should be raised if absolute watertightness is required.

Leakage has the following consequences and disadvantages:

1. The percolation of water through cracks will accelerate the corrosion of reinforcement steel; especially if the water is aggressive and contains oxygen.
2. Although tunnels are provided with drainage and pump systems large and especially unforeseen quantities of leakage water may lead to serious problems.
3. Waterpressure under the pavement must be avoided at all costs. If water pressure builds up - and for this only small quantities of water are needed - the road surface will be damaged by the combined action of pressure and traffic. Repair works will become necessary, but if the leakage itself is not stopped, road maintenance has to be repeated often and will involve a great deal of money. For that matter it should be noted that it is usually very difficult to find the exact spot where the water enters into the tunnel. Difficult because the floorslab is fully covered by the pavement.
4. Water dripping from the roof at a fixed point can erode the road surface, while at low temperatures frozen over spots can occur. Due to the fact that these smooth areas are found only locally and are therefore not expected, this may lead to dangerous situations for road traffic.

The above means that although no absolute watertightness is required, leakage must be avoided as much as possible, while for road tunnels water pressure under the pavement is unacceptable.

3. THE DIVISION OF THE TUNNEL INTO SECTIONS

In longitudinal direction a tunnel is divided into sections with lengths of about 20 m. Each section is made as a monolithic concrete structure and is separated from the adjacent sections by expansion joints (figures 1 and 2). The mortise-and-tenon shape of the joint prevents unequal displacements in transverse direction (no sudden jumps in the pavement!). The joints allow reductions in length of the sections due to shrinkage and low winter temperatures while they also allow minor rotations of the sections. For tunnels not founded on piles these rotations can be caused by unequal settlements. In this way large tensile stresses and cracks are avoided.

An immersed tunnel is formed by units with lengths varying between 100 and 250 m. Each unit consists of a number of about 20 m long sections separated by expansion joints. During the floating transport a temporary longitudinal prestressing guarantees that the unit behaves as a monolith. After placing the prestressing is removed while the unit is coupled to the adjacent ones by means of flexible rubber gaskets (the so-called Gina). By this an immersed tunnel is not different from an in situ built structure: the expansion joints every 20 m allow the tunnel to follow unequal settlements without large bending moments and cracks.

4. WATERPROOFING THE TUNNEL STRUCTURE

The two main items are the sealing of the expansion joints and the watertightness of the reinforced concrete structure of the sections. As figure 2 shows the joints are usually provided with rubber-metal joining strips. The strip embedded in the concrete of both sections secures watertightness while allowing motions of the sections in longitudinal direction.

Experience has shown that without special measurements there may be leakage around the joining strip. Especially where concrete has to be placed under the strip (viz. in floor and roof) air pockets can be formed. In order to be sure that no leakage occurs, the joining strip shown in the lower part of figure 2 has been developed in the Netherlands. Foam strips are glued to the steel plates. After the placing of the concrete the foam strip is injected with epoxy resin. In this way any leakage is cut off. The injection is done through cast in pipes. The injection pipes have a spacing of about 5 m.

A steel strip fixed to one of the sections prevents sand grains to enter the joint when it is opened. The presence of sand and other materials would hamper the joint when closing due to the thermal elongation of the sections in the summer.

The watertightness of the joint between the immersed units is secured by the earlier mentioned Gina gasket. As this method is applicable to immersed tunnels only, it will not be dealt with here.

5. WATERPROOFING THE SECTIONS

With a view to the required strength and stiffness roofs, floors and walls have a thickness that in itself is sufficient to make the structure watertight provided the concrete is of good quality. There are however two weak points: construction joints and cracks passing through the full thickness of structural members (flexural cracks - due to bending moments in the cross-section - are limited to the tensile zone only and these cracks

therefore do not pass through the full thickness).

Both find their origin in the fact that - for the sake of a simple and economic construction - first the floor is cast and after that the walls and roof, usually in one pour (see figure 3).

Unless special measurements are taken the bond between the 'old' concrete of the floor and the younger concrete of the wall is not too good. Therefore the construction joint is not watertight. A simple remedy against this is to place a steel plate across the construction joint as is shown in figure 3. The steel plate with a thickness of 6 mm and a height of 400 mm is embedded in the concrete on both sides of the joint. Another method is a good treatment of the top of the upstand before casting the wall. By jetting the surface with steel grit the cement skin is removed, leading to a good bond between old and new concrete. Nowadays this method is preferred to that using the steel plate.

However, the main point is the difference in behaviour between the concrete of the floor, that has already hardened, and the concrete of the walls and roof where the process of setting and hardening still has to occur.

During this process the temperature of the wall initially increases due to the hydration, while later on the temperature will gradually go down until it is equal to that of the open air (figure 4). During the process both the modulus of elasticity and the strength of the concrete will increase starting from zero.

In figure 5 the principle of what happens is shown in a simplified way. Let us first assume that there is no bond and no friction between wall and floor. During the first period of say 2 to 3 days after pouring the temperature of walls and roof will increase. As the concrete is still more or less liquid, one could assume that the shuttering at both end prevents the wall from elongating. After that the temperature goes slowly down during a period of some 7 days. During this period the concrete is solid and the wall reduces in length. This however is only possible if there is no bond and no friction between wall and floor. In reality wall and floor are connected, while the temperature of the floor has increased only slightly. Due to this reduction in length of the lower part of the wall is fully restrained, while the upper part of the walls and the roof have a greater freedom to shorten, being farther away from the floor. The restrained deformation of the lower part will lead to high tensile stresses in longitudinal direction and therefore to cracks passing through the full depth of the walls. These cracks appear every 6 to 7 m and are the main source of leakage of concrete structures.

Of course what has been said above is too much simplified. Actually the concrete is not liquid during the first 2 to 3 days as setting and hardening have already begun. So during the rising of the temperature the concrete will expand, but as this is restrained near the floor compressive stresses will occur (figure 6). However the modulus of elasticity is then so small that the resulting compressive stresses are much lower than the tensile stresses occurring later on during the cooling down period, because the modulus of elasticity has considerably increased in the mean time. Although the initial compressive stresses can be seen as a kind of longitudinal prestress of the wall, they are too small to prevent cracking.

The cracks were the main reason why older Dutch tunnels have been provided with a watertight lining on the outer side of the structure. As the lining was rather costly newer tunnels are made without one, but this is only

allowed if cracks are completely avoided. There are a number of ways to prevent cracking but the most feasible and economic one is to cool the concrete of the walls during the first 3 to 4 days after pouring. Moreover the produced heat can be reduced by applying low cement contents. Where for older tunnels the concrete contains 325 kg cement per m^3 the newer ones are built with only 275 kg. The cement used is of the blast furnace type.

The aim is to keep the maximum temperature of the wall concrete so low that during the cooling off no cracks occur; in other words that the tensile stresses due to the restrained deformations are kept below the tensile strength. Of course one has to bear in mind that the tensile strength increases with time. The artificial cooling is most needed where the extent of restraint is maximum, viz. just above the floor, while for the roof, where there is more freedom of deformation, artificial cooling is not necessary. In between these spots the cooling must be reduced gradually.

Therefore the artificial cooling is effected as shown in figure 7. Each wall is provided with a cooling tube fitted in a zigzag pattern. The tube is placed at the same time as the reinforcement. After pouring the concrete water is pumped through the piping system. The water flows through the wall from the bottom to the top and is heated up during circulation. As a consequence the cooling capacity of the water decreases as it flows upward. The heated up water leaving the top of the wall passes through a refrigerating plant before entering the wall again at the lowest point. In this way the maximum concrete temperature in the lower part of the wall is considerably reduced, while a gradual transition is obtained from this spot to the uncooled concrete of the upper part of the wall and the roof. Sudden jumps in maximum temperature along the height of the wall would result in tensile stresses and possibly in cracks.

It is not always necessary to work with a closed cooling-water circuit. Often use is made of the water pumped up by the deep wells of the dewatering system. This water has a constant low temperature of 8 to 10°C, even in summer. As the deep well system will supply sufficient cooling-water there is no need to install a refrigerating plant.

This way of waterproofing tunnels has been applied in Holland since 10 years. The results with some 8 tunnels are very satisfactory. Compared to a structure with a wierticht lining the cost savings amount to about Dfl. 6000 per running metre of traffic tunnel.

6. STRESS CALCULATION

The aim of design and control of a cooling system is to keep the tensile stresses due to hydration below the tensile strength of concrete. Therefore the designer must be able to predict the temperature development of the concrete in a wall (and roof) with a certain thickness and a certain type of shuttering (insulation). From these temperatures must be subtracted the cooling effect of the water flowing through the pipes. Once the temperatures are known as a function of time the resulting stresses can be calculated. The principle is shown in figure 8. Assume that the decrease in temperature during a certain time interval is ΔT and that ΔT is the same for walls and roof (a 'not cooled' situation). The resulting stresses are then calculated in two steps. In the first one a tensile force F is supposed to act on the upper part of the structure (walls and roof). The force must have such a magnitude that no deformations due to the temperature drop occur.

In other words:

$$F = A_1 \cdot \sigma_1 = A_1 \cdot \epsilon \cdot E = A_1 \cdot \alpha \cdot \Delta T \cdot E$$

In which:

A_1 = cross-sectional area of walls and roof

α = thermal coefficient of expansion

E = modulus of elasticity

In order to make equilibrium a compressive force of the same magnitude (F) is now placed on the full cross-section A_t (= walls + roof + floor) acting in the same working line as the tensile force. The compressive force results in normal (compressive) stresses and bending stresses.

By adding up the stresses caused by the tensile force and the compressive one the stress diagram due to the temperature drop ΔT is found. As mentioned earlier the largest tensile stresses are found in the lower part of the wall.

At the bottom of the figure is shown that these stresses can be reduced considerably by cooling the lower part of the wall.

As the stress distributions for the compressive force show, it has been assumed that the modulus of elasticity is the same for the upper part and for the floor. In reality the floor is more rigid while the modulus of the elasticity of walls and roof increase with time.

Therefore the time is divided into intervals of about 6 hours. During each interval the modulus of elasticity of walls and roof is assumed to be constant (this is also valid for the floor, but there the E remains constant during the whole period). As the temperature change ΔT during the time interval is known, the increase or decrease in stresses can be calculated in the way mentioned before. These stresses have to be added to those resulting from the previous intervals. The sum of these stresses must be smaller than the instantaneous tensile strength.

7. RESEARCH

In order to make the stress calculation and to design the cooling system data must be available concerning the properties of concrete during the first 7 days after pouring and about the hydration heat and the effects of cooling. Initially studies have been carried out by the City Works of Amsterdam and the Locks and Weirs Division of the Dutch Public Works Department. Further research has been done by Committee C-38 of the Netherlands Committee for Research, Codes and Specifications for Concrete (CUR-VB).

The Committee's report will be published in 1983. Amongst others it will contain the results of a great number of laboratory tests on temperature and stress developments as well as theoretical studies.

At the first tunnels where cooling systems have been applied a difference was found between predicted and actual temperature developments. The committee's studies showed that part of the difference can be explained by the fact that the original calculations neglected the influence of the cooling on the hydration process. Moreover it was found that the coefficient of heat conduction and the specific heat of concrete change during the hardening process.

On the basis of these studies a computer programme for temperature developments in the cooled and not cooled part of a concrete structure has been made that leads to better predictions and shortens the design process. As an example of laboratory tests figure 9 shows the influence of time and temperature on concrete properties.

Two different temperature developments have been imposed on test specimens. The red curve represents to a certain degree the temperature behaviour in not cooled concrete, the blue one that of cooled concrete. For each of the temperature curves the concrete properties (viz. the modulus of elasticity, the compressive and the tensile strength) have been determined at different ages between 1 and 10 days after pouring. The results are shown in the three lower graphs. The colours red and blue have been used to mark the influence of the temperature. Unfortunately the tensile strengths for cooled concrete were not available at the moment. Here too the strengths of cooled concrete will be somewhat smaller than those of not cooled concrete.

8. CONCLUSIONS

As I mentioned earlier this system of waterproofing has been used successfully for some 8 tunnels and at costs that are considerably lower than those of a watertight lining.

Nevertheless recent research has greatly improved the knowledge of what exactly happens. Moreover the new computer programme for temperature developments together with the existing programme for stress calculations will facilitate the design of a cooling system. A design in which the following elements have to be determined by a trial-and-error method:

1. the diameter and spacing of the cooling-tubes
2. the discharge of the cooling water and its temperature when entering into the bottom of the wall.

It goes without saying that wherever a computer can be applied to a trial-and-error method a considerable gain of time will be obtained while the designer will be delivered from some unpleasant work.

FREEDOM OF MOTION IN LONGITUDINAL DIRECTION:

- 1° reduction in length : shrinkage, winter temperatures.
- 2° expansion : summer temperatures.
- 3° rotation : unequal settlements.



PREVENTION OF :

- 1° transverse translations: unequal settlements.



- 2° Leakage :

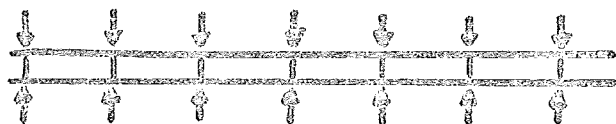


Figure 1:

Requirements expansion joint

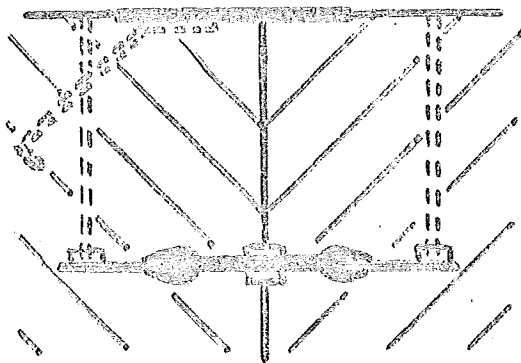
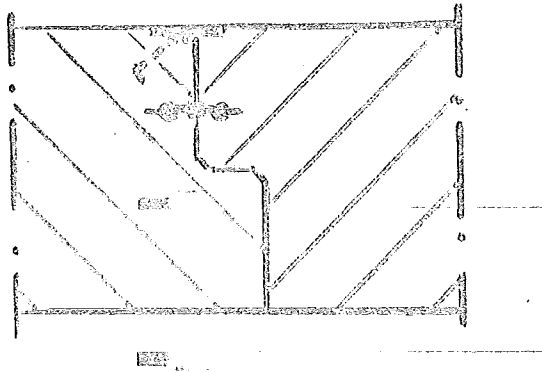
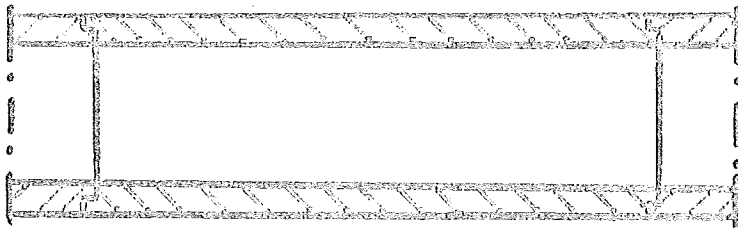


Figure 2 : Expansion joint

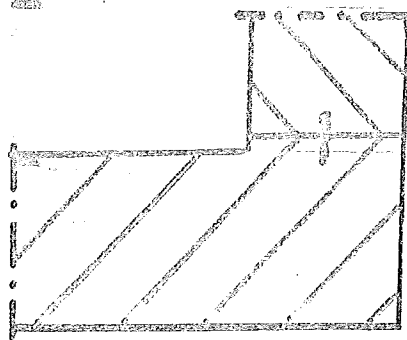
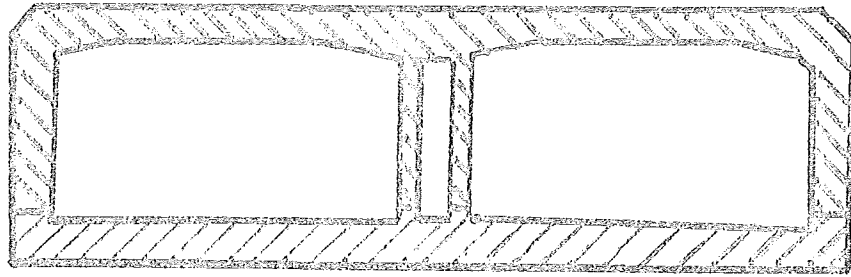


Figure 3

Tunnel cross section
with detail of construction
joint

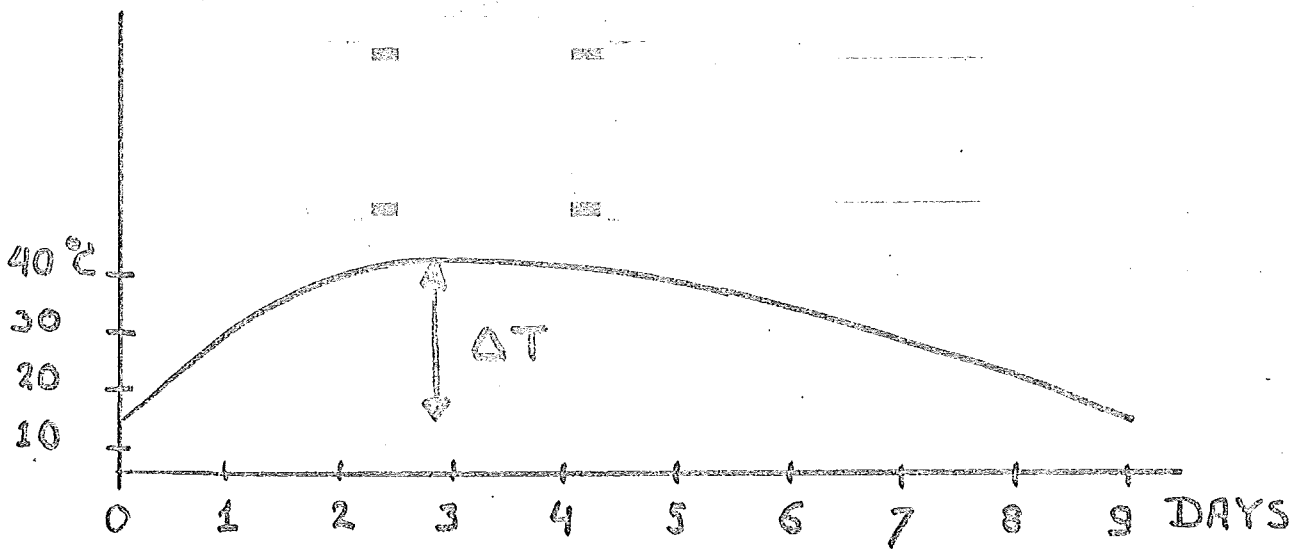
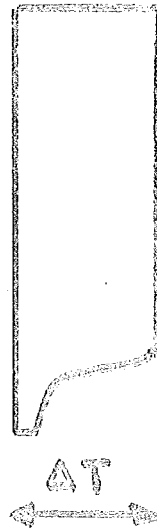
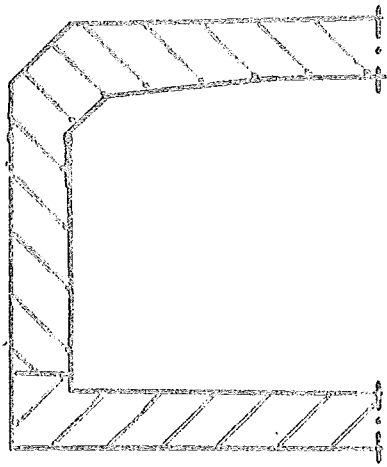


Figure 4 Temperature development due to hydration of walls and roof

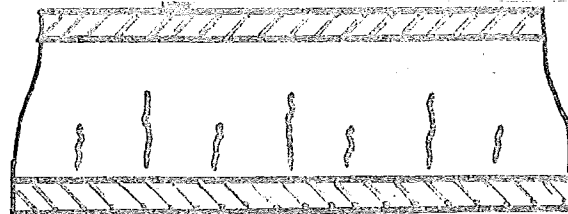
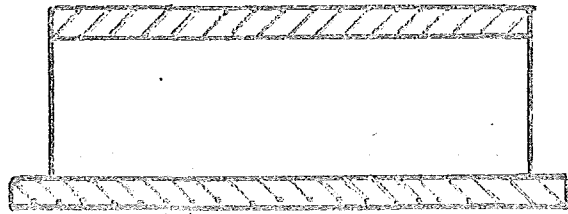
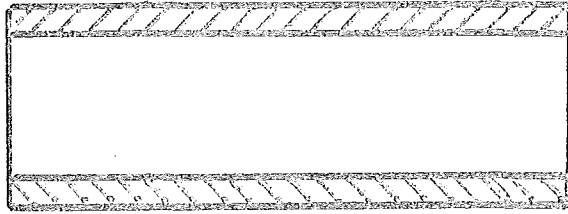


Figure 5: Origin of cracks

STRESS
N/mm²

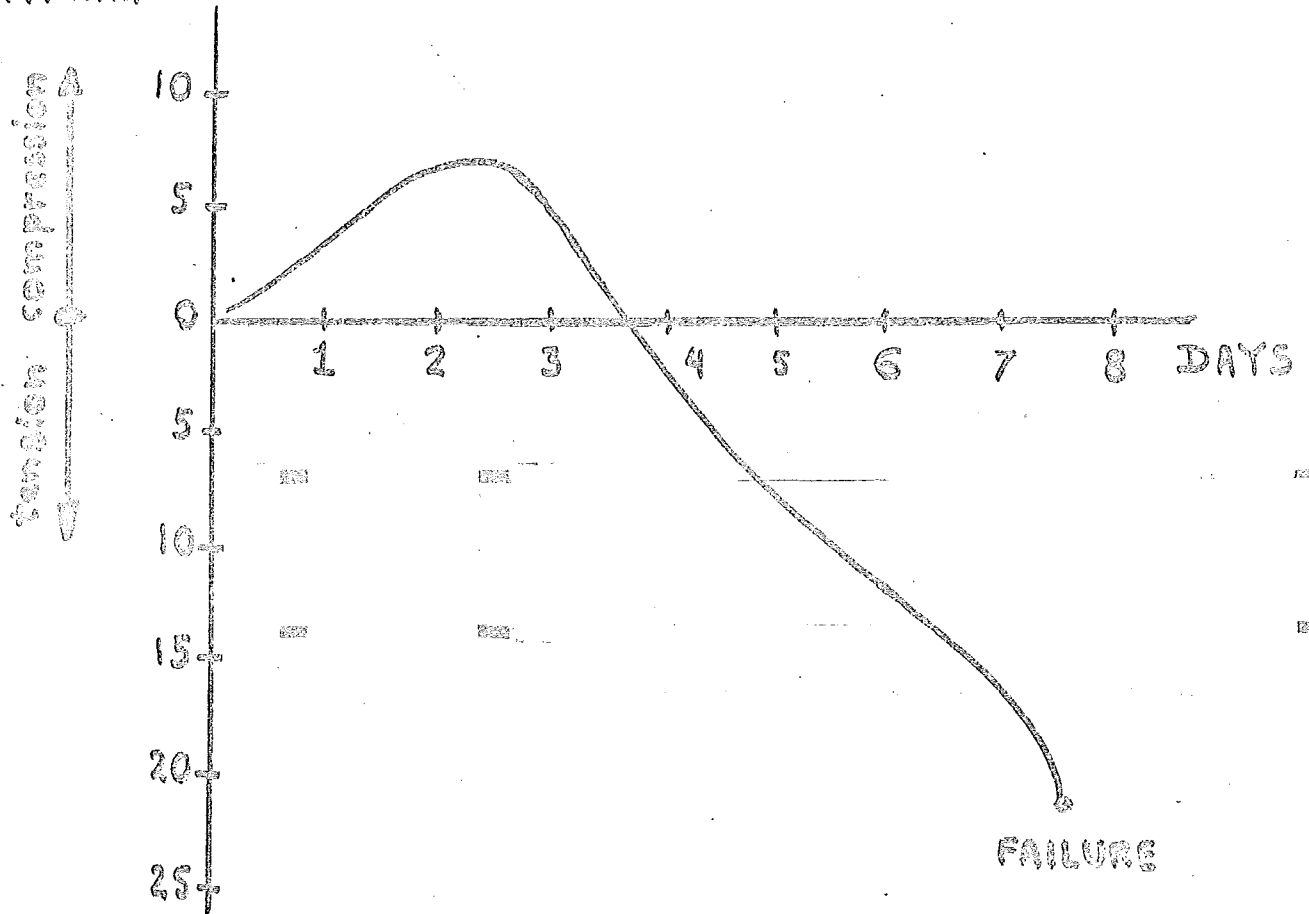
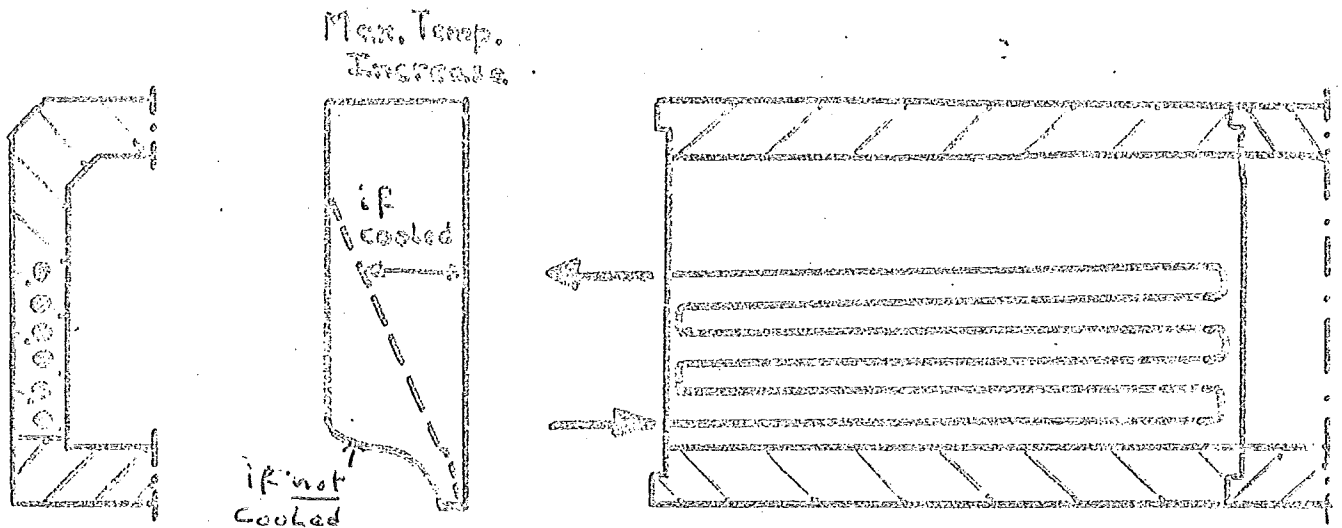
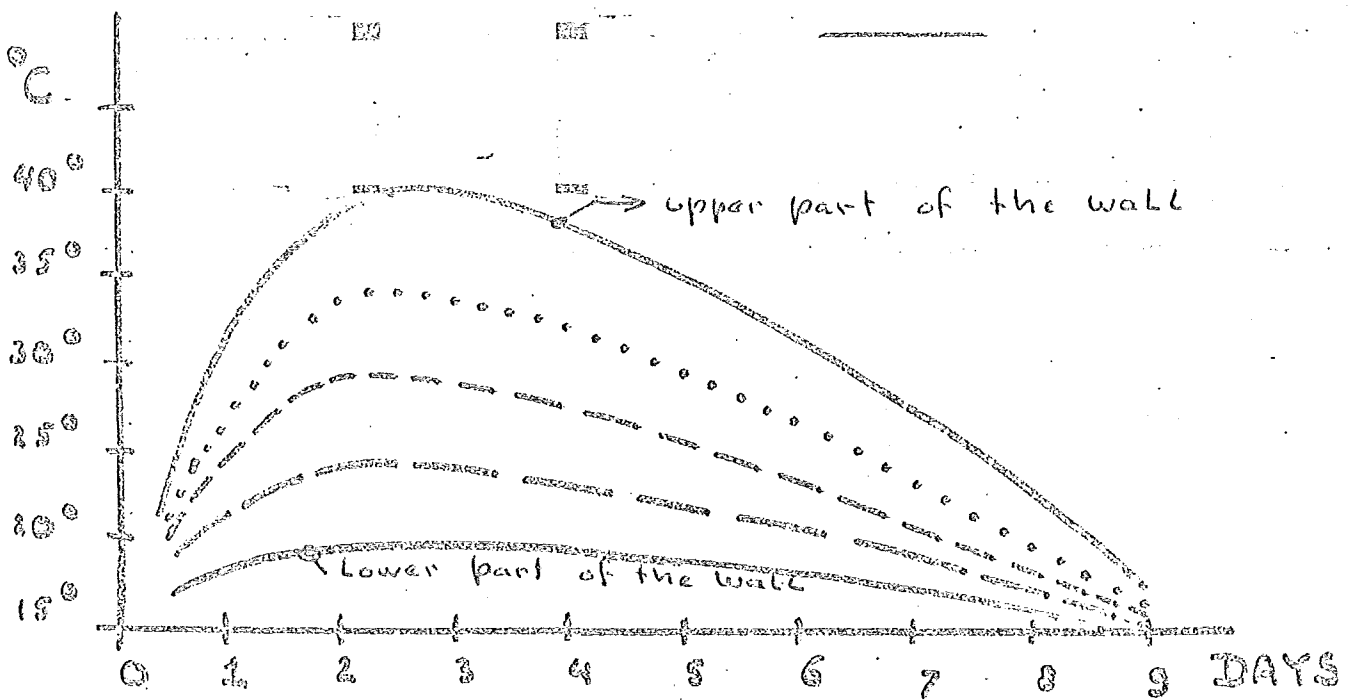


Figure 6: Stresses due to hydration in a concrete prism of fixed length

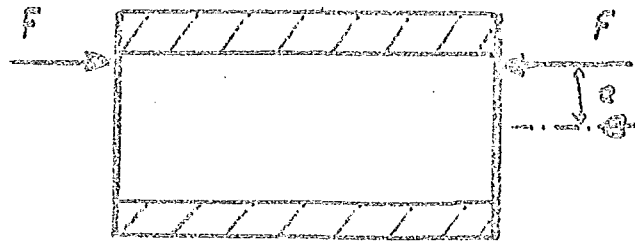
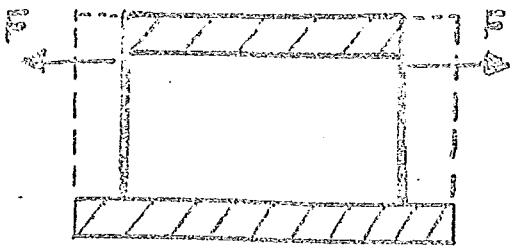


Cooling pipes and maximum temperature diagram



Concrete temperature developments at different heights in the wall

Figure 7 : Cooling system

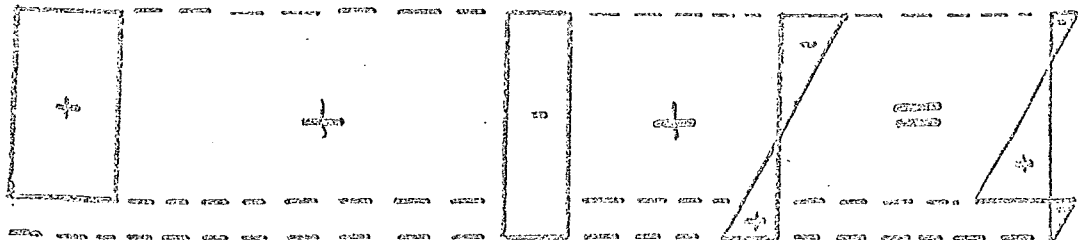


$$C_2 = C.F = \alpha \cdot \Delta T \cdot E$$

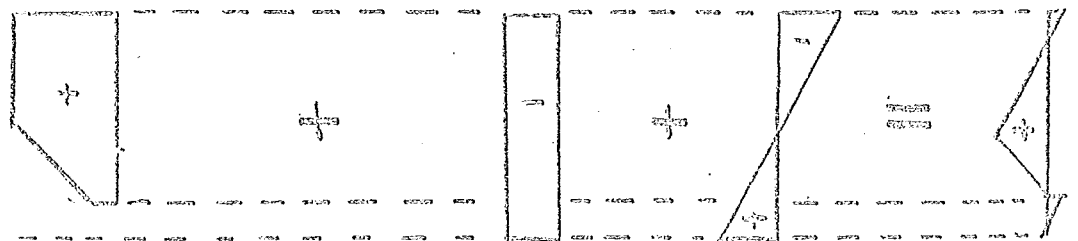
$$F = A_2 \cdot C_2$$

$$C_2 = \frac{F}{A_2}$$

$$C_2 = \frac{C.F}{W}$$



Not Cooled



Cooled

Figure 8: Calculation of stresses due to hydration

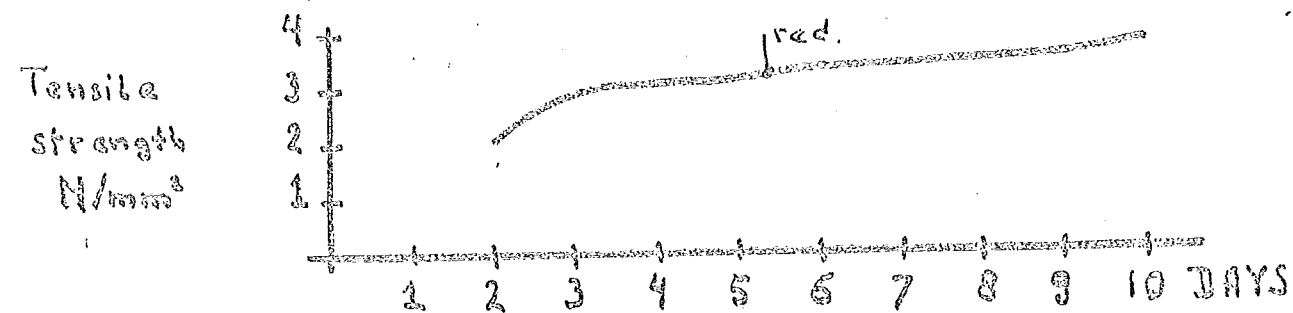
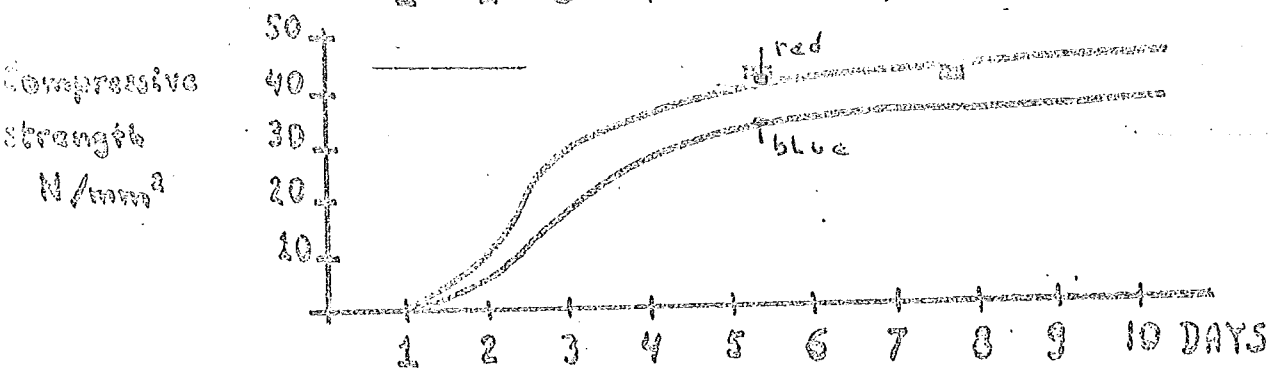
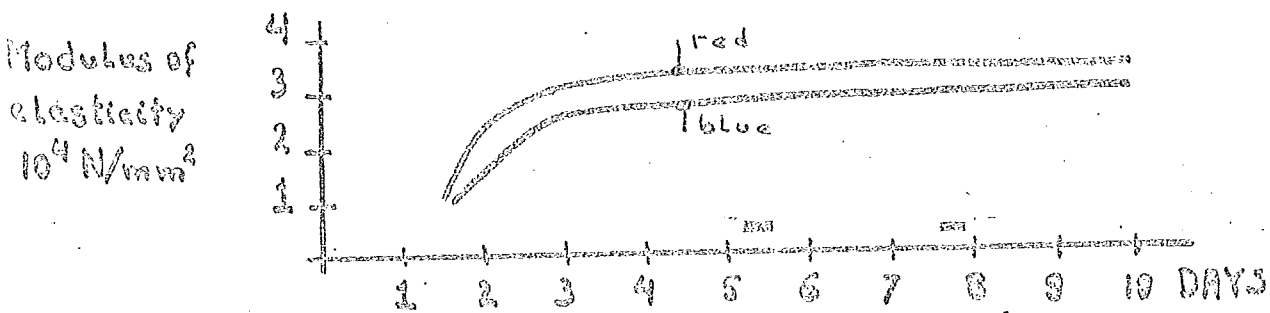
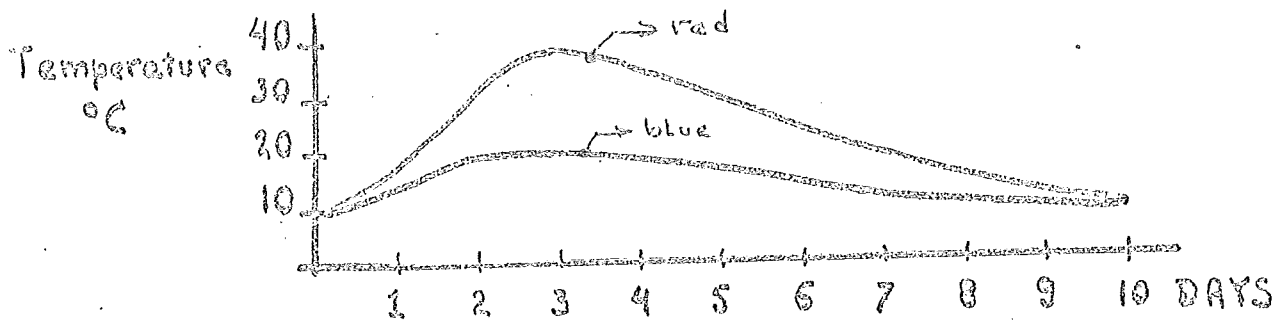


Fig. 9 Concrete properties as a function of time and temperature development