CORRELATION BETWEEN INDIRECT AND DIRECT FROST RESISTANCE INDICES

by

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1. Introduction

Winter climate in Hungary — more generally, in West Europe — sets high demands to the concrete of roads, taxiways, hydraulic engineering structures exposed to water saturation. In winter months, daily maximum is often above, and minimum below zero. Precipitation water fills out concrete surface layers contacting air, exposed, in addition to cyclic freezing and thawing, to the combined mechanical and chemical effect of car traffic, and de-icing salts, deposit and ice.

2. Testing methods

Concrete durability may be characterized by direct and indirect methods based on freezing-thawing cycles, and on the analysis of the pore system, respectively.

Among the direct methods, the cooled-brine cyclic thermal shock test [1], simulating at the same time the abrupt temperature drop in the crust, due to the absorption of melting heat by the salt strewn on the concrete lane [2] is of the most interesting ones.

This method has been made more rigorous by pouring $CaCl_2$ at -17 °C onto water-saturated samples cooled over 0 °C, thereby water froze abruptly upon pouring the brine. We wondered if the melting salt had to be left drying on the sample, to facilitate crystal formation, in order to observe scaling due to crystal pressure. (Crystals and scaling at the leakage spot on the outer wall of a concrete tank filled with warm NaCl solution in Fig. 1 confirm salt penetrating the concrete to be other than harmless.) Of course, drying and resaturating would protract cycle period.

One of the applied indirect tests was that by air void microscopy (ASTM C 457—67 T), using a specially constructed integrating table** (Fig. 2).

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** Mechanical parts have been constructed by István Páger, technician.

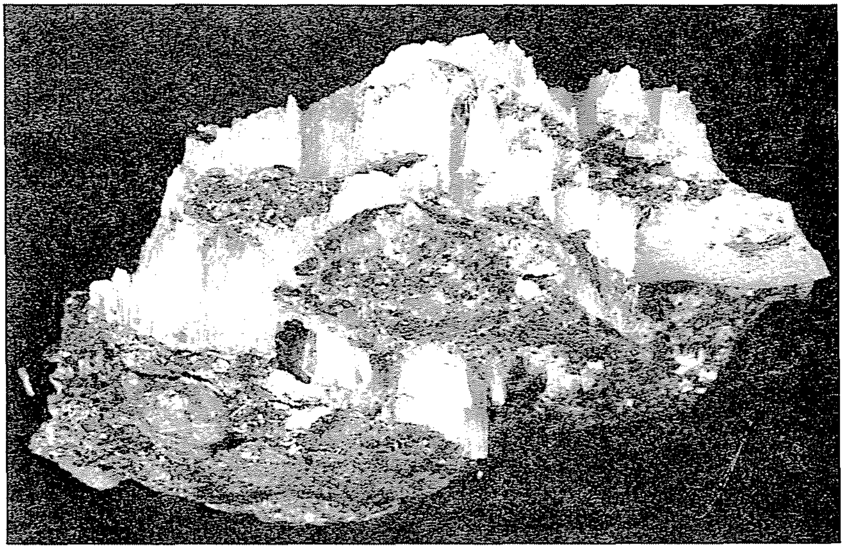

Fig. 1. Scaling on the outer wall of a brine tank due to NaCl crystals

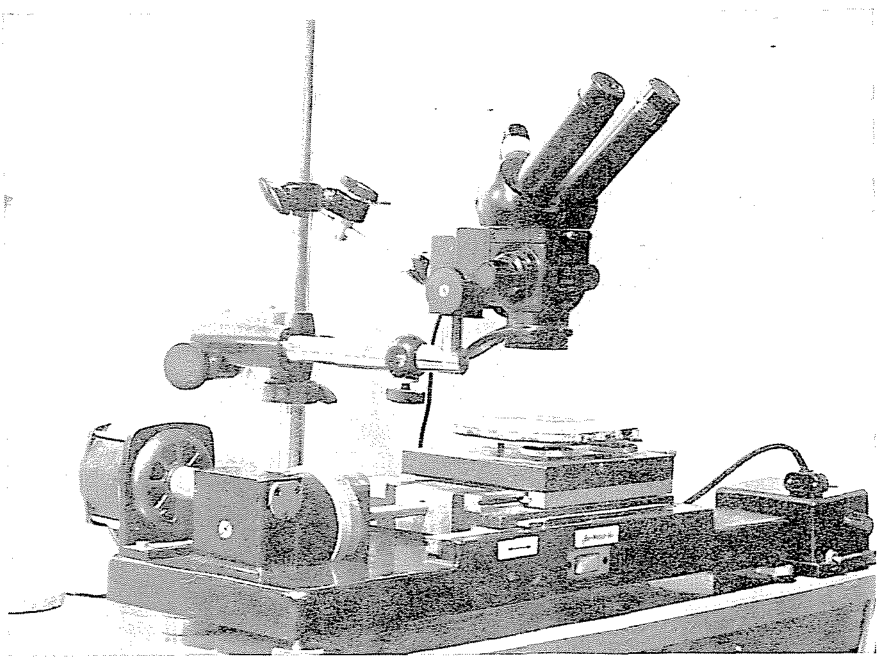

Fig. 2. Integrating stereo-microscope developed at the Department (constructed by István Páger)

Frost resistance criterion in [3] is generally agreed [4, 5], maybe with comments [6, 7, 8] or rejected as labour consuming [9].

Also the American Concrete Institute (ACI) and the Highway Research Board (HRB) furnish qualitative data but mostly for the spacing factor S_f alone, sometimes also for the specific number of air voids n_v, or even for the specific air void surface a_v. The most rigorous system of requirements is that applied by the EMPA research team, involving combined parameters of tensile strength, air percentage and gradual water absorption w_g [6].

The other indirect test method consisted in determining the degree of saturation s_D, else [9] the protective pore ratio p_r against frost cracks, based on the ratio of water absorbed upon gradual saturation w_g to that absorbed at a pressure w_p of 150 tor:

$$s_D = 1 - p_r = \frac{w_g}{w_p} .$$

Drying at 105 °C as final step delivered the possible maximum hence significant s_D value. Saturation degrees s_D before and after shrinkage at 105 °C of the pore system

$$s'_D = \frac{w_g - \Delta w}{w_p - \Delta w} < s_D$$

differed but slightly for the tested concrete of several years.

A close correlation has been reported of [9, 10] between the durability factor (ASTM C 290—67) and the saturation degree or the pore ratio, that is, between a direct and an indirect characteristic corresponding to the loss of dynamic modulus of elasticity E_{din} after c freezing cycles, and to the pore system, respectively.

3. Tested concretes

Saturation degrees s_D, pore spacing factors S_f (in mm) and specific number n_v of air voids of about 15 mm thick slices cut from cores 15 cm dia. of different ages, drilled from concrete roads, and of about 5 cm slices sawn along the plane of symmetry of laboratory-made 12 by 12 by 36 cm prisms; as well as scaling i.e. weight loss of some drilled cores due to the cooled brine have been tested.

Laboratory concretes have been made and tested in conformity with Austrian Motorway Specifications for air entraining agents [11]. Discs with planes normal to the direction of placing have been cut from the cores in order to observe pore system gradients, — and plates with planes parallel to the placing direction from laboratory prisms according to [11]; all these affect somewhat the exact comparison of test results. All concretes were made of neat

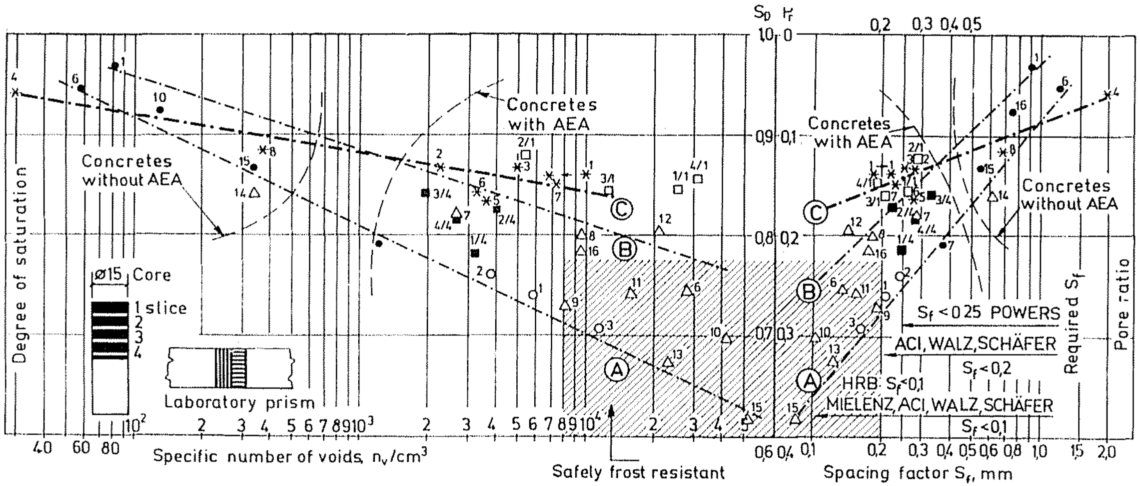

Fig. 3. Specific voids number n_v and spacing factor S_f vs. saturation degree s_D. ● AP cores — 1970 L_{300} [1]; * AP cores — 1971 (Lab.) L_{300} (first slices) [6] I; ○ AP cores — 1972 $L_ö$ (second slices) [5]; □ AP cores — 1973 $L_ö$ (first slices); ■ AP cores — 1973 $L_ö$ (fourth slices); △ Laboratory prisms — 1971 L_{300} [6] II

Portland cement (type ASTM I) at a dosage of about 350 kg/m^3, and at w/c ratios of 0.40 to 0.44. Most of them were admixed with an air entraining agent (Hungarian-made MAVEFOR SKN and KERASOL T, foreign-made BIBEROL-LP), some were made without admixture as a reference.

In Fig. 3 correlations of specific number of air voids n_v, saturation degree s_D and spacing factor S_f have been plotted for four sample sets (three drilled cores, one laboratory concrete each) — microscopy data being in log scale. Irrespective of concretes marked, plots are between limiting straights each side, and averages may be expressed as

$$s_D \cong 0.7 + 0.25 \log 10\, S_f \text{ and}$$

$$s_D \cong 0.943 - 0.09 \log \frac{n_v}{100}\, .$$

Each side, non-admixed concretes are separated; these fall short of $s_D < 0.825$ and $n_v > 10^3$. Provided the most rigorous condition $S_f \leq 0.1$ mm is correct, only concretes with $s_D \leq 0.7$; for $S_f \leq 0.2$ mm, those with $s_D \leq 0.775$ can be considered as safely frost-resistant. Thus, the usual condition $s_D \leq 0.8$ is anyhow too mild.

Plots represent mean saturation degree s_D of the upper 15 mm porous slice, rich in cement stone, and voids data S_f and n_v of the bottom, i.e. single plane of core samples drilled from road concrete; correlation of these data is, however, wrong since — as demonstrated by the variation of s_D with depth — void system parameters of drilled cores are rapidly changing. It is correct (but labour consuming) to determine saturation degree s_D on slices (discs) of which both sides have been surveyed using a microscope, and outcome averages confronted with s_D.

Again, in Fig. 4 an unambiguous relationship is seen between weight loss Δg due to the thermal shock upon applying cooled $CaCl_2$ solution, and saturation degree s_D. (Concretes are those of sample set marked • in Fig. 4; each of the three methods points to the rather poor concrete marked "1.".)

Correlation between s_D, S_f, n_v and $\Delta g\%$ still improves by applying all tests, among them that of the thermal shock, on the same specimen, advisably in the following sequence:

— determination of microscopic features on both surfaces, then removal of the fixing agents;

— water saturation for determining s_D, then vacuum drying at 60 °C max.;

— thermal shock test applying cooled brine on the surface with the worse S_f and n_v values.

Since a close correlation has been proven to exist between s_D determined on the entire volume of a specimen ∅ 15 by 30 cm, and the durability factor

DF representing again the change of an entire concrete volume [9], on the other hand, our described tests support the close correlation between s_D, the air void characteristics interpreted for a given sample plane, and the thermal shock weight loss $\Delta g\%$, the test method for the concrete durability requiring the simplest, the least of laboratory equipment, i.e. determination of the saturation degree can be agreed as qualitative in itself, — except for top layers of road concretes.

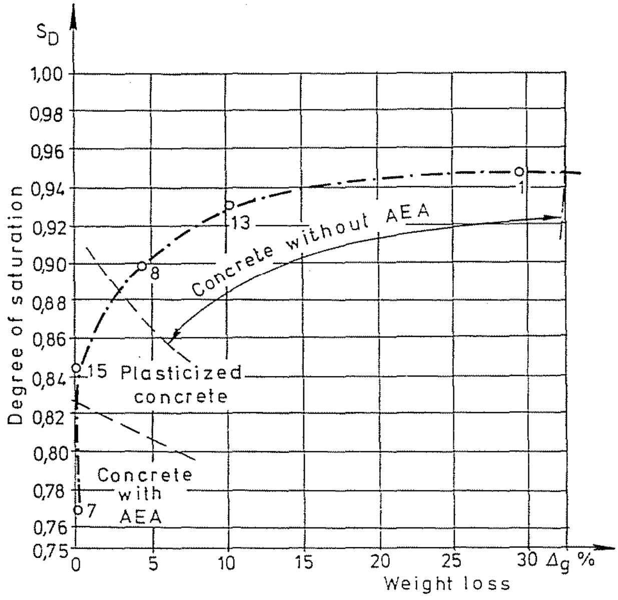

Fig. 4. Weight loss Δg % due to cooled $CaCl_2$ vs. s_D (Samples marked ◉ in Fig. 3)

Summary

Cores drilled from concrete roads and specimens sawn from laboratory prisms have been applied to determine void system characteristics, saturation degree at a pressure of 150 kg/cm^2, and weight loss due to thermal shock upon cooled brine treatment. Average logarithms of spacing factor S_f and specific voids number n_v are linearily related to the saturation degree s_D, and there is also an unambiguous correlation between weight loss Δ g% due to cooling and s_D. Concretes with $s_D \leq 0.75$ can be considered as frost resistant. Real road concrete conditions are in close agreement with test results, and diagrams clearly distinguish concretes made with and without air entraining agent. It would be of interest to reckon also with physical-chemical effects (crystallization) of de-icing salts in predicting the durability.

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