WATER MIGRATION IN CONCRETE AND PERMEABILITY OF THIN-WALLED CONCRETE STRUCTURES

by

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1. General comments. Principles and methods of research

Thin-walled concrete and r.c. structures may be used for water ducts and reservoirs. The thin concrete walls of these structures are, in general, wetted only on one side, hence at the beginning of wetting, water penetrates only from one side. Besides, the penetration of water or water load are not the only stresses applied on the concrete, but also other mechanical effects may act, such as external load inducing internal stresses. Therefore a comparative analysis of permeabilities of loaded and unloaded concrete may be of interest. In general, loads acting on thin-walled concrete structures produce compressive, flexural or tensile stresses. In most cases, the structure is required to remain uncracked under bending or tensile effects. Thus, the permeability of the concrete under load should be assigned to a much lower load than the ultimate one. The failure of the concrete under load is, however, a process where the weaker parts of the concrete structure or the components with inherent stresses may fail or crack already under relatively small loads. A permanent compression may also compact the concrete, thus, from the viewpoints of strength and permeability, it may be superior to the unloaded condition. The water penetrating on one side into the thin-walled concrete structure causes so-called water pressures because on the wet side the concrete expands, while on the other it will contract, thus, soaked concrete may develop internal stresses that are compensated the sooner, the more permeable the concrete, a rather unfavourable property for a reservoir from the viewpoint of imperviousness. Manufacturing technology of thin-walled pipes may result in a so-called layered inhomogeneous concrete structure. Near the inside surface of the green concrete pipe the cement content will be enriched to be unduly poor in the external concrete layer. Such a concrete structure was prepared for the purpose of model tests shown in Fig. 1 together with the composition and porosity of the model. The porosity of each layer has been calculated assuming the hydration to be from 50 to 66 per cent. This was intended as the model of the hardened concrete. The layer structure was compacted to make the concrete layers coherent, i. e., interacting against load and water pressure.

For other tests, the specimens were constructed from homogeneous

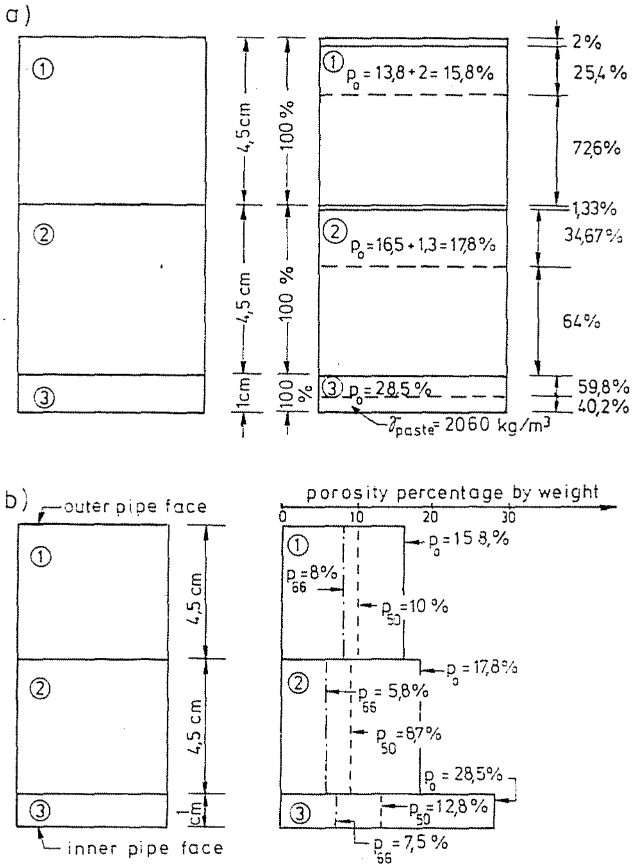

Fig. 1. Structural model for a 3-layered inhomogeneous concrete unit (e.g. concrete pipe)

a) Model of freshly mixed concrete ($\varrho_c = 3.03$ g/cm³)

Concrete composition:

1. cement = 350 kg/m³
   w/c = 0.395
   γ_{concr} = 2390 kg/m³
   γ_{paste} = 1924 kg/m³
   air = 2%
2. cement = 550 kg/m³
   w/c = 0.30
   γ_{concr} = 2060 kg/m³
   γ_{paste} = 2390 kg/m³
   air = 1.33%
3. cement = 950 kg/m³
   w/c = 0.30
   γ_{concr} = 2380 kg/m³

Concrete porosity (initial):

air 2%
cement paste 25.4%
aggregate 72.6%

air 1.33%
cement paste 34.67%
aggregate 64%

cement paste 59,8%
aggregate 40.2%

b) Porosity model of hardened concrete

1st layer:
cement = 350 kg/m³
w/c = 0.395
2nd layer:
cement = 550 kg/m³
w/c = 0.30
3rd layer:
cement = 950 kg/m³
w/c = 0.30

Legend:
p_0 = initial porosity (of freshly mixed concrete)
p_{50} = porosity of concrete hydrated to 50%
p_{66} = porosity of concrete hydrated to 66%

(non-layered) concrete. The grade of concrete was B 280 and B 450, with a continuous aggregate grading, the maximum size of particles being 20 mm at an earth-moist consistency and 2 to 3 cm slump. The composition of the concrete was that prescribed for normal water-tight concrete.

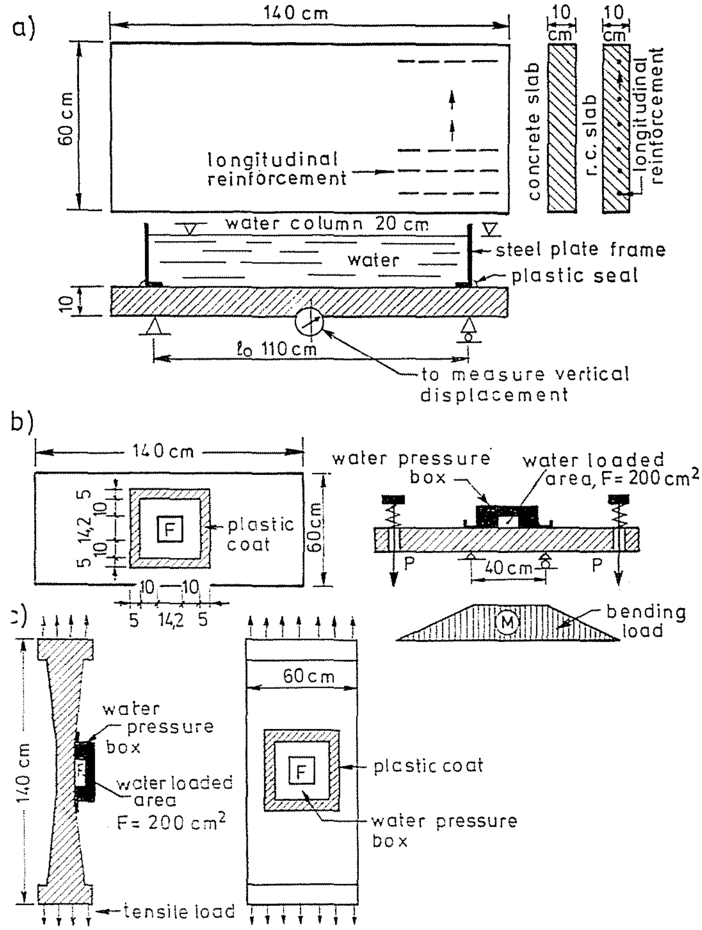

Fig. 2. Concrete specimens and test arrangement. *a)* Low water pressure (unilateral wetting); *b)* Combined effect of bending load and water pressure; *c)* Combined effect of tensile load and water pressure (10 cm unit thickness at the spot under water pressure)

The thin-walled bending specimens to be exposed to one-sided wetting (Figs 2a and 2b) were 10 cm × 60 cm × 140 cm slabs without reinforcement or reinforced at one side (with about 1 per cent reinforcing steel). The reinforcement consisted of hot-rolled plain steel of 8, 10 or 12 mm diameters. For testing the imperviousness under tension (Fig. 2c), I sections were produced with the former dimensions, to obtain clamping heads. Both sides of the tensile slab specimens had reinforcements of the same percentage.

The specially constructed testing equipment permitted to apply permanent internal stresses of 5 to 40 kp/cm^2 either in tension or in bending on the hardened concrete slabs.

The penetration of the water was observed at low water pressure corresponding to a 20 cm water column to investigate the effect of one-side wetting on load-free units (see Fig. 2a). The other series of tests delivered permeability values in dependence on external loads, under water pressures of 0, 4, 8, 12 and 16 atm. (see Figs 2b and 2c).

The amount of water penetrated into the units and the deformation of these latter were measured. From the amount of water penetration during 24 hours (in certain cases during 8 hours) specific permeability values (the so-called k-factors) were calculated in g/100 cm^2 · h and plotted in diagrams.

In the following, a summarized exposition will be given of the phenomena with the remark that the experiments are not yet completed, they are actually in course.

2. Effect of moderate water pressure (one-side wetting) on the deformation of self-supporting r.c. slabs

In Figs 3, 4 and 5, the deformations of plain concrete and reinforced concrete slabs loaded by a 20 cm high water column are represented as a function of water penetration time. The essential is how much the vertical displacement of the central cross-section of the simply supported concrete slabs loaded with their dead weight will be from the beginning to the end of the one-side wetting (i.e., during about 100 hours).

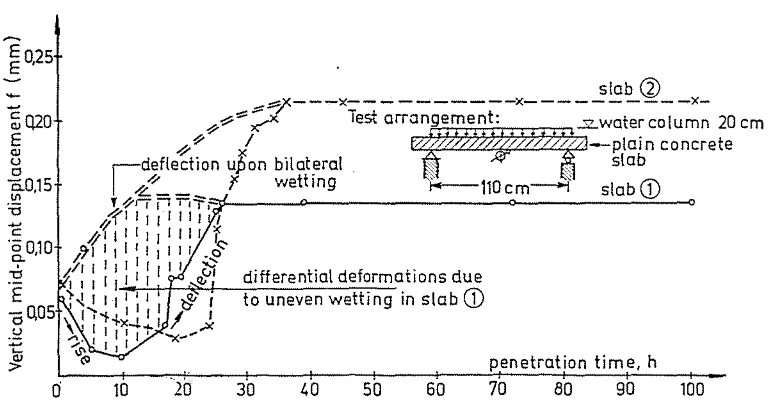

Fig. 3. Effect of one-side wetting on the vertical displacement of the middle cross-section of a self-supporting plain concrete slab

2.1. *Analysis of two plain concrete slabs according to Fig. 3*

The phenomenon: At the beginning of water penetration the upper zone of the concrete cross-section of the slabs wetted at the top lengthens, hence in the first 10 to 20 hours, the vertical mid-slab motion is an uplift rather than a deflection, while during the further penetration of water, there is a mid-slab displacement downwards, and after 20 to 40 hours the movement will die away. The two slabs presented were more permeable than the average.

Conclusion: The one-side wetting produces deformation differences in the cross-section of the concrete slab. These differences are compensated the sooner (see the vertically hatched areas in the figures) and die away the sooner, the higher the coefficient of permeability.

2.2 *Analysis of r.c. slabs wetted on the reinforced or non-reinforced side according to Figs 4 and 5*

The phenomena: Fig. 4 shows the initial differential deformations of the slab wetted at the reinforced side to soon decrease. Differential deformations due to wetting at the non-reinforced side will, however, be reduced slowly, persisting for about twice as long a time as shown in Fig. 3 (about 50 hours).

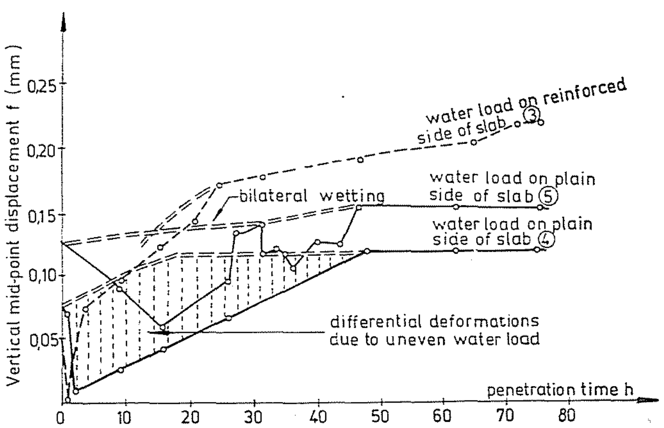

Fig. 4. Effect of one-side wetting on the vertical displacement of the middle cross-section of a self-supporting concrete slab with 14 mm reinforcement

Fig. 5 refers to a concrete of low permeability, not soaked completely even after 200 hours, on account of which the differential deformations subsist. The initial vertical displacement under the effect of wetting is upwards directed and the displacement changes but slightly in time. The water penetrates at the reinforced side more than at the side without reinforcement.

Conclusions: Even reinforced slabs undergo vertical displacement due to the differential deformation of extreme fibres upon water penetration.

Changes of the extreme fibre length of r.c. slabs differ depending on whether the water contacts the unreinforced or the reinforced side. In the latter case the reinforcement counteracts the swelling of the wet side to a cer-

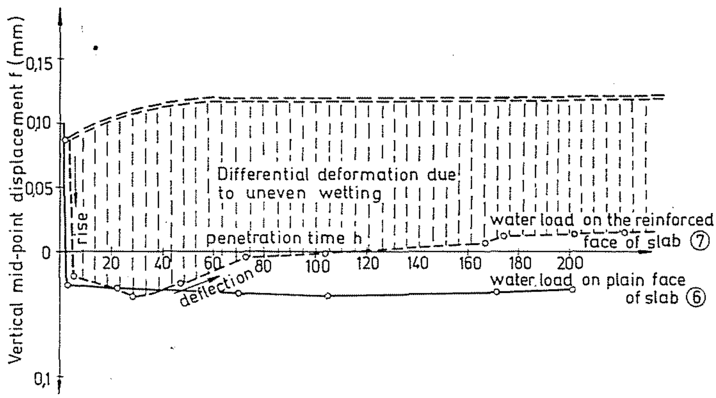

Fig. 5. Effect of one-side wetting on the vertical displacement of the middle cross-section of a self-supporting concrete slab with 10 mm reinforcement

tain degree, reducing the amount of vertical displacement due to water penetration. Wetting the unreinforced side causes a more important vertical movement of the slab. Wetting the reinforced side, the wet side swells sooner because the deficiencies in the concrete at the reinforcement let the water in. Soaking of more compact concretes is a slower process, and therefore also the differential deformations due to wetting persist longer.

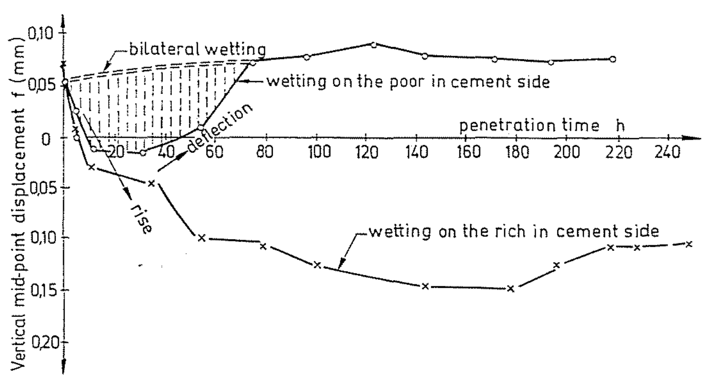

Fig. 6. Vertical displacement of the middle cross-section of a layered inhomogeneous concrete slab under the effect of one-side wetting (three-layered model as shown in Fig. 1)

2.3 *Analysis of the layered inhomogeneous concrete slabs according to Fig. 6*

The phenomenon: One-side wetting causes a larger vertical displacement in the concrete slab in the case where the layer richer in cement is wetted.

Conclusion: The uneven deformation of a concrete poorer in cement due to water migration is smaller than that of a concrete rich in cement. Therefore, the wetting stresses are lower if e.g. the layered concrete slab begins to be wetted at its more porous surface. This confirmed the practical phenomenon common for concrete pipes that the externally dry pipeline will commonly be cracked, damaged in the first period of the water-pressure test, mainly not under the effect of water pressure, but only of the protracted internal soaking.

3. Combined effect of tensile load and water pressure

The I-shaped reinforced concrete slabs in Fig. 2 were manufactured of concrete grades B 280 and B 450. The specimens were tested for water permeability unloaded or exposed to tensile stresses of 5, 10 and 15 kp/cm^2,

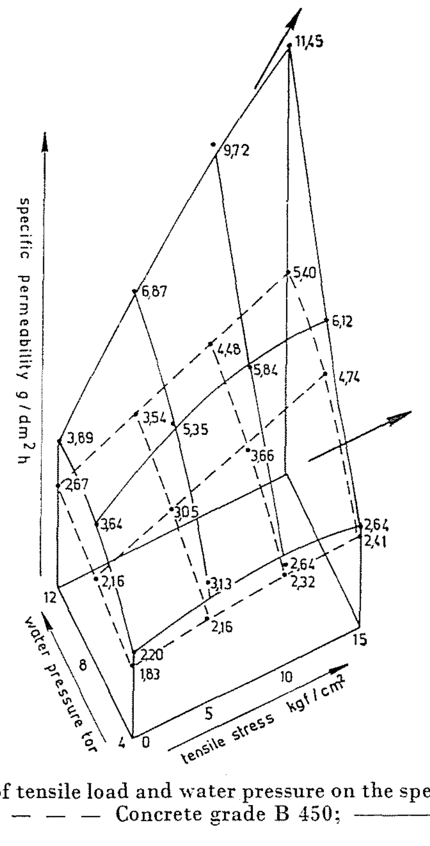

Fig. 7. Combined effect of tensile load and water pressure on the specific value of permeability of a r. c. slab. Legend: — — — — Concrete grade B 450; ——— Concrete grade B 280

applying sustained water pressures of 4, 8 and 12 atm. The variation of specific water permeabilities vs. tensile stress and water pressure is shown in Fig. 7. The water infiltrated at one side into the tensioned slabs, both sides being of the same quality because of identical reinforcement and mould. The permeability values of concretes B 450 and B 280 are represented by dashed and by

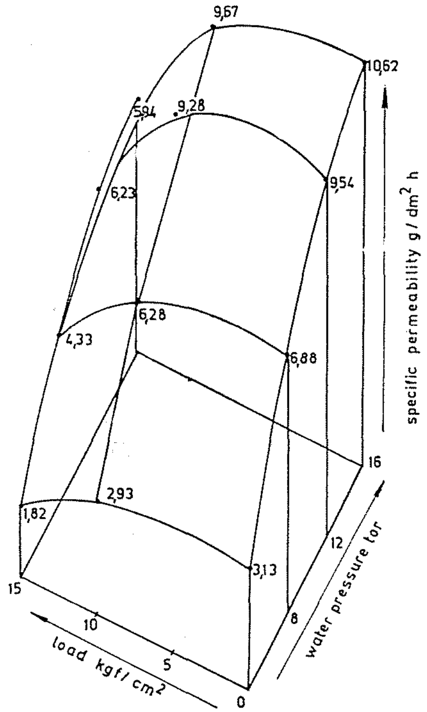

Fig. 8. Combined effect of flexural load and water pressure at the compressed side on the specific value of permeability of a r. c. slab

full lines, respectively. The permeability and its increase for a more porous concrete of lower strength is seen to be higher for an increased tensile stress. This increase is particularly critical in case of a simultaneous high water pressure because the characteristic permeability of unloaded concrete grew by as much as 100 to 275 per cent under a water pressure of 12 atm and a tensile stress of 15 kp/cm^2. Thus, the permeability of a concrete structure subject to tension may be twice and even four times higher than its unloaded value.

4. Combined effect of flexural load and water pressure

The slabs with unilateral reinforcement were exposed to bending load so that the extreme fibres developed stresses of 5, 10, 15, 20, 25, 30, 35 kp/cm^2

at the bending moment maxima. However, the structure remained crackless, i.e. it was in the so-called first stress state. A sustained water load of 4, 8, 12 and 16 atm was applied on the slab at the bending moment maximum on either the side of the unreinforced compressed zone or on the — reinforced — tensile side of the structure. The results obtained in case of a water load acting

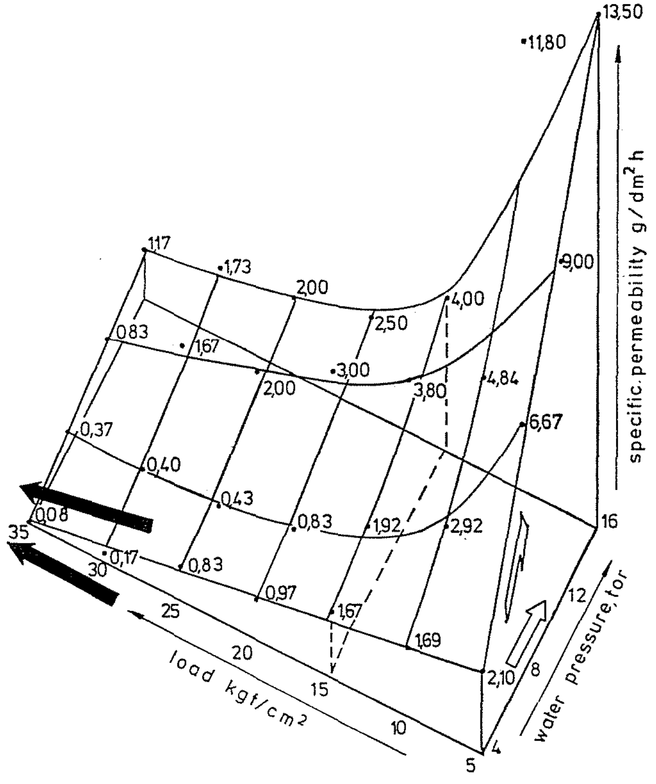

Fig. 9. Combined effect of flexural load and water pressure at the tensile side on the specific value of permeability of a r. c. slab

on the compressive and the tensile side are plotted in Figs 8 and 9, respectively.

The research work performed to now showed the flexural stress not to be prejudicial to water tightness until the structure remained crackless. Moreover, bending reduced the permeability value in comparison with the unloaded structure. Investigation of these phenomena will be continued in order to reach the required conclusions and for checking the results obtained so far. Water load applied on the compressed side results in lower permeability values than that on the tensile side. As concerns, however, the problems of deformation due to wetting, it is likely to be more advantageous to expose a reinforced concrete reservoir to water load at its tensile surface. But the effect of sustained differential deformations due to water load acting at the compressed side may be compensated by a certain percentage of compressive reinforcement.

Summary

Thin-walled r. c. structures — e.g. concrete pipes or r.c. reservoirs — exposed to water penetration behave at a difference to small specimens tested for water tightness. Therefore the deformation of thin-walled concrete units was tested partly for one-side wetting, and partly for the combined effect of water pressure and external load. It has been stated that the water penetrating from the side of the more impervious layers causes more prolonged differential deformations than that infiltrating at the more porous side. Wetting of layered inhomogeneous concrete structures, for example, concrete pipes, at the interior side richer in cement, long lasting and high internal stress may develop. The permeability values of even crackless concrete or r.c. structures under tensile load may be two to four times higher than that of unloaded structures. Bending did not impair watertightness. It is more advantageous to apply water load at the tensile side of flexural structures but detrimental load effects at the compressed side may be compensated by applying extra compressive reinforcement.

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