Lok-strength

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The compression strength of concrete is normally determined by crushing cast test specimens. However, the concrete in test specimens may deviate significantly from the concrete in the structure to be controlled because the concrete in the structure may have been subjected to different transport, casting, compaction and curing than the concrete in the test specimens.

For the past 13 years work has been going on, partly at the laboratory and partly in practice, on a method permitting determination of the compression strength of the concrete in the structure itself. The force required to pull out test bolts embedded in the structure is measured, after which an empirically established, linear relationship is used for conversion of the measurements to the cylinder compression strength of the concrete.

In the following a description is given of the development of the method and of the tests by which a suitable method for practical use has been arrived at.

INTRODUCTION

In 1959 the Danish Society of Chemical, Civil, Electrical and Mechanical Engineers appointed a working committee on concrete control. The committee was assigned the task of preparing proposals for bringing up to date the Code of Practice for the Structural Use of Concrete.

The members of the committee rapidly agreed that one of the fundamental problems of concrete control was that strength requirements were made to the concrete in the structure, while the control was carried out on cast test specimens, which could only demonstrate the potential strength of the concrete. Only by measurements on the structure itself it would be possible also to check that important factors such as the transport of the fresh concrete, casting, compaction and curing, had not had a deleterious effect on the strength of the concrete. It was therefore found very desirable to arrive at a control method with the following characteristics:

The measurements should be made on the concrete in the structure.

The method should have the character of a destructive method.

The measurements must be easy to carry out.

The method must be cheap.

In the spring of 1962 the author devised the method that is known today as lok-strength testing. In brief the method is as follows: a disc embedded in the concrete is extracted through a cylindrical counter-pressure member. The force required for punching out a small piece of concrete has a good correlation with the compression strength of the concrete. The Danish word for punching is "lokning" (in German, Lochen). The word lok-strength is therefore used for the force required to punch out a small piece of concrete of specified geometry.

The first investigations were carried out in August 1962 in Dr. Anders Nielsen's laboratory at the Building Division of Danmarks Ingeniørakademi. For these investigations use was made of the equipment available at the laboratory. In February 1963, with the support of H. Jacob Nielsen's Fund, work began on the development of special laboratory apparatus. From then until 1966 the author carried out a large number of tests at The Danish National Institute of Building Research at a department led by Niels Munk Plum. Concurrently with these investigations an apparatus was developed which could also be used on building sites. From 1967 to 1968 the method was tested in practice by Per Dragsholt, of Modulbeton A/S.

During this six-year period, all tests carried out showed that the punching strength is a suitable measure of the compression strength of the concrete when this is to be measured in situ. At the Nordic Concrete Research Congress in Göteborg in 1969 the author presented a short report on the research work and the practical investigations carried out with the method.

In 1969 the Danish Society of Civil Engineers requested the Department of Structural Engineering of the Technical University of Denmark to carry out a number of control tests. Investigations made in 1969 to 1970 verified the correlation between the cylinder compression strength of the concrete and the lok strength. These results were published in 1970 and were presented at the Nordic Concrete Research Congress in Åbo in 1971.

THE METHOD

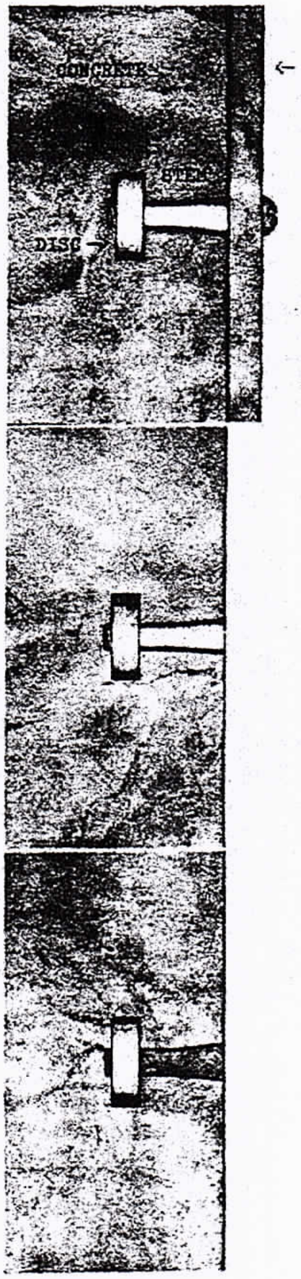
A test bolt consisting of a screw with a long shank, **the stem,** and a circular nut (diameter 25 mm) **the disc,** was mounted on the inside of the form, figure 1, after which the concrete was cast. The formwork was stripped, figure 2. The stem was unscrewed, figure 3, and the traction apparatus mounted, figure 4. The force, the lok-strength, required to extract the disc through the cylindrical counter-pressure member, figure 5, is a measure of the compression strength of the concrete.

When control is to be carried out the concrete in the structure is loaded to the specified strength. If the concrete at the measuring point satisfies the strength requirement unloading may be carried out without any damage to the structure. The method is therefore non-destructive when the concrete has satisfactory strength properties. If the strength at the measuring point is insufficient, there will be a hole in the concrete measuring about 1 inch in depth and 2 inches in diameter. The remaining part of the structure will be undamaged.

AUTHOR'S INVESTIGATIONS

The present investigations have been carried out to arrive at suitable dimensions for the test bolt and traction apparatus and to demonstrate a relationship between the lok-strength and the cylinder compression strength.

The first dimension to be determined was the embedment depth (length of stem) of the disc. A great embedment dapth would ensure that the test covered more than the outermost shell of the concrete and that big stones, too, would be subjected to the loading, and would prevent rust damage if the discs were not extracted. On the other hand, the stem must not be so long that a large part of the concrete would be damaged in case of rupture. Moreover, as the pull-out force would presumably increase with the embedment depth, a long stem would necessitate



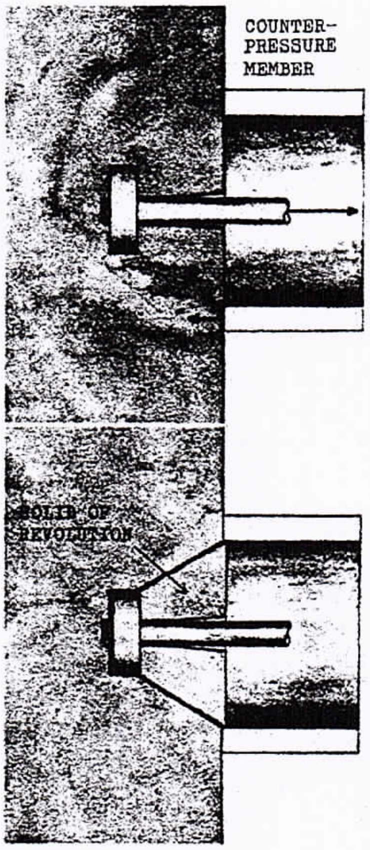


Figure 1–5. 1) The test bolt mounted on the inside of the form and the concrete cast. 2) The formwork is removed. 3) The stem (shaft) of the test bolt is screwed out. 4) The traction rod is screwed into the disc and the counter-pressure member is mounted on the surface of the concrete. 5) A small piece of the concrete is punched out.

the use of rather large testing apparatus.

The above factors led to the adoption of a embedment depth of 25 mm.

First Pilot Test.

From descriptions of similar experiments [6], it was known that the extracted concrete would be a truncated cone. The sole purpose of the first test was therefore to obtain information on the magnitude of the pull-out force and the relationship between the force and the diameter of the disc when the counter pressure member was so large that the line of the rupture at the concrete surface occurred within, not at, its circumference.

Thirty small cylinders with a diameter of 175 mm and a height of 80 mm were used for the tests. A disc was embedded in each cylinder, see figure 6 a. The diameter of the discs varied between 20 and 40 mm. The concrete required for the tests was produced from three batches with the same mix proportions. Five ordinary cylinders with a diameter of 150 mm and a height of 300 were cast from each batch for compression tests.

The average batch strength measured on the five ordinary cylinders was found to be 20.9, 19.7 and 19.7 MN/m². An analysis of variance showed no significant difference in the strength of the three batches, the F-test giving the critical value $P_c = 28\,\%$*).

The force required to press the disc out of the concrete was measured in an ordinary press in an arrangement as shown in figure 6 b. The disc was pressed out of the concrete by a metal ball acted on by a mandrel.

The result was rather surprising. The punched-out piece of concrete was not a truncated cone, but a solid of revolution with a generatrix which went practically asymptotically towards the surface of the concrete, figure 7.

Eleven of the thirty small cylinders broke at the middle, see figure 6 a. The results of the remaining nineteen measurements are shown in figure 8. It will be seen that a doubling of the diameter of the disc would mean that an approximately 18 % higher force would be required for punching out the disc, i.e. that a change of 1 mm in the diameter of the disc largely corresponds to an increase in the force of about 1 %.

Thus, the diameter of the disc does not appear to have had any very great influence on the magnitude of the force. The diameter was therefore, rather arbitrarily, made 25 mm. This was the

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*) The critical level, P_c, is the smallest significance level at which the hypothesis would be rejected for the given observations. This number gives an idea of how strongly the data contradict (or support) the hypothesis, and enables the reader to reach a verdict based on the significance level of his choice.

diameter of the disc in all the following tests and, as mentioned above, also the embedment depth.

Second Pilot Test.

The most interesting question to be clarified was the relationship between the pull-out force and the cylinder compression strength of the concrete. The purpose of the second pilot test was therefore to elucidate this problem.

Four batches of concrete of different strengths were mixed. Five ordinary cylinders (diameter 150 mm, height 300 mm) were cast from each batch for determination of the compression strength, together with six small cylinders (diameter 175 mm, height 80 mm) with an embedded disc (embedmene depth 25 mm, diameter 25 mm).

The pull-out force was determined by punching out the discs, as described under the first pilot test, cf. figure 6 b, the counter-pressure being achieved by means of rings with an internal diameter exceeding 130 mm in order to keep the surface rupture within the circumference of the rings. One of the small cylinders from the batch with the highest compression strength broke. Figure 9 shows the results obtained with the remaining twenty-three cylinders.

For each batch, the average cylinder compression strength is marked on the abscissa, while the distribution of the pull-out force is plotted on the ordinate. At 20 MN/m² six observations are included from the first pilot test, for which discs with a diameter of 25 mm were also used, cf. figure 8.

As will be seen from figure 9, it is evident that the relationship between the pull-out force and the cylinder compression strength is not linear. It follows from this that the stress field in the rupture surface cannot be equal to the stress field occurring during crushing of cylinders. The concave graph in figure 9 is similar to the curves obtained from tests in which the tensile strength of a given concrete is related to the compression strength. There is therefore reason to assume that the method can be used for the determination of the tensile strength of a concrete provided the diameter of the counter-pressure member is about 130 mm.

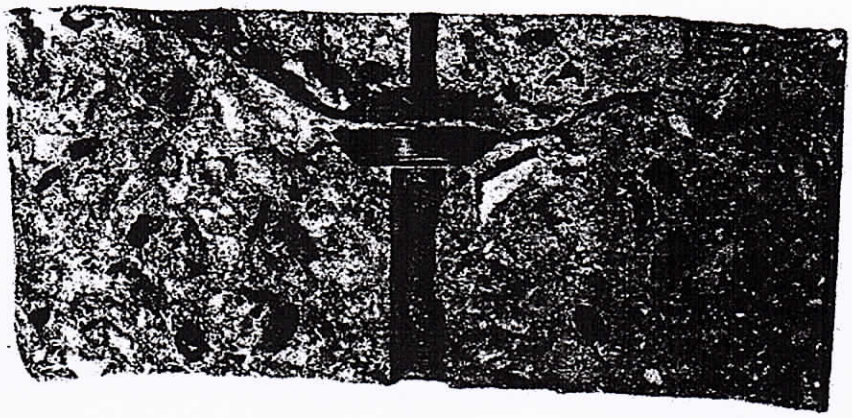

Figure 6 a. A disc embedded in the test specimen, diameter 175 mm, height 80 mm.

As the graph in figure 9 levels out when the compression strength increases, a small difference in the magnitude of the pull-out force will correspond to a very significant difference in the cylinder compression strength. This means that a conversion from pull-out force to compression force cannot be carried out with reasonable accuracy.

Therefore, if the method is to be used for the determination of the compression strength of a concrete, a more linear relationship must be achieved. For this reason a third pilot test was called for to investigate the relationship between the magnitude of the pull-out force and the proportions of the extracted solid of revolution.

Third Pilot Test.

The height and the minimum diameter of the solid of revolution were already fixed at 25 mm. It was therefore sufficient to vary the maximum diameter of the solid of revolution, i.e. the diameter of the counter-pressure member.

The earlier tests had shown that the rupture occurred within the circumference of the counter-pressure member. Therefore, it was found unreasonable to increase the diameter of the counter-pressure member. As, on the other hand, a reduction of the diameter will result in a reduction in the curved surface of the solid of revolution, the pull-out force must be expected to be smaller unless the stress field in the curved surface changes character.

If, on the other hand, the pull-out force is increased when the curved surface is reduced, this must mean that the stress field changes. The purpose of the third pilot test was therefore to investigaste the pull-out force at various diameters of the counter-pressure member.

Three batches of concrete with different mix proportions were made. Four ordinary cylinders were cast from each batch for determination of the compression strength, together with six small cylinders with discs embedded. The discs in these cylinders were punched out as described earlier, see figure 6 b. Rings with diameters varying from 50 to 130 mm were used as counter-pressure member. A single test specimen from the weakest batch broke prior to testing and three test specimens from the strongest batch broke during the punching-out of the discs. The results measured on the remaining fourteen specimens are shown in figure 10, where the pull-out force is depicted as a function of the diameter of the counter-pressure member.

As a reduction of the diameter of the counter-pressure member (and of the area of the curved surface), thus results in a considerable increase in the magnitude of the pull-out force, this can only mean that the ultimate stress in the curved surface alters character.

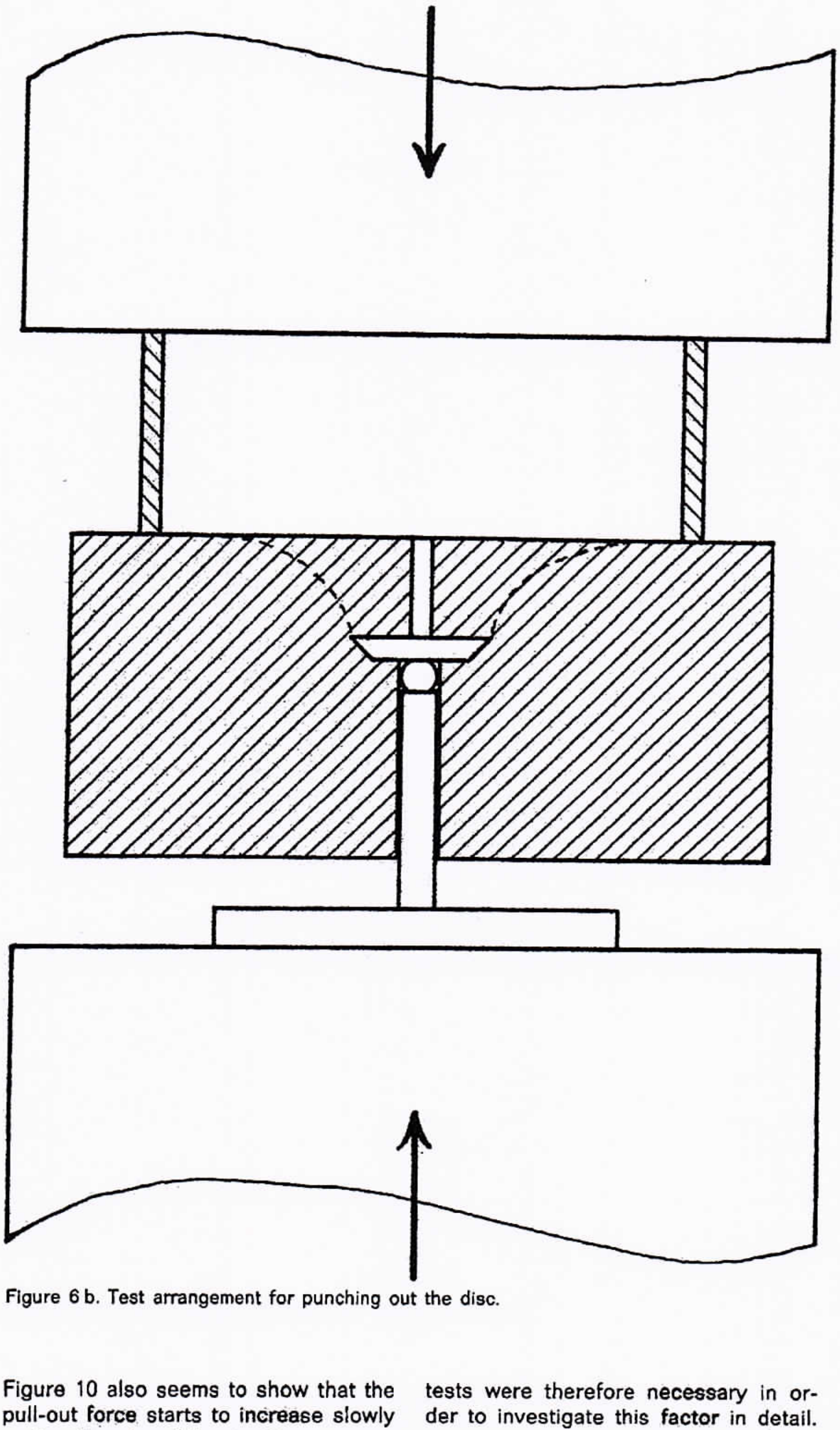

Figure 6 b. Test arrangement for punching out the disc.

Figure 10 also seems to show that the pull-out force starts to increase slowly as the diameter of the counter-pressure member decreases and then increases violently when the diameter has become smaller than 80 to 90 mm. Further tests were therefore necessary in order to investigate this factor in detail.

At the same time as the above-mentioned tests were carried out special laboratory apparatus was developed for extraction of the discs of the test bolts. This made it possible to abandon the test arrangements sketched in figure 6 b, whereby more suitable test specimens could be used. All the following tests were carried out with the new traction apparatus.

First, a prism with octagonal end faces was used. Test bolts were embedded at three different levels spaced at intervals of 70 mm, see figure 11. Four prisms were used with a total of 48 test bolts. A statistical analysis of the data showed a significant difference ($P_o = 0.05\ \%$) between the lok-strength in the three layers. Thus, the average strength in the middle layer was 0.6 kN lower than in the bottom layer and 3.5 kN higher than in the top layer. This difference between the strengths in the three layers would give the observations an unsuitable systematic variation. The prism was therefore replaced by a 1100 x 1000 x 10 mm plate.

A total of five plates were cast, each with a different strength. Thirty-seven test bolts were mounted in the plates and were extracted through counter-pressure members of varying diameter. The pull-out force was divided by the area of the curved surface of the rupture pattern, after which the average of the values corresponding to the same counter-pressure was calculated for each plate. The results as a function of the diameter of the counter-pressure member are depicted in figure 13, which shows that the stress field changes character when the diameter of the counter-pressure member lies between 60 and 90 mm, depending somewhat on the strength of the concrete. The smallest ring diameters were used on a plate with a cylinder compression strength of between 15 and 20 MN/m^2. As will be seen from figure 13, the pull-out force divided by the area of the curved rupture surface is of the same magnitude (15–20 MN/m^2) when the ring diameter is less than 35 mm. This invalidates the assumption that the rupture may be pure tensile or sheer failure.

As will be seen from figure 13, the diameter of the counter-pressure member should be smaller than about 60 mm if the steep part of the curve is to be utilized. On the other hand, a small ring diameter will mean that the pull-force will become very big, and this, in turn, will mean partly that the traction rod of the traction apparatus will have difficulty in holding, and partly that very high compression stresses will occur at the disc-end of the solid of revolution. For example such a small diameter as 60 mm will mean that these compression stresses are about twice the cylinder compression strength of the concrete.

In view of the above the diameter of the counter-pressure member was fixed at 55 mm.

The main test.

All the necessary dimensions had now been fixed, and the time had come to convert the laboratory equipment into a mobile traction apparatus.

The purpose of the main test was to determine an empirical relationship between the lok-strength – the pull-out force measured with the apparatus – and the cylinder compression strength of the concrete.

Only ordinary concrete cylinders (diameter 150 mm, height 300 mm), with a test bolt embedded in the bottom, were used as test specimens. As the third pilot test had shown that the lok-strength measurements were sufficiently accurate to detect differences in strength at levels only 70 mm apart, it was found desirable, initially, to investigate the relationship between the lok-strength at the middle and the bottom of a cylinder.

A total of 20 cylinders were therefore cast, 10 from each of two batches, one with a cylinder compression strength of approx. 11 MN/m² and the other with a strength of approx. 25 MN/m². A test bolt was embedded in the bottom and the middle of each cylinder. The test bolt in the middle was mounted in a special, plane recess. One cylinder broke when the test bolt was extracted.

For the low strength mix, the coefficient of correlation between the strength at the bottom and that at the middle of the cylinders was 0.38, while for the high strength mix, the corresponding value was 0.35, which showed that there was rather poor correlation between the strengths at the two points in question. A two-way analysis of variance, which eliminated the variation between the two mixes, showed that there was a significant difference ($P_c = 4.8\ \%$) in the mean strength at the middle and the bottom. Two regression analyses show that the relationship between the strength at the middle and that at the bottom did not depend on the strength of the concrete mixes ($P_c = 50\ \%$). The common conversion factor was estimated to be 0.957.

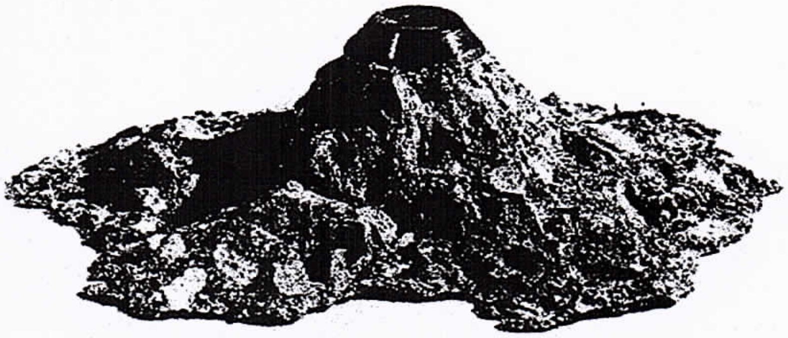

Figure 7. Solid of revolution punched out.

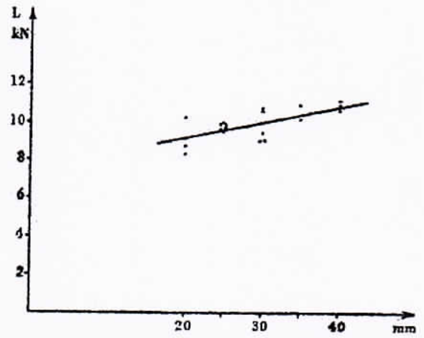

Figure 8. The pull-out force as a function of the diameter of the disc.

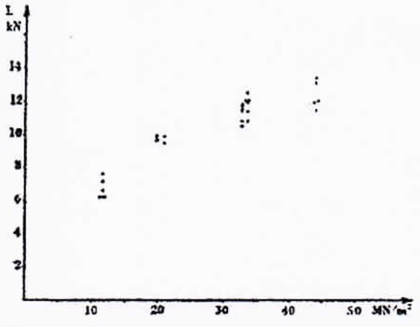

Figure 9. The pull-out force as a function of the average cylinder compression strength of the batches.

A total of 10 batches of concrete with different strengths were used for the main test. Portland cement was used for six of the batches, and Super rapid cement for the remaining four. The maximum particle size of the aggregate was varied, 8 mm being used in seven batches, 10 mm in two batches, and 16 mm in one batch.

One set of 10 ordinary cylinders were cast from each of the 10 batches, i.e. a total of 100 cylinders, all with a test bolt embedded in the bottom. The cylinders were cured standing upright in water for one week. Immediately prior to the strength measurements the 10 cylinders of each set were divided at random, five for testing the cylinder compression strength, and five for measuring the lok-strength. The tops of the compression strength specimens were straightened by means of cement mortar.

After measurement of the lok-strength, the 50 cylinders used for this purpose were crushed, whereby the compression strength of the cylinders was also determined here. This was made possible by the fact that, during the lok-strength tests, the traction force was only increased until rupture was ascertained, after which it was reduced without the solid of revolution being extracted. Of the 50 cylinders, two out of each of the two sets with the highest concrete compression strength broke up during the lok-strength measurement.

It was thus only possible to carry out the double-measurement on 46 cylinders.

Of the 50 cylinders used for the compression tests, the disc was afterwards extracted from 31 bottom-pieces that were still intact after the tests.

If no significant difference could be ascertained between the lok-strength measured on the cylinders crushed first and that measured on those on which the lok-strength was measured first, the 50 pairs of observations on the cylinders crushed first would have provided a perfect set of data for comparison of the lok-strength and the cylinder compression strength because the variation from one cylinder to another would have been eliminated. Correspondingly, we would have had 50 observation pairs from the cylinders on which the lok-strength was measured first if this test had not affected the cylinder compression strength of the concrete. However, it was found that the prior crushing of the cylinders did have a significant effect ($P_c < 0.05$ %) on the lok-strength measured, while the pull on the disc embedded in the bottom of the cylinders did not affect the cylinder compression strength measured ($P_c = 46$ %). It is thus possible to measure both the lok-strength and the compression strength on one and the same cylinder provided the lok-strength, measured at the bottom, is determined first.

On the basis of the 46 observation pairs an investigation was first carried out to see whether the type of cement used (Portland and Super rapid cement) had any effect on the relationship between the lok-strength and the cylinder compression strength. A statistical analysis showed that the type of cement used had no effect, $P_c \sim 50$ %.

It was then investigated whether the maximum particle size (8, 10 or 16 mm) affected the relationship in question. Statistical processing of the data showed that the maximum particle size did have a significant effect ($P_c = 1.2$ %).

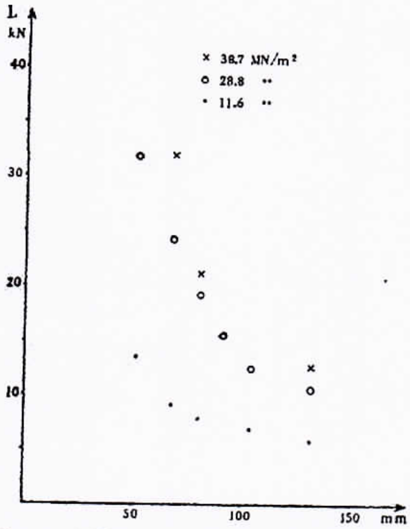

Figure 10. The pull-out force as a function of the diameter of the counter-pressure member.

If the observations corresponding to 8 and 10 mm are collected in one group, the difference in particle size (8 + 10 and 16 mm) will still be significant ($P_c = 2.5$ %), and in any case splitting into 8 and 10 mm will not reduce the residual variance very much.

As the type of cement used was found to have no effect, we can use the simple model

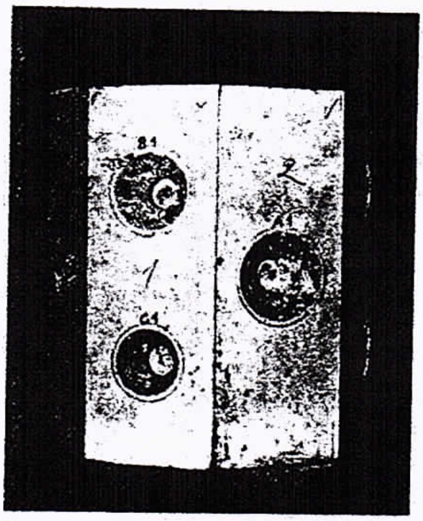

Figure 11. The locations of the test bolts in the prism, height 300 mm.

$$L = a + b\ (\sigma - \bar{\sigma}) + \begin{cases} d_1 \\ d_2 \end{cases}$$

where

L is the lok-strength, kN

a is the average of all lok-strength measured in the test

σ is the cylinder compression strength, MN/m²

$\bar{\sigma}$ is the average of all cylinder compression strengths measured in the test

b is the effect of the cylinder compression strength

d_i is the effect of the particle size, 8 + 10 and 16 mm.

The parameters in the model were estimated by a multivariate analysis of the 46 pairs of observations (the lok-strength being corrected to the strength at the middle of a cylinder by multiplication by 0.957), such that the empirical model can be written

$$L = 29.76 + 0.765(\sigma - 31.92) + \begin{cases} -0.28 \\ 2.26 \end{cases}$$

or

$$L = 5.06 + 0.765\ \sigma, \tag{1}$$

and

$$L = 7.60 + 0.765\ \sigma. \tag{2}$$

The upper equation applies to maximum particle size 8 (or 10) mm, and the lower, to 16 mm. However, reservations must be made in respect of the relationship for 16 mm since only 5 pairs of observations were used for estimation of the constant term. It is perhaps therefore reasonable to point out that, neglecting the variation in maximum particle size, we get a slightly rougher model of the form

$$\begin{aligned} L &= 29.76 + 0.769\ (\sigma - 31.92) \\ &= 5.21 + 0.769\ \sigma \end{aligned} \tag{3}$$

The vertical deviations of the observations from this model (the regression line) are plotted on probability paper, figure 14, from which it will be seen that the deviations are normally distributed with an average of 0 and a standard deviation of 2.40 kN. This indicates that the assumption of a linear relationship between the lok-strength and the cylinder compression strength can reasonably be taken to be correct.

Supplementary statistical analyses show that the standard deviation on the lok-strength and the cylinder strength within each of the 10 concrete batches was 1.76 kN and 1.77 MN/m², respectively. As the average of all observations of the lok-strength and of the cylinder compression strength was 29.76 kN and 31.92 MN/m², respectively, the coefficient of variation for the test as a whole is approximately the same for the two test methods.

SITE TESTS

When the laboratory tests had shown that the method was suitable for measuring the strength of a concrete, it was tested in practice. At the concrete components factory, MODULBETON A/S, Per Dragsholt, laboratory engineer, arranged a test for the purpose of comparing the compression strength of cast cylinders, the strength of cylinders bored out of wall components in the storage yard and the lok-strength measured on the same components.

Two wall components and 2 cylinders, diameter 100 mm, height 200 mm, were cast from each of 3 batches with a maximum particle size of 32 mm. The wall components were cast vertically and cured in steel forms for four hours at 60–70°C and 50–60 % RH. The components were then stripped and sprinkled with water for 8 hours, during which period the temperature of the water was reduced from 40° to 20°C. After this wet-curing, the components were placed in an open storage yard. Four test bolts had been embedded in each wall component, and these were pulled out at the same time as the 2 cylinders mentioned above were bored out.

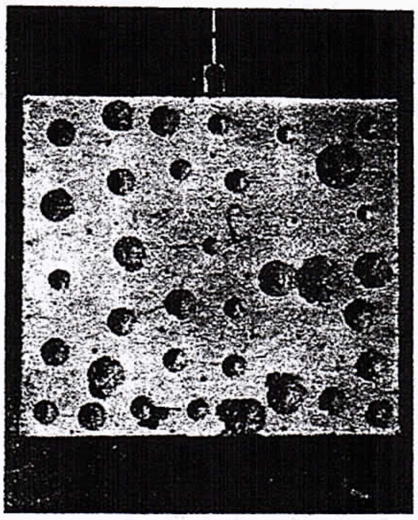

Figure 12. The locations of the test bolts in the plate, 1100 x 1000 x 100 mm.

In figure 15, the average of the 4 lok-strength measurements and the average of the compression strength of the 2 bored cylinders are plotted for each of the 6 wall components. For component No. 3, the plot (28.3, 30.6) deviates considerably from the regression line, but no special reason for this, such as honeycombing, was recorded. As the coefficient of variation for the 4 lok-strengths for this wall component is 21.6 %, whereas the average coefficient of variation for the other 5 components is 11.6 %, it seems reasonable to reject the single lok-strength measurement resulting in the extremely low average. The point thereby moves up considerably, as shown in the figure.

On the assumption that the straight curve in figure 15 represents the correct relationship between the lok-strength and the compression strength of the bored cylinders (diameter 100 height 200 mm, table 1 shows, for each of the mixes A, B and C, the potential strength of the mix, σ_{cured}, measured on the cast cylinders (diameter 100 mm, height 200 mm), the strength of the bored cylinders, σ_{bored}, and the strength obtained when the lok-strength is converted to a cylinder compression strength by means of the straight curve in figure 15.

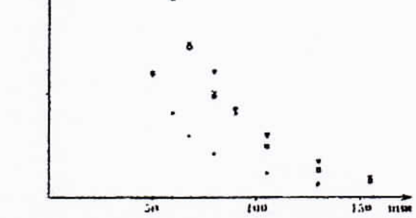

Figure 13. The average pull-out force per unit area of the curved surface of the solid of revolution (ultimate stress) as a function of the diameter of the counter-pressure member.

TABLE 1.

Concrete	σ_{cured} MN/m²	Panel No.	σ_{bored} MN/m²	σ_{lok} MN/m²
A	37.2	1	22.3	23.0
		2	21.5	20.8
B	52.1	3	28.3	27.3
		4	28.9	28.4
C	50.8	5	26:9	27.6
		6	29.4	30.5

As will be seen from the table, there is a remarkable difference between the strength found by means of the cast cylinders and that found by means of the bored cylinders.

INVESTIGATIONS CARRIED OUT AT THE DEPARTMENT OF STRUCTURAL ENGINEERING

After the method developed for the determination of the lok-strength of a concrete had been investigated in the laboratory and tested in practice, the Society of Danish Civil Engineers requested the Department of Structural Engineering, Technical University of Denmark in the following abbreviated to ABK) to verify the applicability of the method.

The Laboratory (ABK) arranged comprehensive tests with the following independent variables:

Cylinder compression strength, which varied between 5.8 and 53.5 MN/m².

Curing time, which was chosen as 7 and 28 days.

Curing conditions: the test specimens were cured in 3 different ways: 1) ordinary curing in a water tank, 2) curing for 3 days in a water tank, followed by storage in the laboratory atmosphere, 3) cured for the

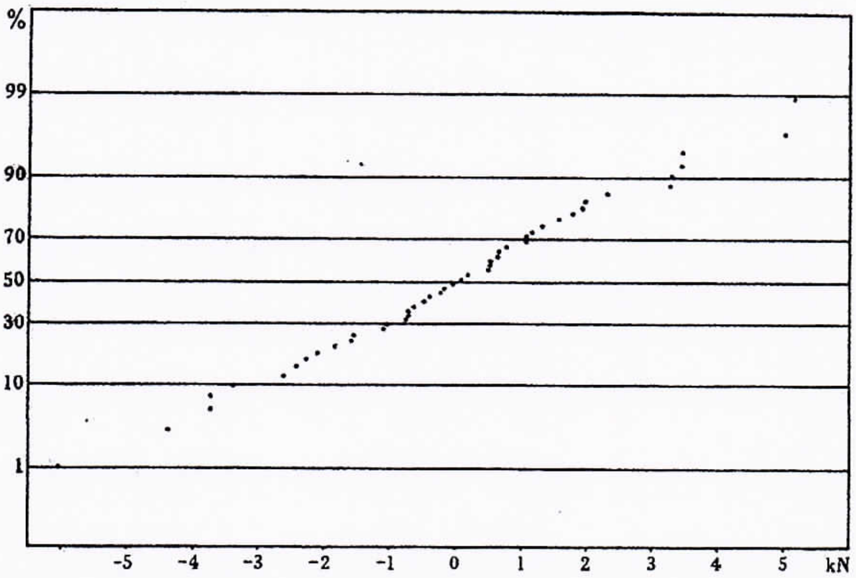

Figure 14. The cumulation distribution of the deviation of 46 lok-strengths from the regression line (3), plotted on probability paper.

entire period in an incubator at 45°C with air circulation.

Maximum particle size: 16 and 32 mm.

A total of 50 batches of concrete were produced, from each of which 5 ordinary cylinders (diameter 150 mm, height 300 mm) were cast for determination of the cylinder compression strength, and 5 cubes (200 × 200 × 200 mm), with a test bolt embedded in two opposite sides, whereby the lok-strength could be tested twice on each cube.

The results of the tests are summarized in Report No. S3/69 1970 [1] and Report No. S3/69 1974 [2] from the Laboratory.

ABK kindly provided the author with a copy of the original data for inclusion in his own data-analyses.

The data from the last 8 batches were omitted from the total set of data because the lok-strength in these test series was measured with a slightly different apparatus than that used in the first tests carried out at ABK and in the author's own tests. The changed apparatus resulted in a slight alteration in the values measured, although big enough to show statistical significance, $P_c \sim 1\%$. Data from one further batch were omitted because 4 of the 10 lok-strengths were recorded as values in excess of the maximum reading of the apparatus.

On the remaining data, which comprised 5 cylinder compression strengths and 10 lok-strengths from each of 41 batches, the average cylinder compression strength and the average lok-strength were calculated for each mix. These sample means were used as observations in a multi-variate analysis [7].

The following linear model was used in the analysis:

$$L = a + \begin{cases} b_1\sigma \\ b_2\sigma + c\delta + \\ b_3\sigma \end{cases} \begin{cases} \tau_1 \\ \\ \tau_2 \end{cases},$$

in which,

L: the lok-strength, kN

a: a constant

σ: the cylinder compression strength, MN/m²

b_i: the effect of the cylinder compression strength corresponding to the 3 methods of curing

δ: maximum particle size of aggregate, mm

c: effect of maximum particle size of aggregate

τ_j: effect of curing time, 7 and 28 days.

The hypothesis: "the curing time has no effect" can be accepted, since $P_c \sim 50\%$. The model can therefore be reduced to

$$L = a + \begin{cases} b_1\sigma \\ b_2\sigma + c\delta. \\ b_3\sigma \end{cases}$$

The hypothesis: "the relationship between the lok-strength and the cylinder compression strength is independent of the maximum particle size of the aggregate" must be rejected, since $P_c << 0.05\%$. Similarly, the hypothesis: "the coefficient b_i of σ is independent of the method of curing" must be rejected, since $P_c < 0.05\%$. On the other hand, there was no significant difference, $P_c \sim 45\%$, between the two coefficients of slope, b_1 and b_2, corresponding to curing in water and curing first in water and then in air, respectively.

For the sake of convenience, but on the safe side, we can, as b_3 is less than $b_1 \sim b_2$, apply a factor of the order of magnitude $b_1 \sim b_2$ as coefficient for σ. The factor b_3 is only applicable in cases in which the concrete in the structure has not been cured in accordance with the specifications. If, therefore, $b_1 \sim b_2$ is applied instead of b_3, the method will be slightly restrictive in respect of incorrect curing. Therefore, in the following analysis, the data from the 15 batches used for test specimens cured in an incubator will be omitted.

The linear model will be reduced correspondingly to

$$L = a + b\sigma + c\delta.$$

Estimation of the parameters resulted in the empirical relation:

$$L = 0.182 + 0.282\delta + 0.950\sigma. \qquad (5)$$

In the new Danish Code of Practice for the Structural Use of Concrete it is specified that the cylinder compression strength must be measured on ordinary cylinders without a fibreboard pad between the cylinder and the pressure plates of the press. In the investigations carried out by ABK, the cylinders were crushed with a pad placed at each end of the cylinder.

It was therefore found desirable to bring ABK's results in line with those of the author and for this purpose 7 batches with different strengths were produced, and from each of these 10 cylinders were cast. Five of each set of 10 cylinders were crushed on ABK's compression testing machine with pads while the other five were crushed without pads on the testing machine used in the author's tests. By means of data from the crushing of the 70 cylinders, the parameters in the relation

$$\sigma_{PKH} = -0.314 + 1.146\,\sigma_{ABK},$$

between the results obtained at the two laboratories were estimated. In the equation, σ_{ABK} and σ_{PKH} give the respective cylinder compression strengths in MN/m² measured at ABK and on the press used by the author.

When the cylinder compression strength, σ, included in equation (5) is corrected by means of the above correction formula, the relationship between the lok-strength measured in kN and the cylinder compression strength measured in MN/m² becomes

$$L = 0.44 + 0.282\delta + 0.829\sigma\ , \qquad (6)$$

where δ is the maximum particle size of the aggregate, measured in mm. For $\delta = 16$ and 32, the expression can be written up to

$$L = 4.96 + 0.829\sigma\ , \qquad (7)$$

and

$$L = 9.48 + 0.829\sigma\ , \qquad (8)$$

respectively.

COMPARISON OF RESULTS

For the author's tests, aggregate with a particle size of 8 and 16 mm was used, while in the ABK-tests, aggregate particle sizes of 16 and 32 mm were used. It was therefore only possible to compare the results in respect of particle size 16 mm.

For this comparison use was made of the corrected ABK-data (corrected to values corresponding to the new Danish Code of Practice) and the corrected PKH-data (lok-strength converted to middle of a cylinder). As each cylinder compression strength included in the foregoing analyses of the ABK-data was the average of five single observations, the ABK-averages were given the weights 5 in the comparative analysis.

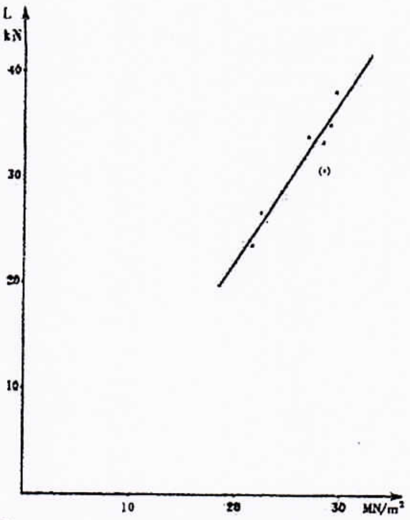

Figure 15. The average lok-strength as a function of the average compression strength of bored cylinders, diameter 100 and height 200 mm.

In the analysis of the data it was investigated whether all data were compatible with a single relation or whether it was necessary to work with two different relations, one for ABK-data and one for PKH-data. It was not possible to ascertain any significant different, $P_c \sim 80\%$, which indicates that the results were comparable. The common relation for 16 mm particle size is

$$L = 5.10 + 0.825\,\sigma\ .$$

The parameters of this relation do not deviate very much from the parameters in formula (1), which was valid for maximum particle size 8 mm. It therefore seems reasonable in practice to use the common formula

$$L = 5.10 + 0.806\,\sigma\ ,$$

for all particle sizes smaller than or equal to 16 mm.

CONCLUSIONS

The purpose of the present paper is to report the tests carried out since 1962 for the purpose of investigating the relationship between the lok-strength of a concrete and its compression strength measured on cylinders with a diameter of 150 mm and a height of 300 mm.

There is nothing to indicate that the relationship between the two strength measurements is non-linear. It has been ascertained that the maximum particle size of the aggregate influences the relationship, i.e. influences the measured lok-strength and/or cylinder compression strength, such that a relation between the lok-strength measured in kN and the cylinder compression strength measured in MN/m² must be expressed by the following two formulae for 16 and 32 mm maximum particle size:

$$L = 5.10 + 0.806\,\sigma \qquad (16\text{ mm})$$

and

$$L = 9.48 + 0.829\,\sigma\ . \qquad (32\text{ mm})$$

The parameters in the first formula are based on 176 cylinders and 299 measurements of the lok-strength, while the parameters in the second formula are estimated on the basis of measurements on 44 cylinders and 90 measurements of the lok-strength.

In one of the investigations, 41 pairs of measurements of the lok-strength and the cylinder compression strength were made on a concrete with a maximum particle size of less than 10 mm. The coefficient of correlation for these data was 0.985. From the same data, the standard deviation on the lok-strength was calculated to be 2.31 kN.

To sum up, it can be concluded that there is an extremely good correlation between the lok-strength of a concrete, its cylinder compression strength and the maximum particle size used in the concrete. This relationship can best be described as follows:

The variance of all lok-strength measurements carried out – totalling 389 – can be calculated to be 166.8 kN². When the variation in the cylinder compression strength and the variation in maximum particle size are eliminated, this variance can be reduced to 3.7 kN^2, or only 2.2%. As far as is known, such precision cannot be achieved with any other indirect test method yet developed for concrete.

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