An experimental study of the relation between the properties of fresh and hardened concrete

Autor(en): **Bergström, Sven G.**

Objekttyp: **Article**

Zeitschrift: **IABSE publications = Mémoires AIPC = IVBH Abhandlungen**

Band (Jahr): **13 (1953)**

PDF erstellt am: **22.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-13194

An Experimental Study of the Relation Between the Properties of Fresh and Hardened Concrete

Etude expérimentale des relations entre les propriétés du béton frais et du béton durci

Untersuchung über die Beziehung zwischen den Eigenschaften von frischem und erhärtetem Beton

Sven G. Bergström, D. Eng., Research Engineer, Swedish Cement and Concrete Research Institute, Stockholm, Sweden

Introduction

In the General Report on Theme C submitted to the 4th congress, it is pointed out, among other things, that certain general principles have been established for determining the composition of a concrete mix to comply with definite specified requirements for the properties of the hardened concrete. Furthermore it is stated that some important problems met with in proportioning concrete must be solved by means of experiments in each individual case. For example, it is necessary to determine whether the workability of the fresh concrete is adequate, in order to prevent a reduction in the strength of the hardened concrete and its resistance to frost action as a result of insufficient consolidation. The choice of an appropriate grading curve of the aggregate is of great importance since this curve has a considerable influence on the resistance of concrete to frost action. Moreover, segregation of fresh concrete during compaction must be avoided because segregation is liable to cause the formation of areas of weakness in the hardened concrete. Accordingly, it is necessary to study the properties of fresh concrete in order to ensure that the hardened concrete shall have certain definite characteristics.

In the first section of the present paper, an account is given of the tests which have been made for this purpose at the Swedish Cement and Concrete Research Institute, Stockholm, and of the apparatus which has been devised at the Institute for determining the properties of fresh concrete. In the second section of this paper, a brief review is made of the tests which have been made up to now in studying the relation between the properties of fresh concrete and certain characteristics of hardened concrete which are important from an engineering standpoint. This section of the paper is confined to studies dealing with strength, resistance to frost action, shrinkage, and creep, which appear to be the fundamental factors determining the quality of concrete used for load-bearing structures.

A. Tests on Properties of Fresh Concrete

1. Description of Apparatus

The apparatus employed for studying the properties of fresh concrete consists, in principle, of a mechanical system whose natural oscillations are damped by the concrete. The damping increases as the concrete becomes stiffer. The oscillating system consists of a vertical torsional shaft (1) (Fig. 1). The

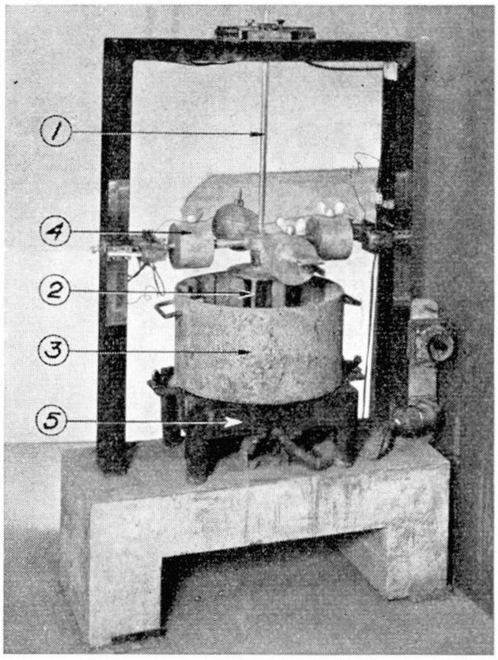

Fig. 1. Deformability meter shown without recorder

upper end of the shaft is clamped, and its lower end fitted with blades (2) is inserted in the concrete. The container (3) is filled with the concrete. The shaft makes torsional oscillations whose frequency can be controlled by means of the weights (4) attached to cross arms on the shaft. The concrete container is bolted to the vibrator (5). Measurements of the oscillations can therefore be made during vibration of concrete or while the concrete is at rest after varying periods of vibration.

The oscillation is set up by an instantaneous impulse, which is produced by discharging condensers through the electromagnets fixed at the ends of one of the cross arms. The oscillations are recorded photo-electrically.

In the tests made up to now, the maximum amplitude of the system has varied from about 0.003 to 0.005 radians, and the period of oscillations was 0.7 to 0.8 sec. The vibrator is the same as that used in the *VB* Consistometers[1]) (acceleration 3g, frequency 50 cycles per second).

A more detailed description of this apparatus has been published by Eriksson [1], while Forslind [2] has set out the physical considerations regarding the rheology of fresh concrete which have guided the choice of the measuring system.

The result of the measurements is presented as the inverse of the logarithmic decrement of the damped oscillation, and this value is considered to be characteristic of the deformability of fresh concrete. The apparatus is therefore called the "deformability meter" or "plastometer".

2. *Fundamental Test Results*

One of the great advantages offered by the apparatus described above is that it permits measurements to be made in the course of vibration and after varying times of vibration, so that the deformability of concrete can be studied as a function of the time of vibration. This study has been found to be of fundamental importance in assessing the quality of fresh concrete, and hence, to a certain extent, also the quality of hardened concrete. Tests carried out both on cement mortar and on concrete have shown that three different types of mixes can be distinguished, viz., mixes characterised by falling, invariable, and rising curves of deformability against time of vibration (Fig. 2). A falling deformability curve indicates segregation, the reduction in deformability being due to the fact that the concrete gives off excess water and mortar. In some cases, this leads to direct contact between the particles of coarse aggregate. Segregation can be diminished, e.g. by reducing the water-cement ratio, by reducing the quantity of cement paste, or by using a finer aggregate grading. Successive changes of the concrete mix lead to the ideal case of invariable deformability during compaction. This case is represented by a horizontal deformability curve, which can be regarded as a characteristic of a *stable mix*.

If the measures taken to prevent segregation

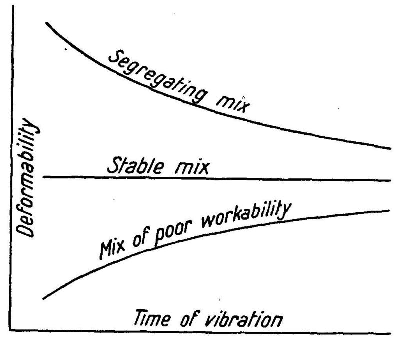

Fig. 2. Characteristic types of deformability curves

[1]) The *VB* Consistometer is the apparatus normally used in Sweden for the control of the consistency of concrete which is to be compacted by vibration.

are carried farther, the deformability curve tends to become a rising curve. If the deformability curve of a mix continues to rise even after a considerable time of vibration, the mix is characterised as poor in workability, since the work of compaction is not completed until the deformability has reached its maximum.

It is to be noted, however, that the diagram shown in Fig. 2 is considerably simplified. Among other things, the shape of the deformability curve during the initial part of the period of vibration has not been taken into account. It has been found, at any rate when the consistency of the concrete was suitable for vibration, that the line of demarcation between mixes of poor workability and stable mixes is not clearly defined, and that both deformability curves first exhibit a rising portion before the deformability reaches its maximum. After that, the deformability remains constant for a varying period, and then the curves begin to fall. It may in fact be presumed that it is practically impossible to produce a concrete mix whose deformability remains constant for an unlimited time of compaction. Consequently, the general shape of the deformability curve will be similar to that shown in Fig. 3, that is to say, it will consist of a period of compaction for a time t_1, a period of stability for a time t_2-t_1, and a period of segregation after time t_2. It has been demonstrated by means of strength tests described later that the period of rise t_1 corresponds to the time required for complete compaction of the concrete. The fact that a falling deformability curve indicates segregation can be observed with the naked eye in more or less extreme cases. In placing high-quality concrete, particularly in structures exposed to severe weathering, it is obviously advisable to avoid segregating concrete, i. e. concrete having a falling deformability curve. The fact that the mix tends to segregate during compaction shows that the water in the concrete is insufficiently fixed, and will impair the resistance to frost action and some other properties of the hardened concrete. Moreover, segregation gives rise to the formation of areas of weakness in the concrete after compaction, and these weak spots can easily be damaged by frost. A typical example is the layer of excess mortar which often collects on the surface of concrete pavements, and which can be expected to result in scaling.

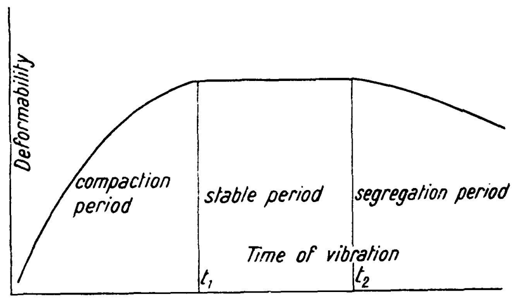

Fig. 3. General character of the deformability curve

It is thus evident that concrete mixes characterised by falling deformability curves should not be used. On the other hand, those concrete mixes which exhibit a long period of rise t_1 are not to be recommended either, because their workability is poor, and hence there is the risk of insufficient compaction. The ideal is represented by the stable mix, which possesses the greatest possible deformability without segregation.

This reasoning ignores the fact that stability is a relative concept. A concrete mix is stable under vibration for a certain definite time t_2 (Fig. 3) using the vibrator of the deformability meter, and this time must be related to the method to be used for compacting the concrete on the site. It is therefore illogical to require a concrete mix which is to be compacted by hand to have the same stability as a mix which is to be consolidated by means of high-powered surface vibrators. Theoretically speaking, the length of the period of stability could be determined from a relationship between the characteristics of the vibrator, e.g. its acceleration, and the time t_2, but this relationship is so far unknown. At the present time, it is therefore necessary to determine the period of stability on the basis of experience. In practice, in proportioning concrete for air field pavements, which is compacted by means of powerful surface vibrators, we have found that a value of t_2 lying between 4 and 5 minutes was a reasonable requirement. A closer investigation of this important question is included in our research programme, but has not yet been started. In the tests dealing with the relationships between the properties of fresh and hardened concrete which are described below, the problem of the choice of t_2 need not be taken into consideration since the test specimens were compacted by the vibrator of the deformability meter.

3. *Examples of Effects Produced by Variations in a Concrete Mix*

It has previously been pointed out that simple changes in a concrete mix can convert the shape of the deformability curve from one predominantly falling into one predominantly rising. This is illustrated by the following three

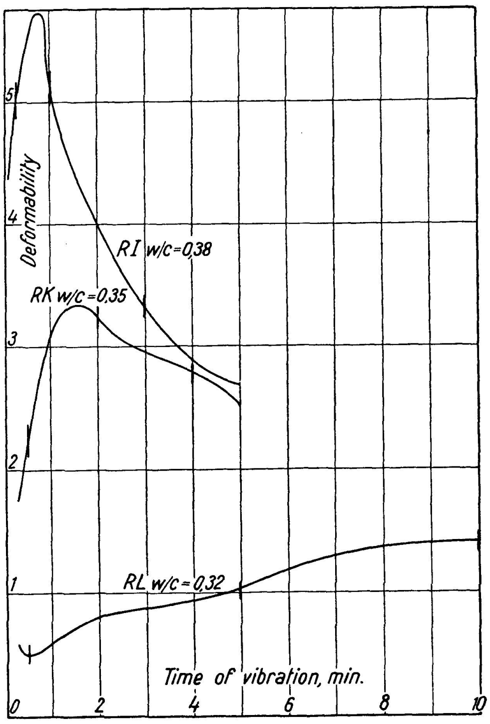

Fig. 4. Effect of variations in the water-cement ratio at a constant cement paste content and a constant grading. The letter symbols refer to the respective mixes and the vertical dashes mark the times of vibration in the tests described in Section B

examples, the first two of which refer to the investigations reviewed in Section B.

The effect of variations in water-cement ratio is shown in Fig. 4, which relates to a cement mortar having a constant grading (maximum particle size = 4 mm), a constant percentage of cement paste (44 per cent by solid volume of the constituents of the mix) and water-cement ratios of 0.38, 0.35, and 0.32 by weight. The highest value of the water-cement ratio used in this series resulted in a markedly falling deformability curve, which indicates segregation, while the workability of the mix with the lowest value of this ratio was so poor that the test specimen had to be compacted by the vibrator of the deformability meter for some 8 minutes in order to ensure complete compaction.

Fig. 5 shows the effect of variations in cement paste content (48, 46, 44, 42, and 40 per cent by solid volume of mix) at a constant water-cement ratio of 0.35 and a constant grading. This test series was also made on cement mortar.

Fig. 6 illustrates the effect of variations in the grading of a concrete mix having a constant cement content of 350 kg/m^3 and a constant water-cement ratio of 0.43. The grading was varied by changing the ratio of fine aggregate to coarse aggregate. The figures on the deformability curves express the quantity of coarse aggregate as a percentage of the total quantity of aggregate.

Figs. 4 to 6 show characteristic examples of the variation in the shape of the deformability curve which always takes place when the concrete mix is changed in one of the ways indicated above. The general results of all our tests made with the deformability meter, which are described at greater length in a separate publication [3], can be summarised in the graph reproduced in Fig. 7. It is seen that the shape of the deformability curve can be transformed from rising into falling by

1. an increase in the water-cement ratio at an unchanged grading and an unchanged cement paste content,
2. an increase in the quantity of cement paste at an unchanged water-cement ratio and an unchanged grading,
3. an increase in the percentage of coarse aggregate at an unchanged water-cement ratio and an unchanged cement paste content.

Experience indicates that all the measures enumerated above cause the concrete to become more fluid, with the result that the risk of segregation increases. Furthermore, it is to be noted that these measures also impair the resistance to frost action, as has been demonstrated by Loe and Sparkes [4]. This confirms the previous statement that those concrete mixes which are characterised by falling deformability curves result in a lower resistance to frost action than stable mixes.

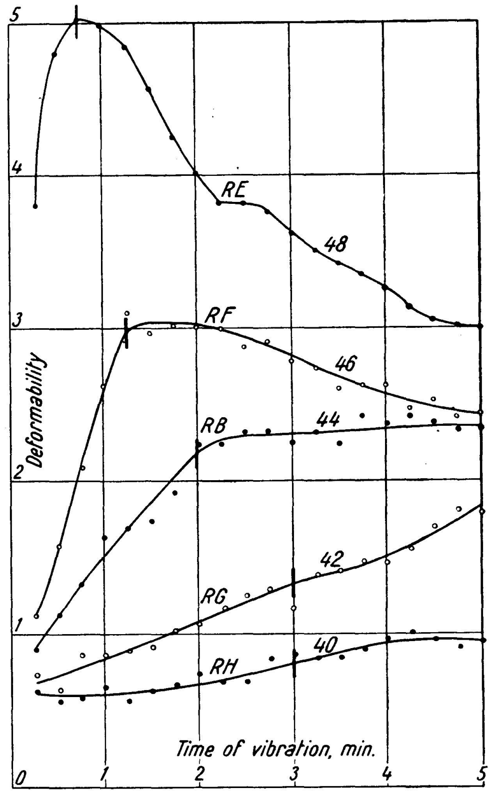

Fig. 5. Effect of variations in the percentage of cement paste at a constant water-cement ratio and a constant grading. The figures above the curves express the cement paste content in per cent by solid volume. The letter symbols refer to the respective mixes and the vertical dashes mark the times of vibration in the tests described in Section B

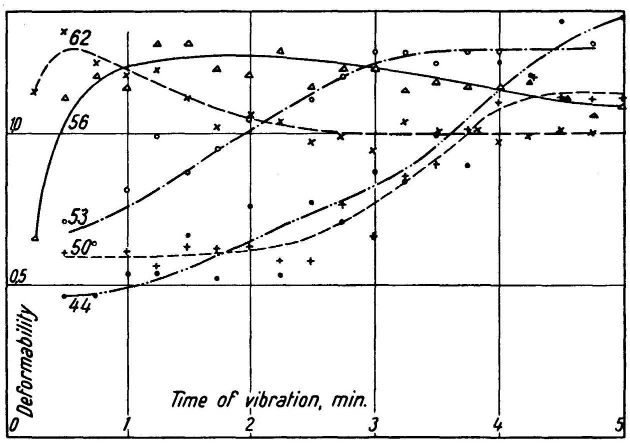

Fig. 6. Effect of variations in grading at a constant water-cement ratio and a constant cement content. The figures above the curves express the amount of coarse aggregate in per cent of the total aggregate

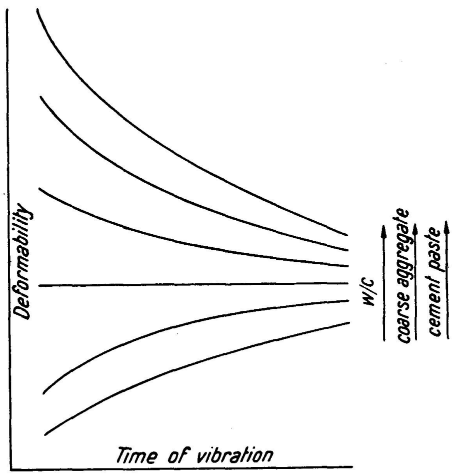

Fig. 7. Scheme summarising the results of tests on various concrete mixes

B. Tests of Properties of Hardened Concrete

The test results presented in this section were obtained from an extensive investigation which is still in progress. These test results are therefore only preliminary, and are far from complete. We shall confine ourselves to some typical results, in order to illustrate the reasoning advanced in the preceding section.

1. Strength

It is generally known that the strength of concrete is largely controlled by the water-cement ratio, the curing and compaction being equal. This consideration alone is sufficient to show that the deformability curves cannot be any guide to the absolute value of the strength, for, as may be seen from Fig. 7, any deformability curve can be obtained at the same water-cement ratio by varying the grading or the cement paste content. On the other hand, in accordance with the reasoning in Section A concerning the interpretation of rising deformability curves, it is to be expected that the strength will be reduced below its value for complete compaction if the time of compaction is less than t_1 (Fig. 3). A series of tests was carried out in order to examine this variation in strength. In this series, the test specimens were compacted by means of the vibrator forming part of the deformability meter, and the time of vibration was varied within the range covered by the deformability curve. The mixes were varied in such a manner that the time t_1 required for reaching the deformability maximum extended throughout the range of 1/2 to 10 minutes. Figs. 8 and 9 show the results obtained from the tests made on two mixes in this series. Both mixes consisted of cement mortar having a water-cement ratio of 0.35 and similar gradings, but different cement paste contents, which amounted to 44 per cent and 42 per cent by solid volume of mix (Figs. 8 and 9 respectively). The specimens consisted of bending test beams, 10 cm $\times$ 15 cm $\times$ 80 cm (Fig. 8) and 2 cm $\times$ 5 cm $\times$ 25 cm (Fig. 9). The test specimens were water-cured for 7 days before the bending tests. Figs. 8 and 9 represent the deformability and the strength in terms of the modulus of rupture (mean values of 3 to 5 individual tests) as functions of the time of vibration. In both cases, the deformability curves are similar in shape to the strength curves. This agreement, which was also found to exist in most other tests of this series, confirms the hypothesis that the concrete is not completely compacted until the deformability has reached its maximum.

This series also included tests on very fluid mixes. Their deformability curves exhibited a marked downward trend immediately after reaching the maximum point. As a rule, these mixes required a very short time of vibration in order to reach a maximum deformability, the order of magnitude of this time varying from 30 to 60 seconds. In these tests, the modulus of rupture reached a maximum slightly later than the deformability. It is possible that this delay occurred

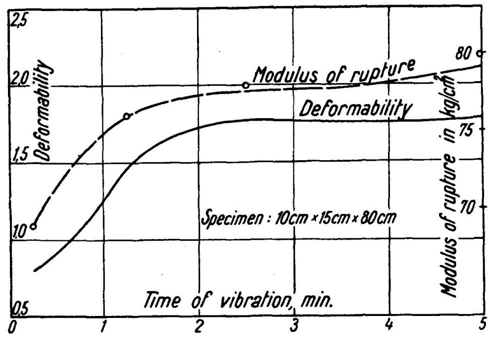

Fig. 8. Example of correlated deformability and strength curves

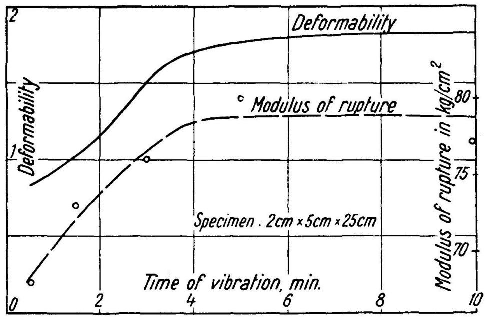

Fig. 9. Example of correlated deformability and strength curves

because these fluid mixes may have segregated as early as during the period of compaction, with the result that the time of compaction t_1 recorded by the deformability meter was too short.

Moreover, these tests have demonstrated that the modulus of rupture was not influenced by extending the time of vibration considerably beyond t_1, even when the mixes were very liable to segregate.

2. *Resistance to Frost Action*

In the freezing and thawing tests described below, the test specimens were frozen in air at $-15°$ C and thawed in water at $+5°$ C. Two freezing and thawing cycles were performed every day, and the test specimens were left in the thawing tank on holidays.

All these tests have so far been made on cement mortar only. It was therefore possible to use small test specimens, which measured 2 cm × 5 cm × 25 cm. This, in turn, permitted the testing of several series of specimens at the same time.

The specimens subjected to the tests which are described in this section were first cured in water at a temperature of $+20°$ C for 7 or 28 days. Different curing conditions were employed in other tests, but they do not fall within the scope of the present paper.

As has been pointed out by Powers [5], the damage produced by freezing and thawing is of two types, viz., gradual scaling of the surface layers and internal disintegration of the test specimen as a whole. These effects were also observed in our preliminary tests, which showed, moreover, that these two types of damage do not necessarily occur at the same time. For mixes having a very low resistance to frost action, the internal disintegration had sometimes advanced so far that the test specimen fell to pieces before it was possible to observe or to measure any deterioration of the surface. In order to form a true picture of the resistance to frost action, it is therefore necessary to make accurate observations of both these types of deterioration. The best method of measuring the surface deterioration is to determine the loss in weight of the test specimens, while the course of internal disintegration can be followed by observing the expansion of the test specimen, the reduction in the modulus of elasticity, or the decrease in strength. The latter method was not considered to be appropriate, firstly, because it requires a very great number of test specimens, and secondly, because the observations cannot be made on the same test specimen. We therefore preferred to measure the loss in weight, the change in length, and the modulus of elasticity in our tests. The modulus of elasticity was determined by means of two different dynamic methods, viz., from the natural frequency of oscillations in bending and from the time of propagation of supersonic waves. For the latter purpose, use was made of a standard measuring device (Mk II B Supersonic Flaw Detector), the time scale of which was calibrated with reference to a steel rod having a known modulus of elasticity. In all tests, the determination of the natural frequency was found to provide a considerably better indication of the deterioration than the supersonic measurements. This was probably due to the fact that the supersonic wave in the latter case was also propagated in the water contained in the test specimen. Only the results of the natural frequency measurements, therefore, are reproduced in this paper.

By analogy with the conditions met with in the strength tests, it is not to be expected that the deformability curve can furnish any information concerning the absolute value of the frost resistance. The deformability properties of mixes having substantially different water-cement ratios can be made

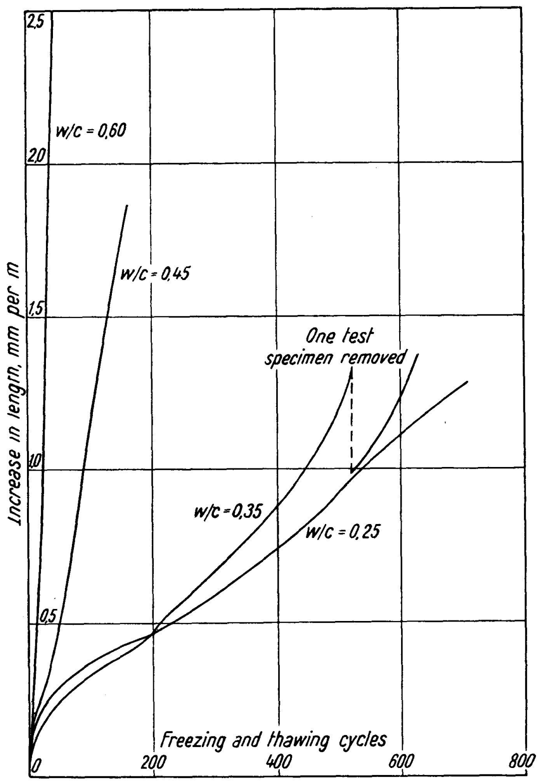

Fig. 10. Increase in length in freezing and thawing tests. Varying water-cement ratio, constant grading, and constant deformability

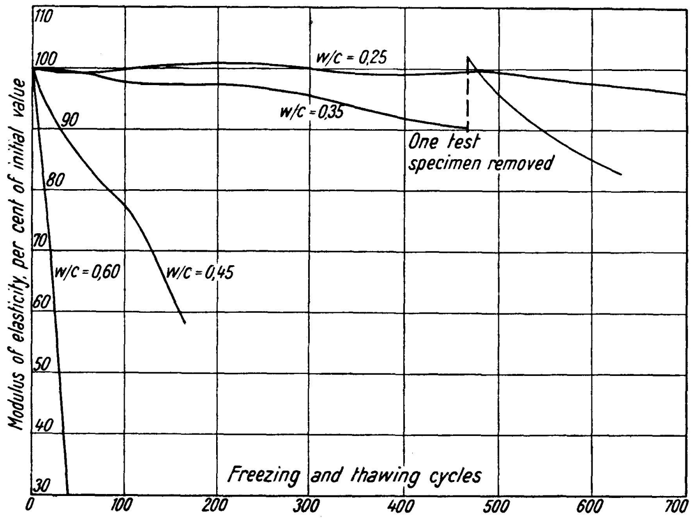

Fig. 11. Change in modulus of elasticity in freezing and thawing tests. Varying watercement ratio, constant grading, and constant deformability

approximately equal by changing the other proportions, but the resistance of these mixes to frost action will nevertheless vary with the water-cement ratio. This is illustrated by one of our test series, in which the grading was fixed, the water-cement ratio had values of 0.25, 0.35, 0.45, and 0.60, and the cement paste content was adjusted so as to obtain deformability curves of roughly similar shape and position. The test specimens were cured in water for 28 days prior to the freezing and thawing tests.

Fig. 10 represents the increase in the length of the test specimens as a function of the number of freezing and thawing cycles, while Fig. 11 shows the variation in the modulus of elasticity, expressed as a percentage of its initial value, with the number of freezing and thawing cycles. Table 1 gives, among other things, the modulus of rupture of the test specimens after the completion of the freezing and thawing tests.

Table 1

Varying Water-Cement Ratio, Constant Grading, and Constant Deformability. Number of Freezing and Thawing Cycles, Increase in Length of Test Specimens, Modulus of Rupture and Modulus of Elasticity as a Percentage of their 28-Day Values after Completion of Freezing and Thawing Tests.

Water-Cement Ratio	Number of Freezing and Thawing Cycles	Increase in Length mm per m	Modulus of Rupture Per Cent	Modulus of Elasticity Per Cent
0.25	710	1.28	89	96
0.35	627	1.38	69	83
0.45	159	1.87	53	58
0.60	56	3.27	~0	~0

It may be seen from the above table that the test results are in close agreement and that they exhibit very large differences in the resistance to frost action. A particularly marked feature of the results is the great reduction in the resistance to frost action corresponding to the increase in the water-cement ratio from 0.35 to 0.45. The comparatively small differences between water-cement ratios of 0.25 and 0.35 seem to corroborate the theory propounded by Powers and Brownyard [6], who state that when the water-cement ratio is less than a definite limiting value, the quantity of freezable water becomes practically equal to zero, and hence the frost action cannot give rise to any deterioration. This limiting value is dependent on the cement quality and on the degree of hydration, but generally seems to lie in the neighbourhood of 0.30 or slightly higher.

Thus, the deformability curve cannot be used for estimating the resistance of any arbitrary mix to frost action. On the other hand, in accordance with the reasoning presented in Section A, the deformability curve can be expected to provide information on the resistance to frost action in the following respects:

1. If the proportions of a given mix are varied, a gradual decrease in the resistance to frost action may be assumed to take place when the shape of the deformability curve changes from rising to a stable stage, and then becomes falling.
2. If the deformability curve is falling, this may lead to the formation of areas of weakness, which are more easliy damaged by frost than the rest of the concrete structure.
3. In so far as the degree of compaction influences the resistance to frost action, this resistance may be assumed to decrease if the time of compaction is less than the value t_1 (Fig. 3) which is required for reaching a maximum deformability.

An indirect reason for the first assumption has already been deduced in Section A, where reference was made to the work of Loe and Sparkes [4] in comparison with Fig. 7. Furthermore, this matter is being studied in the investigations carried out at the Swedish Cement and Concrete Researsch Institute. The results of series Nos. 2, 3, and 4 included in these investigations are available. The principal properties of the mixes used in these series are given in Table 2.

These tests were made on cement mortar only. The maximum particle size was 4 mm. All mixes had the same gradings of aggregate. The deformability curves obtained from test series Nos. 2, 3, and 4 are reproduced in Figs. 5, 4, and 12 respectively.

It may be seen from these graphs that the mixes were proportioned to bring about a systematic variation in the shape of the deformability curves ranging from markedly rising to markedly falling. The only variables in these

Table 2. Properties of Mixes Used in Test Series Nos. 2, 3, and 4.

Test Series No.	Mix	Water-Cement Ratio	Cement Paste Cont. Per Cent by Volume	Consistency VB Units	Consistency Slump cm	Variable
2	*RE*	0.35	48	1.8	4.5	Cement paste content
	RF	0.35	46	3.8	1.5	
	RB	0.35	44	4.3	1	
	RG	0.35	42	6.6	0	
	RH	0.35	40	10.0	0	
3	*RI*	0.38	44	1.7	4.5	Water-cement ratio Time of vibration
	RK	0.35	44	4.6	0.5	
	RL	0.32	44	7.8	0	
4	*RM*	0.45	41.5	3.5	1.5	Cement paste content
	RO	0.45	37.5	6.1	0	
	RN	0.45	33.0	15.5	0	

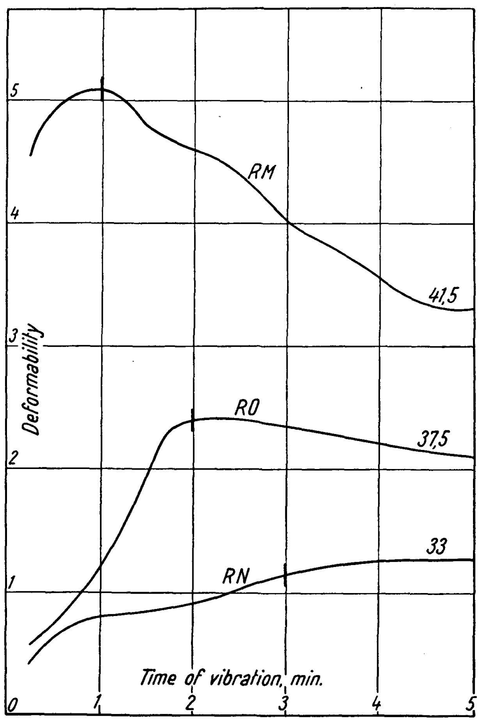

Fig. 12. Deformability curves in the test series No. 4. The figures above the curves express the cement paste content in per cent by solid volume. The vertical dashes mark the times of vibration in the preparation of test specimens

mixes were the cement paste content and the water-cement ratio, but the grading will also be varied in further test series.

In test series No. 2, the specimens representing mixes *RE*, *RF*, and *RB* were vibrated for the same time as was required in order that the deformability should reach its maximum. In the tests of mixes *RG* and *RH*, the time of vibration of the specimens was intentionally chosen so as to be insufficient. This was done to find out whether inadequate vibration would change the rating of the mixes according to their resistance to frost action. The times of vibration are indicated by the vertical dashes crossing the curves in Fig. 5.

In series No. 3, the time of vibration was varied in the tests on all mixes, but the following comparison refers to that time of vibration which corresponds to the period of rise of the deformability curve. All times of vibration are marked by the vertical dashes crossing the curves in Fig. 4.

Finally, mixes *RM* and *RO* in test series No. 4 were vibrated for a time which corresponded to the period of rise of the deformability curve, whereas mix *RN* was slightly under-vibrated. The times of vibration are indicated by dashes in Fig. 12.

In the freezing and thawing tests, each mix was represented by three test specimens. The mean values of the observations made on these specimens are referred to below.

The test specimens used in series No. 2 were cured in water for 28 days prior to the freezing and thawing tests. The curing time for the specimens of the other series was 7 days but mix *RI* is to be excluded from series No. 3 since it was water-cured for 28 days by mistake. The resistance of this mix to frost action was therefore slightly increased.

Figs. 13, 14, and 15 represent the increase in length, the loss in weight, and the change in modulus of elasticity observed in test series No. 2 as functions of the number of freezing and thawing cycles. The tests of mixes *RE*, *RG*, and *RH* are still in progress, but their general trends seem to be so pronounced at the present time that it is possible to draw certain conclusions. The mixes are grouped approximately according to the character of their deformability curves, i.e. according to their cement paste contents. The measurements of the change in length (Fig. 13) show a definite trend towards a greater increase in length in the tests on the segregating mixes, particularly in the case of mix *RF*, although the expected sequence of series *RE* and *RF* was reversed. Only in mix *RF* is the change in the modulus of elasticity (Fig. 15) different from the other mixes, which are grouped closely together. Finally, the measurements of the loss in weight (Fig. 14) exhibit a marked grouping in conformity with the theory.

The reason why the trends are not more sharply defined in the test results may possibly lie in the fact that the water-cement ratio in test series No. 2 was very low (0.35), and was therefore close to the critical limit mentioned by Powers. In such a case, the changes in the other proportions of the mix cannot reasonably be assumed to play any important part. This argument seems to be

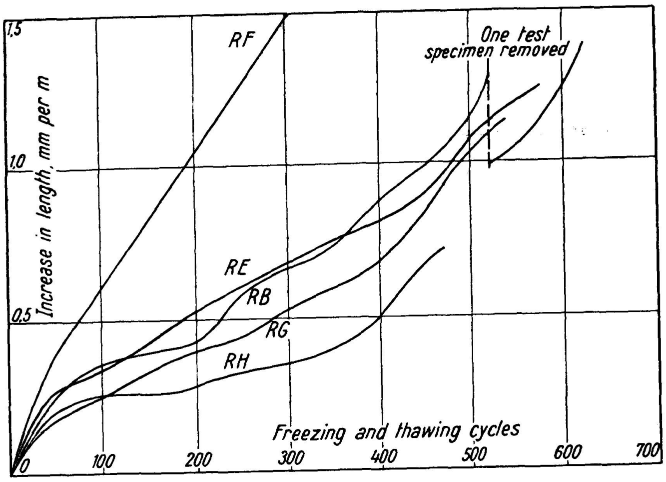

Fig. 13. Increase in length in freezing and thawing tests. Test series No. 2

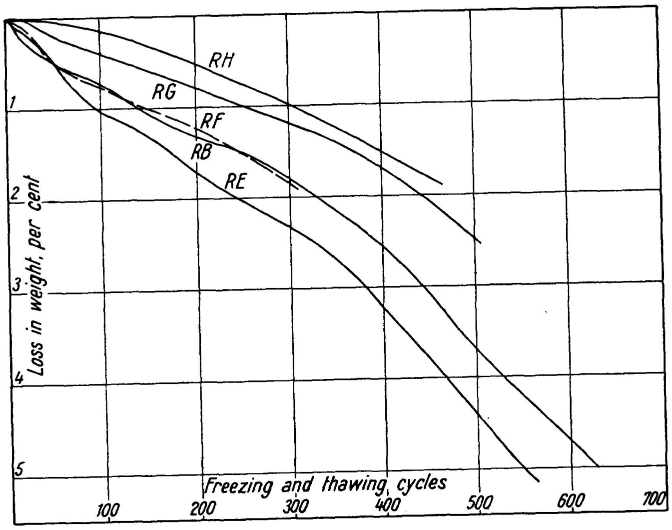

Fig. 14. Loss in weight in freezing and thawing tests. Test series No. 2

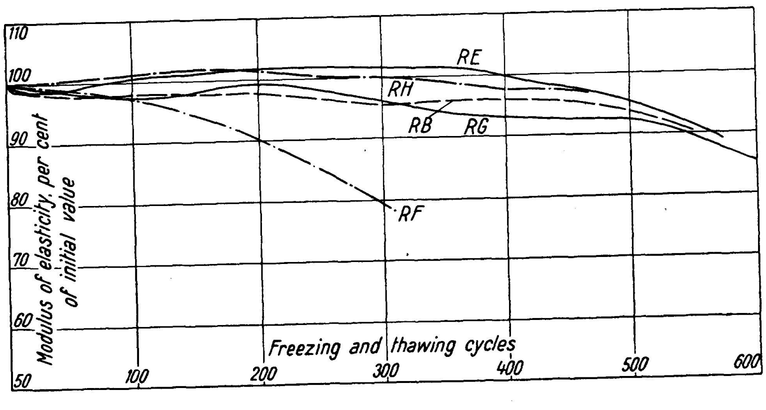

Fig. 15. Change in modulus of elasticity in freezing and thawing tests. Test series No. 2

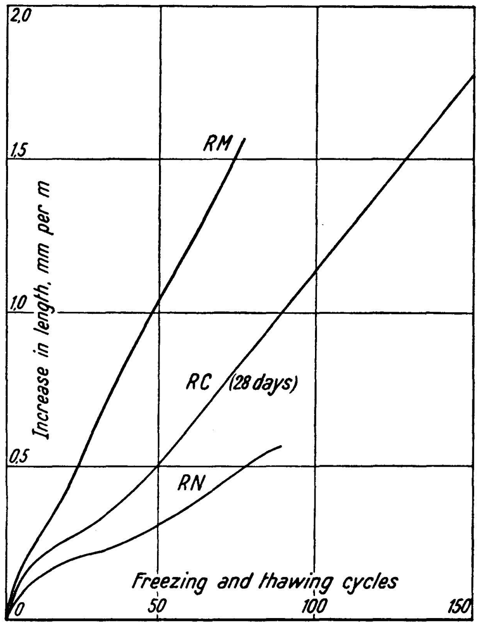

Fig. 16. Increase in length in freezing and thawing tests. Test series No. 4. The mix *RC* had similar proportions to the mix *RO*, but the test specimens were water-cured for 28 days. (For the mixes *RM* and *RN*, the curing time was only 7 days)

confirmed by the results which have so far been obtained from test series No. 4, in which only the cement paste content was varied, as in series No. 2, but where the water-cement ratio was higher (0.45) than in the latter series. Fig. 16 shows the changes in length observed in series No. 4, but it does not yet include the results relating to mix *RO*. Instead, the graph includes a curve which represents the changes in length observed on mix *RC*, which has been tested in connection with other research work, and which has the same proportions as the *RO*[2]). However, mix *RC* had been cured in water for 28 days, and it is therefore likely that its change in length will be slightly smaller than that of mix *RO*. It is seen from Fig. 16 that mix *RM* is markedly inferior to mix *RN* in resistance to frost action, and if mix *RC* is really representative of mix *RO*, then the grouping of the mixes is in complete agreement with our forecast. In addition, the loss in weight and the decrease in modulus of elasticity of mix *RM* were greater than those of mix *RN*.

Finally, if we turn to test series No. 3, it follows from the above reasoning and from the results of the freezing and thawing tests that the resistance to frost action should be at its lowest in the case of mix *RI* and at its highest in the case of mix *RL*. This conclusion is confirmed by the measurements which have been made so far. Figs. 17, 18, and 19 show the increase in length, the loss in weight, and the change in the modulus of elasticity observed in test

[2]) In check tests, the curve referring to mix *RC* has been reproduced with great accuracy.

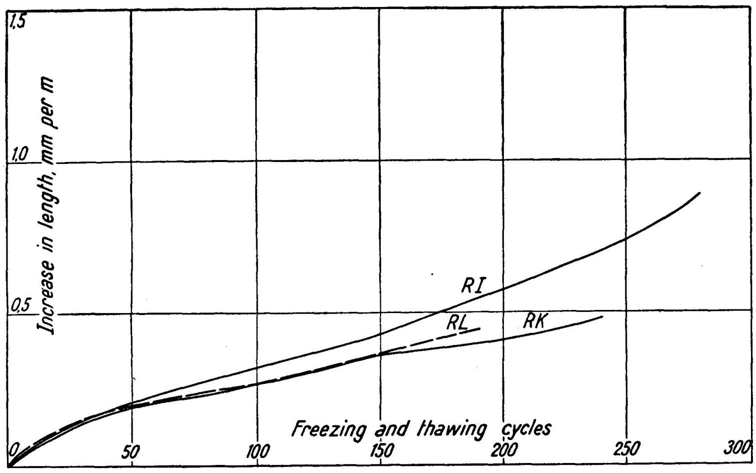

Fig. 17. Increase in length in freezing and thawing tests. Test series No. 3

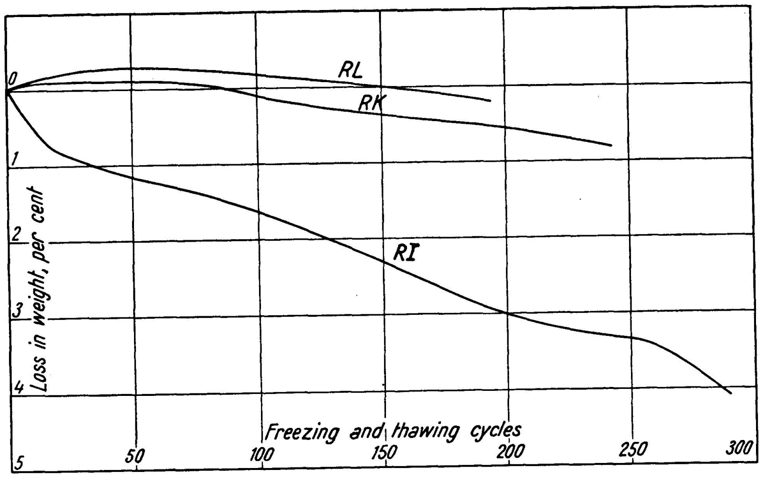

Fig. 18. Loss in weight in freezing and thawing tests. Test series No. 3

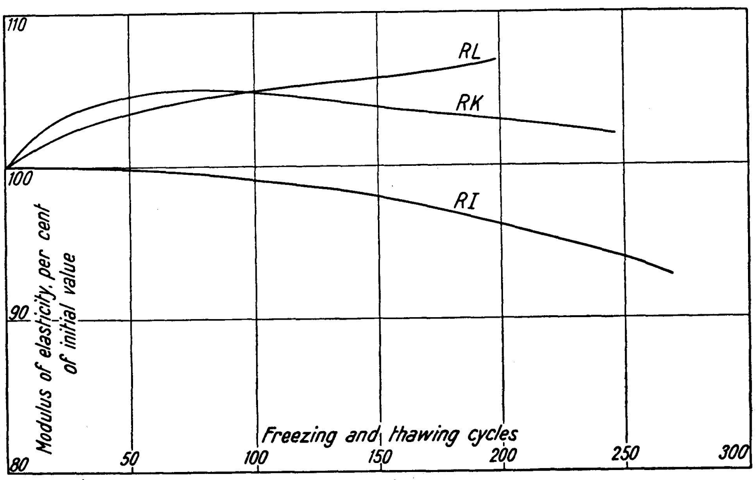

Fig. 19. Change in modulus of elasticity in freezing and thawing tests. Test series No. 3

series No. 3 as a function of the number of freezing and thawing cycles up to 200 or 250. It is clearly seen that mix *RI* exhibits the greatest increase in length (Fig. 17), the greatest loss in weight (Fig. 18), and the greatest decrease in modulus of elasticity (Fig. 19), whereas mix *RL* has given the best results for loss in weight and modulus of elasticity. It is not yet certain whether mix *RL* or *RK* had the smaller change in length.

In this connection it is to be remembered that mix *RI* had been water-cured for 28 days instead of 7, as has been pointed out before, resulting in this mix having smaller changes in length and modulus of elasticity. On the other hand, the prolonged curing in water may have adversely affected the loss in weight of this mix, because a surface coating which was observed on all sides of the test specimens of mix *RI* at the beginning of the freezing and thawing tests, was rapidly scaled off under test.

If we consider that the differences in the proportions of the cement mortar mixes used in this investigation were small, and that the scatter of the observations on the test specimens taken from the same batch is relatively great in freezing and thawing tests, then we are justified in regarding these three test series as a confirmation of our previous statement that those changes in the proportions of a concrete mix which convert the shape of the deformability curve from rising to falling cause a reduction in the resistance of the mix to frost action. However, we have so far no test results of our own concerning the effect of changes in the grading.

The frost resistance of the areas of weakness formed as a result of segregation (see Point (2), p. 60) has not yet been subjected to a close study. The testing methods which we have used up to now are not suitable for this purpose. Special tests on surface-vibrated concrete have therefore been planned, but these have not yet been started.

The effect of the time of vibration on the resistance to frost action was examined on mixes *RI*, *RK*, and *RL* by means of a method which was similar to that employed for determining the variation in strength with the time of vibration. In order to keep the number of test specimens within reasonable limits, only three values of the time of vibration were used for each mix, viz., a value resulting in obvious under-vibration, a value corresponding to the maximum deformability, and a value resulting in over-vibration. These values were 15 sec., 1 min., and 3 min. for mix *RI*, 30 sec., 2 min., and 4 min. for *RK*, and 30 sec., 5 min., and 10 min. for *RL*. These times are marked by the vertical dashes crossing the deformability curves in Fig. 4. Up to the present time, a definite trend has been observed in series *RI* only, and the test results for this series are reproduced in Figs. 20 to 22. It is seen from these graphs that the results corresponding to the shortest time of vibration are worst in every respect, and particularly as regards the changes in length and in modulus of elasticity. This indicates that under-vibration may be really detrimental to frost resistance. From the fact that the relative merit of vibrating for 1 min.

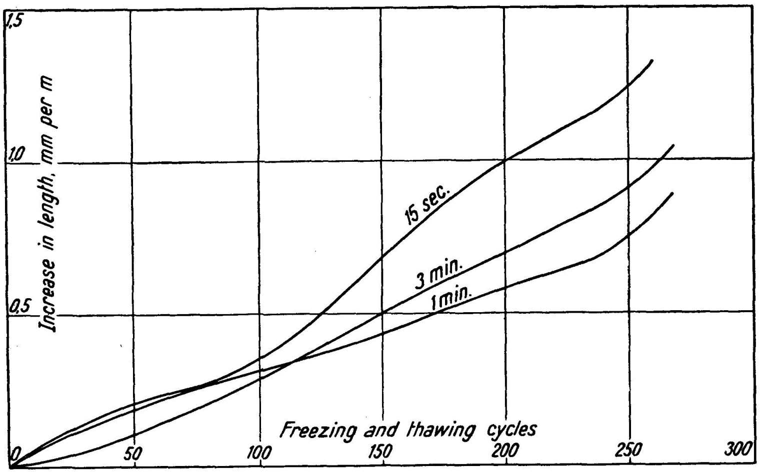

Fig. 20. Effect of variations in time of vibration on the increase in length in freezing and thawing tests. Mix *RI*

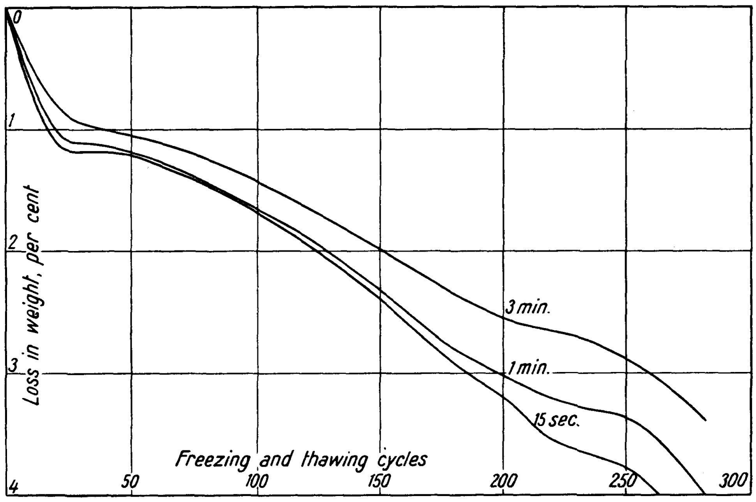

Fig. 21. Effect of variations in time of vibration on the loss in weight in freezing and thawing tests. Mix *RI*

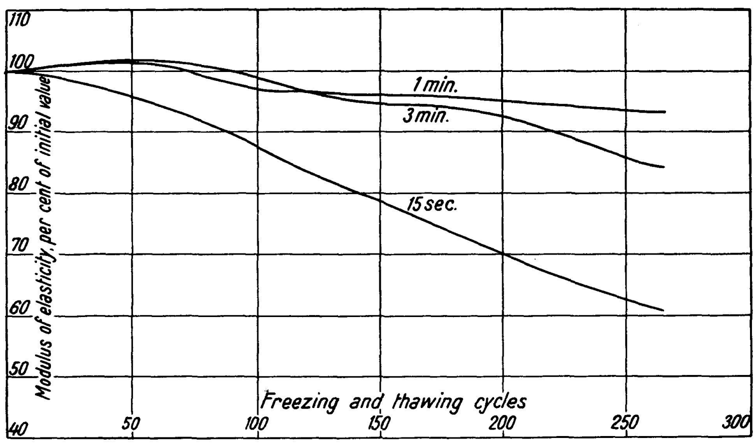

Fig. 22. Effect of variations in time of vibration on the change in modulus of elasticity in freezing and thawing tests. Mix *RI*

or 3 min. is somewhat uncertain it may be inferred that no substantial increase in resistance to frost action has been gained by prolonging the time of vibration beyond the value corresponding to the maximum deformability. On the contrary, it is probable that over-vibration is dangerous under practical conditions, as has already been pointed out in this paper.

3. *Shrinkage*

In a very extensive investigation dealing with the shrinkage of concrete, cement mortar, and neat cement paste, DUTRON [7] has demonstrated that the final amount of shrinkage is almost exclusively dependent on the cement paste content of the mix, if the cement paste is assumed to include that portion of the aggregate which is smaller than 0.1 mm in particle size. This implies that no conclusions as to the average shrinkage of hardened concrete can be drawn from the deformability curve, except in those cases in which the changes in deformability have been caused by changes in the cement paste content. Such cases occur in test series Nos. 2 and 4, cf. Table 2. Shrinkage measurements were also made in these series. However, they have not yet been completed for series No. 4, and the number of test specimens (3) per mix for series No. 2 was too small in relation to the comparatively large scatter of the individual observations to permit any reliable conclusions. Therefore, new shrinkage measurements were carried out on mixes *RE*, *RB*, and *RH*. For this purpose, the number of test specimens per mix was increased to 10. The test specimens, 2 cm × 5 cm × 25 cm, were cured in water for 7 days. They were then stored in air at a relative humidity of 60 per cent, while shrinkage measurements were being taken. As may be seen from Fig. 23, the results of these observations show a distinct difference between the mixes, which are rated in qualitative conformity with DUTRON's results and with the values obtained by means of the deformability meter. The amount of shrinkage increases as the cement paste content of the mix becomes greater.

If the ultimate shrinkage is solely determined by the cement paste content, there should be no difference in the shrinkage of the mixes of test series No. 3, where the water-cement ratio was varied, while the cement paste content was

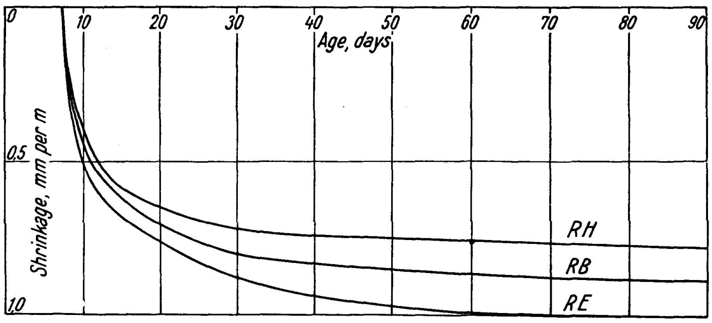

Fig. 23. Shrinkage of mixes in the test series No. 2

maintained constant. In this series, 9 shrinkage test specimens were made for mixes *RI* and *RK*, and 12 for mix *RL*. The test specimens were divided into three groups corresponding to three different values of the time of vibration. However, no significant difference was observed between the amounts of shrinkage corresponding to these times of vibration. It was therefore possible to calculate a mean value for all test specimens of a given mix. This mean value is 0.80 to 0.85 mm per m for series *RI*, 0.80 mm per m for series *RK*, and 0.80 mm per m for series *RL*. Thus, this test has not shown any difference in the shrinkage of these mixes. In other words, the test has confirmed DUTRON's results. Also the difference between mixes *RE* and *RH* in respect of their deformability properties was approximately the same as the corresponding differences between mixes *RI* and *RL*. This indicates once more that the deformability meter cannot be used in general for determining the average shrinkage.

On the other hand, we can state with certainty that a falling deformability curve indicates that the test specimen will have non-uniform shrinkage, with the result that additional stresses are set up in the specimen. Non-uniform shrinkage has been studied by NYLANDER [8], who varied the concrete mix proportions by successively increasing the cement paste content at a given water-cement ratio and a given grading, in other worths, by gradually increasing the tendency to segregation. His tests have conclusively established the fact that the non-uniform shrinkage increases as the concrete becomes more fluid and as the time of vibration becomes longer. It ought to be possible therefore to reduce the resulting additional stresses to a minimum by stabilising the concrete mix.

4. Creep Under Long-Time Loads

Our own investigations concerning the creep of concrete have been carried on for such a short time that reliable results are available for one test series only. This series comprised three cement mortar mixes having the same water-cement ratio and grading but different cement paste contents. Consequently, this series corresponded to series No. 2 used in the freezing and thawing tests. The mix proportions are given in Table 3, and the deformability curves are shown in Fig. 24.

Table 3. Properties of Mixes Used in Creep Tests

Test Series	Water-Cement Ratio	Cement Paste Content Per Cent by Volume	Consistency	
			VB Units	Slump cm
PA	0.35	43	4.9	0.8
PB	0.35	49	0.9	7.5
PC	0.35	37	7.3	0

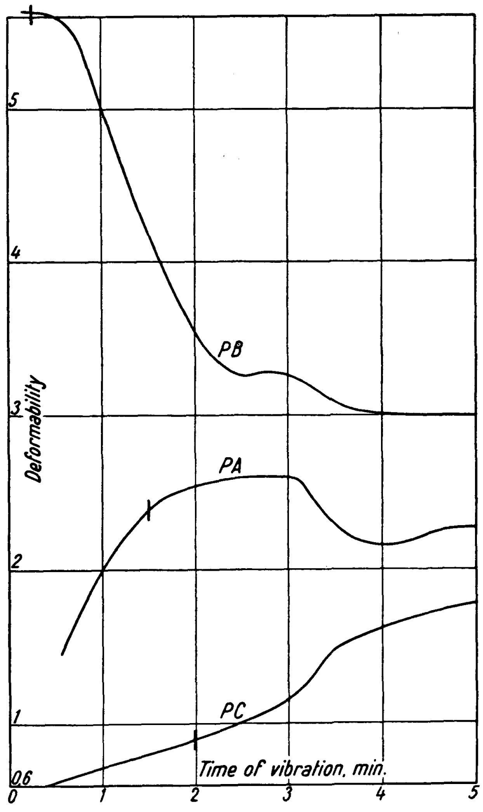

Fig. 24. Deformability curves of mixes for creep tests. The vertical dashes mark the times of vibration in the preparation of test specimens

The test specimens consisted of beams, 2 cm × 5 cm × 40 cm. In the tests of mixes PA and PB, the time of vibration was equal to the period of rise of the deformability curve, whereas mix PC was under-vibrated. The time of vibration is indicated by vertical dashes in Fig. 24.

The test specimens were water-cured at a temperature of 20° C for 28 days. They were then subjected to a load which consisted of a constant bending moment over a length of 28 cm. Each mix used in the creep tests was represented by six beams. Three of them were tested in water, and three in air at a relative humidity of 60 per cent. In addition, the same number of similar test specimens were set up, but were not subjected to any loads, so as to be able to make a correction to allow for the effects of non-uniform shrinkage or expansion.

The load for the beams tested in water was 50 per cent of the ultimate strength, but for the beams tested in air it was only 30 per cent of the ultimate value. The latter value was kept low in order to avoid failure on account of stresses caused by shrinkage while the beams dried.

The load was applied for 100 days. It was assumed that the creep had reached about 90 per cent of its ultimate value by that time. After that, the load was removed, and a study was also made of the recovery.

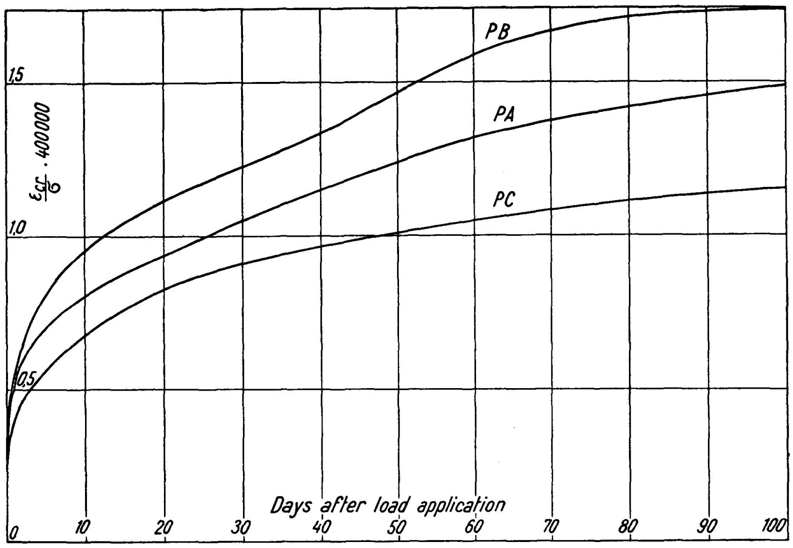

Fig. 25. Ratio of the creep in water to the bending stress. Mixes, see Table 3

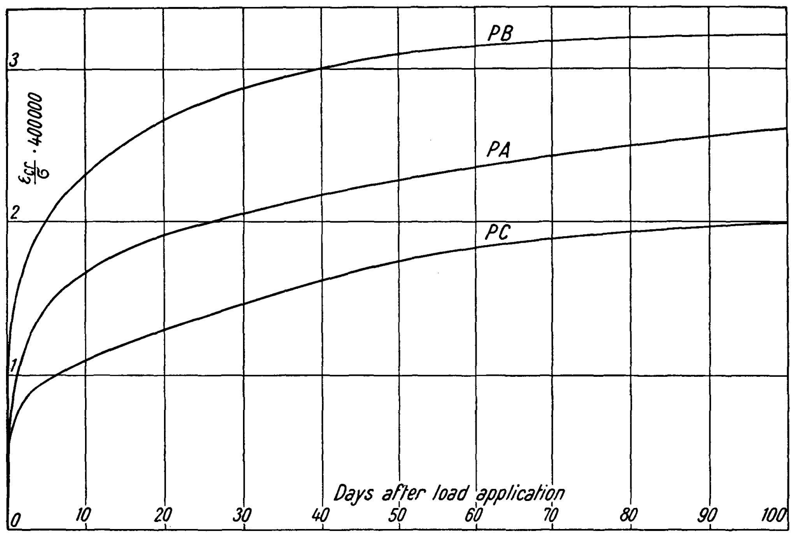

Fig. 26. Ratio of the creep in air to the bending stress. Mixes, see Table 3

The only quantity observed in the tests was the deflection of the beams within the portion subjected to the constant bending moment. In the evaluation of the test results, however, the corresponding strain at the bottom of the cross section, particularly the strain ϵ_{cr} due to creep, was calculated and related to the bending stress σ. The ratio ϵ_{cr}: σ obtained from this test series is shown in Fig. 25 (loading tests in water) and in Fig. 26 (loading tests in air). In both these cases, the grouping of the curves clearly indicates that the amount of creep increases as the cement paste content becomes greater. These tests therefore indicate a correlation between the deformability properties of fresh concrete and the plastic properties of hardened concrete, which is analogous to the correlation found in the shrinkage tests. No reliable results have so far been obtained from those test series in which the deformability properties were varied by changing the water-cement ratio or the grading of aggregate. Nevertheless, an examination of tests made by other investigators and certain tests which have not yet been completed at the Swedish Cement and Concrete Research Institute indicates that the effect of the water-cement ratio may in general be presumed to be the same as the effect of the cement paste content. If this inference is correct, it implies a further correlation between deformability and creep. On the other hand, an examination of the tests referred to above seems to suggest that the grading does not have any appreciable effect on the ultimate amount of creep, but influences only the rate of creep.

Thus, for the time being, we have to confine ourselves to the conclusion that a relationship exists between deformability and creep, which is analogous to the corresponding relationship between deformability and shrinkage.

The results in Figs. 25 and 26, like the others obtained by the author, confirm again the observation made by Davis [9], and others, that the amount of creep is largely influenced by the storage conditions during the loading period. In the case under consideration, the creep values observed in the loading tests in air (Fig. 26) are about twice as high as the corresponding values obtained from the loading tests in water (Fig. 25).

References

1. Eriksson, A., Development of Fluidity and Mobility Meters for Concrete Consistency Tests. Swedish Cement and Concrete Research Institute, Proc. No. 12, 1949.
2. Forslind, E. and Bergström, S. G., Studier rörande råbetongens egenskaper (Studies on the Properties of Fresh Concrete). Swedish Cement and Concrete Research Institute, Bull. No. 12, 1948.
3. Bergström, S. G., Stable Concrete Mixes. Swedish Cement and Concrete Research Institute, Bull. No. 24, 1951.
4. Loe, J. A. and Sparkes, F. N., The Deterioration of Concrete. Some Factors Affecting the Resistance of Concrete to Frost Action. Int. Ass. Bridge Struct. Eng., 3rd Congress, Sept. 1948, Preliminary Publ., p. 201.
5. Powers, T. C., A Working Hypothesis for Further Studies of Frost Resistance of Concrete. Journ. Am. Concr. Inst., Febr. and Nov. 1945.
6. Powers, T. C. and Brownyard, T. L., Studies of the Physical Properties of Hardened Portland Cement Paste. Portl. Cem. Ass., Bull. No. 22, Chicago 1948.
7. Dutron, R., Le retrait des ciments, mortiers et bétons. Bull. techn. 23, Lab. de Rech. et de Contrôle du Groupem. Prof. de Fabr. de Cim. Belgique, Bruxelles 1934.

8. NYLANDER, H., Korsarmerade betongplattor (Concrete Slabs Reinforced in Two Directions). Inst. f. Byggnadsstatik, Kungl. Tekn. Högskolan (Division of Building Statics and Structural Engineering, Royal Institute of Technology), Stockholm, Medd. (Bull.) No. 5, 1950. Particularly pp. 63—68.
9. DAVIS, R. E., Flow of Concrete under Sustained Compressive Stress. Proc. Am. Concr. Inst., Vol. 24, 1928, p. 303.

Summary

Accurate study of the properties of fresh concrete is very useful in the proportioning of high-quality concrete. In this paper, a description is given of an equipment which can be employed for determining the deformability of fresh concrete for varying times of vibration. From the relation between the deformability of fresh concrete and the time of vibration it is possible to draw conclusions concerning the tendency of the mix to segregation and with regard to the time of compaction which is required in order to ensure maximum consolidation. Furthermore, the deformability curves permit certain forecasts to be made in respect of the properties of hardened concrete, particularly its resistance to frost action, but in some cases also its strength, shrinkage, and creep under the action of long-time loads. This is demonstrated by means of tests dealing with the properties of hardened concrete.

Résumé

L'étude approfondie des propriétés du béton frais rend des services importants dans la détermination de la composition du beton de haute qualité. Dans le présent rapport, l'auteur décrit un appareil qui sert à mesurer la déformabilité du béton frais en fonction de la durée de vibration. Du rapport entre la déformabilité du béton frais et la durée de vibration on peut tirer des conclusions pour ce qui concerne la tendance du mélange à la ségrégation et la durée de vibration qui est requise afin que le serrage atteigne son maximum. En outre, les courbes de déformabilité permettent certaines prédictions relatives aux propriétés du béton durci, surtout à sa résistance aux effets du gel, mais, dans quelques cas, à d'autres propriétés aussi, telles que la résistance mécanique, le retrait et les déformations lentes. Des résultats des essais concernant les propriétés du béton durci sont cités pour vérifier les raisonnements présentés dans ce rapport.

Zusammenfassung

Genaue Erforschung der Eigenschaften des Frischbetons ist ein wichtiges Hilfsmittel bei der Ermittlung der geeigneten Zusammensetzung des Betons hoher Güte. Im vorliegenden Bericht beschreibt der Verfasser eine Vorrichtung für die Bestimmung der Verformbarkeit des Frischbetons bei veränderlicher Rütteldauer. Aus der Beziehung zwischen der Verformbarkeit und der Rütteldauer ergeben sich Schlußfolgerungen hinsichtlich der Neigung zur Entmischung und derjenigen Rütteldauer, die zum Erzielen der höchstmöglichen Verdichtung des Gemisches erforderlich ist. Die Verformbarkeitskurven ermöglichen außerdem gewisse Voraussagen bezüglich der Eigenschaften des erhärteten Betons, vor allem über seine Frostbeständigkeit, in einigen Fällen aber auch über seine Festigkeit, sein Schwinden und Kriechen. Die im Bericht angeführten Versuchsergebnisse, die sich auf die Eigenschaften des erhärteten Betons beziehen, bestätigen diese Erwägungen.