VALTION TEKNILLINEN TUTKIMUSLAITOS
THE STATE INSTITUTE FOR TECHNICAL RESEARCH, FINLAND

TIEDOTUS. SARJA III — RAKENNUS. 76

ON THE INTERRELATION OF THE MOISTURE CONTENT AND THE STRENGTH OF MATURE CONCRETE, AND ITS REVERSIBILITY

An investigation on the drying-hardening and wetting-weakening of concrete

S. E. PIHLAJAVAARA

SUOMENKIELINEN YHTEENVETO

HELSINKI 1964

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VALTION TEKNILLINEN TUTKIMUSLAITOS

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"The difficulty is that concrete is not a substance that can be described in terms of a few single-valued characteristics - far from it. Several of its important properties may have any one of a wide range of characteristic values, and these various values may appear in one or another of innumerable possible combinations. Furthermore, different parts of a single specimen may show significantly different characteristics. For such reasons, a statement that is true about the characteristics of a particular specimen, or class of specimens, of cement paste or concrete is liable to be untrue if applied generally".

T. C. Powers

Proceedings of the Fourth International
Symposium on Chemistry of Cement,
Washington 1960
NBS Monograph 43 - Vol. II, 1962, p. 611

FOREWORD

Since 1961, the author has been engaged in a research project termed the "Drying of Concrete". The diminution phenomenon of the moisture content of concrete is one of the principal basic factors in the strength and deformation properties of concrete; generally speaking, it affects all the properties of concrete. This research work has been pursued along two main lines: one of these is an attempt to clarify the drying phenomenon, and the other the effects exerted by drying on the properties of concrete. More generally, the main aims relate to elucidation of both the moisture variations and their effects. This report falls in the latter category, and is one of the preliminary investigations on the subject.

In this connection, it is worthwhile quoting Monfore [1]: "The moisture content of many engineering materials is an important factor not only in the behaviour of these materials, but also to an understanding of this behaviour. This is especially true for concrete, in which the role of water is a vital factor. The moisture condition of concrete at early ages is important in the hydration processes of the portland cement; at mature ages changes in moisture cause dimensional changes and effect strength in a complex manner".

The State Commission for Technology has supported the research on the drying of concrete, and thus this work. Mr. Esko Pihlman has played a valuable part in the investigation. The figures were drawn by Mrs. Irja Tennberg.

The report was written by the author in English direct. The preliminary linguistic checking and corrections were made by Mrs. Rakel Toivola M.A., and the final revision by Mr. Fred. A. Fewster.

The author wishes to express his gratitude to all those whose efforts made this report possible.

March, 1964

STATE INSTITUTE FOR TECHNICAL RESEARCH
Laboratory of Concrete Technology
Physics Section

S. E. Pihlajavaara

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SYNOPSIS

A number of authors, especially Gilkey in 1937 and Mills in 1960, have in common with the present author shown previously that there is great significance attached to the interrelation of the strength properties and the moisture content of concrete. The ratio of the compressive strengths of wet and dry concrete can even amount to 1:1.7. Previous tests indicate that the phenomenon is approximately reversible. With a view to making a more profound study of the interrelation and its reversibility, and verifying earlier results, the author has made additional tests which show that the relationship between the compressive strengths of wet (vacuum-wetted) and dry (105 °C dried) concrete, and the corresponding relationship of flexural strengths are about 1:1.45 and 1:1.45 respectively at 20 °C. As regards the reversibility, the tests show that the wet compressive strength is clearly diminished after the first drying, but that subsequently the wet compressive strength values seem to be reversible. The dry compressive strengths are approximately reversible, and there appears to be a slight trend towards a rise in the strengths with increasing drying cycles. The wet flexural strengths are reversible, but there is a clear reduction in the dry flexural strength after the first drying. The change in strength with the change in moisture content is termed drying hardening, when the increase in strength is the result of drying. When the reduction of strength is brought about by wetting, it is termed wetting weakening. The decreasing sound velocity values, along with the strength values, indicate that the concrete mortar studied suffers from the heavy moisture and temperature variations, especially in the first drying. Furthermore, the test results show that the ultimate degree of wetting of the mortar is gradually

reduced in the drying and wetting cycles. The latter phenomenon is attributable to the irreversibility of the drying shrinkage, which reduces the size of pores in cement paste. - In accordance with an idea presented by Fulton, it seems possible, as is also indicated by this investigation, that the water-absorption method could constitute a supplementary procedure in the testing of cements and concretes.

1 INTRODUCTION

For some tens of years, it has been known that the strength of concrete (together with numerous other properties of concrete) is influenced by the moisture content at test, but it seems that only recently has there been clear recognition that the strength of a concrete cannot be properly specified unless its moisture content is stated [12; see Appendix 1], [13], [2], [3]. The ratio between the compressive strength values of the wet concrete and the same concrete when dry can even amount to 1:1.7 [2], [3]. Knowledge of a phenomenon of such an order of magnitude must be regarded as of great importance in concrete technique. The change in strength values attributable to the change in moisture content probably finds its origin in the changes of the proximity of the particle surfaces and, consequently, in that of the van der Waals forces [4], [14] (See Appendices 2 and 3). The phenomenon accordingly depends upon the microstructure of the cement paste, and is complex in nature [14] (See Appendix 3).

The earlier results arrived at by the author seem to indicate that the change of the reduction in strength is greatest near water saturation point [3]. Conversely, the studies concerned with light-weight concrete [11] show the opposite, the change of the reduction in strength is greatest at the beginning of moistening.

The main purpose of the present study was that of clarifying the reversibility of the interrelation of the moisture content and the strength of a mature concrete.

2 TEST SPECIMENS

In order to study the phenomena stated in the heading, 66 "practically" identical (see Chapter 4) 4 · 4 · 16 cc beams were made of concrete mortar (water-cement ratio 0.56 by weight, cement paste-aggregate ratio 1:1.2 by volume). The cement used was Finnish Portland cement (SITR, Concrete Lab. No. 7100) with a fineness of 3170 cm^2/g (Blaine). The maximum particle size of the standard aggregate was 1.4 mm. The concrete mortar was that generally used for cement testing purposes in Finland, so-called "normal" or "standard" mortar. The average density (mass of volume) of the specimens was 2240 kg/m^3 and the standard deviation in density 10 kg/m^3. Before the tests proper, 33 of the beams were stored in water and 33 of them sealed, both groups being kept in the same room for about 110 days at 20 ··· 22°C. The water-curing was effected in ordinary water from the town mains with no extra additives, in view of the probable minor effect of the water quality on the strength of the 4 · 4 · 16 cm^3 concrete mortar beams [5]. The beams for sealed curing were first (one day after pouring) covered with a plastic sheet consisting of three layers, and tightened with strong adhesive tape. Following this, they were put in desiccator bowls to ensure sealed curing. The calibrated moisture meters (hair-hygrometers) indicated that the relative humidity of the small amount of air in the desiccators was almost constant after a few days; on the completed curing at 110 days, the relative humidity values were 97 ± 1 per cent. This value corresponds to the same partial vapour pressure of water in the concrete mortar (about 18 mm Hg).

At the start of the tests proper, the specimens were cured under sealed conditions or in water for approximately 110 days at about

20 °C. As a consequence, the maturity (degree of hydration) changes ("hydration hardening") during the test procedures could be expected to be virtually insignificant.

3 TESTS

The test programme has been presented in Fig. 1, with the aid of the changes in weight during the various stages of the investigation: after pre-curing under sealed conditions or in water, the specimens were divided into four groups 12 + 12 (sealed pre-curing) and 12 + 12 (water pre-curing), and each group of 12 specimens was subjected to drying and wetting or wetting and drying cycles. The number of the specimens gradually diminished from 12 to 0 as a result of the strength testing of 3 specimens after each cycle. The flexural strength, the compressive strength, the sound velocity (ultrasonic 100 khz pulse velocity) and moisture content (evaporable water at 105 °C) were determined after each testing cycle. During the pre-curing, the tests mentioned were made at 7, 28 and 110 days. It should be noticed that at each testing, three specimens constituted a sample taken to represent the whole population of specimens.

After oven drying at 105 °C until equilibrium (four days), the specimens were deemed to be dry [3], and after vacuum wetting under water at about 20 torr (with water jet pumps) until equilibrium (four days: nights in vacuum and days, i.e. 6 hours, in air pressure before weighing), the specimens were deemed to be wet [6]. However, other tests made in our laboratory, in which the saturation was effected by the employment of high water pressure (150 kp/cm^2), show that all of the pores were not filled during this vacuum treatment. It is also evident that a higher vacuum can produce higher water saturation. Moreover, examination of the broken surfaces after the strength tests showed that they were moist but not wet, and that the air voids were not water-filled. Consequently the mortar tested under wet conditions was not completely water saturated.

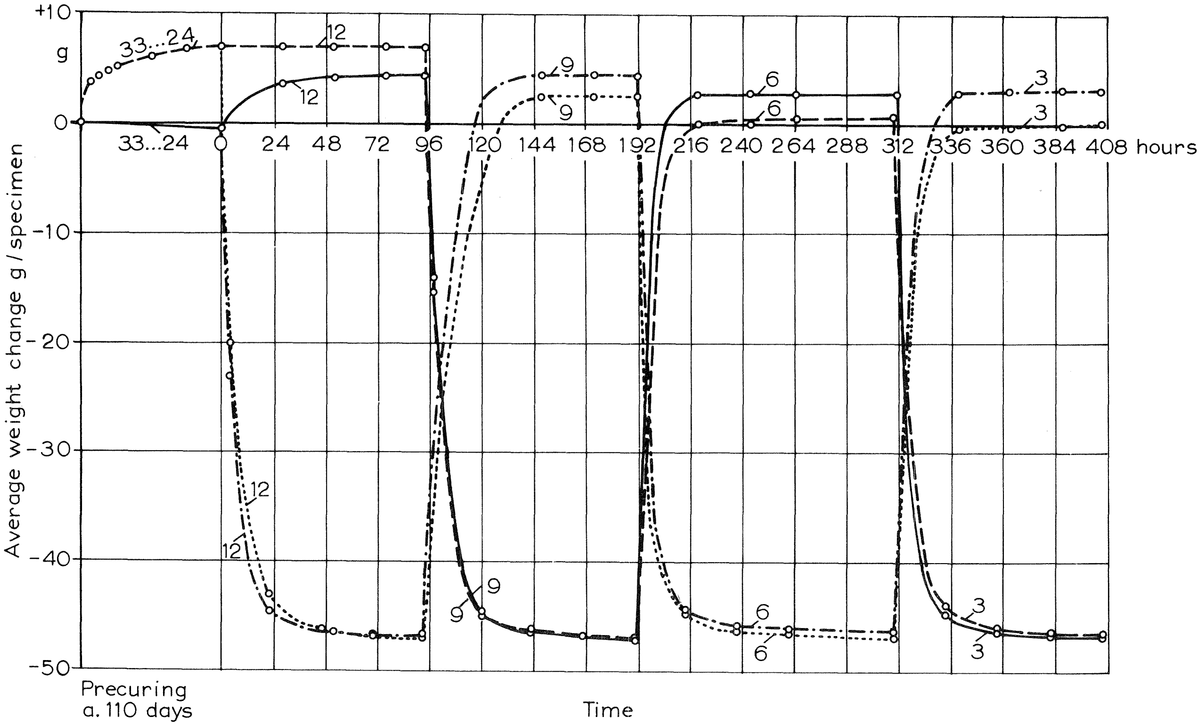

Figure 1. Average weight changes of the gradually diminishing number of concrete mortar specimens (33 ··· 3, sealed pre-curing. 33 ··· 3, water pre-curing) during 110-day precuring (33 ··· 24 sealed, 33 ··· 24 in water) and during the 4-day periods (12 ··· 3, 12 ··· 3, 12 ··· 3, 12 ··· 3) of vacuum-wetting and oven-drying (105 °C).

The changes in the weight and moisture content of the specimens (dry weight about 530, and wet weight about 580 g) were determined by means of careful weighing (accuracy ± 30 mg) before, during, and after the treatments. The wet specimens were carefully wiped until there was no water glistening on the surfaces before weighing.

The specimens taken from the oven at 105 °C following the drying procedure were allowed to reach a room temperature of approximately 20 °C. The cooling was effected in 2 hours in a small wind-tunnel (5 m/s) kept in a climate room (40 % RH, 20 °C). During the cooling period, there was some, probably insignificant, takeup of moisture (approximately 0.5 g per specimen).

The tensile strength of the specimens to be tested under wet conditions was determined immediately after they had been taken from the water, but determination of the compressive strength of the two pieces per specimen was made between 4 cm · 4 cm steel plates after the surfaces had been allowed to dry for about 10 minutes or so in air stream (20 % RH, 20 °C, 2 m/s), to ensure that the test surfaces were approximately similar to the surfaces of the specimens tested under dry conditions.

4 A BRIEF STATISTICAL EXAMINATION

The examination of the strength results of this investigation is substantially based upon the information of the mean value derived from the samples of three specimens. The samples of three specimens thus represent the whole population of specimens. If it is assumed - as seems reasonable - that all of the strength values arrived at from the whole population of specimens form a normally distributed population, then the "true" mean value for the whole population, on estimation with the aid of a mean value m from three specimens taken from the population, is within the range $m \pm \frac{4}{100} \cdot m$, to a confidence of 90 per cent, if it is known that the coefficient of variation is 4 per cent. This must be borne in mind in appraisal of the strength results presented in the following figures, although the mean value seems to be rather reliable. The mean values of compressive strength are somewhat superior, as three specimens yield six compressive strength values (two broken pieces per specimen after flexural strength determination). The selection of this coefficient of variation is based upon the information acquired from previous statistics concerning the beams used in the test: the coefficients of variation are ≤ 4.5 per cent for flexural strength values, and ≤ 4 per cent for compressive strength values at 28 days. The respective average values for the variation coefficients are about 3 per cent and 2.5 per cent.

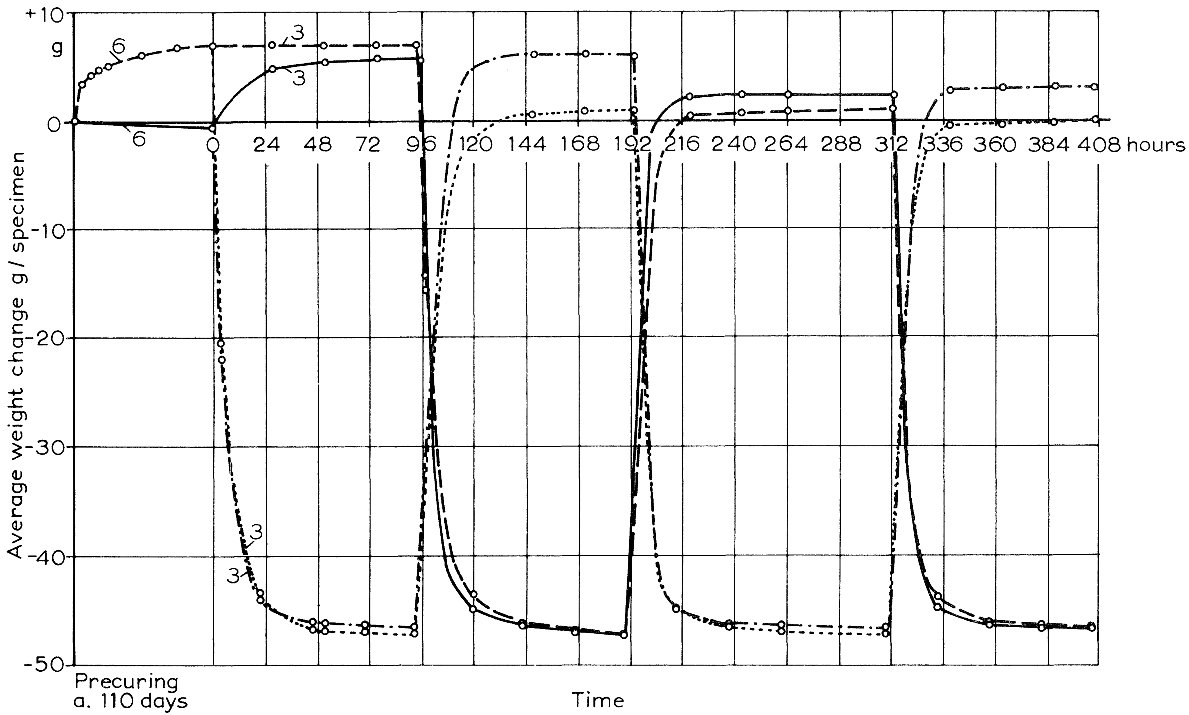

Figure 2. Average weight changes of 3 + 3 specimens pre-cured for 110 days sealed, and 3 + 3 specimens pre-cured for 110 days in water, during periods of 4-day vacuum-wetting and 4-day oven-drying (105 °C). The weight change history of the specimens strength-tested (broken) after the last cycle.

5 TEST RESULTS AND CONCLUSIONS

The test results are presented in Figs. 1 ··· 11.

Fig. 1 shows the average weight changes in the gradually diminishing number of specimens during the pre-curing, and during the testing periods of vacuum-wetting and oven-drying. Three specimens from each group were both strength-tested and sound velocity-tested at the end of each test period; during the pre-curing, the test was made at 7, 28 and 110 days. The individual weight-change histories of the 3 + 3 and 3 + 3 of the specimens, strength-tested after the last cycle, are presented in Fig. 2. The figures clearly illustrate that the wetting ability of specimens decreases as a result of the previous drying: the moisture content of the dried and rewetted specimens is lower than that of the wet specimens not subjected to drying. This indicates that the drying of the specimens brought about a permanent shrinkage which reduced the porosity of the specimens below that of the non-dried specimens. The same effect, nowadays well-known, was obtained by Powers & Brownyard [7] some 20 years ago. The reduction in the size of pores implies that the pores have a greater ability to hold water, in accordance with the theories of adsorption and capillary condensation. However, the latter effect is hardly perceptible in these tests: the equilibrium weights (equilibrium moisture contents) are nearly the same after the oven drying processes, although the re-dried specimens seem to be slightly heavier. This small rise in weight of the dry specimens can also be a consequence of the small increase in maturity (degree of hydration) of the cement paste in the oven-drying processes. At all events, there is no reason to take seriously the very small changes in weight (<1 g per specimen) discernible in these figures, in view of the continuous dissolving of cement minerals in water during the wetting periods.

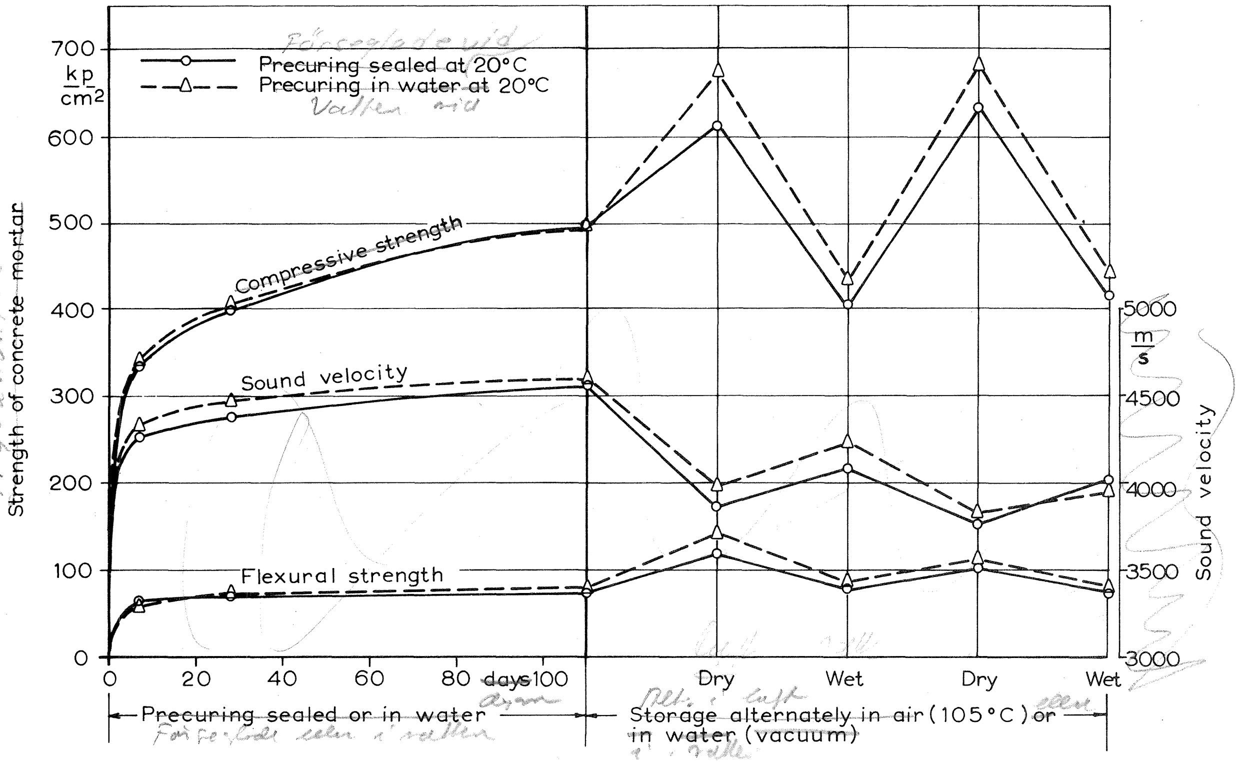

Figure 3. Compressive strength, flexural strength and sound (ultrasonic pulse) velocity of concrete mortar specimens (4 cm · 4 cm · 16 cm) in different degrees of maturity, and under different moisture conditions. Some of the specimens were pre-cured under sealed conditions, and the others in water for about 110 days. The pre-curing ensures a high maturity (a high degree of hydration). After the pre-curing, the specimens were kept alternately in an oven (105 °C) and under water (20 °C) in a vacuum box (a. 20 torr), until equilibrium weight had been attained after 4 days under both conditions. On testing, the temperatures of the specimens were about 20 °C. Each point represents the mean value of three simultaneously-tested specimens (1 flexural strength value, 2 compressive strength values, and 1 sound velocity value, per specimen).

Figs. 3 and 4 show the compressive strength, the flexural strength, and the sound (ultrasonic 100 khz pulse, 50 pulse/second) velocity (time per 16 cm) of the specimens at different degrees of maturity and under different moisture conditions. The degree of maturity of the concrete mortar studied was rather high (about 0.95, see Fig. 10) at the start of the drying and wetting cycles. Thus no substantial increase in maturity can be expected during the cycles; this means that the changes in strength are brought about by other conditions, mainly by virtue of the changes in moisture content. The curves in Figs. 3 and 4 show at the first glance that the interrelation of the moisture content and strength is roughly reversible. Nevertheless, the wet compressive strength clearly falls after the first drying; following this the wet compressive strength values seem to be reversible. The dry compressive strengths are approximately reversible, despite an apparent slight trend towards an increase in the dry strengths with increasing drying cycles. This trend can be attributed to the greater proximity and greater order of the (minor) particles in the mortar being studied, verified by the fact that the porosity, expressed as the ultimate moisture content determined (see Figs. 1 and 2), decreases during the increasing number of drying and wetting cycles. The wet flexural strengths are reversible, but there is a clear reduction in the dry flexural strength after the first drying. The gradual reduction in sound velocity could be interpreted as indicating some internal deterioration (microcracking). If this is correct, it is probable that the deterioration will lead to a gradual reduction in strength, if the concrete is subjected to continuous and large variations of drying and wetting, including large variations in temperature, for instance as in the tests from 20 °C to 105 °C and vice versa. However, as a rule the moisture-content variations of ordinary concrete structures are not large, and involve no considerable and sudden temperature variations. It thus seems moderately safe to presume that the strength variations of ordinary concrete structures brought about by variations in moisture content are virtually reversible. Furthermore, the test results presented in Figs. 3 and 4 indicate that both the compressive strength values and the flexural strength values of the dry concrete mortar studied are about 45 per cent higher than the values of the corresponding wet mortar.

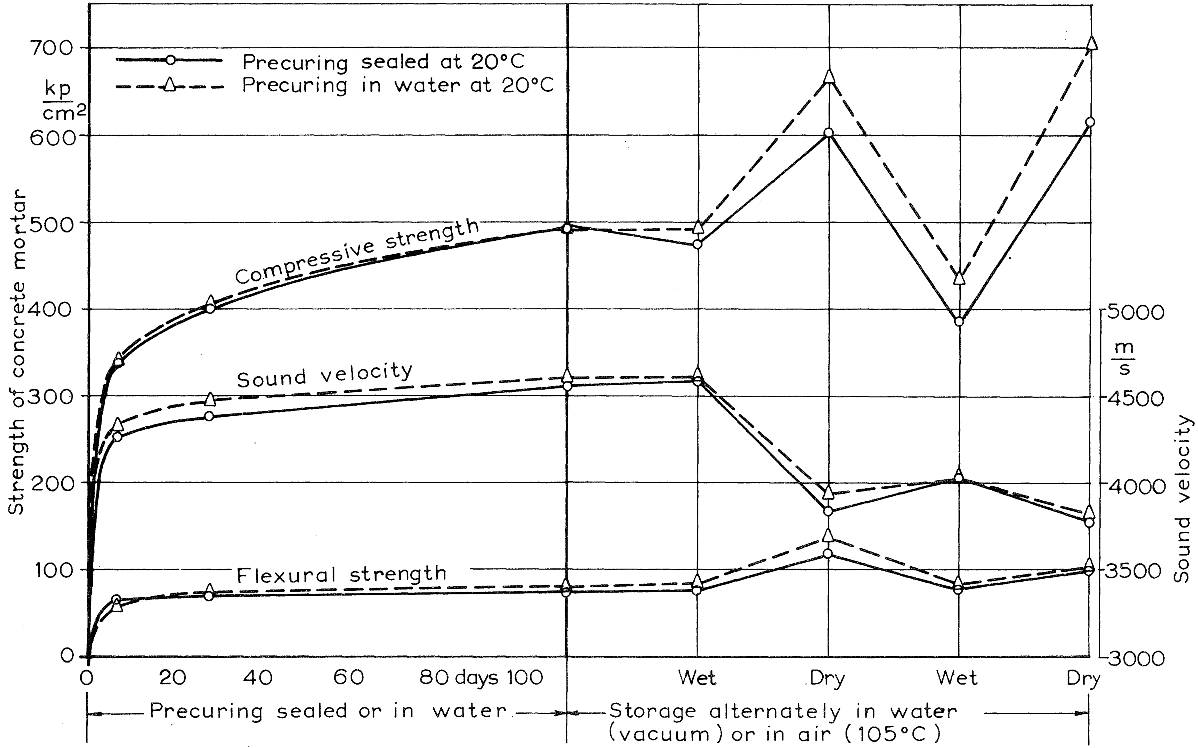

Figure 4. Compressive strength, flexural strength and sound (ultrasonic pulse) velocity of concrete mortar specimens (4 cm · 4 cm · 16 cm) at different degrees of maturity and under different moisture conditions. Some of the specimens were pre-cured under sealed conditions, and some in water for about 110 days. The pre-curing ensures a high maturity (a high degree of hydration). After the pre-curing, the specimens were kept alternately under water (20 °C) in a vacuum box and in an oven (105 °C) until equilibrium weight had been attained, after 4 days under both conditions. On testing, the temperatures were about 20 °C. Each point represents the mean value of three simultaneously tested specimens.

Figs. 5, 6 and 7 present the relationships between the compressive strength and moisture content, between the flexural strength and moisture content, and between the sound velocity and moisture content respectively. On examination of the dry compressive strengths presented in Fig. 5, there can be remarked the trend, already mentioned above, towards an increase in dry strengths with increasing drying cycles. As was stated, this could be attributed to the higher order and proximity of the minor particles in the cement paste brought about by the deformation induced by drying and wetting cycles. Figs. 5 and 6 (as well as Figs. 3 and 4) show that on the average the strength values arrived at for the specimens pre-cured in water are higher than those for the specimens pre-cured under sealed conditions. A reasonable explanation for this could be that the hydration history, including the degree of maturity, differs in each case. The reduction in porosity of the mortar after the first drying is noticeable in Figs. 5, 6, and 7: the highest moisture content was obtained before the first drying. In Fig. 7, the wet sound velocity values clearly evidence the reduction in sound velocity after the first drying. This reduction could be attributed to the microcracks produced by sudden and uneven drying at 105 °C.

Figs. 8 and 9 present the amounts of moisture or "free" water (evaporable water at 105 °C) and fixed water (non-evaporable water at 105 °C) in the mortar during the pre-curing and during the drying and wetting cycles. The figures indicate that the content of fixed water determined is smaller in the specimens pre-cured in water than that in the specimens pre-cured when sealed. This is a misleading result, produced by minerals in the mortar dissolving in the curing water during water curing. If a correction is made for this effect, the results should show the reverse, since it is highly probable (cf. the strength values in Figs. 3 and 4) that the amount of water fixed during water curing must be higher [8]. However, it is probable that this increase is small, by reason of the small permeability of the mortar. In spite of the confusing solubility effect, Figs. 8 and 9 indicate that the change in the maturity of the mortar under examination must have been small during the drying and wetting cycles.

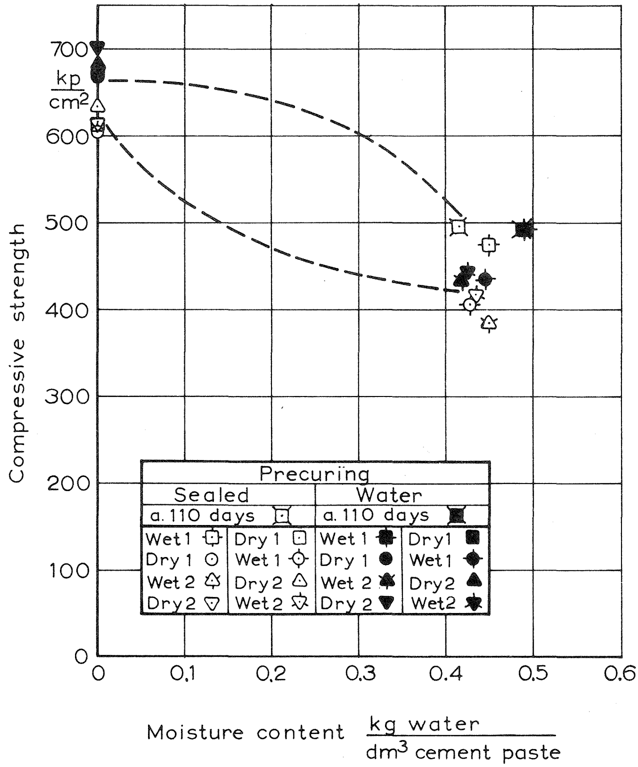

Figure 5. Interrelation of the moisture content and the compressive strength of the concrete mortar specimens under wet and dry conditions. The moisture content is expressed as kg water/dm^3 cement paste. Each point represents the mean value for three simultaneously tested specimens (2 compressive strength values per specimen).

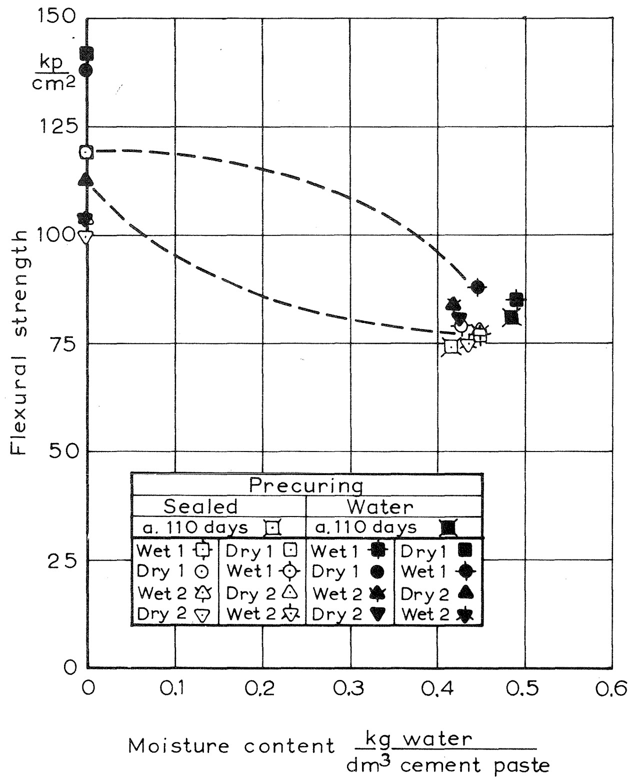

Figure 6. Interrelation of the moisture content and the flexural strength of the concrete mortar specimens. Moisture content is expressed as kg water/dm^3 cement paste. Each point represents the mean value of three simultaneously tested specimens.

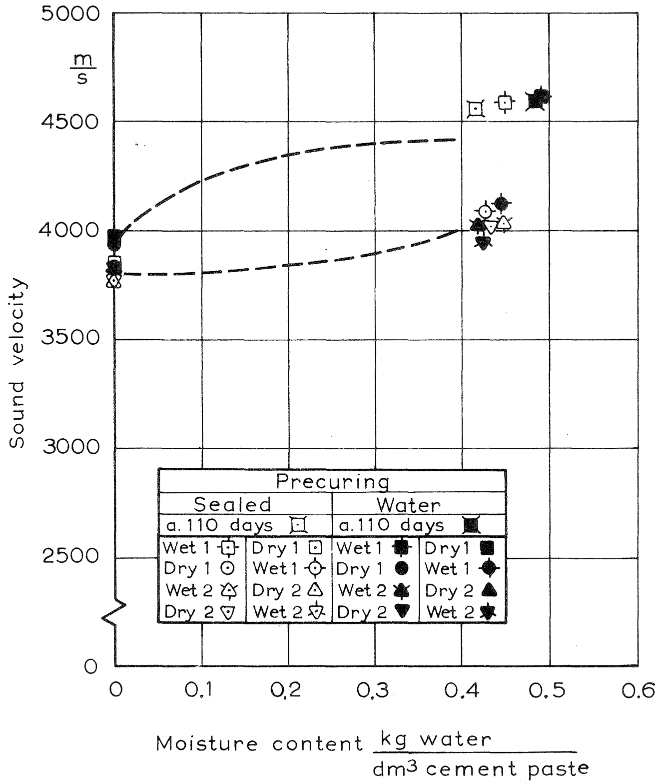

Figure 7. Interrelation of the moisture content and the sound velocity (ultrasonic pulse velocity) of the concrete mortar specimens. Moisture content is expressed as kg water/dm^3 cement paste. Each point represents the mean value of three simultaneously tested specimens.

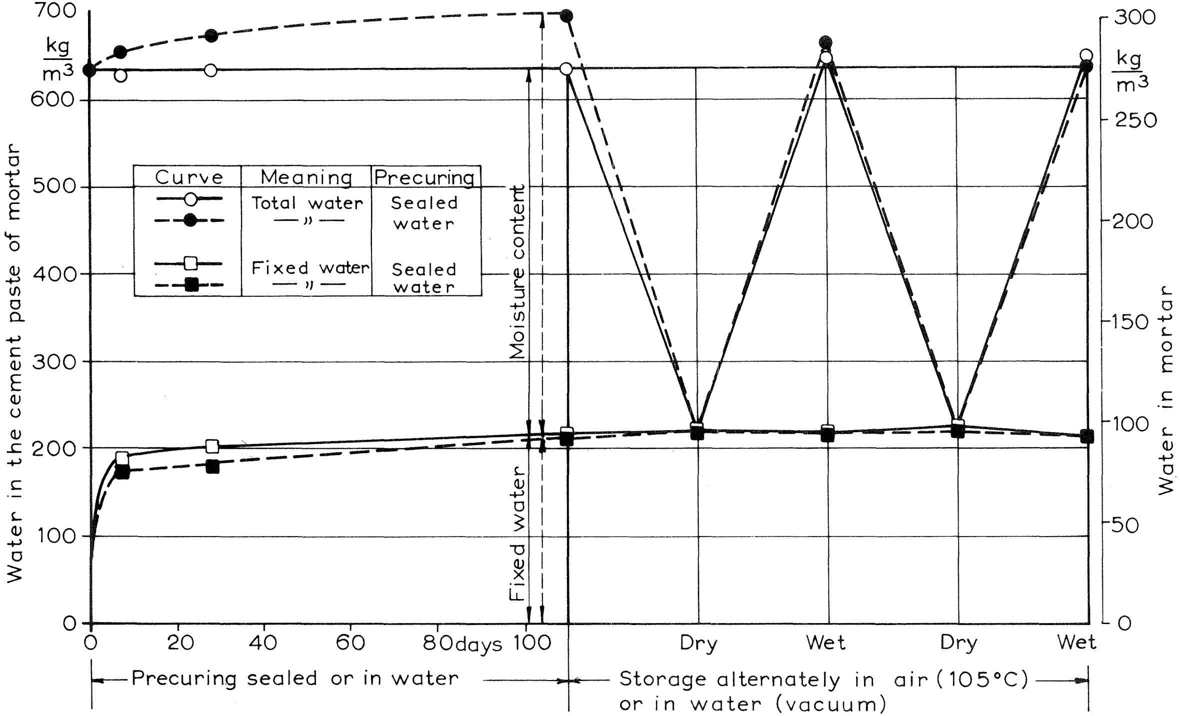

Figure 8. The total water-content history of the concrete mortar specimens. The total water content is divided into two parts: moisture or evaporable water at 105 °C, fixed or non-evaporable water at 105 °C. The test cycles began with drying. Each point represents the mean value of three simultaneously tested specimens. (See the explanation in the text).

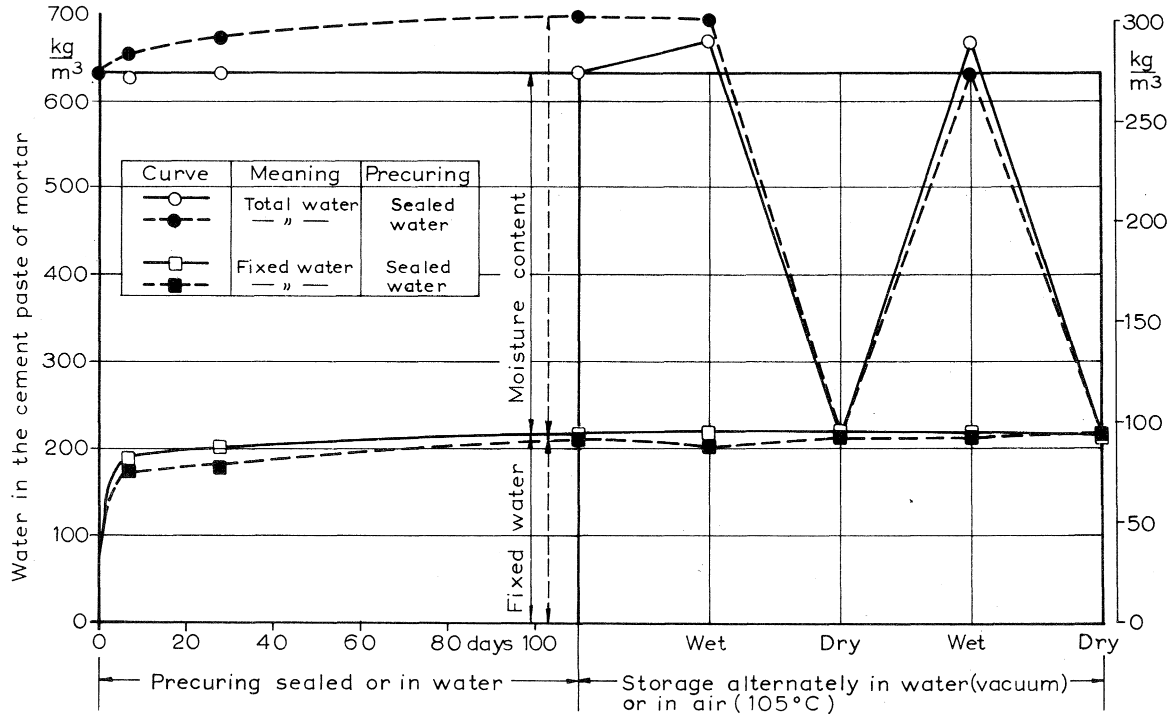

Figure 9. Total-water-content history of the concrete mortar specimens. The total water content is divided into two parts: moisture or evaporable water at 105 °C, fixed or non-evaporable water at 105 °C. The test cycles began with vacuum wetting. Each point represents the mean value of three simultaneously tested specimens. (See the explanation in the text).

The maturity degree of the mortar has been presented in Fig. 10 with the aid of Rastrups' maturity function (3)

$$M = \exp(-d/h^{\frac{1}{2}}) \tag{1}$$

where d is a parameter, and h the time in days.

The curve fitting gives $d = 0.50 \text{ day}^{\frac{1}{2}}$ and

$$w_n/c = 0.20 \cdot \exp(0.50/h^{\frac{1}{2}}) \tag{2}$$

Equation (2) (along with Fig. 10) shows that the fixed water content (w_n in kg per cement in kg) is 20 per cent at $h = \infty$. This maximum value is a "sufficient" one and probably correct for some Portland cements in general [8], and especially for Finnish Portland cement, which contains not only ground clinker, but also mineral additives. The 450-day value obtained previously [9] for a Finnish cement paste, with an original water cement ratio greater than 0.5, was also about 20 per cent. It is well known that the maximum value for Portland cements can be somewhat higher.

"The rate of absorption of water by a hydrating portland cement may be regarded as indicative of its rate of hydration. For a given cement, hydrating under standard test conditions, there is a characteristic relationship between the weight of water adsorbed to a given maturity and the compressive strength of corresponding standard vibrated cubes" as presented by Fulton [10]. Fig. 11 shows that this also holds good for the present mortar specimens. It thus appears likely that the water-absorption measurement could constitute a useful supplement to the existing methods for testing portland cement and concrete.

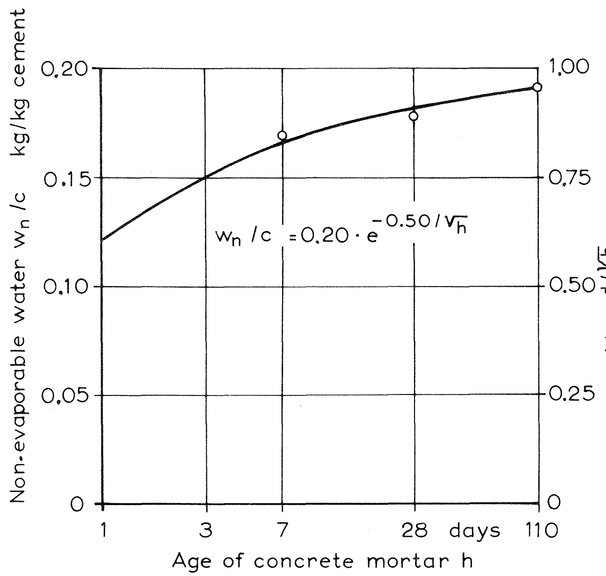

Figure 10. The fixed water content or non-evaporable water content of the concrete mortar studied, during sealed pre-curing at 20 °C. The right vertical axis presents the estimated maturity (degree of hydration). Each point represents the mean value of three simultaneously tested specimens.

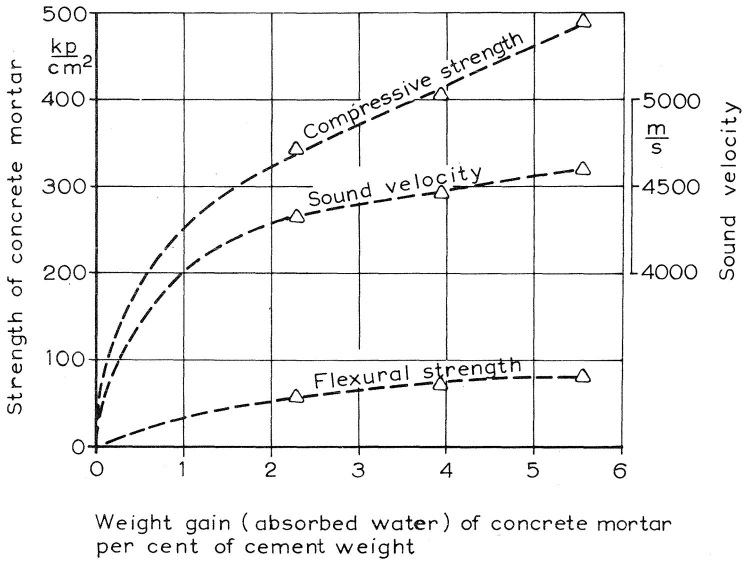

Figure 11. Interrelation of the weight gain or absorbed water of the hydrating concrete mortar specimens and the properties (compressive strength, flexural strength, sound velocity) of concrete mortar. Each value represents the mean value of three simultaneously tested specimens.

6 CONCLUSIVE REMARKS

1. The strength properties of concrete change with moisture content. The effect is of such an order of magnitude that it must be considered very significant.

2. The interrelation of the moisture content and strength is not generally reversible. However, it seems reasonable to assume that in ordinary concrete structures, where the moisture content changes are not very great, and in particular no great temperature changes are involved, the interrelation is virtually reversible.

3. The strength change with the change of moisture content is termed drying-hardening when the increase in strength is caused by drying, and wetting-weakening, when the reduction in strength is caused by wetting.

4. The increase in strength caused by drying is often erroneously ascribed to the increase in degree of hydration or to "hydration hardening".

5. It appears that the only reasonable and generally acceptable standard curing method of reference for concrete is that of curing under sealed conditions. Sealed curing is the only standard hydration condition of reference of which the results do not depend upon the properties (e.g. permeability), the size and form of the specimen. In addition, the temperature changes caused by hydration must be taken into consideration.

KYPSÄN BETONIN KOSTEUSPITOISUUDEN JA LUJUUDEN KESKINÄISESTÄ RIIPPUVUUDESTA

Tutkimus betonin kuivumislujittumisesta ja vettymisheikkenemisestä

YHTEENVETO (Finnish Summary)

Betonin kuivumistutkimukseen, jota on Valtion teknillisen tutkimuslaitoksen betoniteknillisen laboratorion fysiikan osastossa suoritettu pitkäjännitteisenä työnä vuoden 1962 alusta lukien, tavoitteet voidaan jakaa kahteen pääalueeseen: Toinen pyrkii selvittämään itse kuivumisilmiötä ja toinen sen seurausilmiöitä, eli yleisesti sanottuna toisaalta betonin kosteuspitoisuuden muutoksia ja toisaalta niiden vaikutuksia betonin ominaisuuksiin. Tässä tiedotuksessa esitetty tutkimus kuuluu jälkimmäiseen ryhmään.

Tutkimuksen päätarkoituksena on selvittää kosteuspitoisuuden vaihtelujen vaikutusta lujuuden palavuuteen. Nyt jo voidaan perustellusti olla sitä mieltä, että yksinomaan betonin kosteuspitoisuuden muutokset voivat aiheuttaa merkittäviä lujuudenmuutoksia, sillä onhan asia esitetty jo 1930-luvulla [12] (Appendix 1). Tässä ei siis tarkoiteta kosteuspitoisuuden vaikutusta sementin veteen yhtymiseen, siis veteenyhtymiskovettumiseen. Jo suoritettujen tutkimusten mukaan, mm. [2], [3], [10], voi kuivan betonin puristuslujuus olla 70 % vastaavan märän betonin puristuslujuutta suurempi. Mainittu ilmiö aiheutuu todennäköisesti hiukkasten pintojen välisten etäisyyksien muutoksista eli siis van der Waals'in voimista [4], [14] (Appendices 2 and 3). Tästä seuraa, että ilmiö riippuu sementtiliiman hienorakenteesta ja on siis näin ollen mutkikas.

Mitä tulee lujuuden palautuvuuteen, reversibiliteettiin, on luultavaa, että pienissä kosteuspitoisuusvaihteluissa on saman kosteuspitoisuuden omaavalla betonilla sama lujuus, mutta miten on asian laita silloin kun betonin kosteuspitoisuusvaihtelut ovat suuria. Edellä esitetty tutkimus on pyrkinyt nimenomaan selvittämään tätä jälkimmäistä kysymystä, joskin päätarkoituksen ohella on kertynyt muitakin tietoja.

Koekappaleina käytettiin 66 kappaletta ns. normaalilaastiprismoja $4 \cdot 4 \cdot 16\ cm^3$, joita käytetään Suomessa sementin normaalikoetuksessa. Näiden koekappaleiden ominaisuuksien hajonta on aikaisempien tutkimusten mukaan varsin pieni, joten ne soveltuivat tutkimukseen hyvin. Esisäilytys ennen koetta suoritettiin siten, että 33 koekappaletta säilytettiin vedessä ja 33 koekappaletta suljetusti noin 110 vrk. Suljetut koekappaleet oli kääritty kolminkertaiseen muovikalvoon, joka oli suljettu liimanauhalla. Suljetun säilytyksen varmistamiseksi nämä koekappaleet asetettiin lisäksi eksikaattoreihin. Kalibroidut hiushygrometrit osoittivat, että eksikaattorien vähäisen ilmamäärän suhteellinen kosteus oli koko säilytysajan noin 97 ± 1 %, joten suljetusti säilytetyssä betonilaastissa, jossa vesisementtisuhde on 0,56, on vesihöyryn paine noin 18 mm Hg. Kaikkia koekappaleita säilytettiin ilmastohuoneessa, jonka lämpötila on noin 20 °C. Esisäilytyksen aikana ja sen päättyessä (7, 28 ja 110 vrk:n iässä) suoritettiin puristuslujuuden, taivutuslujuuden, äänen nopeuden ja kosteuspitoisuuden määritykset (3 + 3 + 3 ja 3 + 3 + 3 koekappaletta). Kosteusvaihtelukokeiden alkaessa oli siis jäljellä 24 + 24 koekappaletta.

Koekappaleita tutkittiin, jos ei oteta lukuun esisäilytysaikana suoritettuja määrityksiä, kahdessa kosteustilassa: lämpökaappikuivatuksen (105 °C) ja tyhjökaappikastamisen (20 torr) jälkeen. Kosteusvaihtelut olivat siis varsin ankarat. Lujuus- ja äänennopeusmääritykset suoritettiin koekappaleiden ollessa noin 20 °C lämpötilassa. Märkien koekappaleiden taivutusvetolujuusmääritykset suoritettiin välittömästi vedestä oton jälkeen, mutta märkien koekappaleiden puristuslujuus määritettiin vasta, kun koekappaleiden pintoja oli kuivattu noin 10 min. ajan tuulettimen ilmavirrassa 20 °C:ssa. Näin saatiin märkien ja kuivien koekappaleiden ja puristuskoneen puristavien metallipintojen välinen kitka samanlaiseksi.

On huomattava, että kolmen koekappaleen sarja muodosti tässä tutkimuksessa "näytteen", jonka avulla koko betonilaastin muodostamaa "perusjoukkoa" tutkittiin. Aikaisemmat tutkimukset (sementin koetus) olivat osoittaneet, että laastiprismojen lujuuden variaatiokertoimelle voitiin kiinnittää arvo 4 %. Jos perusjoukon lujuusarvot ovat normaalisti jakautuneita, niin voidaan arvioida, että kolmen koekappaleen antaman keskiarvon m avulla saatu perusjoukkoa edustava "oikea" keskiarvo on $m \pm \frac{4}{100} \cdot m$ noin 90 %:n luotettavuudella. Tämä on siis pidettävä mielessä kuvissa esitettyjä lujuusarvoja tarkasteltaessa, vaikkakin keskiarvo näyttää siis varsin luotettavalta. Puristuslujuusarvot ovat vielä jonkin verran luotettavampia, koska kolme koekappaletta tuottaa 6 puristuslujuusarvoa (taivutuslujuusmäärityksen jälkeen on kustakin koekappaleesta kaksi osaa, joista puristuslujuus määritetään).

Koetulokset osoittivat, että sekä kuiva puristuslujuus että kuiva taivutuslujuus olivat noin 45 % suuremmat kuin vastaavat märkälujuudet. Mitä tulee lujuusarvojen palautuvuuteen kosteuspitoisuusvaihteluissa, niin märkä puristuslujuus pieneni selvästi ensimmäisen kuivumisen jälkeen, mutta tämän jälkeen ovat märkäpuristuslujuudet palautuvia. Kuivat puristuslujuudet olivat suunnilleen palautuvia, joskin ne näyttävät jonkin verran kasvavan kuivatuskertojen kasvaessa. Märät taivutuslujuudet ovat palautuvia, mutta kuiva taivutuslujuus pienenee selvästi ensimmäisen kuivatuksen seurauksena. Pienenevät äänennopeusarvot ja myös lujuusarvot osoittavat, että tutkittu betonilaasti on kärsinyt raskaissa kosteus- ja lämpötilavaihteluissa, erityisesti ensimmäisessä kuivatuksessa. Kokeet osoittavat edelleen, että laastin suurin vedenottokyky pienenee kuivatus- ja kosteusjaksojen kasvaessa. Tämä ilmiö johtuu kuivumiskutistumisen palautumattomuudesta, joka pienentää sementtiliiman huokoisuutta.

Fultonin idean mukaan on havaittu, että betonin lujuuden kasvua voidaan seurata vedessä säilytetyn betonin vedenabsorption avulla. Tätä menetelmää voitaisiin käyttää sementin ja betonin koetuksessa apumenetelmänä.

Lopuksi on esitetty seuraavat huomiot:

1. Betonin lujuusominaisuudet vaihtelevat kosteuspitoisuuden vaihdellessa. Ilmiö on sellaista suuruusluokkaa, että sitä on pidettävä erittäin merkittävänä.

2. Betonin kosteuspitoisuuden ja lujuuden keskinäinen riippuvuus ei ole yleisesti ottaen palautuva. Kuitenkin näyttää järkevältä olettaa, että betonirakenteissa, joiden kosteuspitoisuus- ja erityisesti lämpötilavaihtelut eivät ole kovin suuria, mainittu riippuvuus on käytännöllisesti katsoen palautuva.

3. Kosteuspitoisuuden muutosten aikaansaamia lujuudenmuutoksia kutsutaan kuivumislujittumiseksi, kun lujuuden kasvu aiheutuu kuivumisesta, ja vettymisheikkenemiseksi silloin, kun lujuuden väheneminen aiheutuu kastumisesta.

4. Betonin lujuuden kasvu, joka on johtunut kuivumisesta, tulkitaan usein virheellisesti johtuneeksi hydrataatioasteen kasvusta eli "veteenyhtymiskovettumisesta".

5. Suljettu säilytys näyttää olevan ainoa järkevä ja yleisesti hyväksyttävä perussäilytysmenetelmä. Ainoastaan suljetussa säilytyksessä ei tulos riipu betonin ominaisuuksista (esim. läpäisevyydestä) eikä koekappaleen koosta ja muodosta. Tämän lisäksi on kiinnitettävä huomiota veteenyhtymisen (hydrataation) aiheuttamaan lämpötilan nousuun.

REFERENCES

1. Monfore, G. E., A small probe-type gage for measuring relative humidity, Journal of the PCA research and development laboratories. 1963:May.

2. Mills, R. H., Strength-maturity relationship for concrete which is allowed to dry. Haifa 1961. [Proc. 1 RILEM Symposium on Concrete and Reinforced Concrete in Hot Countries. Haifa, July 1960].

3. Pihlajavaara, S. E., Notes on the drying of concrete. Helsinki 1963. [Valtion teknillinen tutkimuslaitos. Tiedotus. Sarja III - Rakennus 74 (State Institute for Technical Research, Report. Series III - Building 74]. (In English).

4. Powers, T. C., Physical properties of cement paste. Washington 1962. [Proceedings of the Fourth International Symposium on the Chemistry of Cement held in Washington 1960. U. S. Dep. Commerce. Nat. Bur. Stand. Monograph 43 - Vol. II]. (See Appendix 2).

5. Sawamura, M. & Kawada, N. & Miyano, K., Effect of curing water on the strength of mortar. Semento Konkuriito No. 191, - 9 - 14 (1963). Chemical Abstracts Nr. 9, April 29, 1963.

6. Kroone, B. & Crook, D. N., Studies of pore size distribution in mortars. Mag. Concrete Res., 1961: November.

7. Powers, T. C. & Brownyard, T. L., Studies of the physical properties of hardened Portland cement paste - Part 2. J. Am. Concr. Inst., 1946:Nov., p. 266.

8. Copeland, L.E. & Kantro, D.L. & Verbeck, G., Chemistry of hydration of Portland cement. Washington 1962. [Proc. Fourth Int. Symp. on Chemistry of Cement held in Washington 1960. Nat. Bur. Standards. Monograph 43 - Vol. I].

9. Pihlajavaara, S.E. & Pihlman, Esko, Suomalaisen tavallisen betonin ja magnetiittibetonin sekä niiden raaka-aineiden ominaisuuksista. (On the properties of Finnish ordinary and magnetite concrete, and their constituents). Helsinki 1961. [State Institute for Technical Research, Concrete Lab. Duplicated]. (In Finnish only).

10. Pihlajavaara, S.E., Johdatus betonin kuivumisilmiöön. (Introduction to the drying phenomenon of concrete). Helsinki 1964. [State Institute for Technical Research, Concrete Lab. Duplicated]. (In Finnish only).

11. Purins, E., Tryckhållfasthet och elasticitetsmodul och deras variation med fukthalten hos cementbunden lättbetong. Göteborg 1963. [Chalmers Tekniska Högskolan]. (In Swedish only).

12. Gilkey, H.J., The moist curing of concrete. Eng. News Record, 1937:Oct. 14. (Gilkey's figure of the principle involved presented in La Londe & Janes: Concrete Engineering Handbook, Mc Graw-Hill, 1961, Fig. 1 ··· 14). (See Appendix 1).

13. Troxell, G.E. & Davis, H.E., Composition and properties of concrete. Mc Graw-Hill, 1956, p. 191.

14. Grudemo, Å., Microstructure of Hardened Cement Paste. Washington 1962. [Proc. Fourth Int. Symp. on Chemistry of Cement held in Washington 1960. U.S. Dep. Commerce. Mat. Bur. Stand. Monograph 43 - Vol. II] (See Appendix 3).

An extract from the pioneer paper

THE MOIST CURING OF CONCRETE

by H. J. GILKEY

Data from a decade of testing to establish proper curing and test conditions on a par with water-cement ratio in affecting concrete strength

ENGINEERING NEWS-RECORD October 14, 1937, p. 630 ··· 631

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We are so prone to think of the cement factor or the water-cement ratio as being the item that determines the strength of a concrete, that it is difficult to realize that by curing and test condition alone the one-year compressive strength may often be made to vary between 45 and 135 per cent of the standard cured 1-yr. strength, moist at test.

Referring to the illustrative age vs. strength curves of Fig. 1, specimens standard cured (continuously moist and saturated at test) will give strengths corresponding to the very heavy curve, S.

If at any age a specimen is removed from its moist environment and subjected to ordinary air exposure, the strength increases quite rapidly during a period of from 1 to 3 weeks, depending upon the size of the specimen and the dryness of the air. This increase is due solely to drying since dry concrete is stronger than the same concrete if saturated. Gain in strength then ceases since the excess moisture necessary for continued hydration is no longer present. In some cases, the strength then remains nearly constant, although in many other cases there is a slow reduction in strength with added lapse of time, the strength eventually falling somewhere between the highest attained and that possessed by the concrete at the time it was removed from a moist environment to dry air.

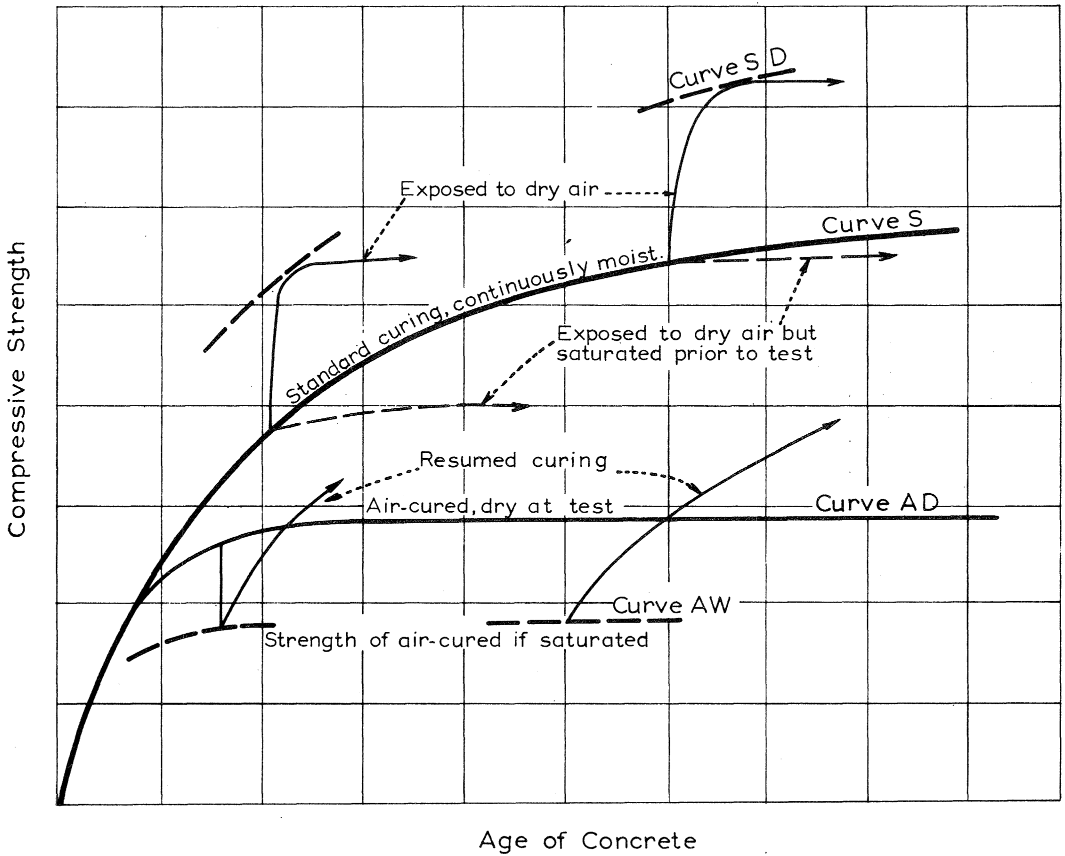

Figure 1 (Appendix). "Typical diagram showing the nature of curing, air-drying, resoaking, and resumed curing effects on the compressive strength of concrete".

The heavy dashed lines at the top of Fig. 1, labeled SD (standard cured, dry at test) when connected form an upper envelop or locus of maximum attainable strengths. The compressive strength of each standard-cured, airdried specimen rises to tangency with the curve SD and turns more or less abruptly to the right and continues horizontally or even somewhat downward from it.

That the increase in strength upon exposure to the air is a drying and not a curing phenomenon is demonstrated by its reversibility. Re-saturation by immersion for from 12 to 24 hr., immediately reduces the strength to that upon exposure or to a still lower value if there has been retrogression with continued air exposure after the maximum strength was attained. Some retrogression seems frequently, though not always, to occur.

The SD envelop lies anywhere from 20 to 45 per cent above curve S.

Curve AD on Fig. 1 represents specimens, air-cured and dry at test. If the specimen after removal from the mold (presumably at the age of 1 day) is placed immediately in dry air, gain in strength ceases within a few days, and the strength remains virtually unchanged with further lapse of time. If, however, such a specimen be immersed for a few hours (12 to 24 hr. is adequate) the saturated strength is from 20 to 40 per cent below the dry-tested strength. The lowest curve, AW (air-cured, wet at test) represents the locus of the lowest strengths attainable for a given mixture, so far as curing and moisture effects are concerned.

Note that specimens cannot cure along either the curve SD, the locus of highest strengths attainable, or along AW. If an air-cured but saturated specimen remains moist, curing will resume as shown on the diagram.

An extract from the paper

PHYSICAL PROPERTIES OF CEMENT PASTE

by T.C. POWERS

PROC. FOURTH INT. SYMP. ON CHEMISTRY OF CEMENT, WASHINGTON 1960. Mat. Bureau of Standards, Monograph 43 - Vol. II, p. 602, 603.

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"Although there is such evidence that the strength of cement gel is a function of its chemical composition, there is no evidence that some of the chemical species present do not contribute to strength. By means of a simple demonstration, Czernin made it clear that the physical state of the solid material may be responsible for strength [99]. He demonstrated (A) that a mixture of 100 g of coarse quartz and 20 g of water was without strength, (B) that when the quartz was pulverized to "cement fineness", the same proportions exhibited some strength and (C) that when the quartz was pulverized so as to have a surface area of 20.000 cm^2/g, a cylinder molded with the aid of a press could support more than a 10 kg load. Czernin remarked that in cement paste the surface area is not 20.000 but 2.000.000 cm^2/g and thus "... the high strength attained by the cement in time is entirely plausible". Such strength is presumably due to the proximity of surfaces and van der Waals forces, as discussed in section 7. Since all the major components of hydrated cement are found in substances having high specific surface area, all contribute to at least the van der Waals source of strength. On the other hand, it seems unlikely that the strength of cement gel is due exclusively to physical forces. For reasons already given, it seems probable that there are many points of chemical bonding between the particles. Whether or not all chemical species contribute to this source of strength cannot be said. As to the relative importance of the two sources of strength, one can only speculate. When a specimen of cement paste is dried in such a way as to avoid excessive stresses during drying, the specimen becomes stronger as its evaporable water is lost; in fact, if some of the chemically combined water is removed, there is gain in strength. In terms of van der Waals forces, this gain of strength could be accounted for in terms of the reduction in average distance between surfaces in the cement gel. There is evidence also that new chemical bonds may be formed during the process of drying (see section 8)".

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An extract from the paper

MICROSTRUCTURE OF HARDENED CEMENT PASTE

by ÅKE GRUDEMO

PROC. FOURTH INT. SYMP. ON CHEMISTRY OF CEMENT, WASHINGTON 1960. Nat. Bureau of Standards, Monograph 43 - Vol. II, p. 645

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"In view of the great variability of microstructures in different cement pastes, it seems that the only property remaining for a characterization of cement gel is the enormous specific surface area developed in the collapsing anhydride structures due to the penetration of water through them. The importance of the evolution of large surface areas in materials possessing hydraulic properties has been particularly stressed by Powers [98], and by Brunauer [99]. However, as is also emphasized by these authors, it is not only the development of surface, but also the nature of links formed between surfaces that determines the properties of cohesion and strength development in a paste. These links or bonds between surfaces may be largely of physical nature (absorption forces), possibly acting via intermediate layers of water molecules, but in view of the dimensional stability of hardened paste it seems that some parts of the interacting surfaces must be connected by means of strong chemical bonds (valence forces) formed in the process of a direct superposition and intergrowth of surface lattice structures. One of the objects for future cement research is to establish the nature of these links between surfaces, and the relative preponderance of different types of forces at various stages of hardening. The application of results obtained in structural studies on more well-crystallized materials may prove helpful in solving this problem".

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