EFFECT OF HYDRATIONAL DEFORMATIONS ON THE STRENGTH OF CONCRETE MADE WITH CEMENT CONTAINING GYPSUM

by

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(Received February 5, 1973)

1. General remarks

The structure of cement stone and concrete develops as a result of significant chemical and physical changes. Our investigations have been concerned with an essential parameter of this intricate process, i.e., course of hydrational deformations and effect on the structural development, strength and the so-called inelastic behaviour of concrete.

The development and effects of hydrational deformations are correlated to the change of gypsum content in the cement. In recent years, the cement is known to be admixed with ever more gypsum, in order to improve steam-curing properties of cements and concretes. That is why this paper is concerned with hydrational deformations developing during steam-curing related to the increasing gypsum content in the cement. Concrete steam-curing may produce hydrational deformations also independently of the gypsum content of the cement, for example, during heating of the green concrete, owing to the uneven expansion of the concrete components. These deformations are mainly influenced by the storage of green concrete before steam-curing and the heating rate. Test results in Fig. 1 are relating to the maximum and the residual swelling of steam-cured concrete. To keep low the hydrational deformations during steam-curing it is recommended to leave a rest of about four hours to the concrete before curing. This means that steam curing should not begin until the process of cement hydration is beyond the initial setting. From Fig. 1 it is evident that at the beginning of steam-curing an intense heating causes significant deformations if the period of resting was too short.

All these were only said to point out that the effects of steam-curing are also influenced by the method of curing. Further, it should be noticed that besides the significant effects of the hydrational deformations, also other chemical and physical phenomena affect the structural development and characteristics of the concrete. Hydration deformations are mostly understood as swelling in a saturated steam chamber (at least 95% r.h.). During hydration the cement paste and concrete is known, however, not to swell exclusively but also shrinkage might be associated with the development of the structure. Hydration shrinkage also causes internal stresses and damages in the concrete.

An important shrinkage may impair the strength and elasticity of the concrete if it results from an improper storage producing rapid drying. The damages in the structure due to hydration swelling do not coincide with those due to shrinkage, nevertheless, they act similarly. In Fig. 2, the tendency of the correlation between swelling and strength loss of the concrete in steam curing is

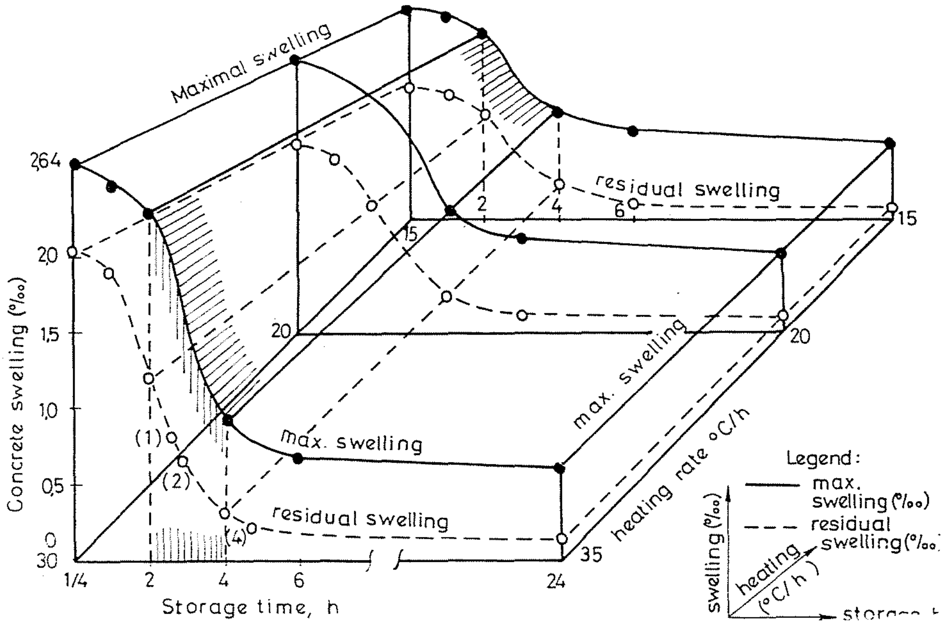

Fig. 1. Effect of storage time and heating rate on swelling during steam curing, (Isothermal temperature: 80 °C)

seen, and so are the limitations of hydration deformations in the concrete due to the reinforcement, a tendency decreasing parallelly to the increase of the reinforcement percentage. To have a more complete picture of the factors affecting the structure of the steam-cured cement stone, let us shortly recapitulate the deviations between air-cured and steam-cured cement pastes;

— in the steam-cured cement paste, the hydrate crystals are much greater, the surface of the tobermorite system decreases, the hydration products are more concentrated around the cement particles and thus, *the hydration structure is the more damaged, the more intense the curing, further, for equally hydrated cement pastes the final hydration structure will be the better, the lower is the initial hydration temperature;*

— *initially in steam curing, swelling takes place, a part of which* due to different thermal expansions of the paste components, the incoherent processes, the intensive heat evolution, temperature differences between steam chamber

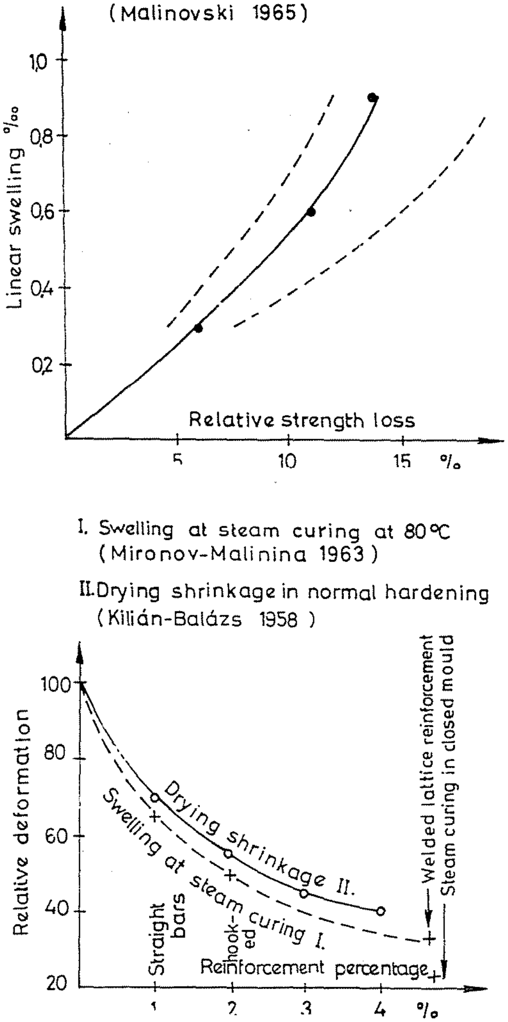

Fig. 2. Relation between swelling and strength and restrained hydrational deformation in reinforced concrete. *a)* Effect of swelling due to steam curing on the compressive strength loss at 28 days of age; *b)* Reduction of swelling and shrinkage (restrained hydrational deformation) upon increase of reinforcement percentage

and cement paste etc., *is residual* causing differential loosening depending on the paste specimen size, the free surface areas, the method of curing and the paste composition;

— swelling and water migration during curing results in an inhomogeneous cement stone structure, namely loosening, cracking, porosity and capillary water loss of the cement stone steam cured in formwork is *more intense near the free surfaces* (in case of open top) than inside (see Fig. 3);

— steam curing enhances the effect of incoherent processes also present in air curing, adding to the importance of the free CaO, MgO, C_3A and gypsum contents, etc., not to be treated in detail, further, *it also increases the internal stresses in the hydrating cement stone;*

— thus, *curing relatively impairs the physical and mechanical properties*, strength and deformation characteristics of the cement paste to the degree of how much the quoted adverse phenomena evolved.

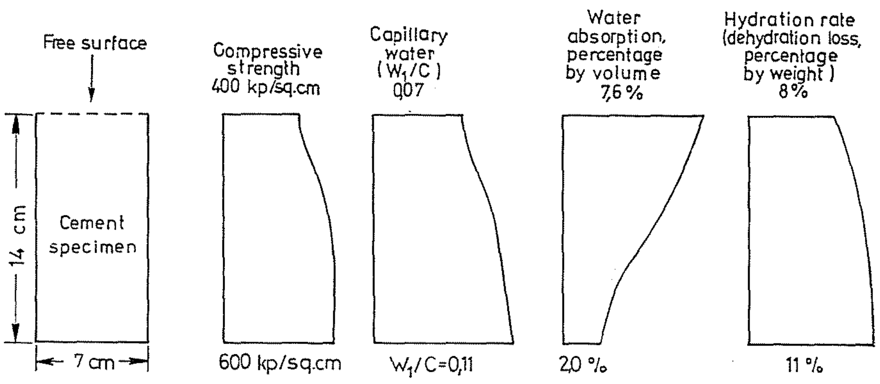

Fig. 3. Variation of the structural characteristics of cement stone along the depth of the open-top specimen steam-cured in steel form at 80 °C without storage during 6 hours

It should be noticed that only the basic phenomena were summarized, and mainly from the physical point of view. In general, steam curing is not advantageous to the final state of the cement paste to a degree depending on the cement type, paste (concrete) composition, curing method and others.

In conclusion: The steam-cured cement paste is a stone-like porous, brittle matter with mechanical properties essentially depending on the porosity of the primary structure and the physical and physico-chemical processes involved in the development of the hydration structure, and on the structural defects.

2. Combined effect of gypsum content and steam curing on the hydration deformations and on the mechanical properties of concrete

In general, the grade of a concrete is expressed by its compressive strength. There are, however, two properties, complementary to the comparison of concrete grades.

The development of the structure of a concrete, its inelastic behaviour can be checked to a degree by following the deformation of the specimens up to failure. Upon gradual loading a state is arrived at where the transversal deformation (i.e., perpendicular to the load direction) increases by more than that parallel to the load direction. This may be called the lowest value of the critical load capacity of the loaded concrete. Otherwise, also the degree of curvature of the compression diagram clearly represents the inelastic behaviour of the concrete.

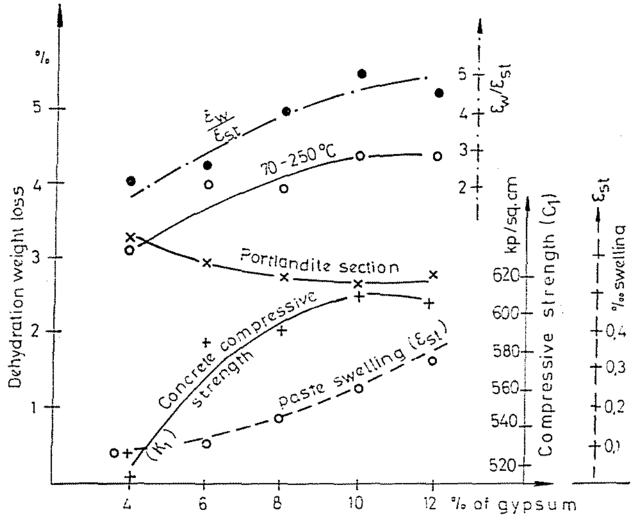

Fig. 4. Portlandite content of the steam-cured cement stone, bound water content released between 70 and 250 °C, hydration swelling and compressive strength vs. gypsum content (Kilián—Székely, 1967)

Let us return to our basic problem, the steam-cured concrete.

The gypsum content of the cement affects steam curing in a number of ways still debated. In fact, the effect of the gypsum cannot be described as simply as JIRKU did it by the C_3A content and grinding fineness alone. The optimum content of gypsum in the cement related e.g. to the compressive strength is significantly affected by the process of hydration. Our investigations (KILIÁN—SZÉKELY) established that — as shown in Fig. 4 — a higher gypsum content increases swelling, reduces the portlandite content and increases water content released between 70 and 250 °C, as described in an earlier publication. Gypsum content variation has also been observed to affect compressive strength else than tensile strength.

Tests were made on neat Portland cement grade C 600 (marked DCM 600 P.C.) containing 10% or 12.24% of C_3A.

As concerns the gypsum content optimum for compressive strength, in Figs 5, 6 and 7, the initial and 28-day compressive strengths have been plotted as a function of cement grinding fineness.

The gypsum content optimum from strength aspects was found to decrease with concrete age and with rising steam curing temperature. The gypsum content delivered by JIRKU's formula seems to be optimum for about the final concrete strength while that calculated by RÉVAY's formula is an optimum in case of earlier strengths (See Fig. 7).

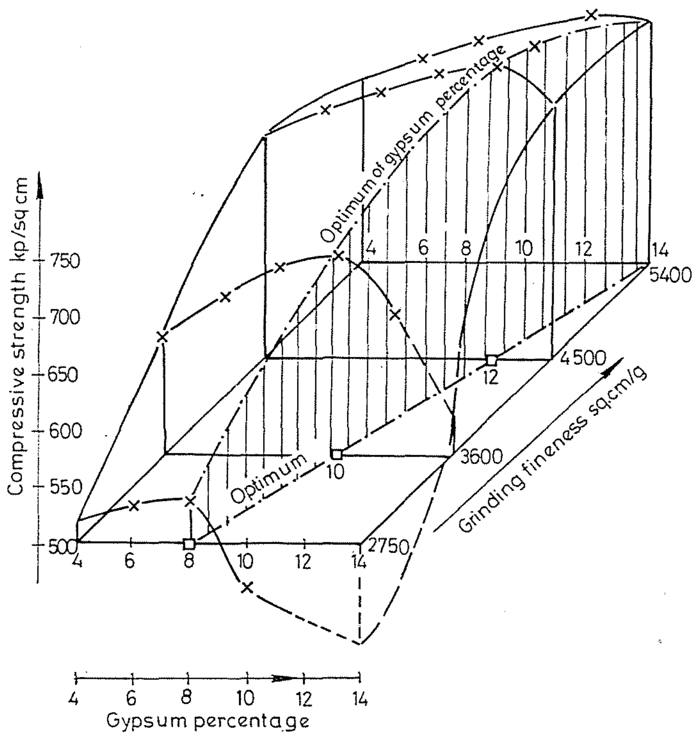

Fig. 5. Effect of gypsum content and cement fineness on the 1-day strength of a concrete after steam-curing

The gypsum content was found to affect the structure and the mode of failure of steam-cured concretes as follows (Figs, 8 and 9):

— in accordance with the previous statements, the strength of both steam-cured and air-cured concretes rapidly decreased with the increase of a gypsum content in excess of 6 to 8 per cent (this was found earlier to be the limit of the optimum gypsum dosage),

— *the lower limit of the critical load capacity of loaded concretes did not reduce significantly until the swelling rate during steam curing remained low* (up to 8 per cent of gypsum),

— *a gypsum content abruptly increasing the swelling rate does not only reduce considerably the strength of concrete but also the value of the critical load capacity characteristic to the structure loosening of the loaded concrete,* thus verifying the great hydration deformations to destroy the structure,

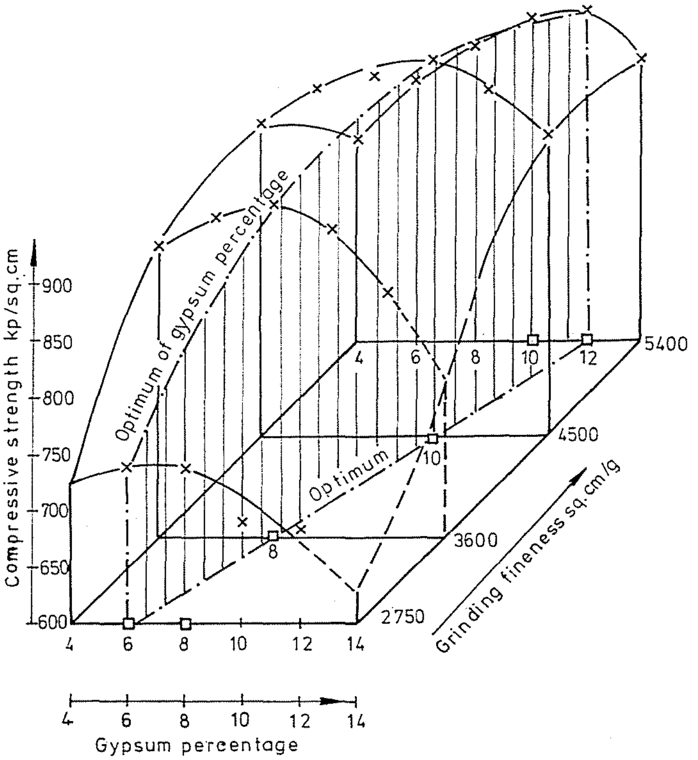

Fig. 6. Effect of gypsum content and cement fineness on the 28-day strength of a concrete after steam curing

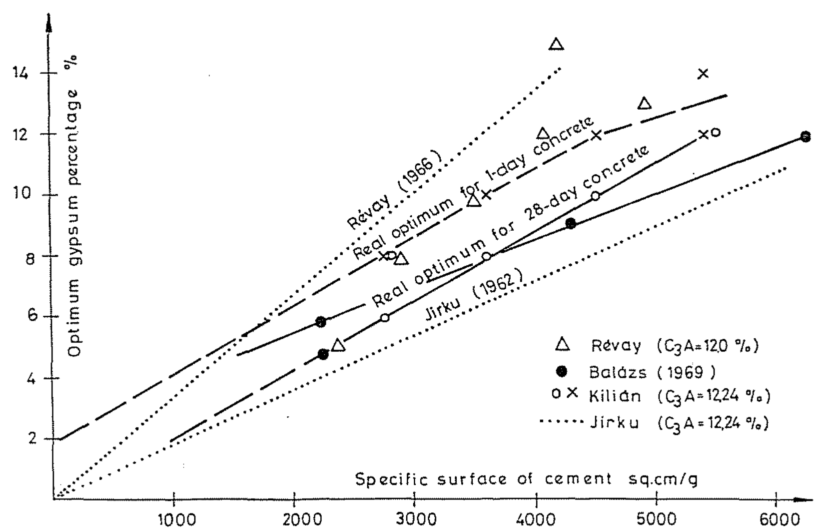

Fig. 7. Relations between the gypsum content actually optimum from the viewpoint of the strength of steam-cured concrete and the theoretical optimum proposed by several authors

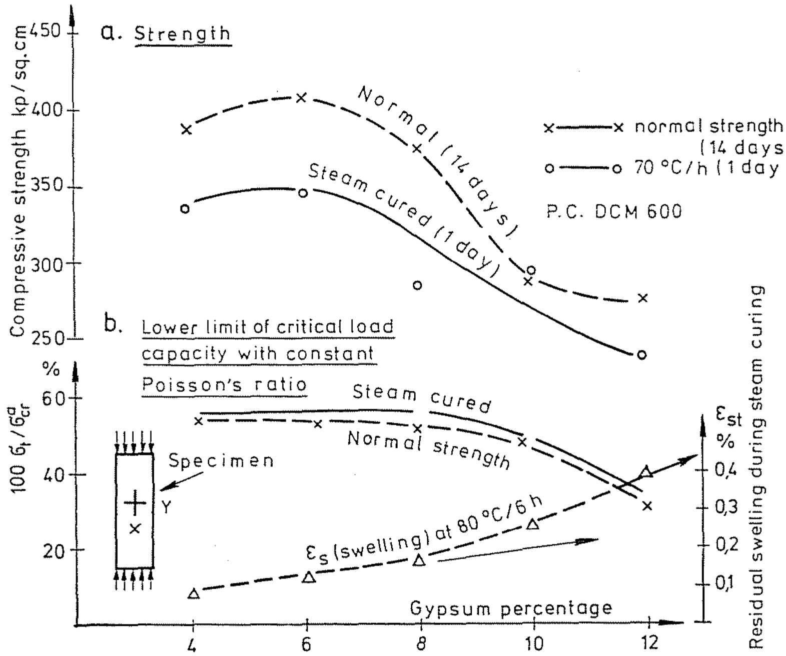

Fig. 8. Effect of the gypsum content and deformation due to hydration on the lower limit of the critical load capacity of concrete

— *similar methods are valid for evaluating the effect of cement dosage and of aggregate package for both steam-cured and air-cured concretes* (Fig. 9), hence

— *the lower limit of the critical load capacity of loaded concretes is reduced with the increase of aggregate package* (i.e., with a lower cement content),

— *the lower limit of the critical load capacity of steam-cured concretes is, in general, lower than that of air-cured concretes*, hence

— *compression diagrams of steam-cured concretes are, in general, bent stronger than are those of air-cured concretes, explaining for statements found in publications that also their moduli of elasticity are lower* (by 10 to 15 per cent). (See also relevant research by ARMUTH, 1967.)

As a conclusion, it may be stated that the comparison between the failure processes of concretes with and without steam-curing is better in pointing out the effect of structural defects and internal stresses on the mechanical behaviour of the concrete than the chemical analysis of the hydrate structure. If the combined effect of gypsum admixture, concrete composition and the curing method causes only slight swelling (or shrinkage), then both the gypsum dosage and the steam-curing method leading to the highest concrete strength can be considered as optimal. A concrete composition causing accelerated hydrational deformations during steam-curing impairs the structure,

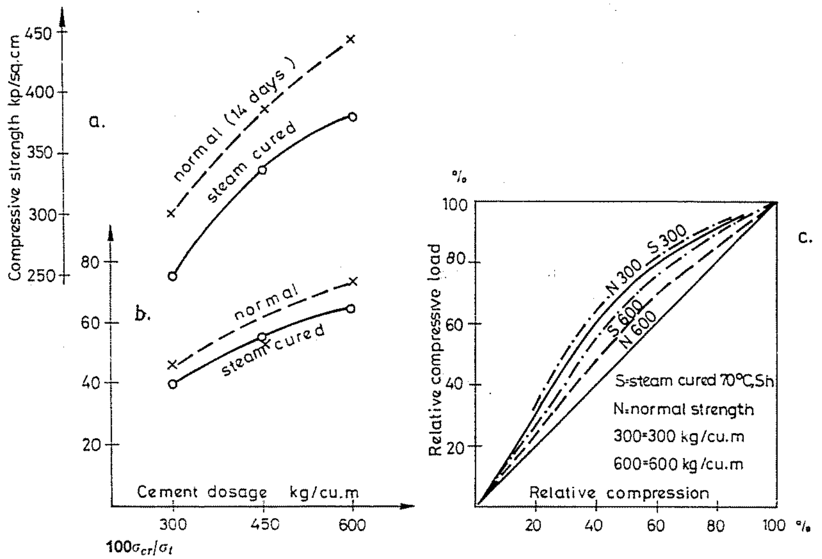

Fig. 9. Load capacity and compression diagram curvature of steam-cured and air-cured concretes vs. cement dosage

strength and stability of the concrete. The composition parameters of steam-cured concrete — either cement type or gypsum dosage — may only be optimized by observing throughout the processes of hydrational deformation during steam-curing and of load induced changes in steam-cured concretes rather than the ultimate values alone.

Summary

The development of cement paste and concrete structure is significantly affected by the deformations due to hydration, a problem discussed in relation to concrete swelling due to steam-curing, strength and inelastic behaviour. The technological conditions of swelling in steam-curing are briefly treated and, in the first line, the effects of the gypsum content of the cement are analysed. The lower limit of load capacity and critical strength of steam-cured concretes begins to decrease with increasing gypsum content where hydration swelling highly increases. Compression diagrams of steam-cured concretes are, in general, bent stronger than those of air-cured ones, but moduli of elasticity are commonly by 10 to 15 per cent lower than that of these latter. The optimum gypsum content in the cement and the optimum method of steam-curing can be determined more accurately if deformations due to hydration are known, in addition to ultimate strength values, processes of concrete deformation under load have to be followed and analysed.

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