

Pull-out testing by

LOK-test and CAPO-test

with particular reference to the in-place concrete of the Great Belt Link

Storebælt



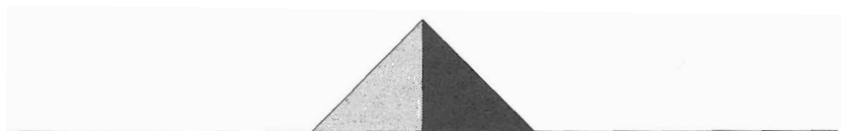
Pull-out testing by

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with particular reference to the in-place concrete of the Great Belt Link

Revised edition November 1993

Claus Germann Petersen and Ervin Poulsen



D A N S K B E T O N I N S T I T U T A / S

This book series published by Dansk Betoninstitut A/S is for use in connection with courses for A/S Storebæltsforbindelsen and includes:

- *Ervin Poulsen*: »Background for requirements to concrete and reinforced concrete, especially for concrete in structures for the fixed link across Storebælt«. Published December 1991 and June 1992.
- *Ervin Poulsen*: »Control and evaluation of concrete work, especially for concrete in structures for the fixed link across Storebælt«. Published June 1991 and September 1992.
- *Jens Frandsen*: »Planning and executing of concreting and curing, especially for concrete in structures for the fixed link across Storebælt«. Published July 1992 and November 1992.
- *Claus Germann Petersen og Ervin Poulsen*: »Pull-out testing by LOK-test end CAPO-test, especially for concrete in structures for the fixed link across Storebælt«. Published August 1991 and October 1992.

The present publication is produced in compliance with the requirements in »East Bridge Special Specifications, Substructure, SAB-III« December 1991. In addition there are various recommendations which are not specifications and therefore not included in SAB-III. However, experience has shown that pull-out testing using LOK-test and CAPO-test requires a certain guidance and it is with this in mind that this publication has been produced.

SAB-III, December 1991 is expected to be supplemented with various »Change Requests« which therefore are not included in the publication.

In the event of discrepancies between the present publication and the latest edition of East Bridge Special Specification, SAB-III, regarding requirements, numerical requirements etc. it is SAB-III and the authorized Change Requests which are valid.

Preface

This book is written on behalf of the Danish Great Belt Link (A/S Storebæltsforbindelsen) by In-Situ Test of Copenhagen and The Danish Concrete Institute.

The Great Belt Link's Special Specifications for Concrete Works (in Danish named the SAB) requires inspection and testing of the in-place concrete compressive strength. For this purpose the SAB specifies the application of pull-out testing by LOK-test and CAPO-test according to the Danish Standard DS 423.31.

As a copart of the contract the Contractor and the Employer's Representative must attend seminars on concrete technology and concrete testing related to the specifications given by the SAB. The seminar manuals in total outline the background and comment on the basic requirements of the SAB in relation to all aspects of the concrete materials, the mix design, mixing, transportation, casting, compaction, curing conditions, control measures and the documentation.

This part of the seminar manuals is intended to serve as a practical guideline for the training of the Contractors' technicians who have been selected to perform the LOK-test and the CAPO-test and for the inspectors supervising the testing. The technicians must attend a course where the theoretical background is given as well as practical skills in how to perform the testing. After the course, diplomas are issued to those participants who have passed the final examination with a satisfactory result.

The material outlines the background of pull-out testing with LOK-test and CAPO-test, the test equipment and how the testing is performed correctly. The statistical interpretation of the test results is given in details. For a complete and comprehensive description of the test equipment and the test procedure it is advisable to read the instruction manuals submitted by the manufacturer of the test equipments, Germann Instruments A/S.

The manual has been written by Claus Germann Petersen, In-Situ Testing A/S and Ervin Poulsen, AEC Consulting Engineers A/S with the support of Peter Mogensen and Finn Bach, The Danish Concrete Institute A/S.

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This publication is produced for A/S Storebæltsforbindelsen for use as course material. As well as forming the basis for courses for contractors it can also be used as a handbook for planning and execution of pre-testing and control testing of concrete. Therefore, included in the publication are chapters which deals with the background of pull-out testing of concrete more detailed than at the courses.

The chapter on »Inspection and Testing by LOK/CAPO-tests« deals with the considerations of the specifications in FAB and SAB as well as the chapter on »Requirements of Strength measured by Pull-Out Testing«.

The chapter on »Relation of Pull-Out Force versus Compressive Strength« describes in detail how the laboratory determination of the relation should be planned and executed, if required. For ordinary use the information given in the chapter »Conversion Formulae for Pull-Out Force to Cylinder Compressive Strength« form the necessary basis for converting the pull-out force measured to cylinder compressive strength.

At the end of the publication appendices are included regarding decision rules which FAB and SAB require to be used for control testing of concrete using LOK-test and CAPO-test. Furthermore in the appendices there is a summary of inspection, pull-out testing and the decision rules.

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Background of LOK-test and CAPO-test

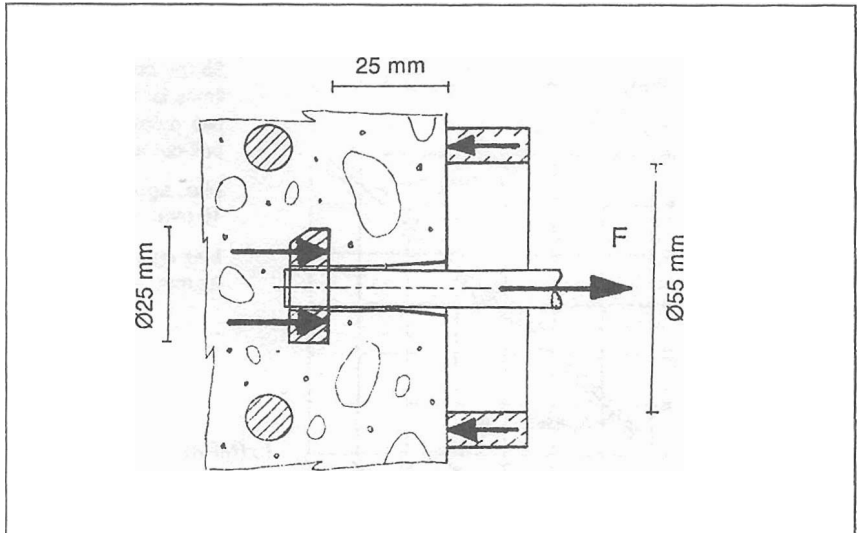
In this section the background of the LOK-test and the CAPO-test pull-out testing is mentioned briefly. A more detailed description of the testing itself is given on page 31-47.

Operation principle

The fundamental principle behind pull-out testing with LOK-test and CAPO-test is that test equipment designed to a specific geometry will produce results (pull-out forces) that closely correlate to the compressive strength of concrete. This correlation is achieved by measuring the force required to pull a steel disc or ring, embedded in the concrete, against a circular counterpressure placed on the concrete surface concentric with the disc/ring.

The steel disc is only for fresh concrete. For hardened concrete, an expandable steel ring is used instead. This ring expands to fit a specially drilled hole and routed recess in the concrete. The first method, shown in figure 1 using the

Figure 1. The LOK-test testing principle. A steel disc 25mm in diameter is embedded in the fresh concrete at a depth of 25 mm and pulled, after hardening of the concrete, towards a counterpressure, 55mm inner diameter, placed on the surface. The pullforce »F« is a measure of the compressive strength of the concrete, see figure 3.



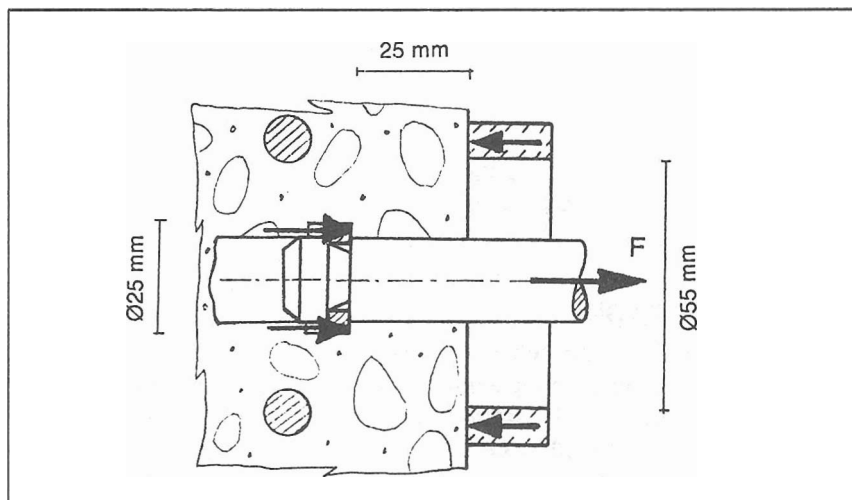
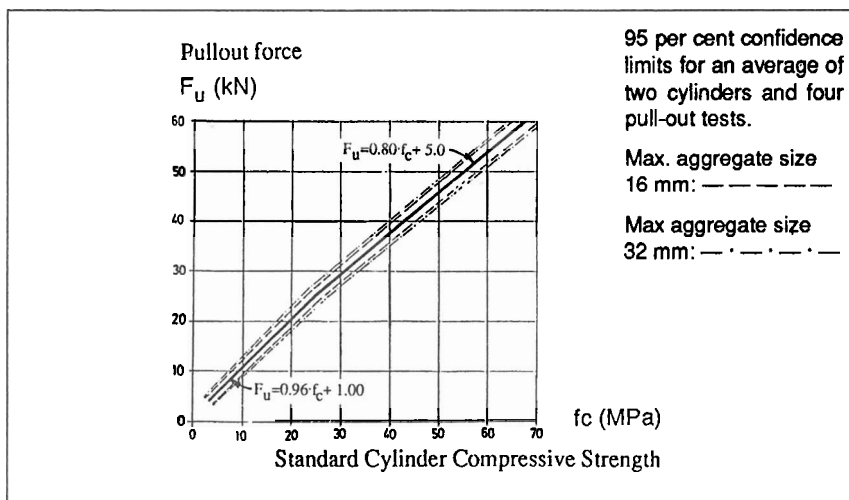


Figure 2. CAPO-test testing principle. In a drilled and recessed hole, 25 mm below the surface, an expandable ring is inserted and expanded to a 25 mm in diameter dimension. The ring is at the time of testing pulled towards a counterpressure, 55 mm inner diameter placed on the surface. The pull-out force »F« is a measure of the compressive strength of the concrete, see figure 3.

Figure 3. The correlation between LOK-test and CAPO-test pull-out forces and the 150 mm × 300 mm standard test cylinder compressive strength. The dotted lines indicate the 95 per cent confidence limits for an average of two cylinder tests and four pull-out tests if the maximum aggregate size is 16 mm or 32 mm.



cast-in steel disc, is called LOK-test («LOK» is the Danish designation for »punch«). The second method, shown in figure 2 using the expandable ring, is called CAPO-test («CAPO» stands for »Cut And Pull-Out«). The diameter of both the disc and the ring is 25mm. The distance to the concrete surface is also 25 mm. The inner diameter of the counterpressure is 55mm.

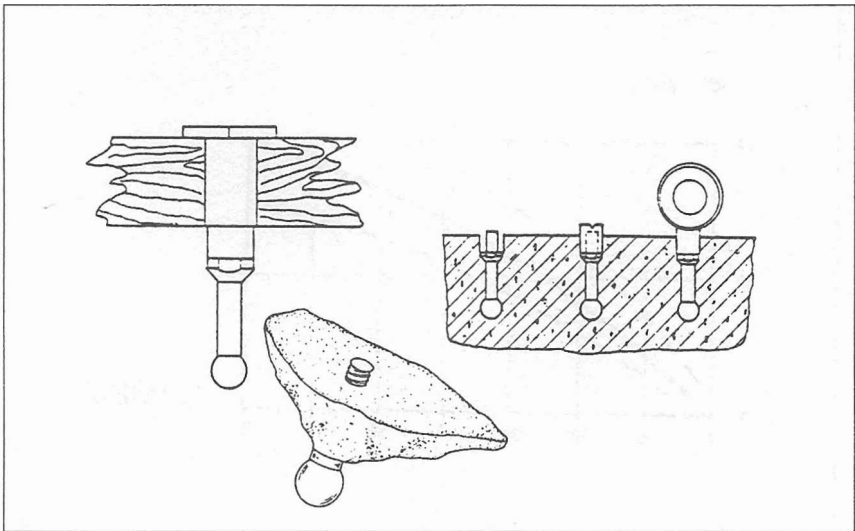
The relationship between the pull-out force F_u in kN (kilo Newton) and the compressive strength f_c in MPa (Mega Pascal) is given in figure 3. The compressive strength is measured on standard cylinders 300 mm high and 150mm in diameter, according to the Danish Standard DS 423.20.

By measuring the pull-out force of a cast-in disc or expanded ring, the compressive strength of in-situ concrete can be determined from the relationship in figure 3 to a great degree of confidence.

Historical development

During the 1930s in the USSR, *V. Volf* and *O. A. Gershberg* described, c.f. [Skramtajef, 1938], a version of pull-out testing. A ball cast into the concrete was pulled out, but without the use of a counterpressure. The failure becomes »trumpet«-shaped as shown in figure 4. The pull-out force is with this system a measure of the tensile strength. Since the tensile strength depends on the com-

Figure 4. Pull-out testing with the Volf-Gershberg method, utilizing a cast-in ball pulled out without the use of a counterpressure. The failure becomes »trumpet«-shaped and the pull-out force is with this system a measure of the tensile strength.

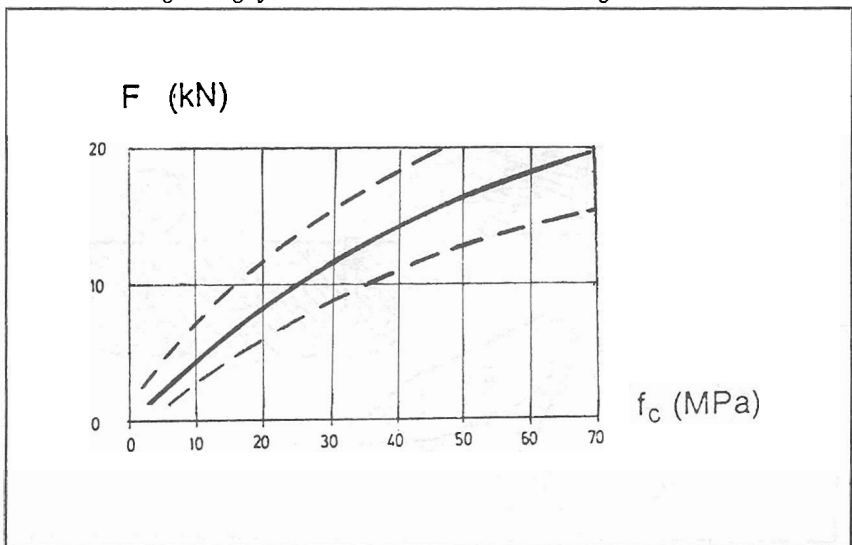


pressive strength of concrete, it is also possible to relate the pull-out force to the compressive strength. The relationship is, however, nonlinear as indicated in figure 5 and consequently the uncertainty of the strength estimate is considerable in the normal strength range from 10 MPa to 60 MPa or higher.

LOK-test

In the 1960s, Peter Kierkegaard-Hansen of Denmark initiated the development of a pull-out test named the LOK-test [Kierkegaard-Hansen, 1975]. His intention was to accurately measure the compressive strength of the cover layer, the critical layer as far as durability is concerned. The dimension of the test was chosen with this in mind as well as ensuring that reinforcement was kept outside the failure zone. His major contribution was to apply a counterpressure, placed on the concrete surface, to pull against the disc, in contrast to the method suggested by *V. Volf* and *O. A. Gershberg*. In a series of tests, Kierkegaard-Hansen varied the diameter of the counterpressure and found that the pull-out force in kN was almost identical to that of the cylinder compressive strength in MPa as stated in Danish Standard DS 423.20 for a counterpressure inner diameter of 55mm.

Figure 5. The principal relationship between the pull-out force and the concrete cylinder compressive strength of concrete using the Volf-Gershberg method. Notice, that the relationship is nonlinear and only with a small increase when concrete strength is increasing. Consequently, the uncertainty of the strength estimate is considerable in the normal strength range from 10 MPa to 60 MPa or even higher.



CAPO-test

In 1975, *Claus Germann Petersen*, also of Denmark, developed the CAPO-test [Petersen, 1980]. This test system was designed to measure, at random, the compressive strength in-situ according to the same pull-out principle as with LOK-test, without a disc pre-embedded in the concrete. Dimensions identical to LOK-test were chosen except for the centre hole left by the stem. Instead of a 7mm hole, as for the LOK-test, an 18 mm hole was chosen as the minimum possible.

The following is the CAPO-test procedure in short: First the reinforcement is located by a covermeter and the position of the test is chosen to ensure that the failure cone is well outside reinforcement disturbance. The surface has to be smooth and plane, otherwise it is planed with a diamond wheel. Using a water-cooled diamond bit, an 18 mm diameter by 60 mm deep hole is drilled perpendicular to the plane concrete surface. Then a 25 mm diameter recess is routed at a depth of 25 mm with a diamond tool. An expandable ring is inserted through the hole in the recess and expanded by means of a special expansion tool. Finally, the ring is pulled out through a 55 mm counterpressure placed concentrically on the surface as with LOK-test. The pull-out force is measured and transformed to compressive strength.

Preliminary investigations carried out at the Department of Structural Engineering, the Technical University of Denmark, [Krenchel, 1982], established that the pull-out force measured with CAPO-test had the same relationship to the cylinder compressive strength as measured with LOK-test. This rather surprising and interesting finding was later confirmed by the Cement and Concrete Institute (CBI) in Sweden [Bellander, 1983] and the Civil Engineering Department of University of Liverpool in England, [Bungey, 1983].

Relation between pull-out force and the compressive strength of concrete

Since then, a great number of correlation series has been carried out all over the world, both in laboratories and on site. The correlation between pull-out force and compressive strength was investigated for any possible influence by the following parameters: type of cement, w/c -ratio, air entrainment, flyash, admixtures, fibers, aggregates (type, shape, source, and maximum size), age and types of curing conditions.

Based on 24 such major correlation series, covering 4253 pull-out tests and 2963 reference compression tests, the conclusion is that the correlation curve in figure 3 is relatively stable, regardless of the parameter investigated.

The investigations covered aggregate size up to a maximum of 38 mm. Only when using lightweight aggregates and pure mortar another correlation was found. The findings are mentioned in details below.

Theoretical and experimental investigations

Between the years 1976 and 1985, a number of theoretical and experimental investigations were conducted to account for the excellent correlation between pull-out force and compressive tests of standard reference specimens. The following are three of these investigations.

Calculation by plasticity theory

In 1976, *B. Chr. Jensen* and *M. Bræstrup* made the first investigation into the failure mechanism of a LOK-test. For their analysis, they used Coulomb's criterion for sliding failure. They concluded that *»the pull-out force is directly proportional to the compressive strength of concrete«*, [Jensen, 1976].

Calculation by finite element analysis

In 1981, *N. S. Ottosen* published the results of a nonlinear finite element analysis to explain the failure mechanism of a LOK-TEST. His conclusion is *»that large compressive forces run from the disc in a rather narrow band towards the counterpressure. This constitutes the load carrying mechanism. Moreover, the failure in a LOK-test is caused by crushing of the concrete, not by cracking. Therefore, the force required to extract the embedded steel disc is directly dependent on the compressive strength of the concrete in question«*, [Ottosen, 1981].

Experimental findings

The failure mechanism was further investigated experimentally by *H. Krenchel* in 1985. He loaded LOK-test inserts to different loading levels on the load-displacement curve. Afterwards, the test sample was saw cut through its axis, the surface was ground smooth and impregnated with epoxy containing a fluorescence dye to reveal cracks under ultraviolet light. The results published in 1985 are given below [Krenchel, 1985], see figure 6.

Krenchel states: *»The internal rupture during this type of test is a multistage process where three different stages, each with different fracture mechanisms, can be clearly separated. In the first stage, at a level of about 30-40 % of the ultimate load, tensile cracking begins, starting from the notch formed by the upper edge of the pull-out disc. These cracks run out in the concrete at a pronounced open angle (cone angle between 100 degrees and 135 degrees). The total length of this first crack is typically 15-20 mm from the edge of the disc. In the second stage of internal rupture, a multitude of stable microcracks are formed in the above mentioned truncated zone. The main direction of these cracks, running from the top of the disc to the bottom of the counterpressure, form a cone angle of approximately 84 degrees. The formation of this second cracking pattern is parallel with the formation of increasing vertical mi-*

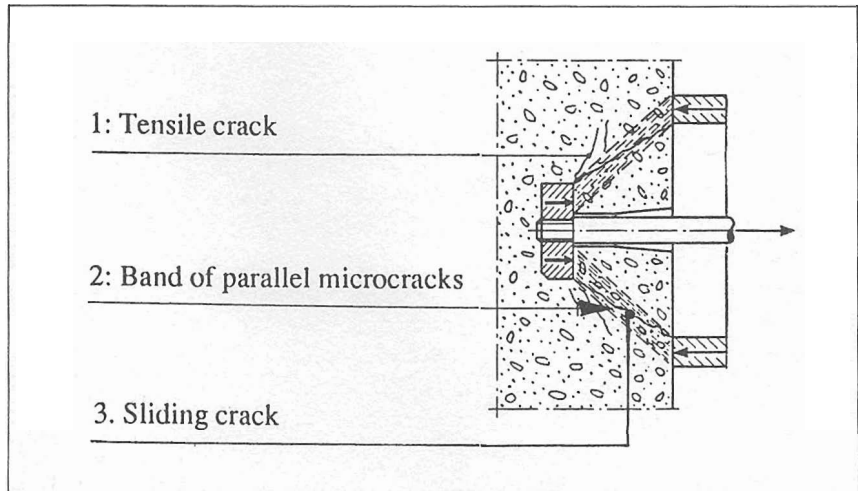
crocracks inside a concrete cylinder or prism during ordinary uniaxial compressive tests. Development of the acoustic emission activity during this second stage of the test also follows a function quite parallel to the AE-development of ordinary uniaxial compressive tests. If more and more oil is pumped into the pull-out machine, even after the load has stabilized at the peak point, the third stage of internal rupture occurs. This forms a tensile/shear crack running all the way around from the outside edge of the disc to the inside edge of the counterpressure ring. The final pull-out cone angle, which can be noticed if the cone is pulled out, is about 62 degrees."

Kenchel concludes: »Since the microcracking of rupture stage number two is responsible for and directly correlated to the ultimate load in this testing procedure, it seems quite logical that such close correlations to the concrete compressive strength will always be obtained«.

Applications

Compressive testing of standard cylinders, cast, compacted and cured according to the Danish Standard DS 423.23, indicates the potential strength that a given concrete mix can obtain. Concrete made in this manner is, in other words, »lab-crete«, the best possible.

Figure 6. The crack formation during a LOK-test. First a tensile crack (1) is formed running out from the disc edge into the concrete. Then, a band of parallel microcracking (2) emerges between the disc and the counterpressure. At the maximum pull-out force, a sliding failure crack (3) is formed between the outer edge of the disc and the inner edge of the counterpressure.



The concrete in-place, the »real-crete«, will reach the same compressive strength if the workmanship (casting and compaction) and the curing conditions are similar and if the testing is performed at the same maturity as the »lab-crete«, that is after 28 days at 20 degrees Centigrade.

Pull-out testing, according to Danish Standard DS 423.31, makes it possible to measure the compressive strength of the structure for the following purposes:

- Controlling the workmanship and the curing conditions of the completed structure, especially the cover of the reinforcement, the »cover-crete«, which is critical in terms of durability.
- Timing of early and safe loading operations of the structure during hardening, e.g. in relation to stripping of forms, removal of shores, lifting, or tensioning.
- Evaluating the time of termination of winter protection or curing.

The first purpose may be considered after comparing the »lab-crete« cylinder results (DS 423.23) with testing of the »real-crete« with LOK-test and CAPO-test (DS 423.31) related to cylinder compressive strength at 28 maturity days. Alternatively, pull-out tests made on trial castings cast and cured satisfactorily may be compared directly with test results during construction at equal maturities.

The second and the third purpose may be utilized when the maturity in-place indicates that the strength has reached a specific level in critical parts of the structure. To verify the actual in-place strength, pull-out testing can then be applied to make sure the strength of the in-place concrete is present as intended.

Should the compressive strength need to be tested deeper than at the cover layer, so called »Depth LOK-test inserts« can be placed on extension tubes and embedded at the required depth. ■

Conversion formulae for pull-out force to cylinder compressive strength

The LOK-test and the CAPO-test determine a compressive strength property by means of a pull-out force. One may argue that by applying a pull-out force, the tensile strength is measured. This argumentation is correct if the counterpressure is *not* applied, but with the counterpressure the pull-out force crushes the concrete between the LOK-test insert and the counterpressure. Thus, it is a measure of the compressive strength.

During a LOK-test and a CAPO-test, a triaxial compressive stress condition is created in the concrete. It is complicated to calculate the stress distribution, but it can be done. However, for practical purposes it needs not to be done. Comparative measurements between the pull-out force and the compressive strength of reference tests specimens, e.g. cylinders 300 mm high and 150 mm in diameter as stated in Danish Standard DS 423.20, have been made.

The procedure used for the comparisons has usually been to cast-in LOK-test inserts, centrally placed in the bottoms of the cylinders, in sufficient quantity to enable comparative measurements, e.g. after 1, 2, 3, 5, 7, 14 and 28 maturity days and even more.

A basic rule in all pull-out testing is to keep a minimum distance of 100 mm between the center of the insert and the edges or corners of the concrete. Otherwise, severe radial cracking may occur, due to a splitting tendency of the concrete, resulting in lowering of the pull-out forces. This tendency is primarily dominant at higher strength levels or when large and hard aggregates are used. Because the minimum distance cannot be maintained in a 150 mm cylinder bottom, the solution has usually been to tighten the bottom of the cylinder in a steel ring or to perform pull-out testing on 200 mm cubes with the inserts centrally placed in the vertical faces.

The pull-out test is then conducted exactly to failure *and no further*. The test equipment is unloaded and removed. The cylinder is then loaded to failure in a compression machine. From this comparative testing corresponding values of pull-out force and compressive strength are found. A detailed guideline for conducting such a correlation program is given in Appendix 2.

In figure 7, the conducted correlation series reported in 1984 are summarized using standard cylinders as reference specimens. The pull-out force F_u in kN is shown, measured with LOK-test or CAPO-test, in relation to cylinder compressive strength in MPa.

The following parameters were studied: types of cement, w/c -ratio, air entrainment, fibers, flyash, admixtures, aggregates (type, shape, source and maxi-

mum size), age, and type of protection during curing. The maximum aggregate size investigated was 38 mm. Only with the use of lightweight aggregates or pure mortar another correlation was found.

Conversion formulae

Based on a statistical analysis of the test data (regression analysis), the recommended general conversion equation between the pull-out force F_u in kN and the compressive strength f_c in MPa (measured according to the Danish Standard DS 423.23) is as shown in figure 3:

$$(1) \quad F_u = 0.96 f_c + 1.00 \quad \text{for } 2 \text{ kN} \leq F_u < 25 \text{ kN}$$

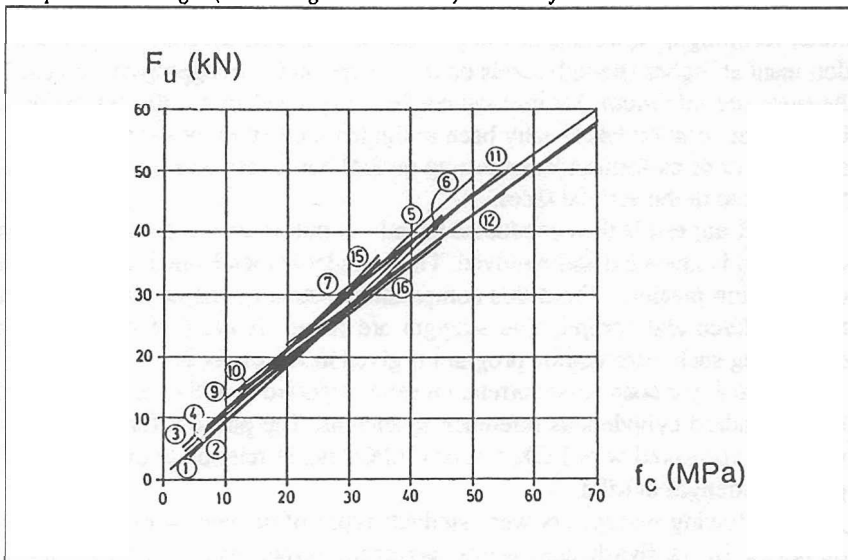
$$(2) \quad F_u = 0.80 f_c + 5.00 \quad \text{for } 25 \text{ kN} \leq F_u < 60 \text{ kN}$$

If the compressive strength of the concrete has to be calculated from known pull-out forces, the opposite relations are used:

$$(3) \quad f_c = \frac{F_u - 1.00}{0.96} \quad \text{for } 2 \text{ kN} \leq F_u < 25 \text{ kN}$$

$$(4) \quad f_c = \frac{F_u - 5.00}{0.80} \quad \text{for } 25 \text{ kN} \leq F_u < 60 \text{ kN}$$

Figure 7. Pull-out force measured by LOK-test or CAPO-test compared with cylinder compressive strength (according to DS 423.23) in 16 major calibration series.



Variation of pull-out forces

Experience has shown that the coefficient of variation (in per cent):

$$(5) \quad V = \frac{s \times 100}{\bar{f}_c} \text{ per cent}$$

is almost constant, regardless of the strength level tested at. In the equation above, s is the standard deviation in MPa and \bar{f}_c is the average strength in MPa. Thus, the coefficient of variation V is used to characterize the variation of the test results.

The variation of »lab«crete

If pull-out tests are performed at the bottom of vertically cast and compacted cylinders of normal concrete, the average coefficient of variation is 7.5 per cent, based on 957 test results.

Performed on the vertical faces of 200 mm laboratory cubes of normal concrete, the average coefficient of variation is 9.9 per cent, based on 2084 test results. The cylinders are always cast in three layers, each compacted on a vibration table. The 200 mm cubes are also cast in three layers, but usually by hand rodding.

If the variation of the cylinder compression strength is eliminated, the variation of the pull-out testing is considerable lower than stipulated above. In one such investigation, the coefficient of variation of pull-out testing was found to be 2.2 per cent [Kierkegaard-Hansen, 1975].

The variation of »real«crete

The following average coefficients of variations for pull-out testing of structural elements have been found to be:

- Beams and columns at the same horizontal level, based on 324 pull-out tests:
 $V = 7.8$ per cent.
- Bottom of slabs, based on 4190 pull-out tests:
 $V = 9.4$ per cent.
- Walls and foundations at the same horizontal level, based on 753 pull-out tests:
 $V = 10.0$ per cent.
- Top of slabs, based on 274 pull-out tests:
 $V = 12.5$ per cent.

- Gunit concrete, based on 150 pull-out tests:
 $V = 13.4$ per cent.
- Damaged structures, based on 1001 pull-out tests, randomly distributed:
 $V = 14.7$ per cent.

The variations shown are the total variations composed of the within-test variation as well as the normal variation of strength from batch to batch.

Sources of errors

To correctly perform pull-out testing by LOK-test and CAPO-test the following conditions have to be observed:

- The geometry of the pull-out proportions has to be correct.
- The test surface has to be plane and perpendicular to the centerline of the disc or the ring.
- No reinforcement or foreign bodies be allowed close to the failure zone.
- A 100 mm minimal distance to edges or corners should be maintained.
- A 200 mm minimal distance between two pull-out tests has to be observed.
- The pull-out force has to be supplied at a constant rate and at a speed which ensures a minimum duration of the pull-out test of 15 seconds.
- The hydraulic pull-out machine has to be filled sufficiently with oil and have no oil leakages for the peak load to occur. Also the instrument's calibration between readings and the actual pull-out force has to be stable and checked as instructed.
- When performing CAPO-test the surface planning, the drilling of the centerhole, the routing of the recess and the expansion of the insert should be made in one sequence immediately followed by the pull-out. This is to ensure that the use of water in the first three steps will not penetrate into the concrete significantly and affect the strength during the pull-out testing.

Detailed operational criterion for correctly performed LOK-test and CAPO-test are given in the following chapter and in appendix 8. ■

Inspection of failure modes

The reliability of pull-out testing should not be compromised by failure modes that display an abnormal appearance. Guidelines for a correct failure mode are stated below. Typical failures are further illustrated by photos in appendix 8.

LOK-test

The LOK-test cast-in disc may be loaded to a required strength. Without rupturing the concrete, the test is a fully non-destructive test method. Alternatively, the disc may be loaded exactly to failure or fully dislodged. If not pulled out, the surface may not need repair. Otherwise, a repair mortar would be applied to fill out the cone hole as will be mentioned later.

If »loading exactly to failure« is followed, the only visible crack on the surface should be a 55 mm diameter crack following the inner diameter of the counterpressure with the cone slightly raised (0.1-0.5 mm) from the surface.

Fully pulled out, the failure cone should be limited towards the surface by a sharp 55mm in diameter circle edge. This edge acts as a »proof of correct testing«. It should be noted that the failure may look rather irregular despite the test being good *if* the test equipment is pulled in or twisted by the termination of the test while trying to release the cone from the concrete. To avoid situations like this, only fully oil-filled equipment should be used to ensure maximum travel of the main piston (5.5 mm) and the instrument should be supported when the dislodging occurs. If pull-out is still not possible, even when the instrument turning handle is fully contracted and no more travel is left, install the extra travel ring in front of the counterpressure. This is done after the instrument has been uncoupled. Then the pull-out sequence is terminated and the cone will come out.

If other types of cracking occurs on the surface (radial cracking or spalling) the test is rejected. The bottom boundary of the failure cone should be equal to the disc's 25 mm diameter placed at a depth of 25 mm.

The types of failure modes are illustrated in figure 8 (for inserts loaded »exactly to failure«) and in figure 9 (for inserts pulled fully out). The photos, figure 56 and 57 of appendix 8, illustrates failures of correctly performed LOK-tests.

CAPO-test

The CAPO-test failure cone is always pulled out fully since the pull-out bolt has to be reused. Again, in regards to the reliability of the test, the upper failure cone edge has to be sharp and 55 mm in diameter, see figure 58. If the failure

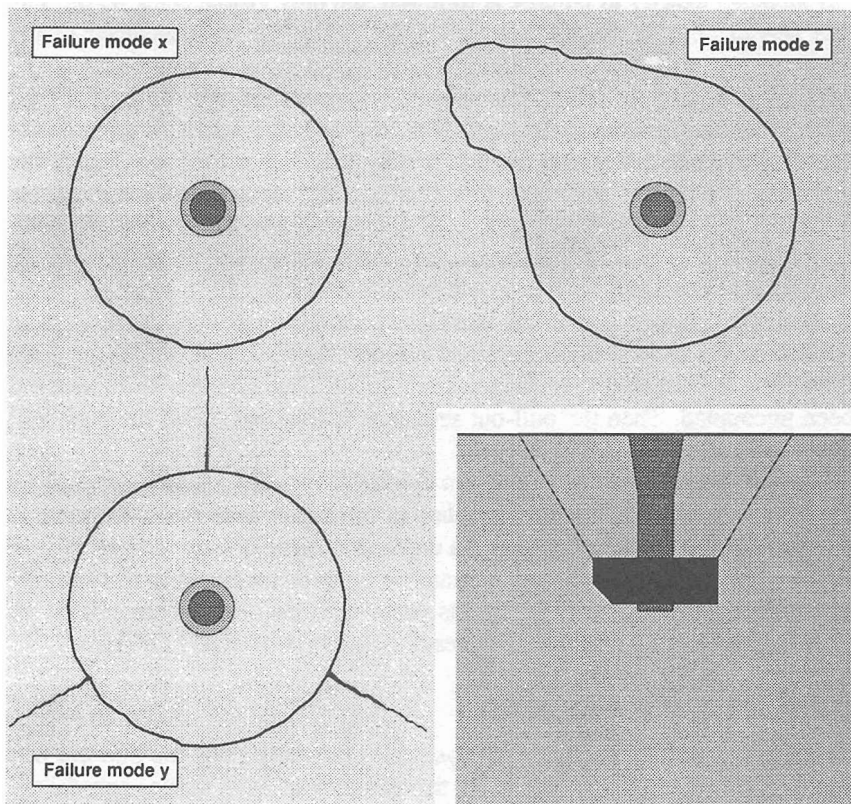
occurs outside this diameter, the reason may be that the surface is not plane. Also, no radial cracking must be visible. Such cracking typically shows up when the minimum distance of 100 mm to edges and corners has not been observed or the centreline of the expanded insert has not been perpendicular to

Figure 8. Typical LOK-test failure modes conducted »exactly to failure« with the cone lifted only 0.1-0.5 mm from the surface.

Failure mode x. This is the acceptable type of failure mode. The only visible crack is the 55 mm crack formed by the inner diameter of the counterpressure

Failure mode y. Radial cracking appears outside the circular 55mm crack. Typically the reason is that the minimum distance to edges and corners (100 mm) or between two tests (200mm) has not been observed. The test is rejected.

Failure mode z. Spalling appears outside the circular 55mm crack. Typically the reason is a non-plane testing surface or that the insert has not been installed perpendicular to the test surface. The test is rejected.



the surface. Failures outside the 55 mm counterpressure inner diameter or radial cracking causes the test to be rejected.

The CAPO-test ring has to be installed and fully expanded at a depth of 25 mm below the test surface and the diameter of the routed recess and the expanded ring has to be 25 mm with tolerances as prescribed page 51. ■

Figure 9. Typical LOK-test failuremodes where the failure cone has been fully dislodged.

Failure mode x. This is the only acceptable type of failure. Outside the sharp edge formed by the 55 mm inner ring of the counterpressure, there is no sign of cracking.

Failure mode y. Radial cracking appears outside the circular 55 mm edge. Typically the reason is that the minimum distance to edges and corners (100 mm) or between two tests (200 mm) has not been observed. The test is rejected.

Failure mode z. Spalling appears outside the 55 mm in diameter edge. Typically the reason is a non-plane testing surface or that the insert has not been in stalled perpendicular to the test surface. The test is rejected.

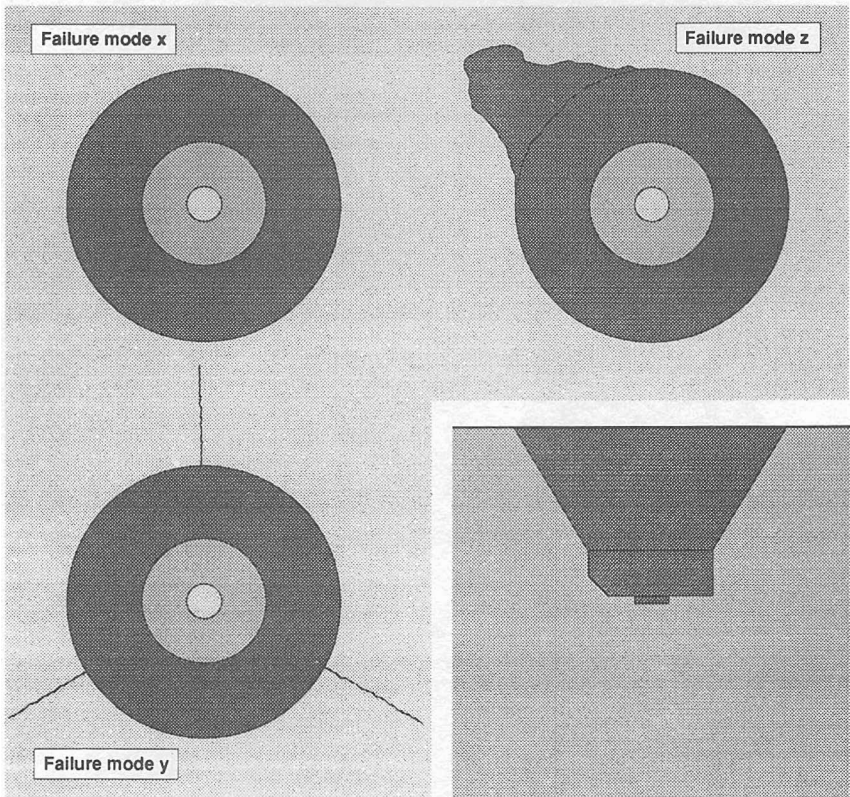
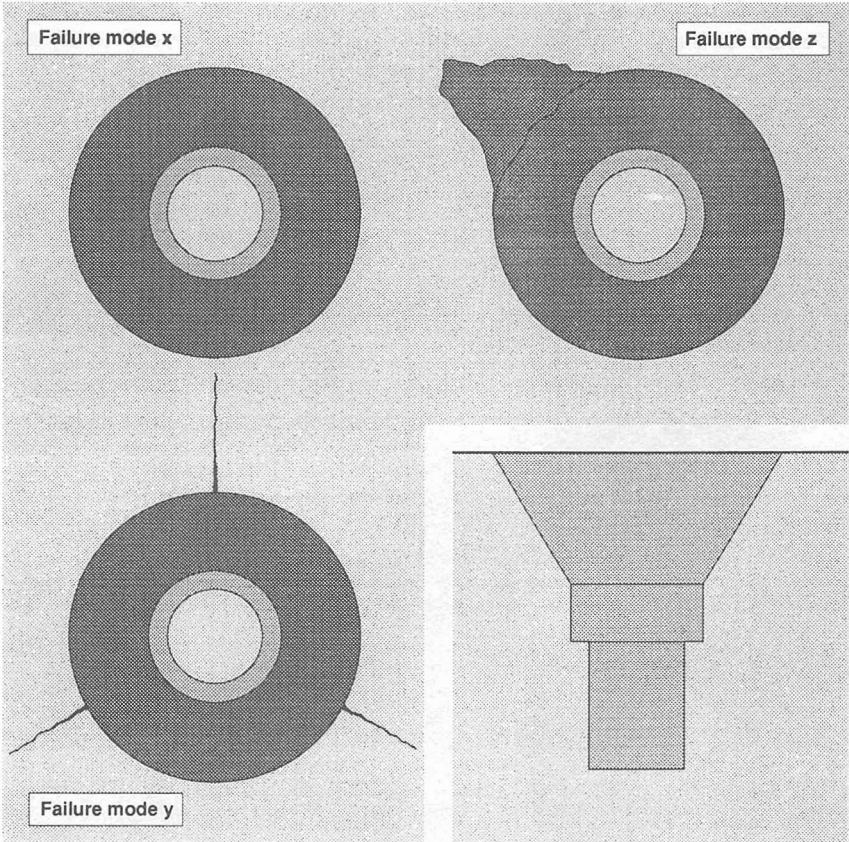


Figure 10. Typical CAPO-test failure modes (the pull-out cone is always fully dislodged from the concrete).

Failure x. This is the only acceptable type of failure mode. Outside the sharp edge formed by the 55 mm inner ring of the counterpressure, there is no sign of cracking.

Failure y. Radial cracking appears outside the 55 mm in diameter edge. Typically the reason is that the minimum distance to edges and corners (100 mm) or between two tests (200 mm) has not been observed. The test is rejected.

Failure z. Spalling appears outside the 55 mm in diameter edge. Typically the reason is a non-plane testing surface or that the centreline of the expanded ring has not been perpendicular to the surface. The test is rejected.



Requirements of strength measured by pull-out testing

Unless otherwise stated, testing of the concrete compressive strength in-place takes place by means of LOK-test and CAPO-test according to the Danish Standard DS 423.31 and the SAB-amendment to DS 423.31. The evaluation of the test results has to be conducted in accordance with the decision rule in the Danish Standard DS 411, 3rd edition from 1984. To facilitate the evaluation, the tables 8.1.1a and 8.1.1b are given as shown in appendix 5, table 7 and 8.

The Great Belt Link specifications, SAB, concludes that it is necessary to devise supplementary requirements and to clarify a number of issues related to the implementation of pull-out testing. These will be mentioned in the following.

Requirements of the SAB

The DS 423.31 is reproduced in appendix 3. This Danish Standard was published in 1984 and has not been revised ever since. The following amendments and changes in relation to this standard should be noted:

- According to the standard, the method used should be correlated to compressive strength for a given mix. Based on the experience with the correlations, see figure 7, which was published after the issue of the standard, there are strong reasons to believe that one general correlation exists for normal concrete between pull-out force and each type of standard reference specimen used, for example, cylinders (DS 423.20) as shown in figure 3. As mentioned earlier, an exception is the use of lightweight aggregates or pure mortar and the correlation has not been investigated for maximum aggregate size larger than 38 mm.
- DS 423.31 mentions that the duration of a pull-out test should be 120 seconds, plus/minus 30 seconds. Experience and investigations (e.g. in the UK) have shown that the test result is unaffected by the speed of loading as long as the pull-out test lasts longer than 15 seconds and the loading rate is uniform.
- According to the standard, maximum load should be indicated by the equipment gauge, e.g. by a slave needle, after the peak point of the load-displacement curve has been passed. Practice has shown that if the stiffness of the instrument is sufficient, the maximum pullforce is kept steady for 2-3 seconds before the pointer falls slowly back making the peak easy to read. This is a special feature of the LOK-test equipment. Furthermore, a slave needle will affect the test results. Also the use of such an arrangement will prevent the gauge from being filled with a dampening medium and a small air bubble which is essential for the stability of the calibration between the reading in kN of the gauge and the true pullforce in kN. Therefore, the

LOK-test equipment is not supplied with a slave maximum gauge indicator unless explicitly stated and ordered on special request.

Requirements of the SAB-amendment to DS 423.31

The SAB-amendment is reported in appendix 4. Detailed specifications for the use of LOK-test and CAPO-test are given as far as positioning of single tests, acceptance criteria for correct testing and regulations for the repair of failure holes.

Requirements of the SAB and the General Note

The requirement of the SAB to use pull-out testing according to DS 423.31 is motivated by the desire to measure the compressive strength in-place. Needless to say, it is a prerequisite that the potential strength of the concrete (»lab«crete) be present. This is, however, not sufficient for the SAB.

The SAB requires the actual compressive strength of the concrete in-situ, measured by LOK-test and CAPO-test, to fulfill the requirements of the General Note at the same time that the appropriate homogeneousness be evaluated by pull-out testing. The comments for applying this approach are as follows:

Strength requirements

The required characteristic values of the compressive strength determined by cast cylinders after 28 days of maturity is stated in SAB's General Note and is dependent on the type of concrete. For concrete type A and B, specified for the East Bridge the characteristic compressive strength shall not be less than 45 MPa.

With in-place pull-out testing, 80 per cent of these requirements has to be fulfilled, i.e. 36 MPa for concrete type A and B, specified for the East Bridge.

The SAB and its General Note also states requirements for some of the characteristics of the concrete influencing the strength (air content and w/c -ratio). However, the major concern for acceptance is if the transportation, the casting, the compaction and the curing of the concrete have been executed according to the specifications of the SAB. Experience has shown, specifically, that the formsystems used and the curing of the concrete may be critical factors of the concrete quality in-place and the acceptance of the LOK-test and the CAPO-test results.

Statistical interpretation

The Danish Standard DS 411 requires that all the pull-out testing results for a control section be evaluated by means of the rule of decision for statistical interpretation of concrete strength given in DS 411, 3rd edition, clause 8.1.1 (see appendix 5). The SAB implies the DS 411 to be in effect.

All the pull-out forces have to be measured at 28 maturity days or corrected to this maturity if the testing takes place one or two days later.

The strength-maturity relationship has to be documented at the trial casting.

Control testing

If the required strength is not harmonized with other requirements of the concrete mix, a fairly large deviation of the in-place strength may be the consequence. The desired uniformity of the in-situ concrete, which the SAB emphasizes, will not then be achieved. Consequently, the SAB introduces, in addition to the decision rule in DS 411, the following rule for control testing of a control section:

»Based on pretesting and trial casting of the mix used, the contractor has to declare an upper and lower limit for the variation of the pull-out test's pull-out forces. This range has to be accepted by the supervisor. In a control section, the measured pull-out forces have to be within the tolerance declared by the contractor and accepted by the supervisor. The evaluation takes place by means of alternative control as outlined in DS 423.1«

For the East Bridge of the Great Belt Link the tolerance has been established by the owner to ± 7 kN, c.f. table 14 of the SAB.

Supplementary testing

The number of LOK-test inserts placed in a control section has to be established before the concrete is cast in-place and the inserts have to be attached to the formwork at the selected locations. If the number of tests in a control section is not sufficient for acceptance, the control may be supplemented by a number of CAPO-tests.

To avoid supplementary testing with CAPO-test, a larger number of LOK-test inserts may be installed in the fresh concrete (to be decided by the contractor) and used only if supplementary testing is needed.

Total inspection

The Danish Standard DS 423.1, 2nd edition from 1985, distinguishes between inspection by random testing and total inspection depending on the number of the batches of an inspection section tested.

Inspection by random testing is performed if a specified number, fewer than the number of batches of an inspection section, is tested. That is if the number of observations are smaller than the number of batches. The decision rule for acceptance is given in appendix 5.

Total inspection is said to be performed if the observations from all batches of an inspection section are interpreted. A batch is accepted if the observation falls within the prescribed limits. An inspection section is accepted if all the batches are accepted.

The Danish Standard DS 423.1 requires that an inspection section having three or less batches always should be tested by total inspection. The SAB presupposes that Danish Standard DS 411 is being applied.

The contractor is free to choose between inspection by random testing or by total inspection for an inspection section containing more than three batches.

Rejection

As mentioned above, the SAB contains two criteria for acceptance of the pull-out forces of the in-place concrete:

- The first criterion is, that the required characteristic value of the in-place compressive strength is achieved after 28 maturity days. This is a code requirement, stated in the Danish Standard DS 411.
- The second criterion is, that the coverlayer of the structure has to achieve a quality measured by pull-out tests after 28 maturity days to be within the tolerances as declared by the contractor and approved by the Employer's Representative. This is to make sure that the casting of the concrete, the compaction and the curing of the concrete have not caused a larger intensity of defects than accepted at the pre-testing and the trial casting.

Both requirements have to be fulfilled at the same time. The consequence of rejection is, nevertheless, different in both cases:

- If the required strength by measuring in-place with pull-out testing is not documented by means of DS 411, the cause of rejection must be confirmed by cylinder compression tests, petrographic analysis (to evaluate the effects of workmanship) and by the curing conditions. In principle, rejected in-situ concrete has to be demolished and rejected concrete elements must not be erected.
- If the second requirement is not fulfilled, the coverlayer of the structure has not obtained the needed quality as far as durability is concerned. The SAB allows such coverlayer to be supplementary tested by CAPO-test. If such test results also fall outside the established tolerances, the cause for rejection has to be found, and adjustments made.

Example 1. A concrete type B, according to the General Note, has to have as a minimum a characteristic strength of 35 MPa after 28 maturity days evaluated by pull-out testing. In a control section consisting of 75 cubic meter of concrete (12 batches), the strength is measured with LOK-test. The declared and approved interval for the pull-out forces is 35 to 45 kN at 28 maturity days.

Inspection by random testing is performed by testing three of the twelve batches at random, each by two LOK-test inserts. Each observation two LOK-tests are placed in the same horizontal layer within a circle of 300 mm and with an internal distance of minimum 200 mm.

Using COMA-meters to measure the concrete maturity, the testing takes place after 28 maturity days according to the pull-out standard DS 423.31. The results are given below in table 1 in kN pull-out force and converted into cylinder compressive strength by means of the general correlaton in figure 3.

According to DS 411, table 8.1.1a (table 7, page 108), the coefficient of va-

Test no.	Pull-out forces		Average kN	Cyl. strength MPa
	kN	kN		
LOK 1	35.8	34.0	34.9	37.4
LOK 2	33.8	34.6	34.2	36.5
LOK 3	36.2	34.4	35.3	37.9
<i>Average</i>	-	-	-	37.3

Table 1. Test data from pull-out testing by LOK-test, c.f. example 1.

riation is $\delta = 0.16$ for $f_{ck} = 35$ Mpa when testing in-situ. As shown in table 8.1.1b (table 8, page 109), the factor $k_n = 1.31$ for the number of observations $n = 3$ and the coefficient of variation $\delta = 0.16$.

The concrete of the inspection section fulfills the requirement in DS 411, as:

$$37.3 \text{ MPa} > 0.80 \times f_{ck} \times k_n = 0.80 \times 35 \times 1.31 = 36.7 \text{ MPa}$$

However, the measured pull-out forces do not fall within the declared and approved tolerance of 35 to 45 kN.

The testing has shown that even if the concrete is in compliance with the strength requirement in the SAB, an adjustment of the concrete mix recipe has to take place due to the required uniformity consideration, if this is the cause of non-compliance. Control testing of the adjusted concrete mix recipe may take place by calculation or by pull-out testing performed on test specimens from a trial casting. If the change in the mix design is only of a limited nature, no trial casting is required, c.f. SAB clause 4.5.7.14.

Example 2. A casting of 24 cubic meter of concrete, delivered in three batches of each 8 cubic meter (type B), has to have a characteristic strength of a minimum of 35 MPa at 28 maturity days. The declared and approved interval is 25 to 35 kN.

Total inspection is performed by 3 tests, each consisting of 2 LOK-test inserts, placed in each batch. The decision rule of each observation to be minimum $0.80 \times 35 \text{ MPa} = 28 \text{ MPa}$ applies.

By means of COMA-meters cast into the in-place concrete, the maturity is measured. At 28 maturity days, the pull-out testing by LOK-test is performed according to DS 423.31. The following pull-out forces are measured and con-

Table 2. Test data from pull-out testing by LOK-test, c.f. example 2.

Test no.	Pull-out forces		Average kN	Cyl. strength MPa
	kN	kN		
LOK 1	27.3	29.1	28.2	29.0
LOK 2	27.2	29.4	28.3	29.1
LOK 3	30.0	28.4	29.2	30.0

verted to cylinder strength as given in table 2.

As will be seen, each observation converted into cylinder strength is higher than 28 MPa. Also all three observations (average values in kN) are within the interval from 25 to 35 kN. Consequently, the in-place concrete fulfills both requirements of the SAB.

Example 3. An inspection section consists of 5 batches. The delivered concrete is of type A with a required characteristic strength of $f_{ck} = 50$ MPa at 28 maturity days. The declared and approved interval of the pull-out forces at 28 maturity days is from 40 to 50 kN. Inspection by random testing is performed with the following results, cf. table 3:

Test no.	Pull-out forces		Average kN	Cyl. strength MPa
	kN	kN		
LOK 1	38.1	41.9	40.0	43.7
LOK 2	40.9	39.9	40.4	44.3
LOK 3	43.4	45.2	44.3	49.1
Average	—	—	—	45.7

Table 3. Test data from pull-out testing by LOK-test, cf. example 3.

As the measured average cylinder compressive strength, 45.7 MPa, is less than $0.80 \times 50 \times 1.24 = 49.6$ MPa it will be seen that the control section cannot be accepted according to the DS 411 requirement (the factor k_n equals 1.24, cf. table 8, page 108, for a coefficient of variation $\delta = 0.14$, table 7, and the number of observations $n = 3$).

It is decided to test the two remaining batches by CAPO-test, by which the total inspection is applied. The CAPO-test results are given below, cf. table 4:

Test no.	Pull-out forces		Average kN	Cyl. strength MPa
	kN	kN		
CAPO 1	42.7	41.9	42.3	46.6
CAPO 2	45.2	44.4	44.8	49.8

Table 4. Test data from pull-out testing by CAPO-test, cf. example 3.

A total inspection has now been applied (each batch in-place has been tested) Then the decision rule applies that all 5 observations have to be greater than 0.8×50 MPa = 40 MPa. As this is the case, the inspection section is accepted according to the first strength requirement of the SAB (DS 411). Also it will be seen that all the observations (average values in kN) are between the limits 40 to 50 kN. Therefore, also the second durability requirement of the SAB is fulfilled. ■

Pull-out testing in practice

In the following the practical part of pull-out testing with LOK-test and CAPO-test is described. As mentioned before, the test equipment and test technique as well as the maintenance of the equipment are outlined in details by the manufacturers instruction and maintenance manuals.

LOK-test in practice

The normal working range of the LOK-test pull-out machine is 0-50 kN (gauge range 0-60 kN). This pull-out machine named »Standard« or »Automatic« may also be supplied with 0-25 kN or 0-40 kN gauges depending on the strength range to be used for the particular purpose of testing. The 0-60 kN gauge has a minimum division of 1 kN, the other two 0.5 kN. For testing at a higher range, the »High Strength« LOK-test pull-out machine, supplied with a 6-150 kN gauge, has to be used. This gauge has a minimum division of 2 kN.

Similar two strength range inserts are available, 0-50 kN inserts and 0-110 kN. The designations of the 0-50 kN inserts are L-40, L-42, L-45 and L-49 respectively and the 0-110 kN's inserts are L-41, L-43, L-46 and L-50 depending on the type of installment. The different insert types are described below.

Before LOK-test can be made, the insert type has to be chosen, the test locations selected and the inserts installed in the formwork prior to casting or during casting (floating insert types L-49 or L-50). At the time of testing the LOK-test instrument should be checked, all parts found present and in clean and undamaged condition.

LOK-test insert types and installation

As mentioned two strength ranges are available. The 0-50 kN inserts (L-40, L-42, L-45 and L-49) and the 0-110 kN (L-41, L-43, L-46 and L-50). The L-45 and the L-46 is the stem and the disc without any attachments, threadlocked to each other and coated. These inserts have to be installed in the concrete as desired by the user.

The L-40 and the L-41 are for nailing to wooden formwork, the L-42 and L-43 for attachment with screws through removable portholes or to steel shutters and the L-49 and L-50 are for floating by finger placement in top surfaces during concreting.

Control inserts, L-40 and L-41

The inserts illustrated in figure 11 are supplied on a watertight masonite plate with four nails for fastening to wooden shutters. The disc part is threadlocked to the stem (to prevent the disc to turn off the stem) and both parts are coated (to avoid adhesion to the concrete).

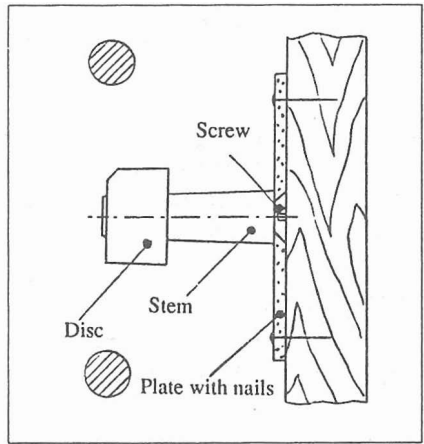
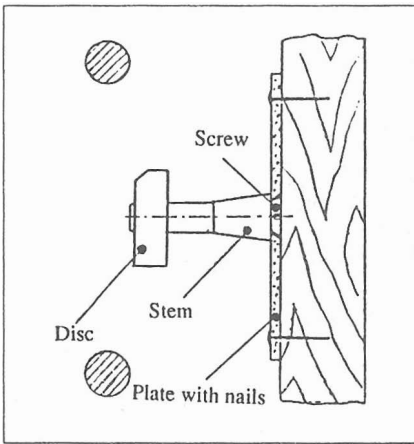
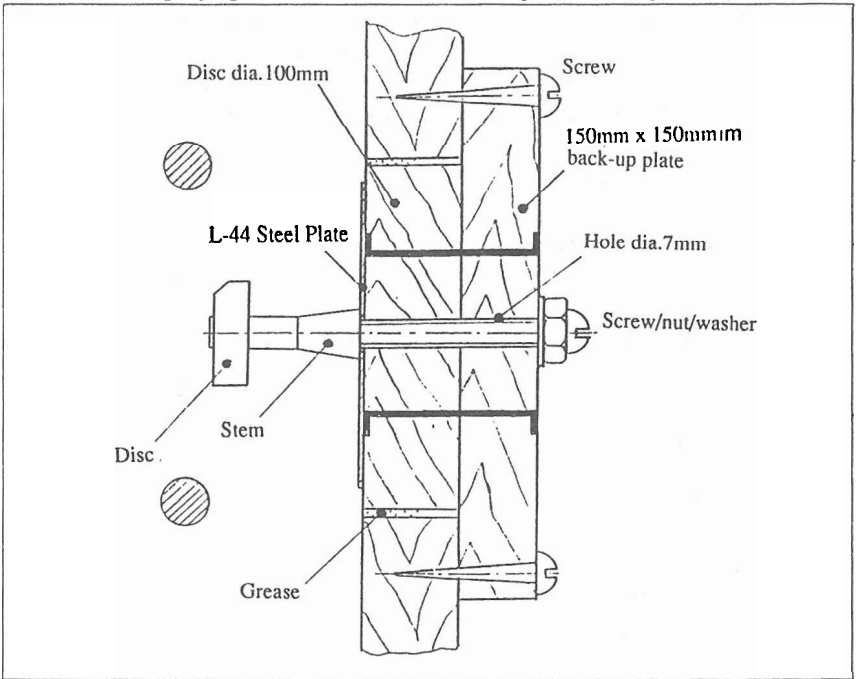


Figure 11. L-40 control insert (0-50 kN) left and L-41 control insert (0-110 kN) right.

Figure 12. Early stripping insert L-42 insert with L-44 steelplate attached through a wooden shutter port hole. A similar attachment may be used through a steelform, if the testing has to be made before the shutter is removed. For high strength insert to be used, the designation is L-43. Note: Always remember to use the L-44 steelplate to install the insert tightly against to ensure a smooth and plane test surface.



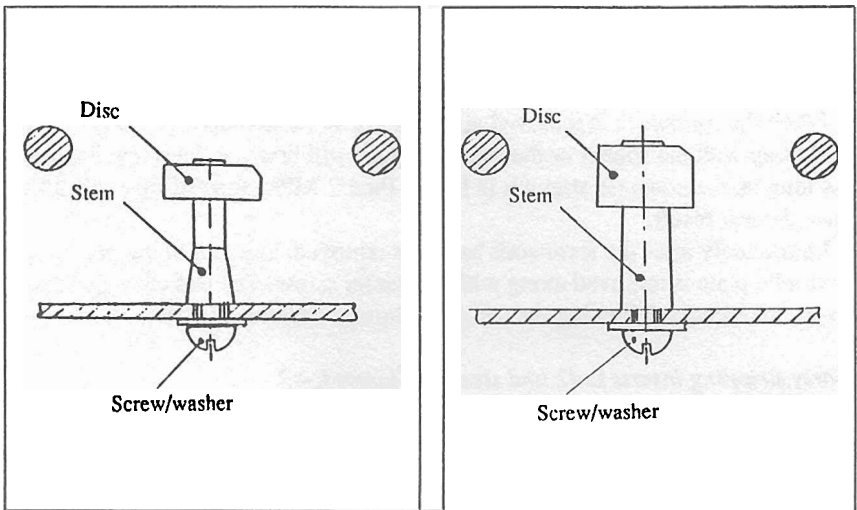
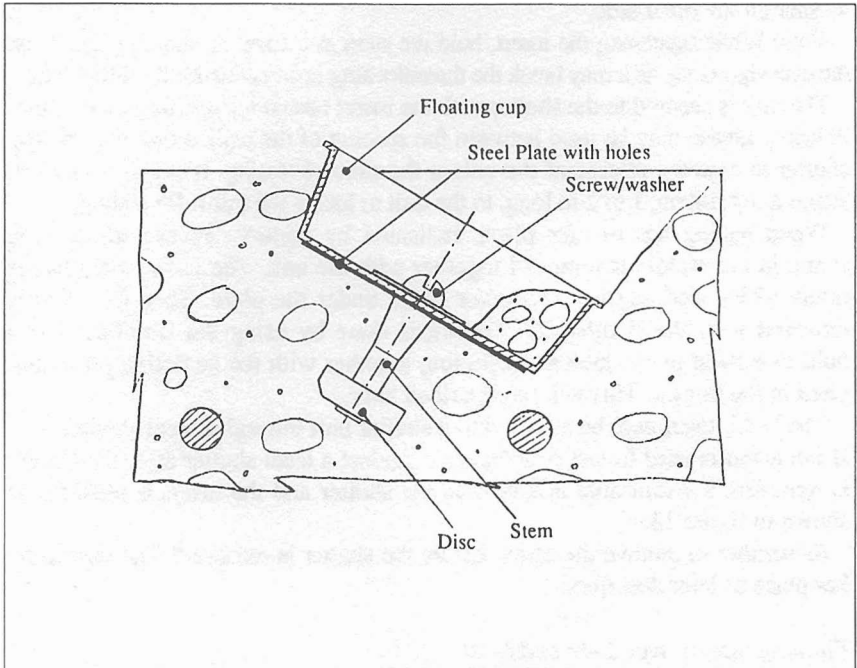


Figure 13. LOK-test insert L-42 (0-50 kN) installed in steel shutter (left) and L-43 (0-110 kN) insert (right) through a 7 mm hole drilled in the formwork.

Figure 14. Floating insert type L-49. If a high strength disc and stem is used the designation is L-50.



The nails must not bend during attachment. Do not hammer the nails so hard that the plate bends or cracks. This would result in an irregular testing surface. Also, do not hit the disc with the hammer during installation.

When the formwork is removed after casting and initial curing, the nails may pull away with the shutter or the masonite plate will break at the screw junction. As long as the concrete strength is higher than 2 MPa, none of this will influence the test result.

Immediately after the formwork has been removed, any remaining part of the masonite plate is removed along with the center screw. The test takes place at a required maturity following the test procedure as described later.

Early stripping inserts L-42 and steelform insert L-43

The insert is delivered with a 7 mm screw, nut and washer. The insert may be used to test through the shutter (wooden or steel) as illustrated in figure 12 or for attachment to formwork by means of a screw, figure 13.

For testing through a shutter before it is removed, a 100 mm in diameter hole is cut in the formwork at the test location. The cut-out disc is attached centrally to a 150 × 150 mm square plate by means of nails or screws as illustrated in figure 12. A 7 mm hole is drilled through the centre. The insert is attached from the casting side, resting against the L-44 steel plate, to the screw, nut and washer on the other side.

Note: While tightening the insert, hold the stem in a fixed position. Do not twist the disc vigorously as it may break the threadlocking unscrewing itself off the stem.

The unit is secured to the shutter with the insert turned against the casting side. A heavy grease may be used between the spacing of the drilled-out disc and the shutter to ease the release of the unit at the time of testing. It is a good idea to attach a red ribbon, 1 to 2 m long, to the unit to locate the insert for testing.

When testing has to take place, indicated by maturity measurements, the screw in the middle is removed together with the unit. The L-44 steel plate is removed by wedging a screwdriver blade under the plate. Then the stem is removed with the stemhandle. Testing is done by using the lengthened pull bolt, extension piece, tube and coupling together with the centering plate supplied in the test kit. This will be described later.

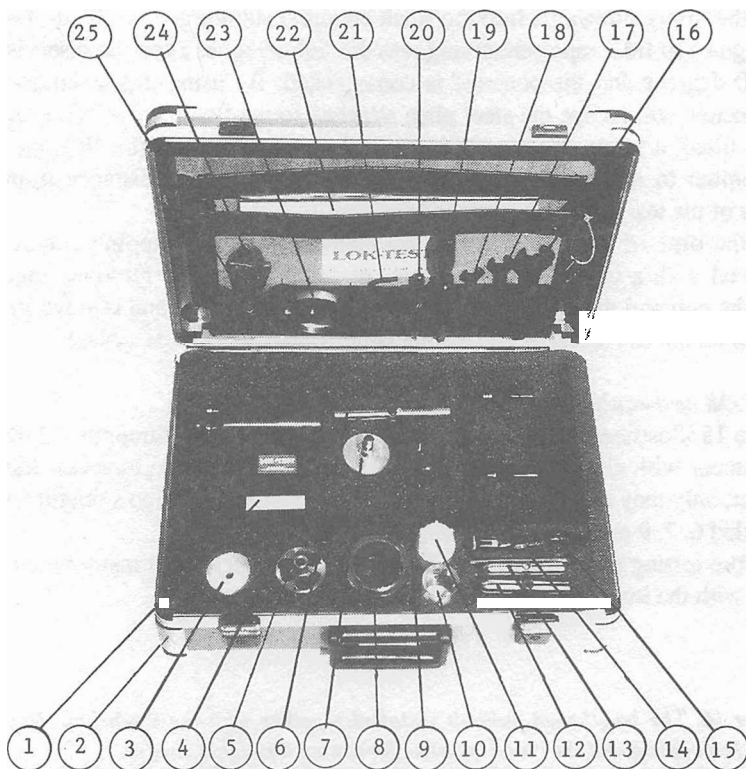
The L-42 insert may be attached to a similar unit through a steel shutter. If the insert is used to test concrete cast against a steel shutter after the shutter is removed, a 7 mm hole is drilled in the shutter and the insert is installed as shown in figure 13.

Remember to remove the screw before the shutter is removed! The testing takes place as later described.

Floating inserts, type L-49 and L-50

For testing of a slab from above, the CAPO-test is recommended to be used as

Figure 15. LOK-test instrument (type High Strength) with accessories.



Content:

- | | |
|---|--|
| <p>1. LOK-test instrument.</p> <p>2. Suitcase with foam insert.</p> <p>3. Centering plate.</p> <p>4. Short pullbolt, 0-50 kN.</p> <p>5. Coupling, 0-50 kN.</p> <p>6. Stem removal tool, 110 kN insert</p> <p>7. Pullbolt with flange, 0-110 kN.</p> <p>8. Extension counterpressure.</p> <p>9. Coupling, 0-110 kN.</p> <p>10. Oil refilling cup</p> <p>11. Oil refilling bottle.</p> <p>12. Stem removal tool, 50 kN inserts.</p> <p>13. Bolt tool.</p> | <p>14. Long pullbolt, 0-50 kN.</p> <p>15. Pliers for stem removal of 50 kN inserts.</p> <p>16. 19 mm and 17 mm wrenches.</p> <p>17. 14 mm wrench.</p> <p>18. 11 mm wrench.</p> <p>19. Large screwdriver.</p> <p>20. Small screwdriver.</p> <p>21. 5 mm Allen key.</p> <p>22. Calibration table with manual.</p> <p>23. Extra travel ring.</p> <p>24. Pliers for stem removal of 110 kN inserts.</p> <p>25. Tube.</p> |
|---|--|

illustrated in figure 34, page 71. The other option is to use the floating LOK-test insert types L-49 or L-50. To test top surfaces reliably, it is important to float the insert sideways into the fresh concrete submerged, 5-10 cm, for the aggregates to float representatively into the failure zone. Then the insert is tilted 30 degrees and the concrete is consolidated. By using this technique, air from below will escape the steel plate attached to the floating cup. To keep the insert tilted, a lump of concrete is poured into one side of the floating cup. Remember to install the insert so deep that the minimum distance from the centre of the test and to the surface is minimum 100 mm.

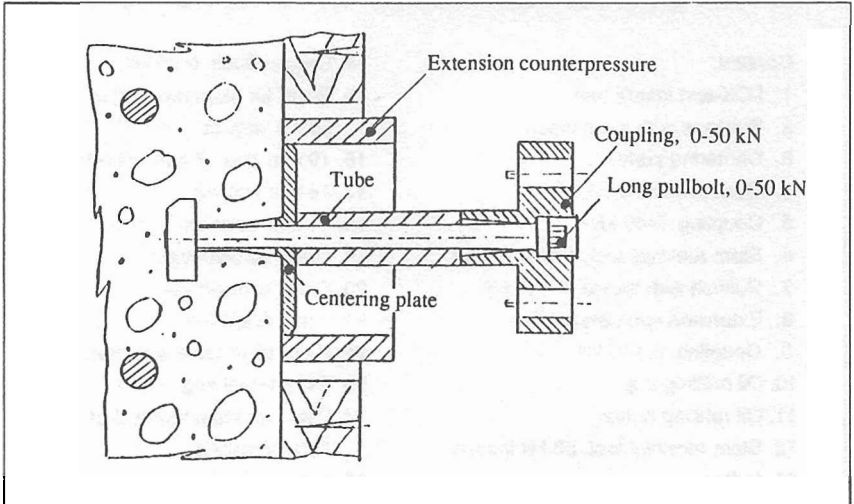
At the time of testing, indicated by maturity, any overlapping concrete is removed with a chisel and a hammer, the centre screw is removed together with the cup and the steel plate below. Blow all dust away and remove irregularities on the test surface. The testing is performed as later described.

The LOK-test equipment

Figure 15 illustrates the complete kit containing the »High Strength« LOK-test instrument with all accessories. The »Standard« and the »Automatic« kits are similar, only they are not supplied with the special tools for high strength testing (labelled 6, 7, 9 and 24).

Before testing takes place, the »Checklist for the LOK-test instrument« supplied with the instrument manual is filled out and signed.

Figure 16. The lengthened pullbolt installed together with the extension piece, the tube, the coupling and the centering plate for testing through a shutter.



Pull-out testing by LOK-test

The testing takes place as follows:

- All insert parts except the disc and the stem, see figures 11 to 14, are removed along with parts of the shutter (see figure 12) if so needed. The testing surface is inspected. No visible flaws are allowed as the surface must be plane (perfectly flat).
- The stem removal tool is screwed into the embedded stem all the way (clockwise). The movement is continued (a hard resistance is felt) and the stem's left-hand thread is turned out. The stem is removed from the stem handle with the pliers and discarded.

Note: Do not reuse the stem since the missing coating and any scratches on the surface may create excessive bonding to the concrete and prevent the stem being removed.

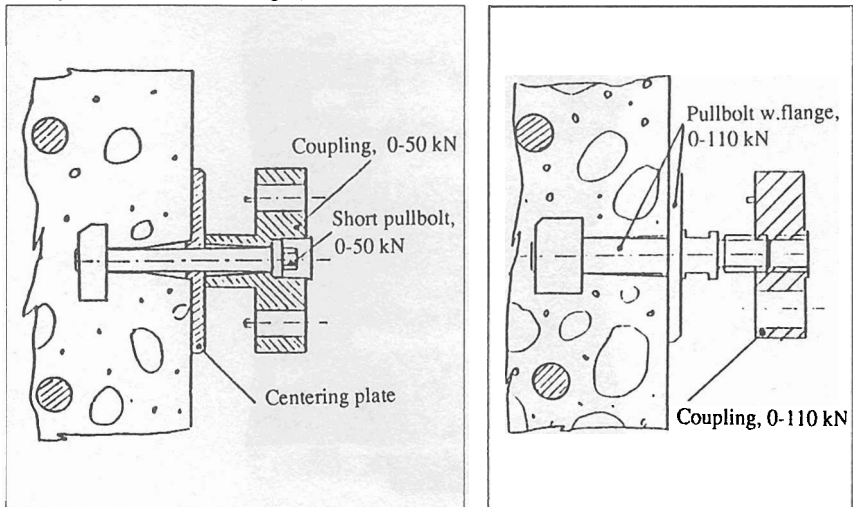
- If the testing has to be done through the shutter or deeper into the concrete than at the surface, the lengthened pullbolt, the extension counterpressure and the tube are used together with the coupling and the centering plate, see figure 16.

With the bolt handle the pullbolt is connected anti-clockwise into the cast-in disc until no further movement is possible, about 6 rotations, and then released 1/2 rotation for the coupling to be free to rotate.

The same procedure may be applied to floating type inserts, figure 14.

- If the testing needs to be done on the surface after the shutter has been removed, the pull-out bolts are installed as shown in figure 17, again by turning them anti-clockwise. For the configuration shown in the left side of

Figure 17. Attachment of pullbolt to disc for surface testing of 0-50 kN inserts (left) and of 0-110 kN inserts (right).



the figure it is important to attach the centering plate with the 11 mm recess turning away from the coupling. Release the pullbolt with the bolt handle 1/2 rotation clockwise if the coupling is not able to turn freely. The figure on the right illustrates the use of high-strength inserts. Here the pullbolt is turned into the disc by means of the 11 mm wrench supplied. Keep on turning the pullbolt until the flange is resting against the concrete surface. Secure the coupling to the pullbolt 1-2 threads.

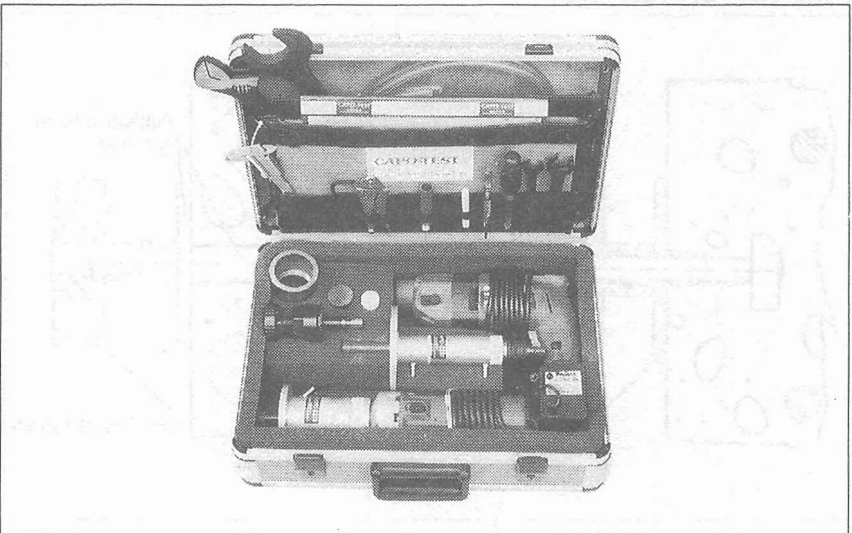
- The telescopic handle of the LOK-test machine is turned counterclockwise 39 rotations to its fully extended position. The three front screws of the machine are guided into the large holes of the coupling. The instrument is leveled to a locking position by pressing the main piston housing towards the concrete surface. The coupling is then turned with two fingers through the port holes 1/4 rotation counterclockwise to fully locked position until a hard resistance is felt.

Note: If it is not possible to couple the equipment, the reason may be that the insert is not cast-in perpendicular to the surface. If this is the case, the test should be rejected. Other reasons may be that the telescoping handle is not fully extended or the coupling parts are damaged.

If the high-strength inserts are tested the instrument is turned clockwise until the front of the casing is resting fully against the concrete surface.

- Loading takes place by turning the handle clockwise. Remaining slack is first taken up, then the gauge pointer starts to move upwards. The loading handle is turned slowly, approximately one rotation every two seconds, clockwise. The gauge pointer will, at the peak load, keep its

Figure 18. CAPO-test preparation kit.



position 1-3 seconds, then it will fall back 1-2 kN.

Note: Always hold one hand on the piston handle (between the two cylinders). Should the pullbolt fail, the equipment will fall down, causing damage to itself. The pullbolts are at delivery tested to 60 kN or 120 kN respectively, but may fail due to wear, non-perpendicular loading or fatigue.

If the disc should not be pulled out, the loading sequence is stopped and the loading handle is quickly turned counterclockwise until the instrument is fully unloaded. Then it is uncoupled and, using the bolt handle (or 11 mm wrench for high-strength inserts) the pullbolt is removed along with the coupling and the centering plate/flange.

The crack following the inner 55 mm diameter counterpressure has to be visible (see figure 56, page 122), otherwise the concrete has not been loaded to failure. Usually the cone is lifted 0.1 to 0.5 mm from the testing surface.

- The maximum pullforce in kN is recorded together with the time of testing, the instrument number and the technician ID. The result is written on the surface of the concrete and in the technicians own personal log-book. Evaluation of the results takes place as prescribed, e.g. in appendix 6, page 112.
- If the testing is performed according to this standard, the cracks formed may be disregarded and no further repair is needed. Alternatively, the cracks may have to be injected with an epoxy. A syringe is filled with epoxy, its needle is pressed through a piece of rubber fitting the 11 mm centerhole and the epoxy is then injected under pressure until it seeps out of the counterpressure crack. The center hole is then closed with a plastic plug or a mortar.
- If the disc inside the concrete may corrode during the servicelife of the structure, the disc needs to be pulled out fully. Then the loading handle of the LOK-test machine is turned all the way clockwise to its fully retracted position. If the machine is fully oil-refilled the 5.5 mm travel of the main piston will usually be sufficient to dislodge the cone. Otherwise, the extra travel ring is mounted in front of the instruments casing after the instrument has been uncoupled. The procedure is then repeated and the cone will be dislodged. The disc is unthreaded from the pullbolt by means of the adjustable pliers and the bolt handle or 11 mm wrench.

The cone hole left in the concrete is blown free of dust and primed with an epoxy glue. Immediately afterwards, the hole is filled with a polymer modified mortar and the surface is smoothed.

CAPO-test in practice

Before the CAPO-test is performed, the testing has to be planned, the equipment checked and found in acceptable condition following the checklist of the manufacturers instruction manual.

The CAPO-test equipment

The following equipment is needed:

- CAPO-test preparation kit, see figure 18.
- CAPO-test suction plate and diamond surface planing wheel, see figure 19.
- CAPO-test pull-out machine with appropriate measuring range, e.g. as the LOK-test machine illustrated in figure 15.
- Sufficient numbers of CAPO-test inserts C-112 (one for each test).
- Covermeter.
- Water container.
- Electricity, extension cord and junction box with 6 outlets.

The CAPO-test preparation kit contains the following components:

1. Counterpressure.
2. Expansion unit with coupling, see figure 20.
3. Diamond recess router with milling machine, 220 VAC or 110 VAC, see figure 22.
4. Alumina suitcase with foam insert.
5. Distance piece, 25 mm.
6. Bottle of CAPO-oil.

Figure 19. CAPO-test suction plate with diamond surface planing wheel.



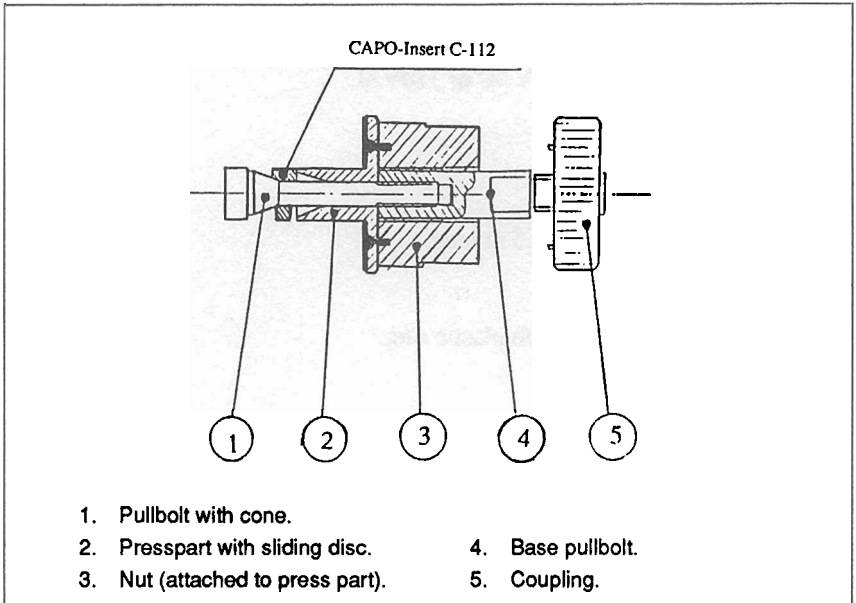
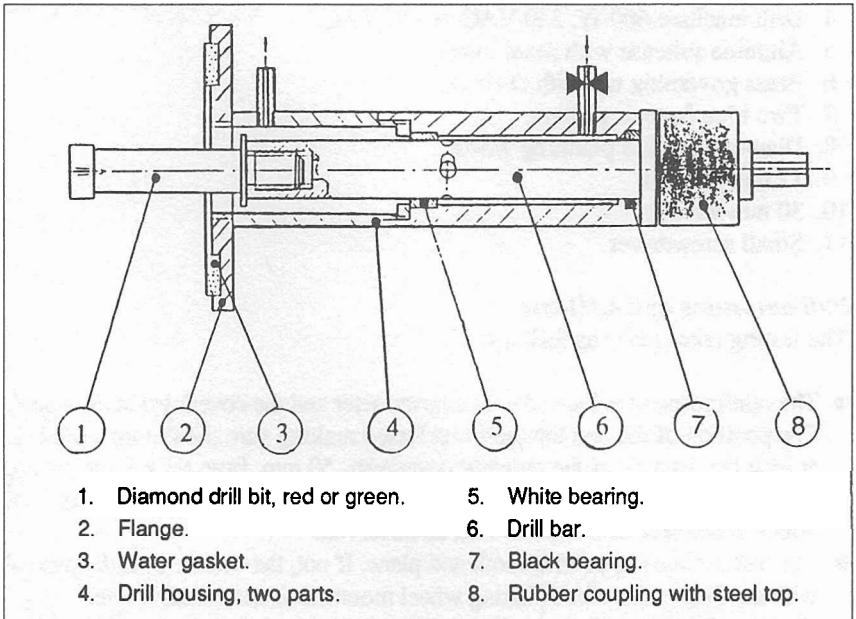


Figure 20. Expansion unit with coupling.

Figure 21. Diamond drill unit.



7. Divepump, 220VAC or 110VAC.
8. Diamond drill unit mounted with green diamond drill bit, see figure 21.
9. Drill machine 600W, 220VAC or 110VAC.
10. Two 17mm wrenches.
11. Two 14mm wrenches.
12. Screwdriver.
13. Tweezers.
14. Two plastic hoses, each 2.5 m long.
15. Marking chalk.
16. Manual.
17. Diamond drill bit, red, with plastic ring.
18. Adjustable pliers.
19. 46 mm wrench.
20. Adjustable wrench, 12".
21. A 4 mm Allen key.

The CAPO-test suction plate with diamond surface planing wheel unit contains the following:

1. Manual.
2. Vacuum pump with vacuum hose and on-off valve.
3. Suction plate.
4. Drill machine 600 W, 220 VAC or 110 VAC.
5. Alumina suitcase with foam insert.
6. Brass governing tap with O-rings.
7. Two blue fastening pliers.
8. Diamond surface planing wheel.
9. 17 mm wrench.
10. 30 mm wrench.
11. Small screwdriver.

Pull-out testing by CAPO-test

The testing takes place as follows:

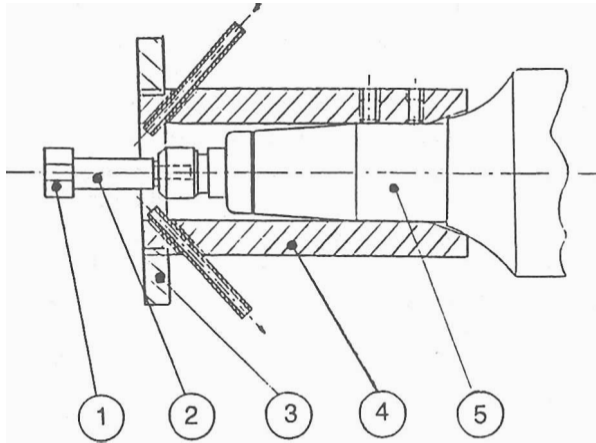
- The reinforcement is located with a covermeter and the coverlayer is measured. The position of the test location is selected making sure the failure surface is at least the distance of the required coverlayer, 50 mm, from the reinforcement. Also the 100mm minimum distance to edges and corners and the minimum 200 mm between two tests should be observed.
- The test surface has to be smooth and plane. If not, the surface must be ground with the diamond surface planing wheel mounted on the suction plate.
- The centre hole is drilled with the diamond drill unit mounted in the drill machine

and supplied with water. The suction plate is again used to control the drilling. If drilled without attachment to the suction plate, drilling takes place to half depth. Then the core is removed with the screwdriver and the tweezers. Resume drilling to full depth of the bit. Then remove the remaining core in the described manner. If drilling takes place by using the suction plate the green diamond drill bit is mounted in the drill unit, otherwise the red bit is used.

- The diamond recess router is inserted in the hole. Water is supplied to one of the inlet nipples and the machine is activated. Routing of the recess takes place until the flange of the router is following the the centre hole of the suction plate by pressing the router flange against the surface and moving it in larger and larger circles. The same procedure is used if the suction plate cannot be applied. Here the recess routing is continued until the diamond shaft hits the drill hole circumference.
- The expansion unit mounted on the CAPO-test insert is inserted in the hole and expanded by means of the adjustable and the 46 mm wrenches. The first wrench holds the base pull-bolt of the expansion unit and the second turns the nut clockwise 9 rotations until the thread of the base pullbolt emerges and a hard resistance is felt. Back off the nut 1/4 rotation.
- The counterpressure is fitted around the expansion unit and the coupling is threaded 1-2 rotations on the thread of the base pull-bolt.
- The pull-machines telescopic handle is fully extended 39 rotations and coupled to the coupling. The coupling is turned 1/4 rotation through the front port holes of the instrument casing as when testing by LOK-test. Remaining slack between the concrete surface, the counterpressure and the instrument is removed by turning the instrument clockwise.
- Loading takes place by turning the handle slowly with a speed of one rotation every 2 seconds. Hold the piston handle located between the two cylinders with other hand. The pointer of the gauge will start to move upwards. Keep on loading at the recommended speed and record the peakload. The pointer will, at the peak load of the load-displacement curve, hold its position for a short moment and then slowly fall back.
- Continue loading using as fast a speed of the loading handle as possible to extract the pull-out cone fully. Do not twist or pull the instrument to release the cone. If there is no more travel left of the telescopic handle, turn the handle anti-clockwise 39 rotations, then turn the equipment clockwise to thread the coupling further on the base pullbolt and repeat the loading sequence. Then the cone will be fully dislodged.

Note: The instrument needs to be fully oil-refilled and the insert has to be correctly installed to make the cone come out in the first loading sequence.

The test result is written on the concrete surface in kN-units together with the time of testing, the instrument and the technician ID-numbers. The result is recorded in the technicians log-book together with other relevant data.



- | | |
|--------------------|---|
| 1. Diamond router. | 4. Router housing with nipples. |
| 2. Router shaft. | 5. Router machine with watertight bearings. |
| 3. Flange. | |

Figure 22. Diamond recess router unit.

Figure 23. The CAPO-test insert is put on the cone pullbolt with the inner sharp edge facing the cone.



- The expansion unit with pulled out concrete cone is uncoupled from the pull-machine, the coupling is unthreaded the base pullbolt and the counterpressure is removed.
- The expansion cone pull-bolt is unthreaded the base pullbolt by means of two 14mm wrenches (*Notice: lefthand thread*). The expanded CAPO-test insert is removed from the cone pull-bolt and discarded.
- After cleaning the parts and oiling the threads and the cone of the cone pullbolt, the parts are assembled as illustrated in the figures 23-27. ■

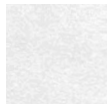
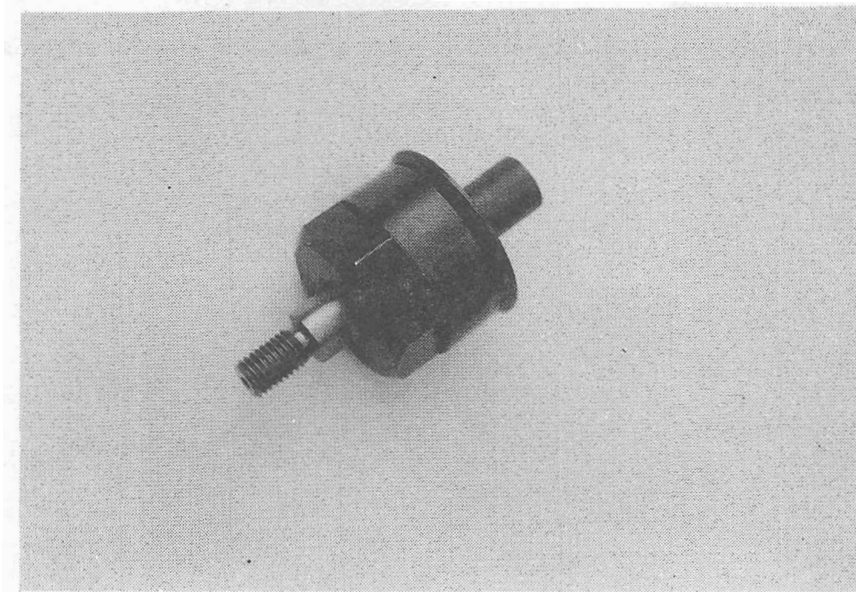


Figure 24. The base pullbolt is fully threaded into the nut with press part. The circle line of the base pullbolt should be flush with the surface of the nut.



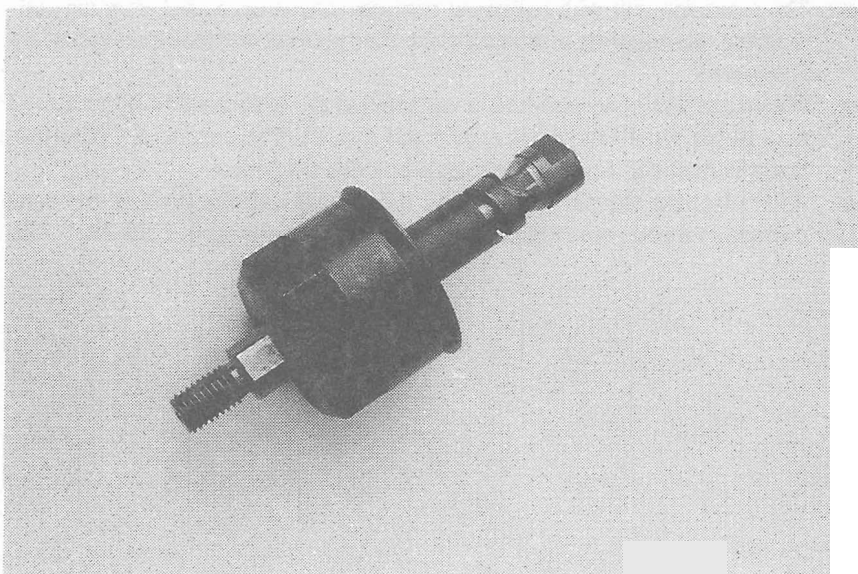
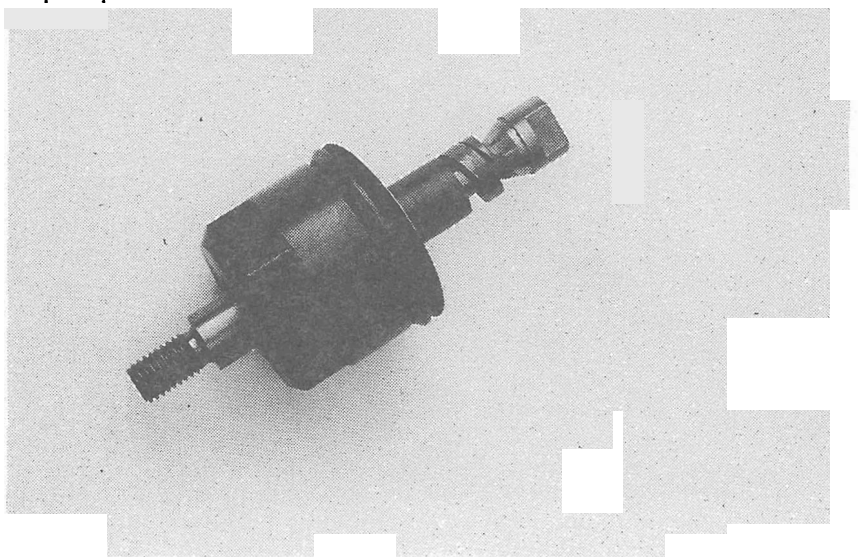


Figure 25. Holding the base pullbolt, the cone pullbolt is threaded fully into the base pull-bolt. Only maximum 0.5 mm clearance between the insert and press part should be present afterwards.

Figure 26. After oiling the sliding disc with CAPO-oil, the disc is mounted the neck of the press part.



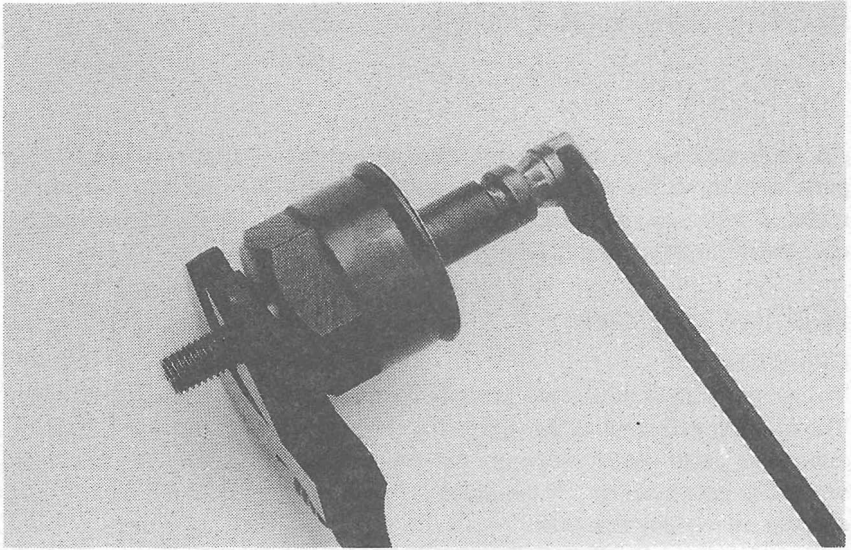


Figure 27. The cone pull-bolt is tightened to the base pullbolt as illustrated (Notice: left-hand thread).

Maintenance of the equipment

All equipment has to be kept dry, cleaned and oiled slightly regularly. The parts have to be free from scratches and damage, otherwise they have to be replaced with new spareparts. The main components of the equipment are checked in the following manner:

LOK-test equipment

Oil refilling

The minimum travel of the main piston of the LOK-test instrument has to be 5 mm. The travel is measured as the difference of the position of the piston from the instrument front casing when the telescoping handle is fully retracted and when it is fully extended. If the travel is less than 5 mm, the following procedure for oil refilling is applied.

The telescoping handle is fully extended (39 rotations). The front end of the small compression cylinder is kept in a fixed position, e.g. in a vice. The instrument may also be coupled to a cast-in insert in a wall or similar. The nameplate on the main cylinder is removed by unscrewing the two small screws. The oil refilling screw under the nameplate is removed together with the small O-ring fitted onto the screw.

The oil refilling cup is pressed into the hole vertically. Then, the telescopic handle is turned clockwise all the way to fully retracted position. Oil and entrapped air will be forced out into the cup. Refill oil from the LOK-test oil refilling bottle supplied into the cup to about 10 mm from the top edge.

The telescoping handle is turned slowly anti-clockwise 39 rotations. The oil will flow into the instrument. Wait until no more oil is flowing. Then repeat the procedure making sure no more air is entrapped in the instrument.

After the final refilling the cup is removed from the refilling hole and excessive oil is poured back into the oil refilling bottle. The oil refilling screw with attached O-ring below is threaded back into place. Do not use excessive force to tighten the screw, otherwise the thread may break. Re-install the nameplate with the two small screws.

Note: The oil coming out of the instrument into the oil refilling cup may be black. This is of no importance for the proper operation of the instrument. But the oil used has only to be the supplied LOK-test silicone oil with a viscosity of 750 centistokes. If other types of oil are used, the special made compression rings will deteriorate and wear out quickly.

Note: Oil needs to be refilled from time to time, even if no leakages are

present, since the silicone oil used is very sticky. It will adhere to the piston cylinder housings and evaporate slowly.

Mending of oil leakages

Oil leakages may show up between the two piston housings around the seals, especially if the instrument has been twisted in or pulled at while releasing the cone failure during testing. In this case the joint connections have to be tightened. To do so, first remove the black piston handle between the two pistons (if attached). This is done by removing the labels and unthreading the two screws with a 5 mm Allen key. Then the two parts of the handle may be removed. Hold the 19 mm wrench on one of the joints close to the main cylinder and tighten the adjacent one with the 17 mm wrench. If oil leakage appears from one of the seals close to the small compression cylinder tighten the tube where the leakage shows up.

Refill the instrument with oil as illustrated above and load the instrument, e.g. on a cast-in insert to say 30 kN or on a calibration unit as later described. Keep the loading handle in the same position. The pointer should not drop. If it does, observe where the leakage is coming from, try to tighten the joints, refill oil and load again. All other types of repairs including oil leakages stemming from worn out pistons, have to be repaired by:

GERMANN INSTRUMENTS A/S

102 Emdrupvej, DK-2400 NV Copenhagen, Denmark

Phone: + 45 31 67 71 17, Fax: + 45 31 67 31 67, Tlx: 16 767 german dk

or by:

GERMANN INSTRUMENTS INC.

8845 Forest View Road, Evanston, Illinois 60203, USA

Phone: (708) 329-9999, Fax: (708) 329-8888

Calibration

The LOK-test hydraulic pull-machine has to have readings in kN (kilo Newtons) calibrated to actual pullforce in kN

- after each 1000 tests,
- at least once a year,
- if the instrument is damaged or serviced or if the gauge is changed.

The calibration is performed on a calibration unit which has been parallel calibrated on a national test machine with authorized certificate.

To conduct the calibration the LOK-test machines telescoping handle is fully extended and the machine is coupled to the calibration unit. This unit has readings in »kg« (kilogram-force) with an accuracy of 0.6 per cent. The instrument is loaded and the comparative measurements are made for each of the smallest division of the instruments scale. The readings are repeated three times and the average is calculated. The actual pullforce in kN is calculated as the kg-value of the calibration unit multiplied by 9.81 over 1000.

The calibration table supplied with each instrument also contain the conversion from actual pull-out force in kN to compressive strength in MPa (Mega Pascal) or psi (Pounds per Square Inch) for standard cylinders (or cubes). This conversion equation is as assigned page 10 (for cylinder strength). If the user of the LOK-test needs to prepare his own conversion equation, the procedure for producing such a relationship is given in appendix 2, page 85.

The calibration sheet further contains the following information:

- Date of calibration.
- Instrument identification.
- Number of calibration.
- Name of personel performing the calibration.
- ID number of calibration unit.
- ID number of parallel calibration machine.
- Controlling officer.
- References.

Furthermore, the instruments nameplate is stamped with the date of calibration and/or service. This date has to match the date of the calibration sheet.

CAPO-test equipment

To preserve the proper functioning of the equipment, all parts have to be inspected after each test series. If the parts are in good working order, clean them with gasoline and lightly oil them. The threads have to be working together smoothly and they have to be oiled with the supplied CAPO-oil. Furthermore, the following units have to be inspected as follows (for a careful description follows the CAPO-test manual issued by the manufacturer).

Diamond drill unit

If water is leaking through the black top bearing, unthread the diamond bit from the drill bar. The top screws placed closest to the bearing in the top part of the drill housing are removed with a screwdriver. The bearing is lifted out with the screwdriver and a new bearing is pressed into place. The top screws

are reinstalled.

The thread of the bit is cleaned. Use a steel brush if necessary. Oil the thread. Press the drill bar back into place gently while oiling the bar and connect it to the drill bit.

If the white bottom bearing is sluggish causing the water to leak (which may be observed when the drilling turns out dry) it has to be replaced. Disconnect and remove the bit from the drill bar.

The two parts of the drill housing are unthreaded, thereby exposing the white bottom bearing. It is removed by pressing a screwdriver towards it from the end of the black bearing side. A new bearing is inserted and the unit is reassembled.

The same procedure applies for installing new black and white bearings of the diamond surface planning wheel unit.

If the diamond bit diameter is less than 18.2 mm, the bit is discarded and a new one installed. If the drill is not running smoothly when connected to the drill machine and turned on, the rubber coupling parts have to be replaced.

Diamond recess router

Check the following dimensions:

- Hold the distance piece of 25 mm between the flange and the diamond router. The distance should be exactly 25 mm. Otherwise adjust the positioning of the housing on the machine by unthreading the two 4 mm Allen screws.
- The router shaft diameter should not be less than 10.5 mm. Otherwise replace it. To do so, remove the housing from the machine and loosen the joint holding the shaft by means of the two 17 mm keys supplied.
- The diameter of the diamond router should not be less than 17.5 mm, otherwise unthread it from the shaft and install a new one. Remember to tighten it firmly to the shaft.

These dimensions are taken together in order to do the following calculation with an example shown:

Diameter of the diamond router	17.8 mm
The minimum diameter of the shaft	10.9 mm
	Difference: 6.9 mm
Drill bit diameter	18.3 mm
Routed hole diameter	Sum: 25.2 mm

This number, 25.2 mm, should be between 25.0 mm and 25.5 mm for the insert to be expanded properly and the test to be correct. ■

Recording of data

The registration of all observations in relation to the quality of the concrete and the testing is relevant since it may turn out to be important for later interpretation of the test results.

Log-book

Each technician performing the testing has to record all relevant test data in a personal test log-book with numbered pages using a ball point or ink pen (no corrections, please!). All relevant circumstances in relation to the testing are recorded:

- Date of testing.
- Instrument identification.
- Last calibration date, reason for last calibration and number of calibration.
- Service report.
- Type of pull-out test: LOK-test or CAPO-test.
- Positioning of the tests and identification.
- Test results (reading and actual pull-out force).
- Weather conditions during testing.
- The concrete maturity at the time of testing and means of measuring maturity device (temperature registration, maturity computer, coma-meter etc.) along with the position of the sensors.
- Type of concrete mix, date of casting, and curing conditions. Also when the formwork was removed.
- Concrete batch identification and position in-place.
- Special conditions related to frost resistance, drying effects, stripping of the shutters, and insulation.
- Remarks regarding any kind of irregularity.
- Remarks to the types of pull-out failures and the pull-out cones (aggregates, entrapped air, porosity etc.).
- Identification of supplementary testing taken.
- Registration of any photos taken.

Recording the maturity

At the trial casting the pull-out testing has to take place at a maturity of 1, 2, 3, 7, 14, 28 and possibly 35 maturity days (i.e. days at 20 centigrades). To do this accurately, it is required to measure the temperature minimum 6 times a day, if so wished. Alternatively, a maturity computer or COMA- meters have to be used, which measures and calculates the maturity automatically, see appendix 7, page 118.

Inspection of the pull-out cone geometry

The equipment necessary for checking the dimensions of the cone hole left standing in the concrete surface is shown in the figures 28-31 ■

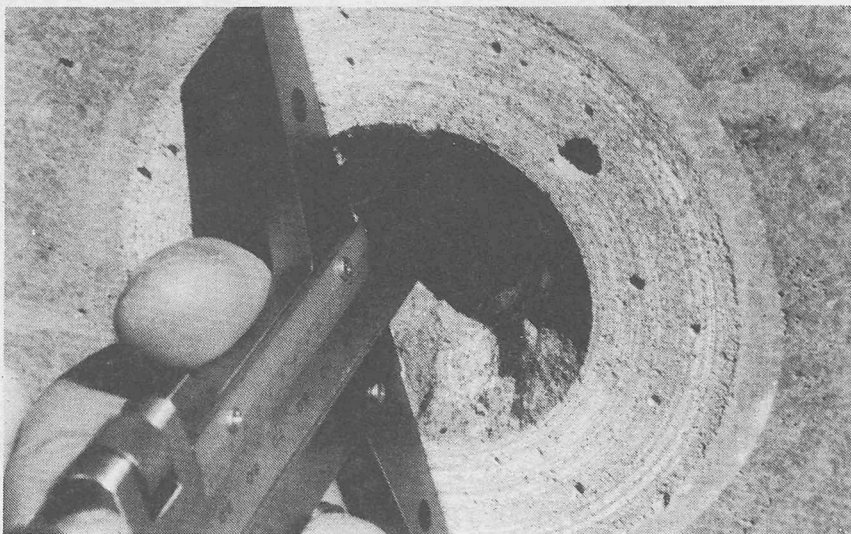
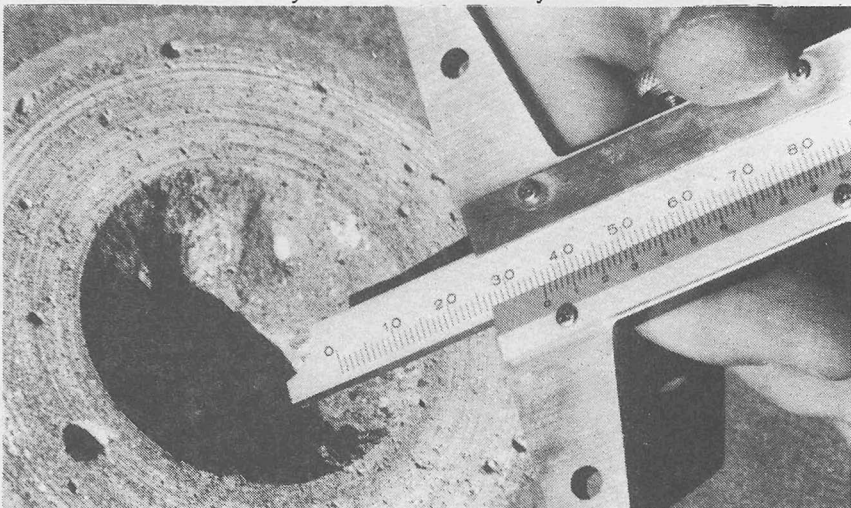


Figure 28. Measurement of the depth of the routed recess after a CAPO-test has been completed. The measurement is made as illustrated by means of a depth gauge.

Figure 29. The measurement is taken as the depth to the backside of the recess and subtracting the depth of the recess hole. The depth to the front side of the recess has to be $25\text{ mm} \pm 0.2\text{ mm}$. Similarly the check is carried out for the LOK-test.



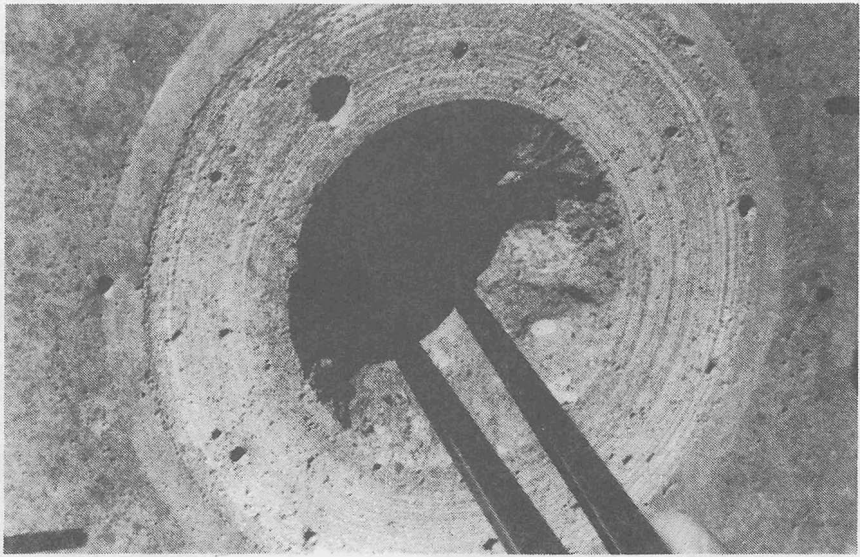
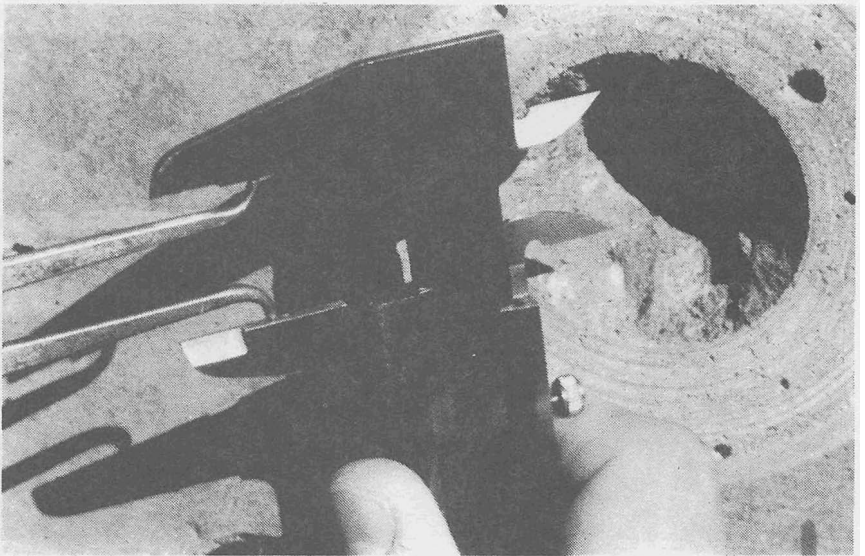


Figure 30. Measurement of the diameter of the drilled hole and the routed recess is made using an inside caliper after a CAPO-test has been performed.

Figure 31. A vernier measures the diameter of the hole(s) as the distance between the inside calipers pins. The diameter of the drilled hole has to be between 25.2 mm and 25.5 mm. The recess diameter tolerances has to be minimum 25.0 mm, maximum 25.5 mm for the CAPO-test to be performed correctly.



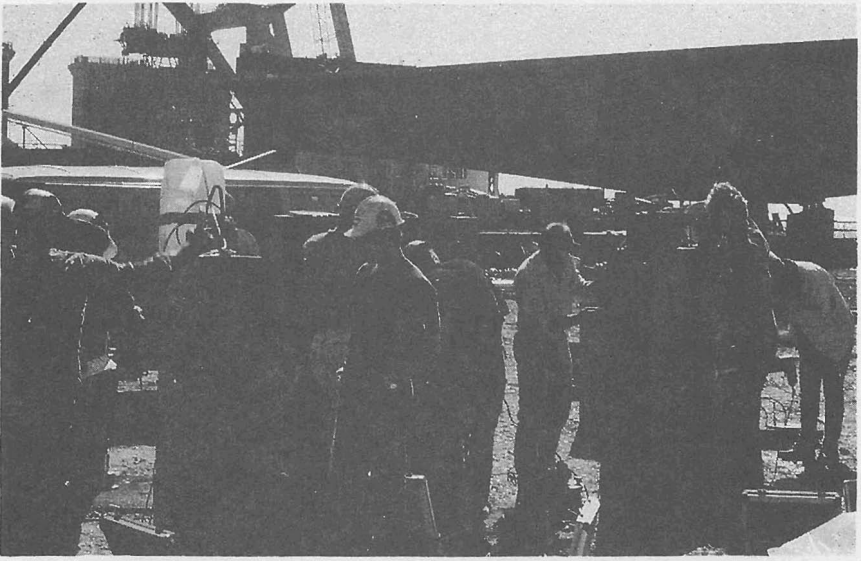
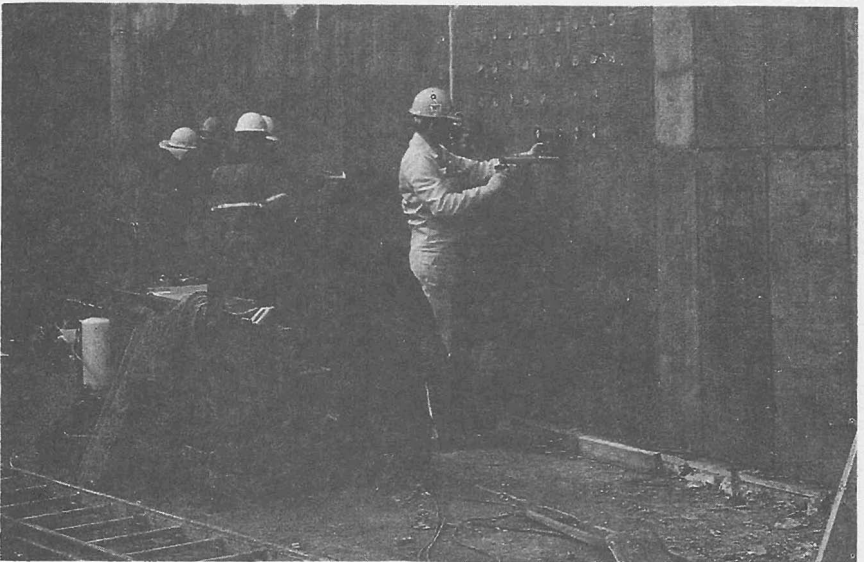


Figure 32. Training of the technicians at the laboratory. A great deal of practice with LOK-test and CAPO-test is a part of the pull-out testing course for the contractor's technicians.

Figure 33. Training of the technicians in the field. The technicians finally pass an examination and a diploma is issued.



Appendix 1.

Inspection and testing by LOK/CAPO-test

Ever since the start of this century discussions have been going on how to control the compressive strength of concrete. Among the issues debated are:

- *Where to measure the compressive strength?*
 - By test specimens cast directly from the concrete plant mixer, vibrated on vibration table and cured in water 28 days at 20 centigrade?
 - By test specimens cast from the concrete truck at the site, vibrated on-site and cured besides the structure?
 - By the structure itself after 28 maturity days under actual curing conditions?

- *When to measure the compressive strength?*
 - After 28 maturity days no matter what type of cement to be used?
 - At the time when the strength in-situ is needed, e.g. in relation to early loading operations as to determine early and safe timing of the stripping of the formwork, removal of reshores or various tension operation?

- *How to measure the compressive strength?*
 - By cast test cubes, 100 mm, 200 mm or 300 mm side length?
 - By various other types of cast prisms with equal side length a of the cross section and a high h , where a relates to h as 1 to 2? (Has h to be 200 mm or 300 mm?).
 - By cast cylinders with diameter d and a high h , where d relates to h as 1 to 2? (Has h to be 200 mm or 300 mm?).
 - By prisms or cores cut or drilled out of the structure? (How should the specimens be prepared and cured before testing in compression, in air or in water?).
 - By means of in-place testing methods testing the concrete structure itself?

The discussion is still going on and will no doubt continue for a long time to come.

In Denmark, the Danish Code of Practice for the Structural Use of Concrete DS 411 specifies the maturity needed before testing may be done, the type and the size of the test specimens and where the testing has to take place, at the same time as it allows in-place testing to be adopted in the actual conditions of particular structures if so desired by the structural engineer or the contractor.

Purpose of inspection and testing

The Great Belt Link Ltd. (A/S Storebæltsforbindelsen) has in SAB, the special specifications for concrete concerning the structures of the fixed link across the Great Belt, in detail specified how the control testing of the compressive strength has to be performed.

For the measurement of the *potential compressive strength* of the concrete, test cylinders (diameter of 150 mm and height 300 mm) according to the Danish Standard DS 423.20 have been chosen.

For measurement of the *achieved compressive strength* of the concrete structure itself the LOK-test and the CAPO-test in-place testing pull-out systems according to the Danish Standard DS 423.31 have been chosen.

The purpose of the testing may differ depending on the interests involved, whether they originate from the owner or from the contractor:

■ *The potential strength of the concrete*

The owner specifies this requirement to make sure the delivered concrete has sufficient potential strength when delivered from the mixing plant, so that the required strength of the structure may be achieved under actual transportation, casting, compaction and curing conditions specified by SAB.

The achieved compressive strength of the structure

The owner specifies this requirement to make sure the needed code-stated safety factor against collapse or local failures is achieved.

The uniformity of the compressive strength of the structure

This requirement is specified by the owner when the required compressive strength for avoiding collapse is (considerable) lower than the compressive strength achieved caused by compliance with durability requirements (mainly w/c-ratio and curing).

■ *Early strength of the concrete*

The contractor typically formulates this requirement. The motive is to speed up a construction schedule (early form stripping, early tensioning of structural elements or otherwise early loading operations).

The use of LOK-test and CAPO-test pull-out testing is in the following commented in relation to this classification and with reference to the Danish Code of Practice DS 411, the SAB and the General Note of the SAB.

Control testing of the 28 maturity days compressive strength

To obtain a required safety against collapses the concrete code requires the potential strength of the concrete to be in compliance with the static calculations made by the structural engineer. The potential compressive strength has to be achieved at 28 maturity days (days of curing at 20 centigrade) regardless of the type of cement to be used.

The potential compressive strength is measured on cylinders, 150 mm in diameter and 300 mm in height according to the Danish Standard DS 423.20.

Requirements of the Danish Code of Practice DS 411

Besides measuring the compressive strength by means of cylinders the code allows determination of the actual strength of the in-place concrete as mentioned in its clause 3.1.3.1 (page 21 of the DS 411):

»The required compressive strength may also be proven to be accomplished by measurements of specimens taken from the finished structure or by indirect in-place testing methods, e.g. according to DS 423.30, DS 423.31, DS 423.32 and DS 312.33, if a correlation between the values obtained by the methods in question and the above described cylinder compression strength values is documented. The requirement is considered to be fulfilled, if the measured in-situ strength is higher than 80 per cent of the required cylinder compressive strength«.

The indirect in-place testing methods mentioned are the following four:

- DS 423.30: Concrete testing, hardened concrete, Rebound Number.
- DS 423.31: Concrete testing, hardened concrete, Pull-Out Test.
- DS 423.32: Concrete testing, hardened concrete, Break-Off Test.
- DS 423.33: Concrete Testing, hardened concrete, Ultrasonic Testing.

In addition to the above mentioned systems, other related methods, e.g. the CAPO-test, have been developed for testing the compressive strength in-place. They are described by e.g. *Claus Schmidt*: »Non-destructive Testing of Concrete«, Concrete Technology Magazine (Beton-Teknik) No. 4/09/1990, Aalborg Portlands Technical Information, CtO (in Danish).

Requirements of the SAB

The LOK-test and the CAPO-test have been chosen by the Great Belt Link Ltd. to inspect and control its concrete works in-situ since they measure the compressive strength of the rebar cover most reliably with a minimum of amount of tests. Also, the reliability of the test has been substantiated carefully by means of comprehensive scientific and practical documentation.

The SAB mentions in clause 4.5.6 dealing with »Inspection and testing of the Composition of the Concrete« in clause 4.5.6.2 the following related to strength measured by pull-out testing:

»As one test (observation) is understood the average of minimum two single test results. The position of the inserts has to be within a circle with a diameter of maximum 300 mm and the minimum distance between inserts has to be 200 mm.

For each 100 cubic meter of concrete a minimum of two observations have to be taken. For each control section a minimum of three observations have to be made. Before the casting of concrete in a control section, the contractor has to submit to the supervision a plan for positioning of the inserts for acceptance.

The testing of the inserts has to take place at a concrete maturity of 28 days at 20 degree Celcius. If the testing is performed at a different maturity (1-3 days difference is allowed) correction of the results has to be made to 28 maturity days.

Each control section has to fulfill the required compressive strength. Furthermore, it has to be documented, that the strength level found at the full scale trial testing, measured by LOK-test and CAPO-test, during production falls within ± 7 kN. If the strength level during production falls outside these tolerances, additional CAPO-tests have to be performed. In case these tests still falls outside the tolerances mentioned, the cause has to be found and correction made accordingly«.

This clause applies for the East Bridge of the fixed link across Great Belt. Almost same wording is found in the SAB for the West Bridge and the Tunnel, only the tolerance has not been specified, but has to be declared by the contractor and approved by the Employer's Representative.

Concerning the strength requirement of the concrete, section 4.3.2 of the SAB states the following text:

»The required compressive strength is given in the General Note. The requirement has to be fulfilled for cast cylinders as well as for pull-out testing performed on the structure, and has to be evaluated according to the Danish Concrete Code DS 411, 3rd edition«.

Requirements of the SAB's General Note

The General Note of the SAB enumerate the following characteristic strength requirements at 28 maturity days, depending on the type of concrete mix:

- Tunnel, type A1: Characteristic compressive strength, 50 MPa
- Tunnel, type A2: Characteristic compressive strength, 40 MPa
- Tunnel, type B1: Characteristic compressive strength, 35 MPa
- West Bridge, type A: Characteristic compressive strength, 45 MPa
- West Bridge, type B: Characteristic compressive strength, 45 MPa
- On-shore bridges, type B: Characteristic compressive strength, 35 MPa
- East Bridge, type A: Characteristic compressive strength, 45 MPa
- East Bridge, type B: Characteristic compressive strength, 45 MPa

The expected 28 days characteristic compressive strength is however, higher than the above quoted caused by some other requirements specified related to the mix design, especially the w/c -ratio and the air content.

It should be mentioned that the required w/c -ratio of the A1, A2 and A-type mixes is the same – a maximum of 0.35 – while the minimum required characteristic compressive strength varies from 50 MPa to 40 MPa. Also, the strength requirement of type A and type B concretes of the West Bridge is equal (minimum 45 MPa), while the maximum w/c -ratio is specified to be 0.35 and 0.45, respectively.

As an example, the characteristic compressive strength of the mix used for the tunnel elements typically reaches 70 MPa at 28 maturity days.

Laboratory concrete and in-place concrete

The SAB requires the potential strength of the concrete to be measured by cast cylinders and to fulfill the minimum characteristic compressive strength requirements as stated above.

The cylinders are cast, compacted and cured perfectly under ideal conditions. Such concrete may be designated as »lab«crete in opposition to »real«crete, i.e. the concrete of the structure cast, compacted and cured under actual conditions.

The *potential compressive strength* as indicated by the »lab«crete (cast cylinders) is a measure of the highest attainable strength for the mix in question, achieved under the most favorable conditions at a degree of compaction as it only occurs in a cylinder.

The *in-place compressive strength* of the »real«crete is the concrete structure's strength achieved under the actual working conditions on-site.

The difference between the potential and the in-place compressive strength is, for the same mix and at the same maturity, consequently a measure of the

quality of the concrete works on-site. Experience has shown that especially the compaction and the curing conditions are critical factors that may reduce the in-place compressive strength relative to the potential considerably. The Danish Code of Practice DS 411 and the SAB accept the in-place strength to be minimum 80 per cent of the potential strength.

Durability

The mix designs of the concrete of structures on the Great Belt Link have been chosen under strength as well as durability considerations. The strength requirement is motivated by the wish to achieve the required safety against collapse and local failures. The durability requirement is put forward to obtain the safety against disintegration during the intended service life of the structure and to minimize the costs of maintenance and repairs in the future.

Durability is achieved by setting up requirements to the concrete materials, its composition, compaction and curing and to make sure that the requirements are fulfilled. Some of the parameters required to be fulfilled to achieve the needed strength and durability, are the same, e.g. the *w/c*-ratio. This means that a durability requirement may cause the concrete to be stronger than strictly needed from a pure safety-against-collapse consideration. In such cases, the durability requirement is said to dominate the strength requirement. This circumstance is typical for the concrete mixes used at the Great Belt Link project.

In-place compressive strength of concrete

The compressive strength of the »real«crete is naturally depending on the potential strength of the concrete delivered to a site, but not only. When the concrete leaves the mixer, it is subjected to transportation, casting, compaction and curing under the actual conditions. The pumping may reduce the air content and 1 per cent lower air content generally increases the strength by 5.5 per cent. For quality control purposes the cylinders should consequently be taken after the pumping.

Inappropriate compaction and curing conditions will reduce the achieved compressive strength of the structure compared to the potential strength. Insufficient compaction and lack of sufficient curing conditions will cause defects (entrapped air, crack formation and low degree of hydration). Such defects will have a significant influence on the compressive in-place strength.

The »real«crete will never be as good as the »lab«crete, even if the compaction on-site and the curing conditions applied are performed as correctly and as carefully as possible. The Danish Code of Practice DS 411 addresses this aspect by »only« requiring the in-place strength to be greater or equal to 80 per cent of the potential strength. The motivation for choosing 80 per cent is partly that the uncertainty of less good compaction and curing conditions exerci-

sed on-site has been reduced considerably by specifying in-place testing.

If the durability requirement dominates the strength requirement, the required in-place strength needs to be formulated not only based on the rule of 80 per cent mentioned in DS 411, but it has to be established based on a trial casting, where acceptable compaction and curing conditions have been exercised. The trial casting is also important in another situation. If e.g. the contractor chooses to produce a concrete with a potential strength much higher than the strength requirement put forward in the SAB to fulfill the durability requirement, the concrete would be »strong enough«, but it could be mistreated and full of defects, which would allow harmful substances to penetrate the rebar cover and thus reduce the durability and the servicelife of the structure.

Strength requirements of the SAB

Consequently, the SAB formulates three strength requirements:

- The potential characteristic compressive strength stated in the General Note of the SAB has to be fulfilled, otherwise the structure itself will not be able to meet the required in-place strength.
- The in-place characteristic compressive strength stated in the General Note of the SAB has to be fulfilled to make sure the required safety against collaps and local failures is achieved.
- The compressive strength of the structures coverlayer has to be of the same order as that of the trial casting, where it is documented that the potential strength, the transportation, the casting, the compaction and the curing of the concrete meet the specifications and where petrographical analysis have demonstrated an acceptable degree of defect intensity. For the tunnel elements, chloride penetration tests have further to prove that the chloride diffusion coefficient of the concrete is less than specified as a maximum.

Some important designations

Practice has shown that it may be difficult to distinguish between the three above mentioned types of requirements and their motivations. In brief, the designation of the three requirements could be:

- Inspection of the *potential concrete strength* of the delivered concrete by means of cast cylinders.
- Inspection of the *in-place concrete strength* of the structure by means of pull-out testing (LOK-test and/or CAPO-test).
- Inspection of the *concrete control parameters* of the rebar cover by means of pull-out testing.

Defect intensity of the rebar's concrete cover

If the curing of the structure is insufficient the following defects may appear:

- *Thermal cracking.* The concrete surface is cooled off quicker than the internal parts of the structure. When cooled off, the surface part of the concrete is contracted, but is prevented from doing so by the inner massive part of the structure. Thus, tensile stresses are created, which may lead to cracking of the coverlayer. Thermal cracking is prevented by insulating the surface in such a manner that the difference in temperature during hardening between the surface and the internal part of the structure is less than specified by the SAB.
- *Shrinkage cracking.* The surface is dried out quicker than the internal part of the structure. Again, if dried out, the concrete surface contracts itself, but is prevented from doing so by the inner massive parts of the structure. Shrinkage stresses develops, which may cause the surface to crack. If the cracking occurs while the concrete is still plastic, the phenomenon is called »plastic shrinkage«. Similarly »drying shrinkage« is said to take place if the concrete has gained strength and no longer is plastic. One should only remember that both types of shrinkage are caused by drying-out of the surface layer.
- *Surface porosities* caused by drying-out of the surface part. Normally, water will be substituted from the inner parts of the structure to the surface, but the very impermeable »three-powder cementing matrix« used in concrete of the Great Belt Link project is unable to do so. Consequently, the hydration of the concrete at the surface is prevented, and the microstructure of the binder of the concrete becomes porous. The result may be a concrete surface without the required impermeability towards aggressive gasses and liquids.

The defects mentioned will only be created at the surface of the structure. This surface is the structures coverlayer, which is supposed to protect the reinforcement against aggressive attacks, and is in this way the critical part of the structure.

Measures of the defect intensity of the rebar's cover

In practice it is impossible to avoid defects of the coverlayer. There will always be a certain tendency to formation of thermal- and shrinkage cracking as well as surface porosities. Therefore, the coverlayer of a structure will usually be less impermeable than the internal parts. When designing or supervising a structure one should always keep in mind:

To design a sufficient impermeable coverlayer protecting the reinforcement in order to improve the durability of the structure. In addition the concrete

behind the coverlayer, the »heart«crete, has to be sufficiently strong to carry the loads.

Concrete surface defects may be observed by petrographic analysis (by plane polished sections and thin-sections) performed on drilled-out cores. Or they can be estimated by subjecting cores taken from the structure to aggressive gasses or liquids and measure the penetration of such gasses or liquids into the concrete (carbonation, chloride ingress etc.) subsequently.

Control parameters

However, petrographic analysis, testing for carbonation and chloride ingress is time consuming, costly and the contractor is normally not able to conduct such test her- or him-self. This type of testing is therefore not practically suitable for conducting a »self-control« to check the defect intensity of the coverlayer. To find a suitable control parameter, the following chain of reasoning is applied:

- Hardened concrete consists of aggregates, a cementing matrix and defects. Control schemes have for the Great Belt Link project already been established for the aggregates and the cementing matrix and its constituents, while the defect intensity may vary.
- The protection of the reinforcement depends on the coverlayers impermeability against aggressive gasses and liquids, e.g. carbon dioxide and chlorides. The impermeability is controlled by the depth of the coverlayer and its soundness.
- The soundness depends on the impermeability of the cementing matrix itself as well as of the defects. If the coverlayer has many defects, the reinforcement will not be protected.
- A coverlayer containing defects has, compared to a »perfect« coverlayer other pronounced characteristics than lower impermeability (or higher permeability). One such characteristic is less strength. It is presumed, that the strength of the cementing matrix has a comparatively small variation.
- A defect coverlayer is weaker than a perfect one. Therefore, it is possible to identify a defect coverlayer by measuring its strength and make comparison with the perfect coverlayers.
- Pull-out testing is the most reliable test system for measuring the compressive strength of a coverlayer (the near-to-surface strength).

Hardening of concrete under hydraulic pressure

Concrete cast in one casting in a tall wall or a column will normally be subjected to a hydraulic pressure. The hydraulic pressure will affect the compressive

strength of the concrete. Therefore, the strength at the bottom of a casting is usually higher than at the top. This phenomenon has to be taken into account when deciding where to place the pull-out inserts.

The SAB clause 4.5.10.10 states in its amendment to the Danish Standard for pull-out testing: *»A test's individual trial is placed in the same horizontal layer with regard to the minimum distance to the edge given in DS 423.31«.*

Expectations of the owner

There are two purposes with the application of pull-out testing of the Great Belt Links concrete works. The first is related to the *strength requirement*, the second to the evaluation of the *durability*.

Strength requirements

The owner requires the compressive strength of the concrete at 28 maturity days to fulfill the requirements stated in the SAB's General Note. This requirement is motivated purely by strength considerations demanded by the static calculations of the structural engineer.

The traditional cylinder testing according to the Danish Standards DS 423.21 and DS 423.23 is a measure of the potential strength of the concrete at a degree of compaction as in a cylinder. The compressive strength of the in-place concrete is, however, depending on the workmanship performed on-site (the casting, the compaction and the curing). This has motivated the owner to specify *»that the compressive strength of the in-place concrete is proven by indirect methods used on the structure«*, according to the Danish Code of Practice for Structural Use of Concrete, DS 411 clause 3.1.3.1.

Demonstration of the strength requirement takes place as outlined in the clause 8.1.1 *»Rule of decision for control«* of the Danish Standard DS 411.

The test frequency follows the guidelines of DS 423.1, 2nd edition, 1985, named *»Testing of concrete – Sampling, inspection and statistical interpretation of test results«*, that is *»2 to 3 samples for each 100 cubic meter of concrete, but a minimum of 3 samples for each inspection section«*. On the other hand, the SAB does not specify a minimum sample size in relation to the number of batches in a inspection section as stated in DS 423.1.

Durability requirements

The owner demands documentation stating that the concrete at 28 maturity days complies with the SAB requirements for impermeability against aggressive substances (gasses and liquids), especially chloride.

This requirement is motivated purely by durability considerations. The

SAB specifies further, but for the tunnel elements only, a required coefficient of chloride diffusion, made necessary by the service life calculations made by the structural engineers.

Testing for chloride ingress

Prior to the start-up of the Great Belt Link project the owner conducted concrete investigations showing that the casting, the compaction and the curing steps have significant effects on the ability to chloride ingress of the concrete used, for which the potential impermeability is satisfactorially. It turned out that defects of the micro- and the macro-structure of the concrete resulting from bad workmanship increased the ability of the chloride ingress drastically.

Consequently, the owner has for the tunnel elements chosen to specify a maximum chloride diffusion coefficient. For all concrete works of the project the owner has specified that the quality is assured by means of control parameters established at trial castings, which have been proven to have a sufficiently low defect intensity and a required impermeability towards chloride ingress.

Measurement of the chloride diffusion coefficient on drilled-out cores is tedious, complicated and time consuming. Such a procedure will not fit into a rational concrete production, where elements are produced rapidly in great numbers. Therefore, the owner chose a low testing frequency for checking the chloride ingress (permeability) of drilled-out cores, supplemented by a high frequency of testing of a control parameter measured in-situ. The owner has chosen the pull-out strength as the control parameter. The pull-out strength will diminish with increasing defect intensity of the concrete, all other factors being constant. This relationship is identical to the relationship found for chloride ingress.

Control parameters

The aimed value of the control parameter and its acceptable tolerances are established a priori, as mentioned, by means of a full-scale trial casting. At this trial casting all concrete requirements have to be fulfilled (compressive strength, defect intensity and, for the tunnel elements, the chloride diffusion coefficient). The expected value is the average value measured and the tolerance is determined from the variation of the single test results. The tolerance has for the East Bridge has been set by the owner to ± 7 kN, c.f. table 14 of the SAB.

Decision rules

In the Danish Code of Practice DS 411 there are no decision rules accepting or rejecting an inspection section based upon inspection and testing the concrete

strength when it is required that the strength obey a minimum as well as a maximum limit. The Danish Standard DS 423.1, 2nd edition, 1985, allows, however, »inspection by attributes« where »yes« or »no« statements are statistically interpreted. The SAB regards the DS 423.1 to be in force.

The variability of the strength of in-place concrete

The compressive strength by pull-out testing is statistically determined by a distribution, a mean value and a deviation. The deviation (or the coefficient of variation) is composed by contributions from a number of different sources described in the following.

Variation of the constituents of the concrete

No matter how homogeneous the concrete materials are, variation will occur. Within one inspection section the variation may be small, even from batch to batch, but from one inspection section to another the mean values will normally vary. Usually, a number of inspection sections will exhibit greater variation than within one control section.

The inspection section of the mix materials will normally not be identical in a concrete production. Thus, there may be a considerable deviation of properties of the mix materials as judged from within an inspection section of in-place concrete.

Variation of the concrete mix proportions

Weight tolerances of the mix proportions are established from batch to batch. The batches will vary within these tolerances. This means that the properties of the concrete, e.g. the compressive strength will vary from batch to batch. The potential compressive strength will consequently not be without variation.

Variation of the potential strength of the concrete

The statistical distribution of the potential strength of the concrete is related partly to the variation stemming from the materials and the mix proportions and partly to the process of mixing. If the concrete production is fully controlled the contribution from the mixing may be insignificant.

Variation of the compaction

The properties of the fresh concrete as delivered from the mixing plant will vary accordingly. In addition, the transportation of the concrete and the pumping may change, especially the air content and air distribution of the mix. As a general rule the strength will increase 5.5 per cent for each lost percentage of air.

The properties of the fresh concrete cast on-site, e.g. the slump, will vary as the materials and the proportions vary. Therefore, the required time of compaction may vary as well, causing the hydraulic pressure of the placed fresh concrete to change from one type of construction element to another, the pressure being highest towards the bottom.

The compressive strength of the hardened concrete will vary accordingly, all other factors being constant. Pull-out testing with LOK-test and CAPO-test will discover such differences.

Variation of the curing conditions

Even in elements produced at a factory, the curing conditions are not the same from element to element. This variation is the important variation to measure, since bad curing conditions may create defects of the cover layer being harmful to the impermeability towards aggressive gasses and liquids.

Correctly planned, the pull-out testing will reveal the effects of curing at the same time as the other types of variations are eliminated (concrete mix proportions, mixing, transportation, casting and compaction).

As part of the pre-testing of the concrete, concrete blocks are manufactured from each batch and cured under controlled conditions. By testing the blocks at the same horizontal layer it is possible to determine the inherent variation at known and acceptable curing conditions.

Example 4. The following example illustrates the variation of the CAPO-test if performed on homogeneous concrete of The Great Belt Link correctly. In the top surface of an abutment of the West Bridge within one batch placed, six tests were made. The test results (pull-out forces) were as follows:

41 kN, 36 kN, 40 kN, 42 kN, 40 kN and 41 kN

The coefficient of variation is 5.5 per cent. The same concrete vibrated on vibration table and watercured in the laboratory exhibited a coefficient of variation of 4.1 per cent, also based on 6 test results.

Placed on a vertical line of an in-situ cast wall cast continuously from one batch, the variation would have been considerable higher with the lowest strength towards the top of the casting. Placed at random all over a structure containing many batches, the variation will be even higher since the difference of the concrete strength from batch to batch is also taken into account now. Therefore, the SAB clause 4.5.10.10 specifies where to place the inserts.

Variation may naturally also occur if the testing by LOK-test and CAPO-test is performed erroneously. The SAB specifies consequently operational criterions

for how to perform the testing correctly, as illustrated in the SAB-amendment to the Danish Standard for pull-out testing, DS 423.31 (SAB clause 4.5.10.10).

Also, the technicians performing the testing has to pass a training course in LOK-test and CAPO-test as illustrated in the Figures 32, 33 and 35, to obtain a diploma needed for performing the testing correctly.

Testing concrete

SAB demands the requirements to be documented and fulfilled. Generally speaking, two types of requirements are specified by the SAB:

- *Numerical requirements of the concrete properties* documented by production control within a control section. The concrete is rejected if the properties are not documented and fulfilled.
- *Tolerance requirements of the control parameters*, which have to be documented to be fulfilled by inspection and testing within a control section. It is the contractor who establishes the aimed values (the averages) at the full-scale trial casting of the control parameters required by the SAB, while the SAB lays down the tolerances, c.f. table 14 of the SAB. In case of non-compliance with the tolerances, the cause(s) has to be found and the error corrected to achieve full control of the concrete production.

Pull-out testing requirements of the SAB

As far as pull-out testing is concerned, the SAB lays down two requirements:

- The first requirement is related to the achieved characteristic compressive strength of the structure. This strength measured by pull-out testing with LOK-test and CAPO-test has to be higher than or equal to what is required in the General Note of the SAB for the type of concrete used.
- The second is related to the variation of the achieved compressive strength of the structure.

The wording of the SAB related to the two types of requirements is as follows, c.f. SAB for the East Bridge, clause 4.5.6.2:

- *LOK-test Strength Requirements.*»The characteristic compressive strength after 28 days maturity determined by LOK-testing shall be higher or equal to 80 per cent of the prescribed compressive strength in the General Note for each inspection section«.
- *LOK-test Production Control.*»Additionally, it shall be documented that the

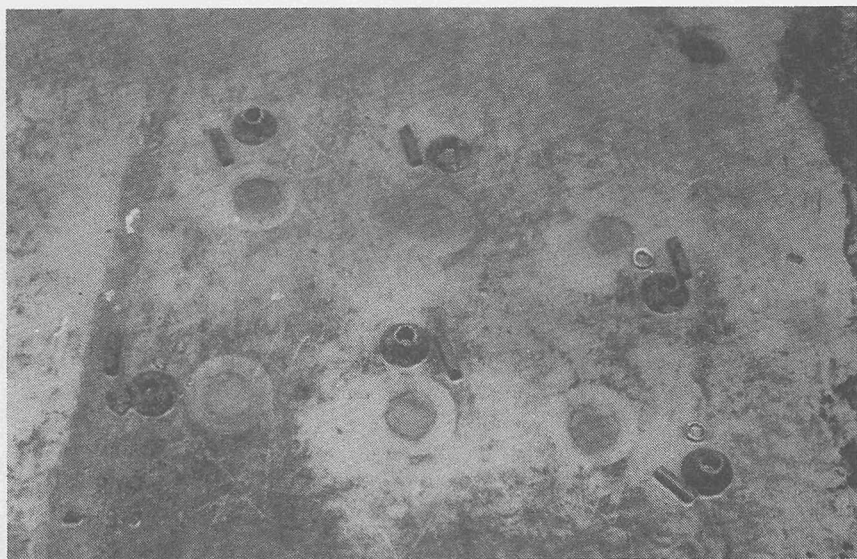


Figure 34. Six CAPO-test completed within one batch placed of an abutment inspection section, the West Bridge.

Figure 35. At the final examination of the technicians performing the pull-out testing. Each technician has to test 6 LOK-test inserts, 6 CAPO-test inserts on-site, report the results and check the test equipment to be in workable condition.



Figure 36. Testing of a caisson by CAPO-test at the final examination.



compressive strength level during production falls within the predetermined maximum and minimum values. The limiting values shall be determined by the Contractor on the basis of the results of the pre-testing and shall be presented to the Employer's Representative for acceptance prior to production. If the compressive strength during production falls outside the predetermined limits, additional CAPO-test shall be performed. If these test results also fall outside the predetermined limits, then adjustment of the mix design or curing procedures shall be made«.

For the East Bridge a tolerance of ± 7 kN is specified in table 14 of the SAB. As far as the West Bridge and the Tunnel is concerned the contractors have to declare the strength level as well as the tolerances for acceptance by the Employer's Representative. For the East Bridge the contractor has to declare only the strength level, which has to be approved by the Employer's Representative.

Consequences of rejection

The decision rule to be used in case of non-compliance of the two requirements has different consequences:

- If the *strength requirement* is not met, additional testing is generally allowed to be made according to more specified rules for acceptance.
- If the *durability requirement* (control parameters) is not met, the cause has to be found and correction implemented. Petrographic thin-section analysis could be applied, if necessary followed up by testing of the chloride diffusion coefficient.

Naturally, there may be other causes for rejection of the durability requirement than failing curing conditions. Insufficient casting and compaction of the concrete and faulty located inserts have equally significant effects as well. The pull-out testing should also be checked to have been performed at 28 maturity days (the maturity registration may be incomplete).

The pre-testing of the compressive strength, SAB clause 4.5.3.2

At the pre-testing of the concrete mixes used at the Great Belt Link test cylinders (dia. 150 mm, height 300 mm) have to be cast. Additional concrete blocks with the dimensions 900×900×500 mm also have to be cast. The following strength investigations have to be performed:

- The strength development of cast cylinders when testing at 1, 2, 3, 7, 14 and 28 maturity days. At each maturity date the compressive strength of the concrete is determined as an average of three cylinders (totally 18 cylinders).
- The compressive strength of drilled-out cores (dia. 100 mm, height 200 mm) at 28 maturity days. The strength is determined by means of two drilled-out cores from each of the six faces of the block (totally 12 cores).
- Pull-out testing at 28 maturity days. Each of the six faces of the block is measured by four LOK-test inserts and four CAPO-test inserts (totally 24 LOK-test and 24 CAPO-test inserts).

Figure 37 illustrates the positioning of the cores and the pull-out inserts.

Full-scale trial casting, SAB clause 4.5.4.14

A test specimen of at least 15 cubic meters of concrete is cast as a trial casting after completion of the pre-testing. Also, cylinders (dia. 150 mm, height 300 mm) are cast. The following investigations have to be made:

- Development of the compressive strength of cast cylinders at 1, 2, 3, 7, 14 and 28 maturity days. Three cylinders are tested at each maturity date and the results are averaged. Total number of cylinders: 18.
- The strength development when using pull-out testing. Two LOK-tests and two CAPO-tests are tested at the following maturity days: 1, 2, 3, 7, 14, 28 and possibly 35. One observation (test result) is the average of testing two test inserts. Total numbers of LOK-test inserts: 14 and of CAPO-test: 14 nos.

The pull-out inserts are placed at the vertical faces of the full-scale trial casting at a the same horizontal level as planned at the production control to eliminate differences in compaction.

Inspection and testing, SAB clause 4.5.6.2

For each inspection section the testing of the compressive strength is performed as follows:

- *The characteristic potential compressive strength* of an inspection section measured on cylinders at 28 maturity days has to fulfil the requirements of the SAB's General Note. The decision rule for acceptance is stated in the Danish Code of Practice DS 411, clause 8.1.1.
- *The characteristic in-place compressive strength* of an inspection section, determined by pull-out testing by LOK-test and CAPO-test at 28 maturity

Figure 37. Above: The positioning of four LOK- and four CAPO-test inserts and two drilled-out cores (dia.100 mm, heigth 200 mm) on each of the four vertical faces of the concrete block (900×900×500 mm).

Below: The positioning of four LOK- and four CAPO-test inserts and two drilled-out cores (dia.100 mm, heigth 200 mm) at the top and the bottom face of the concrete block (900×900×500 mm).

Notice: The cores are drilled out after the completion of the pull-out testing, otherwise the minimal distance requirements for conducting pull-out testing are not observed.

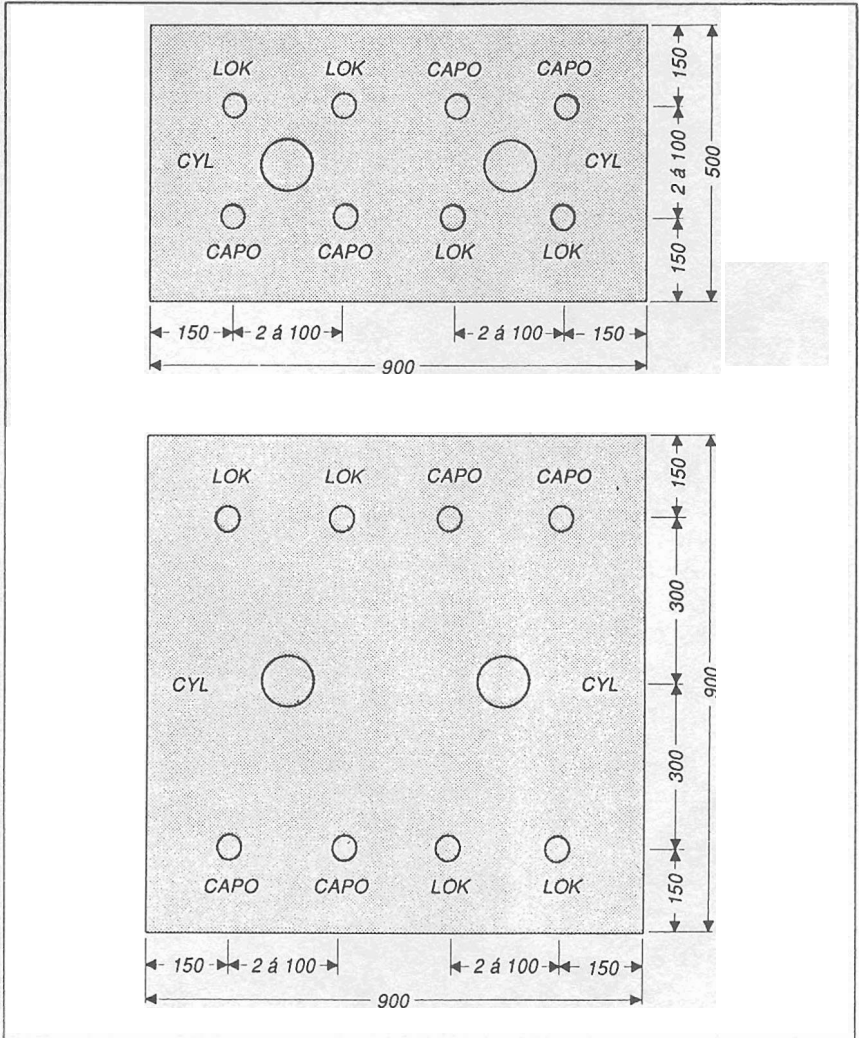
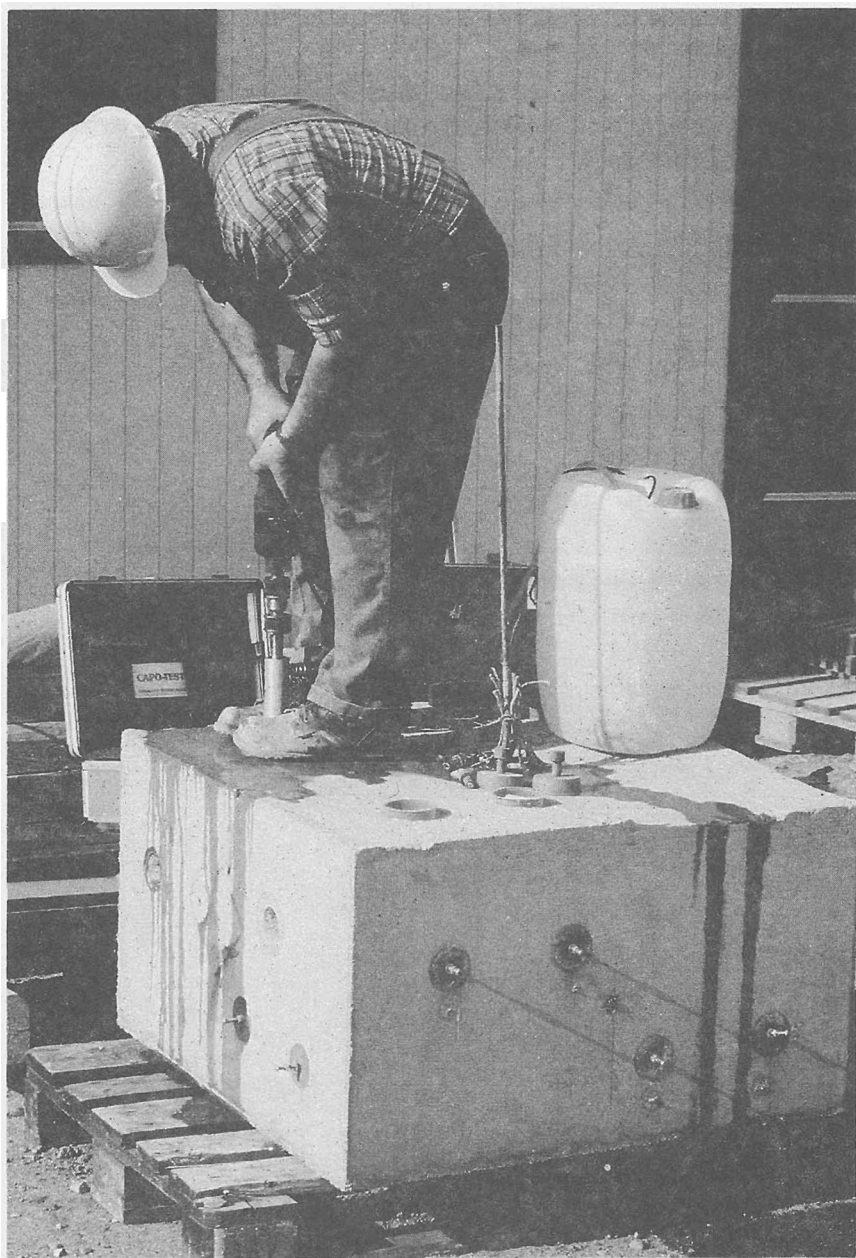


Figure 38. Pre-testing at the East Bridge site in Kalundborg.



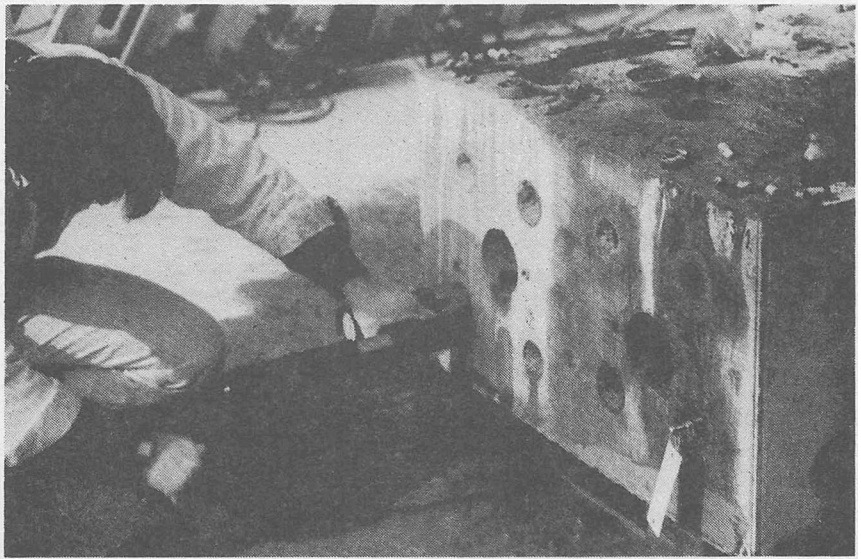
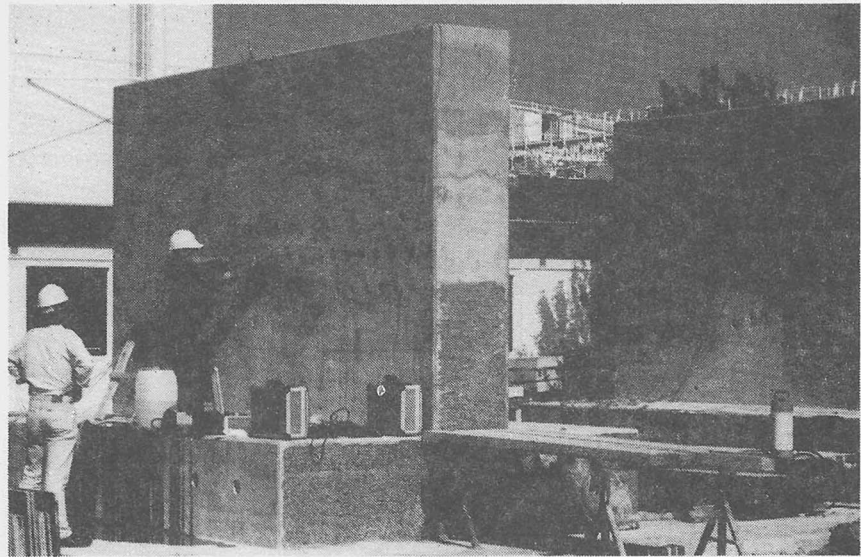


Figure 39. Example of a pre-testing. Pull-out testing by LOK-test and CAPO-test is made as illustrated in figure 37 is shown being performed.

Figure 40. Example of a trial-test is being performed.



days, has to be at least 80 per cent of the required strength in the SAB's General Note. The decision rule of DS 411, clause 8.1.1 applies.

- *The control parameter* for the quality of the coverlayer of the control section is the pull-out forces within the section, at 28 maturity days. The control parameter (in kN-units) has to have a level declared by the contractor and accepted by the Employer's Representative. The declaration is put forward by the contractor after the pre-testing and the testing of the full-scale trial casting have been performed. Also, the deviation from this level has to be declared and accepted according to the conditions. For the East Bridge this deviation has been set to ± 7 kN (c.f. SAB table 14).

Strength development of concrete

In Denmark the formula for strength development of concrete suggested by *P. Freiesleben Hansen* is commonly used. Other formulae may also be used, but the one suggested by Freiesleben is more flexible and adaptable. The formula contains three parameters which have to be determined by experiments. Such experiments may take place in relation to the pre-testing and the testing of the full-scale trial casting according to the SAB.

Strength development of cast cylinders

The equation suggested by Freiesleben is the following:

$$(6) \quad f_{cyl} = f_{\infty} \times \exp[-(\tau_e/M)^{\alpha}]$$

The f_{cyl} is the cylinder strength at a maturity of M . The f_{∞} is a parameter indicating the strength of the concrete for an infinite maturity. This parameter is determined by means of the measured strength development. The τ_e and the α are also parameters which have to be determined from the achieved strength development.

By applying the natural logarithm on each side of the equation the following transformation is found:

$$(7) \quad \ln f_{cyl} = \ln f_{\infty} - (\tau_e/M)^{\alpha}$$

This expression may be re-formulated to:

$$(8) \quad \ln f_{\infty} = (-\tau_e^{\alpha} + \ln f_{\infty}) + \tau_e^{\alpha} \times (1 - 1/M^{\alpha})$$

From this equation it will be seen that if the strength of the concrete is repro-

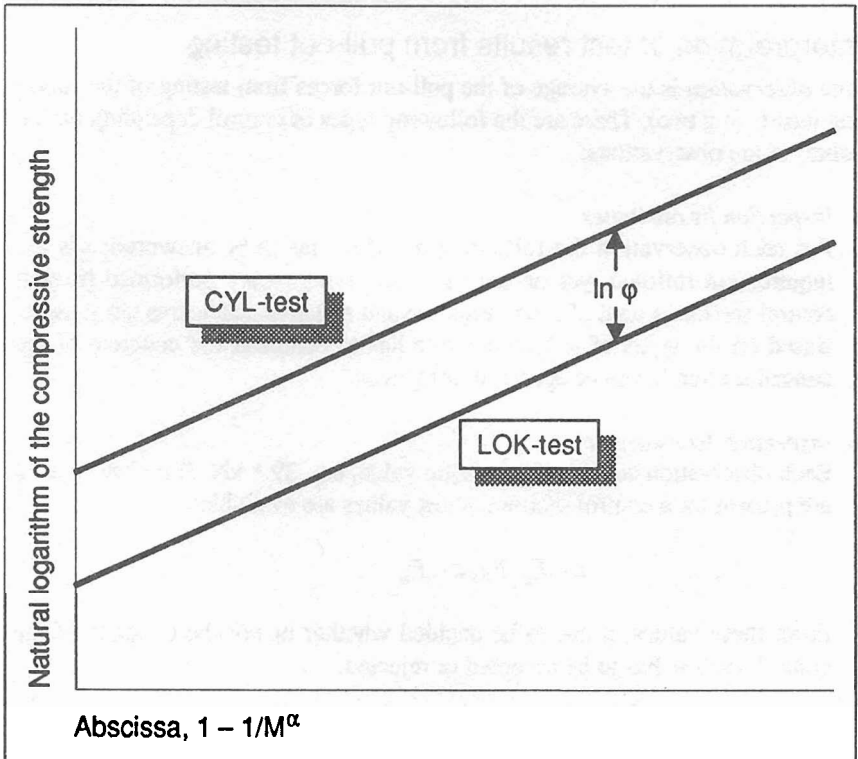
duced in a system of coordinates with $\ln f_{cyl}$ on the vertical axes and $1-1/M^\alpha$ on the horizontal, the graph will become a straight line.

The development of the in-place concrete compressive strength

For in-place testing of the compressive strength one will find that $f_{lok} = \varphi \cdot f_{cyl}$. The factor φ will be constant if the curing conditions are kept constant and presumed the pull-out insert are placed under the same conditions in the casting (same horizontal layer). A change of the parallelism will reveal the variation of the defect intensity of the coverlayer, only.

If the natural logarithm is taken on both sides of the equation $f_{lok} = \varphi \cdot f_{cyl}$ the following equation appears:

Figure 41. If the natural logarithm of the compressive strength of the concrete, determined by cylinders (potential strength) and by LOK/CAPO-test (achieved strength), is reproduced in relation to the value $(1-1/M^\alpha)$, two straight lines are found, one for cylinders and one for LOK/CAPO-test.



(9)

$$\ln f_{lok} = \ln \varphi + \ln f_{cyl}$$

The value $\varphi = 0.8$ (c.f. DS 411, clause 3.13.1) yields $\ln \varphi = -0.2$. If the factor φ is independent of the concrete maturity M , the system of coordinates will consist of two straight and parallel lines, one for f_{lok} and one for f_{cyl} (as shown in figure 39).

Determination of the strength development parameters

The parameters of the Freiesleben formula, the f_{∞} , the τ_e and the α have to be determined from the strength development curve measured by the cylinders at the pre-testing. A non-linear regression analysis of the observations is applied.

If the strength development results from the cylinder testing and from the in-place testing are illustrated in a diagram as shown in figure 41 and the curves obtained are not straight lines or parallel, the cause(s) has to be found.

If a kink appears in the in-place testing curve, e.g. after 14 maturity days, one reason may be failing curing conditions.

Interpretation of test results from pull-out testing

One *observation* is the average of the pull-out forces from testing of the single test inserts (e.g two). There are the following types of control depending on the nature of the observations:

■ *Inspection by attributes*

For each observation the following question has to be answered: »Is the requirement fulfilled, yes or no?« If n observations are performed in each control section, a total of n confirmative and negative statements are present. Based on the types of statements, one has to decide if the concrete of the control section has to be accepted or rejected.

■ *Inspection by measurements*

Each observation consist of a specific value, e.g. 39.5 kN. If n observations are present for a control section, n test values are available:

$$F_1, F_2, F_3, \dots, F_n$$

From these values, it has to be decided whether or not the concrete of the control section has to be accepted or rejected.

The terminology for testing of an inspection section

In the following the terminology standardised by the publication of DS 423.1 (the Danish Control Standard) is used:

- ***Inspection section***

An inspection section is a well-defined and limited part of the structure where testing is performed at a certain test frequency. Within an inspection section, all observations are processed and statistically interpreted as a whole. The interpretation is limited only to the concrete within the section.

- ***Batch***

One inspection section consists of several batches. One batch is the amount of concrete contained in one truckload or otherwise mixed homogeneously.

- ***Sample***

One sample consists of a minimum of two inserts. All test inserts in one batch forms one sample, no matter how many single tests exist.

- ***Measuring result or single-observation***

The pull-out force of on test insert is designated a single observation or a measuring result.

- ***Observation***

The average of the pull-out forces of all test inserts in a sample is named an observation.

- ***Total inspection***

Total inspection is said to be performed if each batch of an inspection section has one sample

- ***Inspection by random testing***

If not all batches of an inspection section are tested, but more than a certain minimum, the inspection is called »inspection by random testing«.

Decision rules

The test results of the inspection section have to be statistically interpreted in order to be accepted or rejected.

Table 5. Interpretation of all observations in an inspection section (first column) in accordance with the decision rule in DS 423.1 is done by comparing each observation with the requirements. In order to accept the concrete in the inspection section the number of non-complying observations must not exceed the numbers in the second column. If, for example, there are 15 samples in an inspection section, the concrete is accepted if at least 14 samples give observations complying with the requirements.

No. of samples per inspection section	Max. no. of observations outside the interval.
3-12	0
13-19	1
20-29	2
30-39	3

Inspection by attributes, DS 423.1

For inspection and testing of the durability requirement given by the SAB it has to be decided if the measured pull-out forces are within or outside the prescribed limits (or tolerance) declared by the Contractor and accepted by the Employer's Representative. The inspection and testing are based on »yes« and »no« statement, i.e. inspection by attributes.

Table 10 of appendix 6 gives the accept (reproduced above) and reject numbers in relation to the number sample size according to DS 423.1. By means of this table it quickly can be decided if an inspection section is accepted or rejected.

Inspection by measurements, DS 411

The problem is to decide if the measured characteristic strength f_{ck} of an inspection section complies with the requirement given by the General Note for the SAB-concrete in question. This takes place as follows.

Total inspection

The number of observations are equal to the number of concrete batches.

Table 6. The value of $0.8 \times k_n \times f_{ck}$ in dependence of the required minimum characteristic strength f_{ck} and the number of observations n .

f_{ck}	35 MPa	40 MPa	45 MPa	50 MPa
$n = 3$	36.67	39.58	44.52	49.47
$n = 4$	36.22	39.15	44.05	48.94
$n = 5$	35.91	38.86	43.72	48.58
$n = 6$	35.69	38.65	43.48	48.31
$n = 7$	35.52	38.49	43.30	48.11
$n = 8$	35.38	38.36	43.15	47.95

All the observations have to be greater than $0.8 \times f_{ck}$. The value of f_{ck} is found in the SAB's General Note for the concrete in question.

Inspection by random testing

The minimum number of observations in relation to the number of batches is given by the SAB and in DS 423.1 (see appendix 6, table 9). The average of all observations of the control section is calculated as f_c . If this average is greater than $0.8 \cdot k_n \cdot f_{ck}$, the inspection section is accepted. The factor k_n depends on the number of observations and of the required minimum characteristic compressive strength. The value of $0.8 \cdot k_n \cdot f_{ck}$ may be tabulated as in table 5 below in dependence of the required minimum characteristic concrete compressive strength f_{ck} and the number of observations n .

The SAB is not requiring inspection by total testing, but if the number of batches are equal to or less than three, DS 423.1 required total inspection. If the number of batches is greater than three, it is the decision of the Contractor to

Figure 42. Knowledge of the method is required when evaluating the result of the pull-out testing, i.e. the pull-out load and the fracture pattern. The supervision has therefore participated in the course.



Appendix 2. Relation of pull-out force versus compressive strength

Theoretically, the LOK-test and the CAPO-test pull-out force may be transformed into the compressive strength of the concrete. This has been demonstrated by a finite element analyses, cf. [Ottosen, 1981]. The pull-out force was found to be proportional to the compressive strength of concrete. Thus, it is possible from a required compressive strength to calculate the corresponding pull-out force and to specify this force in kN-units instead of using cylinder measures.

Traditionally, the compressive concrete strength is measured on cast cylinders (dia. 150 mm, height 300 mm) as known from e.g. Denmark and North-America. However, such testing is not representing the true uniaxial compressive strength, but it indicates a practical measure of the compressive strength of concrete, accepted as a standard.

Before the failure mechanism of pull-out testing was investigated and understood, the practice was to conduct comparative measurements between the pull-out force of a concrete and the compressive strength of concrete cylinder or cube, in order to determine the relation between the two types of measurements.

This procedure was predominant from 1975 and 10 years onwards. The findings from a large number of comparative investigations are today available [Petersen, 1990]. The data substantiate the existence of one universal relationship between pull-out force and compressive strength as measured on specimens (one relationship for cylinders and one for cubes) for any normal type of concrete.

It is also interesting to notice that the experimentally found relationship between the pull-out force and the compressive strength as measured on 150 mm dia., 300 mm height cylinders is in agreement with the findings of the theoretical element analyses, cf. [Ottosen, 1981].

In spite of the experience with the general relationship obtained so far, the user of the LOK-test and the CAPO-test system may still want to determine the correlation for one's »own special concrete mix«. At the planning and the execution of such a relationship it is important to observe a number of basic rules, otherwise the correct relationship will not be found.

To facilitate the planning of the trial and to ease the practical testing, the following pages describe the types of tests to be conducted and especially how they should be performed based on experience from many test series from Denmark as well from especially North-America, cf. [Krenchel, 1984] and [Bickley, 1982].

If the comparative experiment is conducted correctly, the same relationship is found for LOK-test and for CAPO-test no matter what type of normal concrete mixes to be investigated, cf. [Krenchel, 1982] and [Bellander, 1983]). Concretes with maximum aggregate size of more than 38 mm have, however, not been investigated.

It should also be noticed that other relations than the »general one« will be found if lightweight concrete or pure mortar is investigated. This may be important when testing normal concrete, e.g. at the surface of a slab where separation has taken place during casting or consolidation. If the pull-out cone only consists of pure mortar, i.e. with no aggregates visible, an error may be introduced in the measurements by using the »general relationship«. The concrete strength will by means of pull-out testing transformed to concrete cylinder strength in this manner be evaluated too low.

One may only add, that the separation of the concrete is a fault (defect) which should have been prevented, and pull-out testing will clearly reveal it.

Choosing the test specimens

LOK-test and CAPO-test are sensitive test methods. Even small differences in the casting of the concrete, the compaction, the separation, the curing conditions and the maturity of the test specimens will entail significant influences on the relationship to be established. To eliminate such disturbing factors, the pull-out force and the compressive strength have, as a general rule, to be determined on specimens with identical concrete quality.

In Denmark the potential compressive strength is measured on cast cylinders with a diameter of 150 mm and a height of 300 mm, cf. DS 423.20, see figure 43. Consequently, the corresponding pull-out forces have also to be measured on 150 by 300 mm cylinders.

Cylinder compressive strength versus LOK-test pull-out force

A LOK-test insert is attached centrally at the steel mould bottom of a cylinder. This requires a 7 mm hole to be drilled centrally in the bottom, countersunk, for the LOK-test insert to be secured with a screw, cf. figure 44.

Experience has shown, that it is difficult to install a LOK-test insert at the top of a cylinder. If the insert is mounted in the lid, the insert has to be pressed into the concrete rather vertically. Such an operation may remove the aggregates from the failure zone of the pull-out cone, and the test will not be representative of the quality of the concrete of the cylinder.

On the other hand, investigations have shown [Bickley, 1981] that the strength of a correctly manufactured cylinder is not different from the bottom to the top. Thus, the positioning of the LOK-test insert at the bottom is the optimal.

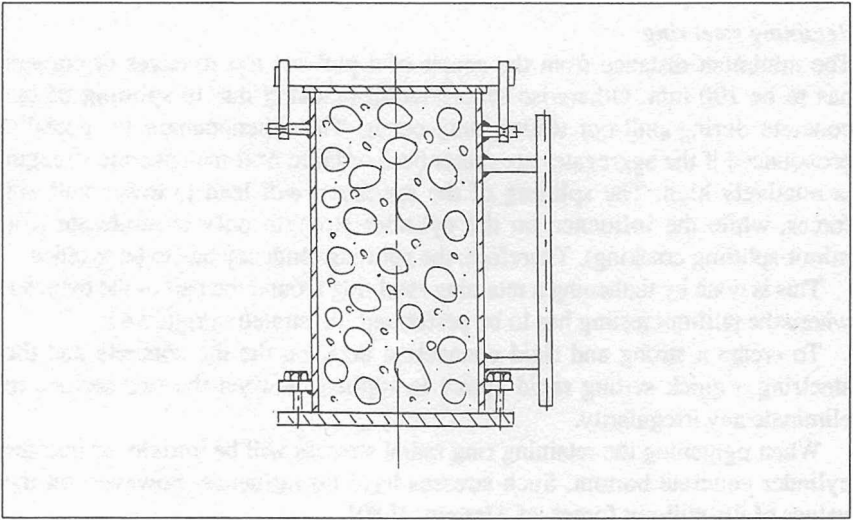
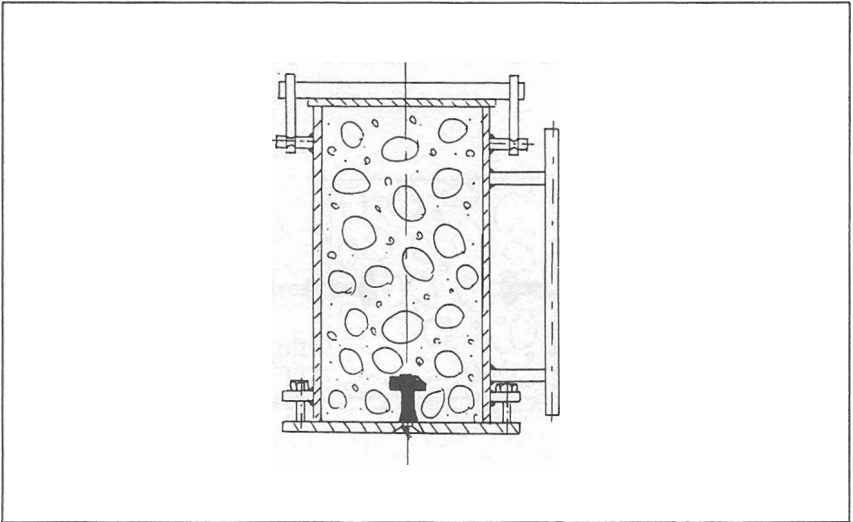


Figure 43. In Denmark the potential compressive strength is measured on cylinders, diameter 150 mm, height 300 mm. The cylinders have to be cast and compacted in steel moulds with DS 423.20 tolerances and cured in water at 20 °C until testing takes place according to DS 423.23.

Figure 44. A cylinder steel mould as shown in figure 40 is supplied with a LOK-test insert at the bottom. The cylinder is cast, compacted and cured as with normal cylinders (DS 423.21). pull-out testing and compression testing of the cylinder may then be performed on concrete with identical quality.



Retaining steel ring

The minimum distance from the center of a pull-out test to edges or corners has to be 100 mm. Otherwise severe radial cracking due to splitting of the concrete during pull-out testing may occur. This phenomenon is specially pronounced if the aggregates are rather hard or large or if the concrete strength is relatively high. The splitting of the specimen will lead to lower pull-out forces, while the influence on the cylinder strength only is moderate (for minor splitting cracking). Therefore, the splitting tendency has to be avoided.

This is done by tightening a retaining steel ring around the part of the cylinder where the pull-out testing has to be performed, illustrated in figure 47.

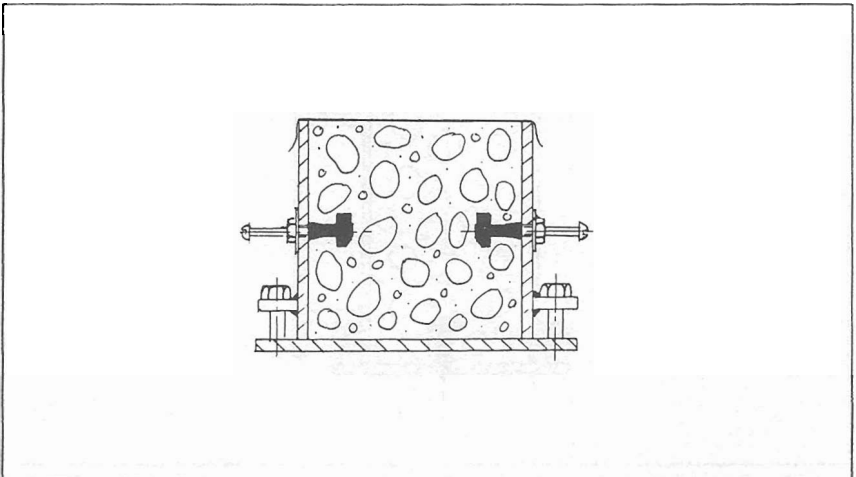
To create a strong and rigid connection between the the concrete and the steelring a quick setting rapid epoxy is applied between the two surface to eliminate any irregularity.

When tightening the retaining ring radial stresses will be introduced into the cylinder concrete bottom. Such stresses have no influence, however, on the values of the pull-out forces, cf. [Jensen, 1980].

Testing

According to DS 423.21 the cylinder has after casting to be placed horizontal in the mould with its slot upwards. This arrangement ensures among other

Figure 45. The smallest test specimen that fulfils the minimum distance requirement of 100 mm from the centre of the test to edges and corners is a 200 mm cube. The cube is supplied with two LOK-test inserts centrally placed on opposite vertical faces as shown. The remaining two vertical faces are used for pull-out testing by CAPO-test to be compared to the LOK-test.



things an uniform concrete quality throughout the cylinder.

Testing of the cylinder takes place at a required maturity. First the LOK-test is performed, then immediately afterwards the compression test is performed. The LOK-test is only performed »exactly to failure«, by which the pull-out cone is not pulled out. It should only be lifted 0.1mm to 0.5mm from the concrete surface. To ensure this small displacement, the LOK-test instrument is loaded just to failure and no further. When the peak-load has been reached and the pointer of the gauge has dropped 0.5 kN to 1.0 kN, the instrument is quickly unloaded.

At the compression test of the cylinder, the slightly dislodged cone will be pushed back into position, and the pull-out testing will have no influence on the cylinder compression test result [Bickley, 1982]. To check this finding, separate cylinders should be cast without embedded LOK-test inserts and tested in parallel to the cylinders containing LOK-test inserts. All cylinders have to be cast identically at the same time from the same batch and vibrated simultaneously on the same vibration table to avoid one-sided errors.

For each cylinder, comparative measurements are found relating LOK-test pull-out force (in kN) to cylinder compression strength (in MPa). By testing at different maturity ages with equal strength gain throughout the entire strength range, the relation between pull-out force and cylinder compression strength may be determined by means of regression analysis.

LOK-test pull-out force versus CAPO-test pull-out force

The described procedure cannot be used for the estimation of the relationship between the CAPO-test pull-out force and the cylinder compressive strength, since pull-out testing by CAPO-test always will leave a fully dislodged cone hole and this cone hole will lower the cylinder compressive strength significantly even if attempts are made to fill-out the cone hole with a quick setting mortar before the compression test is performed.

Therefore, another procedure suggested by *H. Krenchel* [Krenchel, 1982] and used successfully since then, has to be used. Here the LOK-test and the CAPO-test pull-out forces are measured on the same specimen. The specimen has to be as small as possible and it needs to have plane surfaces. Keeping the minimum distance of 100 mm between the centre of a pull-out test and the edge or corners in mind, the only specimen that fulfils such requirements is a 200 mm concrete cube.

Properly cast and vibrated on a vibration table such cubes have been found to have equal LOK-test and CAPO-test pull-out forces at the vertical faces centrally placed [Krenchel, 1982], [Bellander, 1983] and [Bungey, 1983].

Thus, two LOK-test inserts are placed in the steel mould through 7 mm centrally placed holes at opposite vertical faces, cf. figure 45. The two remaining vertical faces are used for pull-out testing by CAPO-test.

When testing the 200 mm cubes at the same horizontal layer with LOK-test and CAPO-test a slightly higher variation of the pull-out results is usually found compared to the variation of the LOK-test results performed at the bottom of the cylinders. The reason is, it is believed, that it is more difficult to make homogeneous cubes than cylinders.

Test program in general

Consequently the following test specimens are needed to conduct a proper relationship program:

- Test cylinder, $d \times h = 150 \times 300$ mm, according to DS 423.20, cast in minimum three equal sized layers of concrete in the steel mould, fastened to and vibrated on a vibration table following DS 423.21 and tested in compression according to DS 423.23. This type of concrete specimen is named »type A specimen«, cf. figure 43.
- Test cylinder, $d \times h = 150 \times 300$ mm, according to DS 423.20, with one LOK-test insert attached through an undersunk 7 mm hole at the bottom, cast in minimum three equal sized layers of concrete in the steel mould, fastened to and vibrated on a vibration table following DS 423.21. The cylinder is tested by LOK-test at a desired maturity, exactly and just to failure according to DS 423.31 with attached retaining steel ring around its end. Immediately afterwards, the cylinder is tested in compression according to DS 423.23. This test specimen is named »type B specimen«, cf. figure 44.
- Test cube 200 mm mounted with two LOK-test inserts centrally placed at two opposite vertical faces of the steel mould through 7 mm holes, cast in three layers in the steel mould, fastened to and vibrated on a vibration table. The cube is tested at a desired maturity first by CAPO-test centrally placed on the vertical faces not containing LOK-test inserts, and secondly with LOK-test on the remaining vertical faces. This test specimen is named »type C specimen«, cf. figure 45.

Testing at different maturities

The testing of the specimens has to take place so that the clusters of comparative measurements are distributed approximately with equal distances throughout the strength range. This may be obtained by testing the specimens at 1, 2, 3, 7, 14, 28 and 35 maturity days.

To obtain a reasonable certainty of the slope of the correlation, it is desirable to have at least a 40 MPa span of the total strength range [ACI, 1989]. For a concrete with a w/c -ratio of 0.4 such a span should be obtained if it is tested at maturities as above mentioned.

Number of tests

Each cluster of observations should contain a minimum of three corresponding values to achieve the needed statistical accuracy [ACI, 1989]. Consequently the following numbers of test specimens are needed as a minimum:

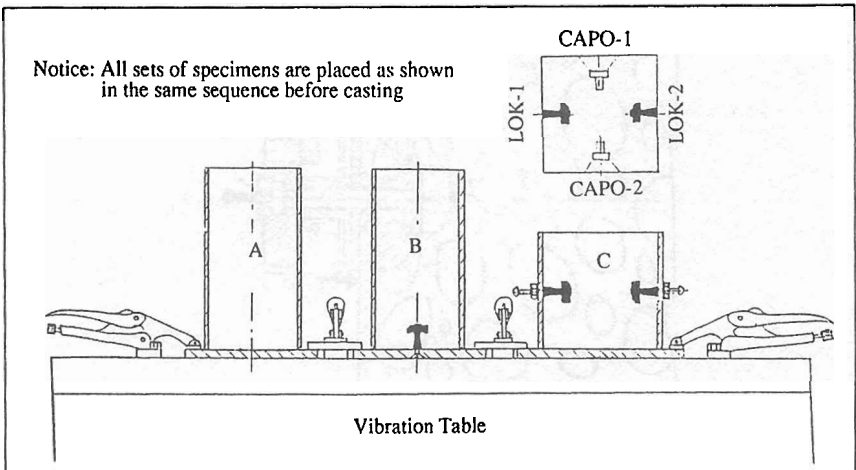
- 21 type A specimens, i.e. cylinders without LOK-test inserts, cf. figure 43.
- 21 type B specimens, i.e. cylinders with LOK-test inserts, cf. figure 44. Each cylinder is supplied with one LOK-test insert at the bottom.
- 21 type C specimens, i.e. cubes with LOK-test inserts, cf. figure 45. Each cube is supplied with two LOK-test inserts at two opposite vertical faces, centrally placed.

For verification of the compression machine used, 20 cylinders are cast separately according to DS 423.20 and DS 423.21. Half of them are tested on the compression machine used for testing of type A and type B specimens, and the remaining half is tested in parallel on an authorized laboratory's compression machine. The testing takes place at 3 and 28 maturity days.

Detailed description of the relation program

In the previous material the background of the relationship program and the required minimum number of test specimens are advised. In the following a

Figure 46. The test specimens are manufactured in sets of three identically in the same manner besides each other (type A, type B and type C specimens), compacted at the same time on the vibration table and cured in water at 20 degree centigrades until the required maturity has been obtained before testing. The LOK-test and the CAPO-test pull-out forces are very sensitive to the variations of the concrete quality of the test specimens.



detailed description of the program is given.

How to manufacture the test specimens

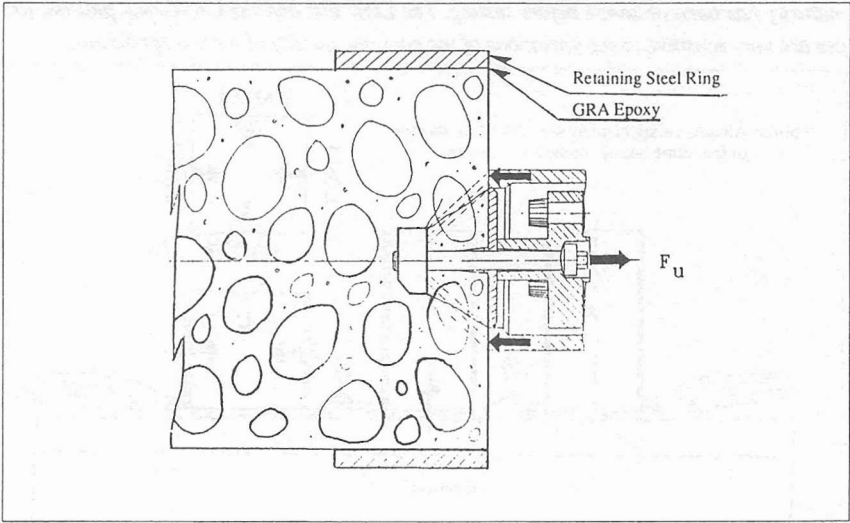
A vibration table is needed with sufficient space for one cylinder mould type A, one cylinder mould type B and one cube mould type C. The moulds, all in steel, have to be clamped to the table as illustrated in figure 46. To fasten the moulds to the table with clamps, 10 mm bolts have to be welded to the table for connection to 10 mm nuts and washers.

A batch is made containing approximately 450 liter of concrete and transported to the laboratory. The concrete has to be stirred continuously. If the air content changes due to pumping on-site, the same pumping technique should be applied to the concrete before casting of the specimens.

One set of test specimens as illustrated in figure 46 is produced in the following manner:

- From the batch the three moulds, type A, type B and type C, attached to the vibration table are filled one third with concrete. Vibration takes place until a thin layer of mortar covers all aggregates and no more air is released.
- Another one third of concrete is filled into the moulds followed by vibration as described above.
- Finally the moulds are filled out with concrete and vibrated. The cylinder lids are twisted in-place and tightened to the cylinders. The free surface of

Figure 47. A 150 mm diameter test cylinder needs a strong clamp to prevent formation of radial cracks which would reduce the value of the pull-out load.



the cubes are planed and smoothened.

- The three specimens in each set are marked with identification codes on watertight stickers attached to the steel moulds, from 1A; 1B; 1C to 21A; 21B; 21C respectively. The figure indicates the number of sets and the letter the type of specimens.

Instead of filling the specimens by three layers, it may be decided to fill them in two layers (permitted by the Danish Standard). If the two-layers-filling is selected, it is advised to fill the cubes so the LOK-test inserts are fully covered by concrete and not splashed by cement paste, vibrate, and then fill the cube to the top and repeat the vibrating.

This process is reiterated 21 times, giving a total number of 63 specimens of which 21 are type A specimens, 21 type B and 21 type C specimens.

From another batch containing approximately 150 liter of concrete 20 cylinders, $d \cdot h = 150 \cdot 300$ mm, are manufactured according to DS 423.21. The cylinders are produced in pairs clamped to the vibrations table; cast, vibrated and supplied with lids as mentioned above. Each pair of cylinders is marked with waterproof stickers labelled 1D; 1E to 10D; 10E.

How to cure the specimens

The curing of the specimens takes place as follows:

- The top surfaces of the cubes are wrapped up in a watertight and close-fitting plastic film directly after casting.
- The cubes are immediately after the above mentioned preparation has been finished placed in a temperature controlled waterbath at 20 degree centigrades together with the cylinders. It is presumed that the cylinder steel moulds are of a watertight type. The cubes are placed vertical as cast, while the cylinders are placed horizontally with the cylinder slot upwards.
- After 24 maturity hours the specimens are taken out of the bath. All screws connected to the inserts are removed and the steel moulds are removed from the specimens. All concrete specimens are marked clearly with watertight stickers with the same ID-number as indicated on the steel moulds. Then the specimens are placed back into the waterbath at 20 degree centigrades.

How to finally mark the specimens

Three sets of specimens, each consisting of type A, type B and type C specimens, are chosen at random from the 21 sets in the waterbath after respectively 1, 2, 3, 7, 14, 28 and 35 maturity days. The three sets are marked with the maturity of the concrete. In this manner each test specimen at this stage has a marking indicating:

- Days of maturity when tested, number of set, type of specimen. A marking

as e.g. 1-17-C shows the specimen to be one day old at 20 degree centigrades at the time of testing, the specimen is from set number 17 and is a cube with two LOK-test inserts.

How to perform the testing

Well ahead of the time of testing, the LOK-test instrument is calibrated as well as the laboratory compression machine. Both the LOK-test and the CAPO-test equipments are cleaned, adjusted and the checklists are filled out and signed.

Whenever the test specimens have achieved the required maturity, three sets of specimens, each consisting of one type A, B and C specimens are chosen at random and tested as follows:

Test specimens type A and type B

The three cylinders type B are first tested by LOK-test at the bottom. On the cylinder circumference where the LOK-test insert is located a thin layer of quick setting epoxy is applied. While still wet, the steel retaining ring is tightened around the end. A plastic wrap may be placed in between to avoid adhesion to the steel ring. The epoxy has to flow out all along the circumference of the ring-cylinder surface connection. Surplus epoxy is removed. The epoxy has to harden. Usually it takes 5 minutes for a quick setting epoxy at 20 degrees centigrade.

Pull-out testing with LOK-test takes place exactly and only to failure as shown in figure 47. The pull-out cone must not be lifted more than 0.1 to 0.5 mm from the testing surface after testing has been completed. This is ensured in the following manner. When the gauge pointer of the instrument during loading has reached the peak-load and fallen back 0.5 to 1.0 kN, the instrument is quickly unloaded. For the experienced technician the cone failure will hardly be visible.

The instrument and the attachment parts to the cast-in disc are removed together with the steel retaining ring. The bottom surface where the testing has been performed is inspected for any radial cracking and, if visible, made clearly visible by means of a speed marker. A photo is taken of the cylinder end with ID-number attached and the type of failure is recorded together with the value of the pull-out force.

After each set of type B specimens have been tested with LOK-test they are tested in compression together with the three type A cylinders. The types of compression failures are recorded along with the compression results.

Figure 8 and 48 illustrates the possible types of LOK-test failures loaded exactly to failure and the types of compression failures.

Test specimen type C

The three cubes at each maturity date are then tested as follows:

Figure 48. Characteristic types of cylinder compression failures.

Failure type a is the normal type of failure. The cylinder has cone-shaped failures at the ends of the cylinder (sliding failures) where the compression plates have been located. This type failure is acceptable.

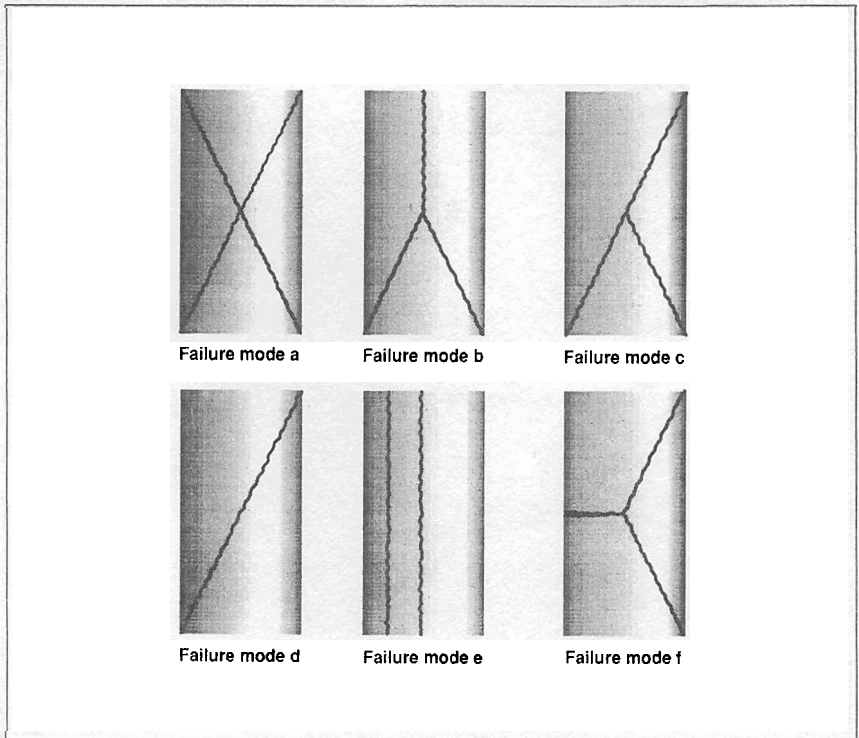
Failure type b is composed of a sliding failure (cone-shaped, cf. type a) below and a separation failure at the top, cf. type e. Separation takes place due to relative small friction between the compression steel plate and the cylinder compared to a cone failure where the friction is relatively larger. This type of failure is acceptable.

Failure type c is a failure composed by a diagonal sliding failure (cf. type d) and a cone shaped failure (cf. type a). This type of failure is acceptable.

Failure type d is called a diagonal sliding failure. This type of failure is acceptable.

Failure type e is a regular separation failure. This type of failure is acceptable.

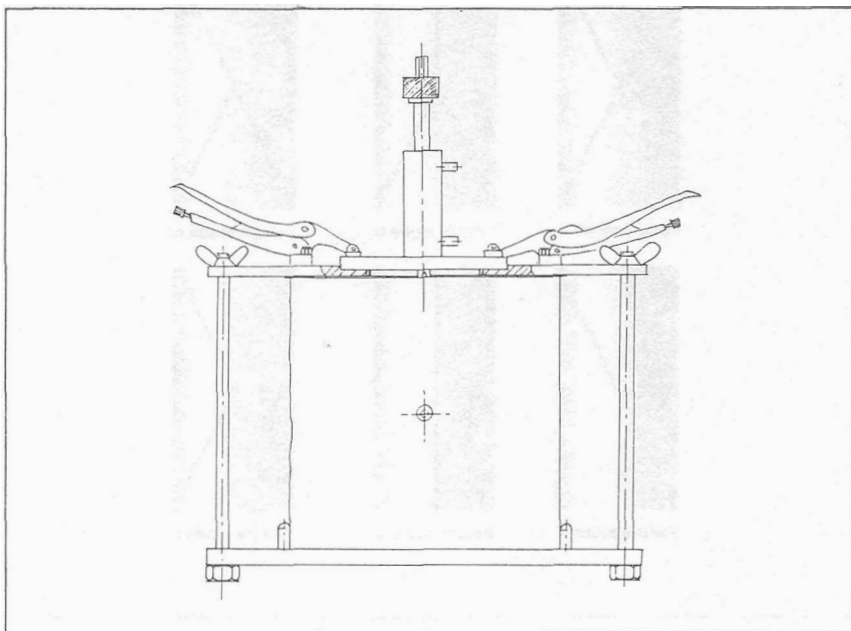
Failure type f consists of separation failure perpendicular to the cylinder axis and tendency to cone-shaped failures to the other side. This type of failure is typical of test cylinders with an excentric load. This type of failure is not acceptable.



- First the LOK-test inserts are tested, again accurately and just to failure. This is to make sure the pull-out testing by LOK-test is not influencing the subsequent pull-out testing by CAPO-test. The LOK-test failures, cf. figure 8, are registered. If visible radial cracking turns up, they are illustrated by means of a speed-marker and photo-registered along with the ID-number. The pull-out forces are recorded.
- Pull-out testing by CAPO-test is performed on the remaining vertical faces, centrally placed. The CAPO-test suction plate is secured to the to the face of the cube by means of a testing rig as outlined in figure 49. The suction plate controls the proper execution of the drilling of the centerhole, the planing of the surface and the routing of the recess with the diamond tools supplied in the CAPO-test kits.

The suction plate with the test rig is removed and the CAPO-test expansion unit inserted in the hole and expanded fully, pull-out testing with CAPO-test is

Figur 49. The 200 mm cube mounted with the suction plate centrally placed on one of the vertical faces not containing a LOK-test insert. The suction plate is kept in-place by means of a test rig. The suction plate controls the drilling of the centre hole, the planing of the surface and the recess routing with the CAPO-test diamond tools.



performed, the peak-load recorded and the cone fully dislodged.

The type of CAPO-test failure is recorded, cf. figure 10. If radial cracking has turned up, the cracking is made visible by means of a speed-marker and photo-registered along with the ID-number.

Test specimens type D and E

Each 10 cylinders of type D and E are in pairs divided in two groups with 5, at random. One group (5 sets of type D and type E) is tested at 3 maturity days, the D types on the compression machine used in the laboratory, and the E type on an authorized testing laboratory testing machine. The remaining cylinders are tested similarly at 28 maturity days. All types of cylinder failures are recorded.

Filing of the specimens

The specimens are kept at the laboratory, pending further investigations. The test specimens, including drilled out cores (for CAPO-test) and pull-out cones are kept in air- and watertight plastic bags, marked clearly and systematically with the ID-numbers.

Interpretation of test results

The following data are now available:

- 21 compression test results from the cylinders type A and matching types of failures
- 21 compression test results from the cylinders type B and matching types of failures together with 21 LOK-test pull-out forces with matching types of failures
- 42 values of LOK-test and CAPO-test pull-out forces from testing of the cubes type C with matching failure types
- 5 compression test results from cylinders type D (lab compression machine) and 5 from cylinders type E (authorized lab compression machine) at 3 maturity days with matching types of failures
- 5 compression test results from cylinders type D (lab compression machine) and 5 from cylinders type E (authorized lab compression machine) at 28 maturity days with matching types of failures

The data have to be used for answering the following three main questions:

- What is the relationship between the cylinder compression strength and the LOK-test pull-out force?
- What is the relationship between the LOK-test and the CAPO-test pull-out forces?
- Is the laboratory testing machine reliable?

Before the questions may be answered, the data has, however, to be evaluated and accepted.

Evaluation of failure modes

Non-acceptable types of failures may occur, even if the technician is highly skilled and conducts the testing carefully.

Evaluation of the cylinder failure modes

The test result is rejected if the cylinder shows signs of eccentric loading resulting in horizontal splitting, failure type *f* of figure 48.

A correctly functioning and calibrated compression machine fulfilling the requirements of DS 423.23 will not cause such an eccentric loading unless the compaction of the cylinder has been performed inadequately.

Evaluation of the LOK-test failure modes

As shown in figure 8 the only acceptable failure is the type *x* failure. If the *y* and/or the *z* type failure modes appears, the test result is rejected.

Evaluation of the CAPO-test failure modes

Similarly, only the type *x* failure of figure 10 is acceptable. If failure modes of the types *y* or *z* emerges, the test is rejected.

The relation between the LOK-test pull-out force and the compressive strength

Before the relation can be found, it has first to be evaluated whether or not the LOK-test insert tested at the cylinder bottom (type B specimen) has had any influence on the subsequent compression testing of the cylinder. Secondly, it has to be demonstrated, that the compression machine used provides statistically the same results as when using the compression machine of the authorized laboratory.

Compressive strength of type A and B specimens

Related and accepted values of the compression testing of type A and type B cylinders are plotted against each other in a diagram.

If, as normally found, the relationship between the two sets of measurements is not significantly different from 1.00, the values plotted have to be close to the 45 degree line of the diagram. This may be seen directly, or a linear regression analysis may be applied.

Compressive strength of type D and E specimens

The average of the five cylinder compression test results and the deviation at 3 maturity days are calculated when using the testing machine (type D specimens) in the laboratory and compared to the matching results from the testing machine (type E specimens) of an authorized laboratory. Similarly the results

are compared at an age of 28 maturity days.

The comparative results should not differ significantly.

LOK-test pull-out force versus compressive strength

If the pull-out testing with LOK-test is shown to have no significant influence on the cylinder strength when testing test specimen type B and the compression testing machine of the laboratory gives the same results as that of the authorized laboratory, the calibrated LOK-test pull-out forces of the type B specimens may be plotted in a diagram relative to the matching cylinder compression test results for each cylinder type B.

Earlier investigations have shown that this relationship consists of two straight lines; one for pull-out force less than 25 kN and one for pull-out forces ranging between 25 kN and 60 kN. Based on this hypothesis, a linear regression analysis may be applied to the data to establish the best fitting relationship.

The relationship found is compared to the international determined and recognized one:

$$F_u = 0.96f_c + 1.00 \quad \text{for } 2 \text{ kN} \leq F_u < 25 \text{ kN}$$

$$F_u = 0.80f_c + 5.00 \quad \text{for } 25 \text{ kN} \leq F_u < 60 \text{ kN}$$

where F_u is the calibrated LOK-test pull-out force in kN and f_c is the calibrated cylinder compression strength in MPa.

When comparing ones own relationship to the above mentioned it should be noticed that the international determined relationship is based on a large number of measurements [Krenchel, 1984], while the just established relationship is determined only from a limited number of comparative tests. If no significant difference is found, the international established relationship should be applied.

LOK-test pull-out force versus CAPO-test pull-out force

For each cube the average of the pull-out forces of the two LOK-test inserts is compared to the average of the pull-out forces of the two CAPO-test inserts in a diagram. In case there is no significant difference between the the two types of pull-out tests, the plotted values should be close to the 45 degree line of the diagram. As mentioned before, the deviation of the pull-out test results measured on 200 mm cubes usually is slightly higher than if cylinders bottoms are tested.

If no significant difference is found between the pull-out forces, the established relationship between LOK-test and cylinder compression strength also applies for CAPO-test.

If a significant difference is found, the relationship between CAPO-test pull-out force and the cylinder compressive strength is established by substituting the LOK-test pull-out force with the pull-out force of the CAPO-test. ■

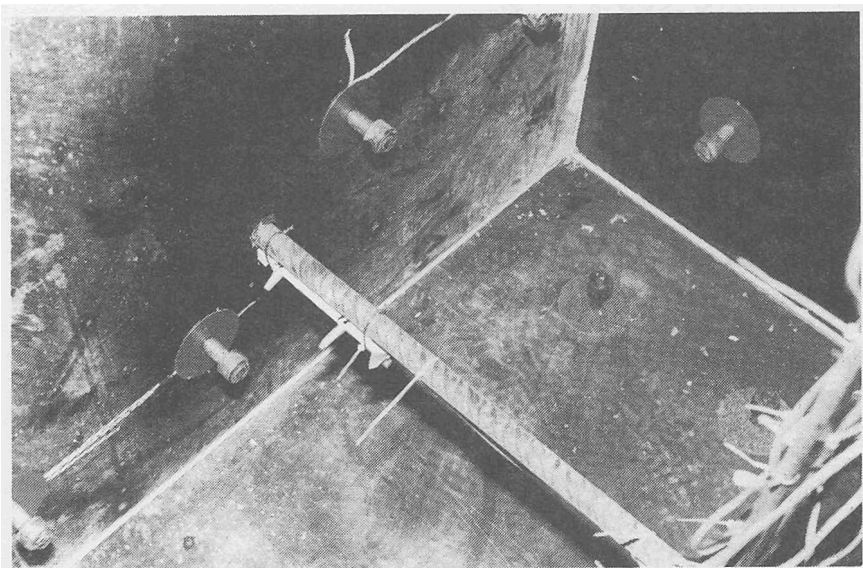


Figure 50. LOK-test inserts installed in a 900×900×500 mm mould for pre-testing the concrete according to SAB-III clause 4.5.3.1 Strength.

Figure 51. pull-out testing by LOK-test and CAPO-test carried out on a 200 mm concrete test cube.



Appendix 3. DS 423.31

The Danish Pull-out Testing Standard

The DS 423.31 was published in 1984. No revisions have been made ever since the issue. The Great Belt Link has found it necessary as part of the contract material to issue an SAB-Amendment to DS 423.31. This amendment is reproduced in Appendix 4 and has to be read in conjunction with the following standard.

1. Purpose and applications

This standard describe the procedure by which a cast-in disc is pulled towards a counterpressure placed on the surface and the pull-out force is measured. According to the method the force can also be applied to a certain value without creating rupture of the concrete.

The method is in general in compliance with ISO/DIS 8046.

The method may be used for evaluation of the compression strength of completed concrete objects presumed the pull-out force has been correlated to compressive strength of the concrete used beforehand.

The correlation between pull-out force and the concrete compressive strength is usually a simple straight-line relation.

The pull-out force may be used to evaluate if the strength of the object has achieved sufficient strength, e.g. for the purpose of:

- Timing of tension operations (prestressing or posttensioning).
- Timing of removal of formwork or supports.
- Terminating the protection against freezing.
- Terminating the curing of the concrete.

The method can not be used if the concrete temperature is below 0 °C.

The number of tests and the age of the concrete at the time of testing is not covered by this standard.

2. Reference

ISO/DIS 8046, Concrete, hardened – Determination of pull-out strength.

3. Sampling

The locations of the inserts, which have to be cast-in, are chosen according to the purpose of the testing. The inserts have to be placed so that the internal distance between the inserts is minimum ten times the diameter of the insert

disc and the distance to edges or corners of at least four times the insert disc. The inserts have to be placed at a minimum distance from reinforcement ensuring the pull-out cone to be the size of the reinforcement or the maximum aggregate size apart from the reinforcement whichever the greatest (cf. figure 52).

The evaluation of the results should be made based on a minimum of six pull-out tests of an inspection section.

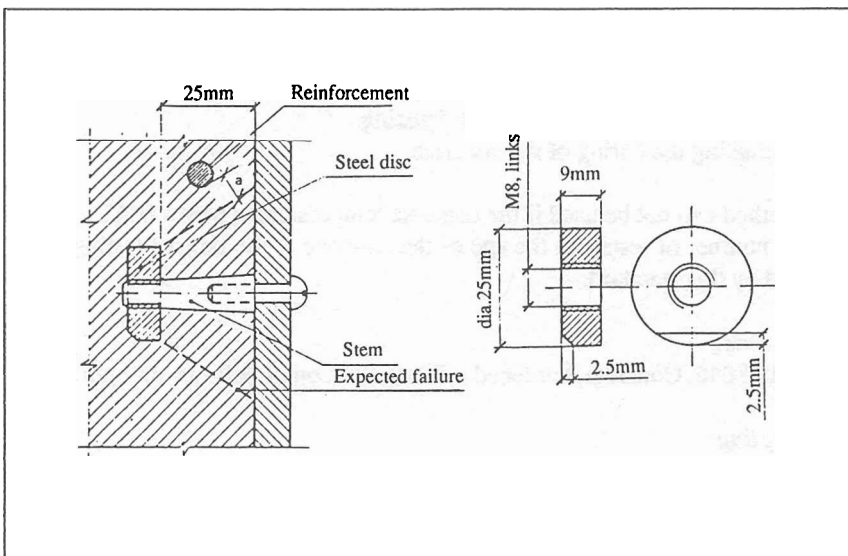
The thickness of the concrete has to be minimum four times the diameter of the insert disc.

4. Test method

4.1 The testing principle

The disc of the insert is cast in the concrete at a certain depth below the surface. The depth is determined by the length of the stem connected to the disc. The stem is removed at the time of testing and a pull-bolt is secured to the disc. The disc is pulled towards a counterpressure placed on the surface concentric with the disc and with a suitable greater diameter than the disc, cf. figure 53. The pulling is made by means of a hydraulic instrument registering the pull-force. The pulling takes place to a certain predetermined value or to failure of the concrete.

Figure 52. The pull-out insert consists of a disc and a stem. The test location is selected so the distance «a» is greater than the dimension of the reinforcement or the maximum aggregate size, whichever the greatest.



4.2 Apparatus

Pull-out equipment consisting of insert (disc and stem), loading system (pull-bolt, counterpressure and hydraulic instrument) and a system for determination of the applied pull-force (a gauge).

The dimensions of the disc and the counterpressure are given in figure 52.

The loading system has to ensure the disc is being pulled centripetal to the counterpressure and perpendicular to the surface.

The tolerances of the dimensions stated has to be within ± 2 per cent.

The loading rate of the hydraulic instrument has to be as stated in clause 4.4.

The peak-load has to be determined with an accuracy of ± 2 per cent. The peak-load should be registered after failure.

4.3 Preparing the testing

The insert is attached to the formwork ensuring the centerline of the insert is perpendicular to the surface and remains so during casting and compaction of the concrete.

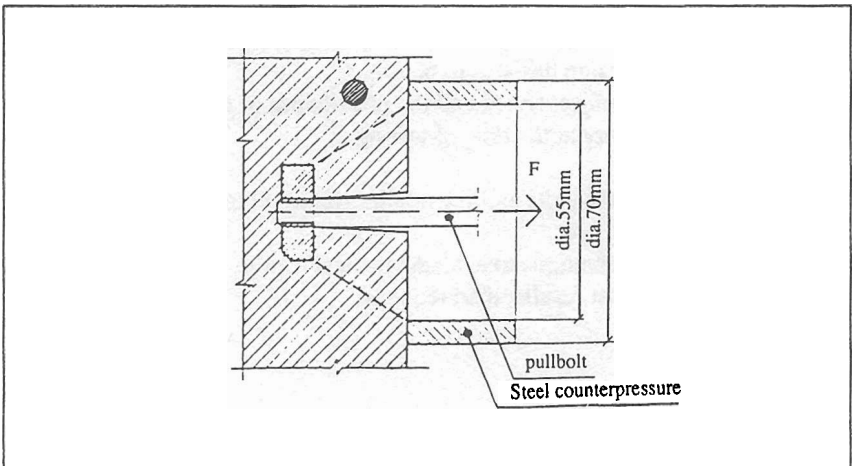
Inserts may also be placed in top surfaces of a casting after the casting has taken place. In doing so, the insert has to be fully submerged into the concrete.

4.4 Procedure

The concrete must not be frozen at the time of testing.

When the testing has to take place, all parts of the inserts but the disc are removed. Also it is made sure the concrete surface to be pulled against is plane

Figure 53. The pullbolt attached to the cast-in disc shown together with the counterpressure placed on the surface.



and smooth.

The pullbolt is threaded into the disc, the counterpressure is placed on the surface concentrically with the disc and the pull-bolt is attached to the hydraulic instrument. Before loading takes place, the concrete surface, the counterpressure and the instrument have to be fully in contact with each other.

If the purpose is to measure the pull-out force, the disc is pulled with a constant speed so failure occurs after two minutes \pm 30 seconds. The peak-load is registered.

If the purpose is only to load the disc to a pre-determined pull-force, the force is applied at a constant rate for the maximum load to be reached within two minutes \pm 30 seconds.

4.5 Stating the test result

The pull-out force or the maximum applied force is stated in kN-units rounded off to the nearest 0.5 kN. At the same time it is stated whether or not failure has occurred.

4.6 Testing report

The testing report has to contain as a minimum the following informations:

- a) The name and the address of the testing laboratory.
- b) The date and the identification of the report.
- c) Description of the test method.
- d) Any deviation from the test method given in this standard.
- e) Name and address of the client.
- f) Name of the technician.
- g) Name of the concrete supplier.
- h) Identification of the concrete used. If a correlation program is performed, the concrete mix design has also to be stated.
- i) Dimensions of the object tested and the positioning of the pull-out inserts.
- j) The concrete maturity at the time of testing.
- k) Date of testing.
- l) The test results in kN-units and the relationship used to compression values in MPa- units.
- m) Other relevant informations to evaluate the test results.
- n) Evaluation of the test results, if so required. ■

Appendix 4.

SAB-Amendment to DS 423.31

The pull-out standard for the LOK-test DS 423.31 was issued in 1984. The Great Belt Link has found it necessary to make an amendment to this standard. The amendment is stated in clause 4.5.10.10 of the SAB and reproduced in the following.

SAB clause 4.5.10.10, Amendment to DS 423.31

Positioning of tests individual trials, acceptance criteria for correct testing and directions for repair of extraction holdes for LOK-test and CAPO-test systems are covered herein:

1. *Positioning of a tests' individual trials*

- 1.1 LOK-tests and CAPO-tests are placed in the same 5 cm from reinforcement.
- 1.2 A test's individual trial is placed in the same horizontal layer with regard to the minimum distance to the edge given in DS 423.31.

2. *Acceptance criteria for correct testing*

2.1 *For LOK-test using L-40 test inserts*

- 2.1.1 Pull-out bolt (L-16) with centre washer (L-15) and coupling (L-13) shall be screwed 6 1/2 turns into the cast-in disk, otherwise the test is disregarded.
Reason: LOK-test insert disks shall be placed 25 mm under the test surface.
- 2.1.2 The activated LOK-test instrument shall be able to be coupled to the coupling (L-13) with centre washer (L-15) and pull-out bolt (L-16) screwed 6 turns into the cast-in disk, otherwise the test is disregarded.
Reason: LOK-test inserts axle shall be at right angles to the test surface.
- 2.1.3 If the loading under testing to breakage in the concrete is interrupted the test is disregarded.
Reason: Repeated testing will reduce the test result.

After testing the breakage cone shall be visible on the test surface bounded by holders 55 mm inner diameter, otherwise the test is disregarded.

Reason: The trial shall be loaded to breakage as the maximum result is desired.

- 2.1.5 If other signs of breakage or spalling outside of the circular 55 mm break occurs, the test is disregarded.

Reason: The test surface shall be plane.

- 2.1.6 The LOK-test instrument shall be recalibrated if the manometer is replaced, in case of service inspection or in case the instrument has been overloaded.

However, calibration shall occur at least once per 1000 tests or at least once per year, otherwise the tests are disregarded.

Reason: The LOK-test instrument's true and indicated pulling force shall be registered and shall be stable.

2.2 *For CAPO-test*

- 2.2.1 If the loading under testing to breakage in the concrete is interrupted, the test is disregarded.

Reason: Repeated testing will reduce the test result.

- 2.2.2 If other breakage signs or spalling outside of the circular 55 mm break boundary at the holders inner diameter occur after complete pull-out of the cone, the test is disregarded.

Reason: The test surface shall be plane.

- 2.2.3 If the depth from the test surface to the cut CAPO-test recessed edge towards the test surface is outside of the tolerance $25 \text{ mm} \pm 0.2 \text{ mm}$, the test is disregarded.

Reason: The CAPO-test insert in the expanded condition shall be positioned 25 mm under the test surface.

- 2.2.4 If the diameter of the expanded CAPO-test insert after extraction of the cone is outside of the tolerance $25 \text{ mm} \pm 0.5 \text{ mm}$, the test is disregarded.

Reason: The CAPO-test insert shall be fully expanded under test.

- 2.2.5 If the diameter of the cut CAPO-test holes is outside of the tolerance $25 \text{ mm} + 0.5/- 0.0 \text{ mm}$ the test is disregarded.

Reason: The CAPO-test hole shall be cut to $25 \text{ mm} + 0.5/- 0.0 \text{ mm}$.

- 2.2.6 If foreign bodies are found in the breakage cone after pull-out the test is disregarded.
Reason: It is the compressive strength of the concrete which shall be measured.
- 2.2.7 The LOK-test instrument shall be recalibrated if the manometer is replaced, in case of service inspection or in case the instrument has been overloaded.
However calibration shall occur at least once per 1000 tests or at least once per year, otherwise the tests are disregarded.
Reason: The LOK-test instrument's true and dedicated pulling force shall be registered and shall be stable.

3. *Repair of break hole*

3.1 *LOK-test break*

- 3.1.1 **If the break cone has** not lifted more than 1 mm above the test surface, a two part rapid hardening epoxy is injected into the 11 mm stem hole to fill the hold and cracks.
- 3.1.2 Otherwise the break cone is extracted fully. If the LOK-test instrument's 5 mm travel is insufficient to remove the cone, a special removal instrument is used. The hole in the concrete is repaired with a polymer modified concrete.
- 3.1.3 Withdrawn LOK-test bolts may no be re-used.

3.2 *CAPO-test break*

The hole in concrete is repaired using polymer modified concrete. ■

Appendix 5. DS 411

Rule of decision for control testing

This standard was issued March 1984 by the Danish Society of Civil Engineers as a 3rd edition. Revisions were made in January 1990. However, the rule of decision for control testing remains the same. The Great Belt Link has used the standard's requirements and stated them in the SAB as far as the characteristic compression strength and the splitting strength of the concrete is concerned.

Clause 8.1.1 Decision rule for control

Analysis of test results in connection with control of the compressive strength should be based on DS 409 The Safety of Structures. The probability mentioned there of immediately accepting a delivery for which the characteristic value achieved corresponds to the lower limit of the desired safety class has been taken as 16 per cent in this code. Analysis of test results for other concrete properties is based on DS 423.1.

Concrete compressive strength

The statistical evaluation of the concrete compressive strength requires knowledge of the coefficient of variation δ . If no other documentation is available, the values specified in table 7 should be used.

If control is performed by sampling inspection a number of samples should be taken and an average value should be determined from these samples. If the average value exceeds the control value $k_n \cdot f_{ck}$ the strength can be accepted.

From the expression

$$k_n = \exp \left[\left(2.28 + \frac{1}{\sqrt{n}} \right) \cdot \delta - 0.1875 \right] \quad (8.1.1)$$

Table 7. Coefficient of variation of the concrete compressive strength given as a function of required characteristic strength f_{ck} by testing after 28 days.

f_{ck} by testing after 28 days (MPa)	5	10	15	20	25	30	35	40	45	50
δ cast cylinders	0.22	0.18	0.17	0.16	0.15	0.14	0.13	0.12	0.12	0.12
testing on com- pleted structures	0.22	0.22	0.20	0.19	0.18	0.17	0.16	0.14	0.14	0.14

the factor k_n is calculated, cf. table 8, which gives a number of values.

The expression (8.1.1) has been derived on the assumption that the value 15 per cent for the coefficient of variation has been used in the determination of the partial coefficient. In addition, a logarithmic normal distribution has been assumed.

Tests in connection with type approval

The tests should determine the average value F of the failure or yield effect. From the expression (8.1.1) the factor k_n is determined as a function of the number of samples n corresponding to $\delta = 0.15$. The load-carrying capacity is acceptable if F exceeds k_n multiplied by the design action multiplied by the partial coefficient of the material which is crucial for the failure, see section 5.3 of DS 411.

Guide: Documentation of the coefficient of variation δ

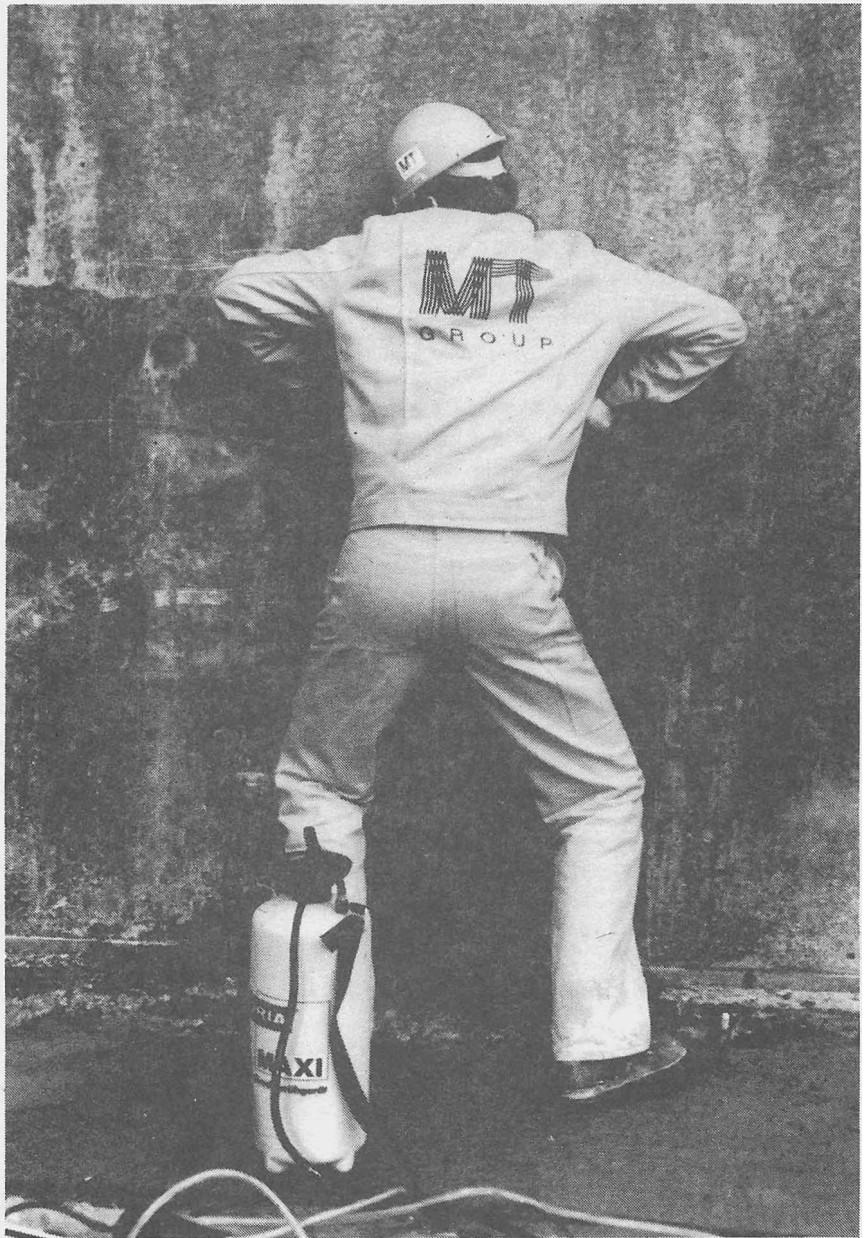
δ can be adjusted in relation to the values in table 7 when one of the following requirements is complied with:

1. If there are at least 40 test results from mixes with the same (nominal) characteristic value, the same type of materials, produced over a period from a minimum of 6 days to a maximum of 12 months in the same plant and with the same laboratory staff, a value of δ should be calculated from formula V 8.1.1 page 111. This value should replace the value taken from table 7 if it deviates from the table value by more than 18 per cent.
2. If there are at least 100 test results from mixes with the same (nominal) characteristic value, the same type of materials, produced within a period of maximum of 24 months in the same plant and with the same laboratory

Table 8. Factor k_n as a function of number of tests n and coefficient of variation δ .

δ	n				
	3	6	9	15	30
0.06	0.98	0.97	0.97	0.97	0.96
0.08	1.04	1.03	1.02	1.02	1.10
0.10	1.10	1.08	1.08	1.07	1.06
0.12	1.17	1.14	1.13	1.12	1.11
0.14	1.24	1.21	1.20	1.18	1.17
0.15	1.27	1.24	1.23	1.21	1.20
0.16	1.31	1.27	1.26	1.24	1.23
0.18	1.39	1.34	1.33	1.31	1.29
0.20	1.47	1.42	1.40	1.38	1.36
0.22	1.55	1.50	1.47	1.45	1.43

Figure 54. Technician performing the expansion of a CAPO-test insert before pull-out testing of a concrete wall.



staff, a value of δ should be calculated from formula V 8.1.1 page 111. This value should replace the value taken from table 7 if it deviates from the table value by more than 11 per cent.

Value of the coefficient of variation δ

A value of δ can be calculated in the following way:

If r test results are found, where r is a multiple of 4, satisfying the conditions for being included in the calculation of the value, these results are divided in chronological order into groups of 4. Mean and standard deviation are calculated:

$m_1, m_2, m_3, \dots, m_p$	mean
$s_1, s_2, s_3, \dots, s_p$	standard deviation

for each of the total number of groups p ($p = r/4$).

From this the value of δ is determined from the formula

$$\delta = \sqrt{p} \cdot \frac{\sqrt{s_1^2 + s_2^2 + s_3^2 + \dots + s_p^2}}{m_1 + m_2 + m_3 + \dots + m_p} \tag{V 8.1.1}$$

Appendix 6. DS 423.1

Statistical interpretation of observations

This standard was issued in March 1985 as second edition by the Danish Society of Civil Engineers. The Great Belt Link has during the creation of the SAB used this standard also for statistical evaluation of other properties of the concrete than the characteristic compression strength and splitting strength. Wherever the SAB specifies another testing frequency than stated in the DS 423.1 the SAB applies.

In the following only rules for determining the size of the inspection section, the sampling and the decisions to be made are included. Observations and evaluation by supplementary testing is not included.

DS 423.1: Sampling, inspection and statistical interpretation of test results

1. Purpose and applications

This standard outlines the general guidelines for control by sampling and the statistical interpretation of observations referring to the properties of concrete and concrete structures where the requirements are expressed as limits (tolerances) within which the properties have to be located.

The purpose of the inspection is to point out whether or not the requirements have been met, concerning the following *properties*:

The materials of the concrete apart from the cement, which is controlled according to DS 427, e.g. the shape of the aggregates, the distribution of the aggregates, the source of the aggregates, humidity, density, content of humic acid, chlorides and sludge.

The composition, e.g. the *w/c*-ratio, content of cement, water, air and sand. Transportation and casting, e.g. the time of transportation, slump and bleeding.

Curing conditions, e.g. the temperature and the temperature gradients.

Strength, e.g. compressive strength, splitting strength and pull-out strength.

and concerning the *structure* itself:

The details of the structural design, e.g. the size of the cover layer, the planeness of the surface and the positioning of the reinforcement.

- The load capacity and the stiffness, e.g. the cam strength and the deflection .

If no specific testing method is required, measurement according to the standard can only take place if a Danish Standard, an ISO-Standard or a CEN-standard exists for the property in question. A summary of the Danish Standards is given in DS 405.0, Test Methods for sand, gravel and aggregates and in DS 423.0, Concrete Testing.

2. References

DS 405.0, Test Methods for Sand, Gravel and Aggregates. Introduction.

DS 411, Concrete Structures.

DS 423.0, Testing of Concrete. Rewiev.

DS 1050, Tolerances in the Building Industry. The use of dimension tolerances.

DS 2163, Statistics. Termonology and Symbols

DS 2184, Sampling procedures and tables for inspection by attributes.

3. Definitions

Structures or deliveries are divided into a number of inspection sections. Within each inspection section a number of samples are taken, and for each sample one or more test specimens are produced on which the control testing of the different properties are made.

The test result of one test specimen is called »a single observation«. The average of single observations is named »an observation« in the statistical interpretation procedure.

If one observation exists for each batch, the interpretation of the observations is called »total inspection« (100 per cent inspection). If the number of batches is greater than the number of observations, the inspection is named »inspection by sample testing«, and the number of observations within one inspection section is called »the sample size«.

One batch is the amount of concrete which is mixed to a uniform consistency. Usually it is the amount of concrete in one truck load, a conical agitator (i.e. a truck mixer).

4. Inspection sections

Before the testing takes place the structure or the delivery of the material is divided up into inspection sections. One inspection section must not exceed 200 batches. Also, the following guidelines are observed:

In relation to durability properties the splitting up in inspection sections is made based on an evaluation of the economic consequences of the risk of statistical rejection (with the concrete actually being acceptable within one

7.5 Tables

Table 9.
Minimum sample size

Number of batches N	Minimum sample size n_{min}
4 - 15	3
16 - 21	4
22 - 27	5
28 - 33	6
34 - 40	7
41 - 47	8
48 - 54	9
55 - 62	10
63 - 70	11
71 - 78	12
79 - 87	13
88 - 96	14
97 - 105	15
106 - 114	16
115 - 123	17
124 - 132	18
133 - 141	19
142 - 150	20
151 - 160	21
161 - 170	22
171 - 180	23
181 - 190	24
191 - 200	25

Table 10.
Acceptance and rejection numbers

Sample size n_{fak}	Acceptance number A	Rejection number R
3 - 12	0	1
13 - 19	1	2
20 - 29	2	3
30 - 39	3	4
40 - 49	4	5
50 - 64	5	6
65 - 79	6	7
80 - 94	7	8
95 - 109	8	9
110 - 124	9	10
125 - 145	10	11

Total inspection has to be performed if N is 3 or less (clause 4).

Table 9 and 10 is given in DS 2184, single sampling for normal inspection (level II) with AQL = 4 per cent.

section) compared to the costs of testing.

As far as strength is concerned the inspection sections are chosen keeping in mind the safety aspect of the particular structural elements, e.g. slabs versus columns.

Once the inspection section has been selected, the contractor or the concrete producer may always subdivide it, if needed.

Within one inspection section the material properties and the conditions of production have to be the same. If they are changed during construction, a new inspection section is commenced.

Also, before the testing is performed, it has to be decided how many batches have to be tested as a minimum, and how many single tests one observation should consist of. The minimum sample size is stated in table 9 of this standard.

When measuring different properties within one inspection section, the sample sizes may differ.

The maximum size of the inspection sections and the number of observations, once chosen, should not be changed during construction.

If an inspection section consists of 3 or less batches, total inspection has always to be performed.

5. Sampling

The sampling has to be made representatively and at random within the inspection section. At the same time the following precautions have to be observed:

The testing has to follow the prescriptions of the test method in question or otherwise as stated in the special concrete working conditions.

The test specimens have to be stored as instructed and must not be damaged from the time of sampling until testing takes place.

Test specimens representing the same control section and the same property have to be handled identically.

6. Observations

If more than one measurement of the same property is taken within one sample, the variation will be less than or equal to the property's variation within the inspection section. Such repeatable measurements have to be averaged representing one observation.

In general each single tests has to be of equal size (e.g. same volume) and all samples have to consist of the same number of single tests.

7. Interpretation of observations

The interpretation may take place by »inspection by sample testing« or by

»total inspection«, and is in general based on inspection by attributes (»yes« and »no« statements). Only the inspection of the strength property is based on variable inspection (e.g. kN- or MPa-units).

7.1 Inspection by sample testing

The requirements may be that the property investigated should not fall outside given tolerances or should not exceed a maximum limit or a minimum limit. The interpretation is made statistically based on all the observations related to the inspection section in question. The requirement is met or rejected as stated in clause 7.1.3 below.

7.1.1 The strength of concrete. Observations related to the compressive strength of concrete are processed as stated in DS 411, 3. edition, March 1984, clause 8.1.1. The tensile strength of concrete is evaluated by means of the same basic principle using the values for the un-documented coefficient of variation as stated in clause 8.1.1. of the DS 411 for testing in-place.

7.1.2 Geometrical dimensions. The observations (e.g. the thickness of walls, cover layers and the dimension of holes) are interpreted according to DS 1050.

7.1.3 Other properties of the concrete. Limits should have been established within the property in question has to fall. The requirement is met as indicated in table 10 if maximum A values falls outside the limits, and rejected if at least R values falls outside the limits. The numbers of observations (n_{act}) has to be greater than or equal to the minimum sample size (n_{min}) of table 9.

7.2 Total inspection

By applying total inspection every batch is checked. The batch is accepted if the observation falls within the prescribed limits.

7.3 Process control

The inspection of a current production may, if so agreed on, be based on the concrete plants own internal inspection, when aggregates, concrete or structural elements is produced in great quantity. The DS 411, 3. edition, 1984 apply for the quality control and the plant has to be affiliated to a certification organization recognized according to the articles of the Danish Society of Civil Engineers. In such cases the requirements of clause 4 of this standard concerning the maximum size of a control section and the minimum sample size may be waved aside. Also, inspection by attributes may be replaced by inspection by variables for other types of properties than the strength if the type of statistical

distribution is documented.

If the process control is outlined according to these guidelines, the acceptance of the production may be determined independent of each single delivery or project.

The interpretation of a material property may in such cases be based on a statistical interpretation partly from the observations of the inspection sections and partly from the current production's database. This requires however the current production to be strictly controlled.

Process control of a current production is founded on ongoing picking out and inspection of samples of the production process. The inspection determines whether or not the production is in control, if the average or the standard deviation is stable or unstable. Only when the production is stable, a qualified statement can be made concerning the performance of the requirements. Properties which are not included in the concrete plants process control have to be evaluated for each delivery by means of inspection by sample testing or by total inspection.

7.4 Observations falling outside the established limits (tolerances)

If the observation of a batch falls outside the established tolerances, the batch may be rejected no matter if the inspection section as a whole is accepted or rejected. Rejected batches may have be corrected or scrutinized inspection as agreed on between the parties. ■

Appendix 7. Calculation/measurements of the in-place concrete maturity

The strength developed by the concrete after casting depends among other factors of the concrete temperature during hardening. In the structure the temperature always fluctuates during hardening. The variation of the temperature depends on the temperature of the fresh concrete, the temperature of the environment, the heat development inside the concrete and the emission of the heat to the environment.

Maturity

According to the »Danish Code of Practice for the Structural Use of Concrete« DS 411, the potential strength of the concrete is measured after the concrete specimens (cylinders) have been cured 28 days in water kept at a constant temperature of 20 °C. If the temperature of the concrete in-place has had a different temperature than 20 °C, the actual measured strength has to be transformed to the strength which would have been achieved if the temperature had been 20 °C.

When testing cylinders the 20 °C requirement raises no problems. The water has only to be kept at constant temperature of 20 °C.

The SAB requires the in-place testing (LOK-test and CAPO-test) of the structure to be performed at 28 maturity days, that is 28 days at 20 °C. At the trial testing of the concrete the SAB requires further that the LOK-test and CAPO-test pull-out testing is done at a maturity of the concrete of 1, 2, 3, 7, 14, 28 and 35 maturity days.

Thus, there is a need for a definition of the concept »maturity« and a transformation methodology to make it possible to calculate to maturity of the in-place concrete based on the actual age in days (or hours) and the temperature history of the concrete. In practice the following definition is used:

If a concrete achieves a certain compressive strength f_c (presumed sufficient moist is present) and the temperature has changed during the period of hardening, the maturity is defined as the time the concrete should have hardened at 20 °C to obtain the same compressive strength f_c .

Experience shows that concrete specimens from the same batch reaches the same strength if the maturity is identical, no matter how the temperature history has been. Only the temperature must not be too high or too low. The SAB establish the maximum temperature to 50 °C. At the same time the SAB requires the temperature never to exceed 70 °C. If the temperature of the concrete falls

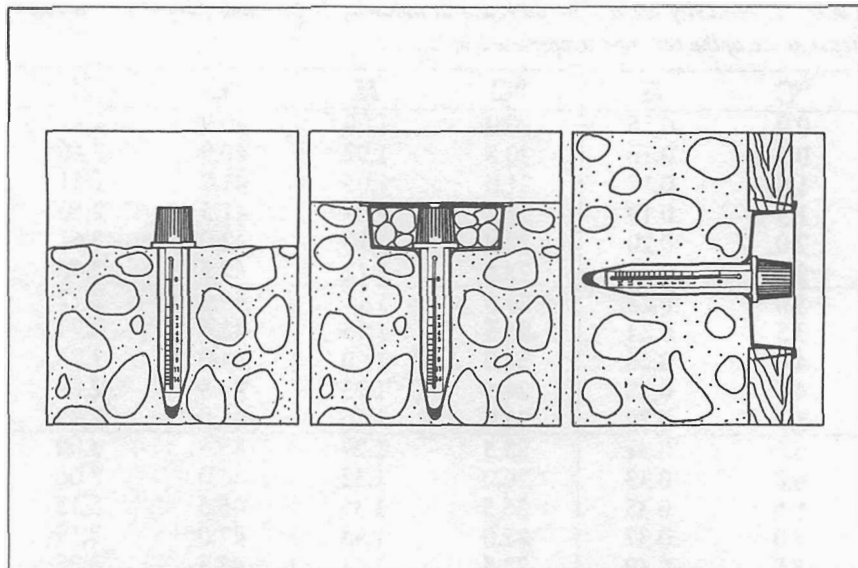


Figure 55. Various COMA-meter installations.

within 50 °C and 70 °C, special investigations have to be made to examine the strength development in relation to maturity.

Measurement of the maturity

Different methods and apparatus exist to measure the maturity of the concrete. The most common are the following:

- Registration of the temperature, manually or automatically, followed by calculation of the maturity as indicated in table 11 and 12 below.
- Maturity computer which automatically measures the concrete temperature and the time and calculates the maturity.
- COMA-meters which automatically measures the concrete maturity, cf. figure 55.

The first two mentioned methods requires thermal wires (thermal couples) to be cast into the concrete while the COMA-meter is activated by breaking its capillary tube, threading it to a container, which is pressed into the fresh concrete. At the time of testing the evaporation of the liquid of the tube is directly indicating the maturity readable on an attached scale. If the first option is chosen, the temperature has to be measured at regular intervals and the maturity calculated afterwards.

Table 11. Maturity table. The increase in maturity H per time period is shown in dependence of the concrete temperature in $^{\circ}\text{C}$.

$^{\circ}\text{C}$	H	$^{\circ}\text{C}$	H	$^{\circ}\text{C}$	H
0.0	0.15	20.0	1.00	40.0	2,41
0.5	0.16	20.5	1.02	40.5	2,46
1.0	0.17	21.0	1.05	41.0	2,51
1.5	0.19	21.5	1.07	41.5	2,56
2.0	0.20	22.0	1.10	42.0	2,61
2.5	0.21	22.5	1.12	42.5	2,66
3.0	0.23	23.0	1.15	43.0	2,72
3.5	0.24	23.5	1.18	43.5	2,77
4.0	0.26	24.0	1.20	44.0	2,83
4.5	0.28	24.5	1.23	44.5	2,89
5.0	0.29	25.0	1.26	45.0	2,95
5.5	0.31	25.5	1.29	45.5	3,00
6.0	0.33	26.0	1.32	46.0	3,06
6.5	0.35	26.5	1.35	46.5	3,13
7.0	0.37	27.0	1.38	47.0	3,19
7.5	0.39	27.5	1.41	47.5	3,25
8.0	0.41	28.0	1.44	48.0	3,32
8.5	0.43	28.5	1.47	48.5	3,38
9.0	0.45	29.0	1.51	49.0	3,45
9.5	0.47	29.5	1.54	49.5	3,51
10.0	0.50	30.0	1.57	50.0	3,58
10.5	0.52	30.5	1.61	50.5	3,65
11.0	0.55	31.0	1.64	51.0	3,72
11.5	0.57	31.5	1.68	51.5	3,80
12.0	0.59	32.0	1.72	52.0	3,87
12.5	0.62	32.5	1.75	52.5	3,94
13.0	0.64	33.0	1.79	53.0	4,02
13.5	0.67	33.5	1.83	53.5	4,10
14.0	0.70	34.0	1.87	54.0	4,17
14.5	0.72	34.5	1.91	54.5	4,25
15.0	0.75	35.0	1.95	55.0	4,33
15.5	0.77	35.5	1.99	55.5	4,41
16.0	0.80	36.0	2.04	56.0	4,50
16.5	0.83	36.5	2.08	56.5	4,58
17.0	0.85	37.0	2.12	57.0	4,67
17.5	0.88	37.5	2.17	57.5	4,75
18.0	0.90	38.0	2.22	58.0	4,84
18.5	0.93	38.5	2.26	58.5	4,93
19.0	0.95	39.0	2.31	59.0	5,02
19.5	0.98	39.5	2.36	59.5	5,12
20.0	1.00	40.0	2.41	60.0	5,21

Date and time	t hours	θ °C	Mean °C	H –	Δt hours	ΔM hours	M hours
1/4, 0925	0	15	20.0	1.00	24.0	24.0	0.0
2/4, 0930	24	25	26.5	1.35	24.0	32.4	24.0
3/4, 0920	48	28	30.0	1.57	24.0	37.7	56.4
4/4, 0930	72	32	31.0	1.64	24.0	39.4	94.1
5/4, 0935	96	30	27.5	1.41	24.0	33.8	133.5
6/4, 0930	120	25	24.0	1.20	24.0	28.8	167.3
7/4, 0930	144	23	23.0	1.15	24.0	27.6	196.1
8/4, 0925	168	23	21.5	1.07	24.0	25.7	223.7
9/4, 0920	192	20	20.0	1.00	24.0	24.0	249.4
10/4, 0930	216	20	19.5	0.98	24.0	23.5	273.4
11/4, 0920	240	19	18.5	0.93	24.0	17.2	296.9
12/4, 0940	264	18	18.0	0.90	24.0	21.6	314.1
13/4, 0935	288	18	17.5	0.88	24.0	21.1	335.7
14/4, 0945	312	17	17.0	0.85	24.0	20.4	356.8
15/4, 0930	336	17	16.5	0.83	24.0	19.9	337.1
16/4, 0920	360	16	16.0	0.80	24.0	19.2	397.1
17/4, 0925	387	16	16.0	0.80	24.0	19.2	416.3
18/4, 0930	408	16	15.5	0.77	24.0	18.5	435.5
19/4, 0930	432	15					454.0

Table 12. Example of maturity calculation. The concrete temperature is 15 °C at the time of casting. The temperature is measured each 24 hours. After 432 hours the concrete has achieved a maturity of 454 maturity hours or 18 maturity days.

Tabulations

To calculate the increase of the maturity when the temperature is known for a (short) time period table 11 is used. Table 12 illustrates such a calculation.

Example 6. A concrete mixture is cast 1990-04-01 at 0925 hours. The temperature of the concrete is 15 °C. The temperature of the concrete is measured each 24 hours as shown in table 12. After 432 hours this concrete has achieved a maturity corresponding to 454 maturity-hours, found according to the calculation shown in table 12. ■

Appendix 8. Illustrations

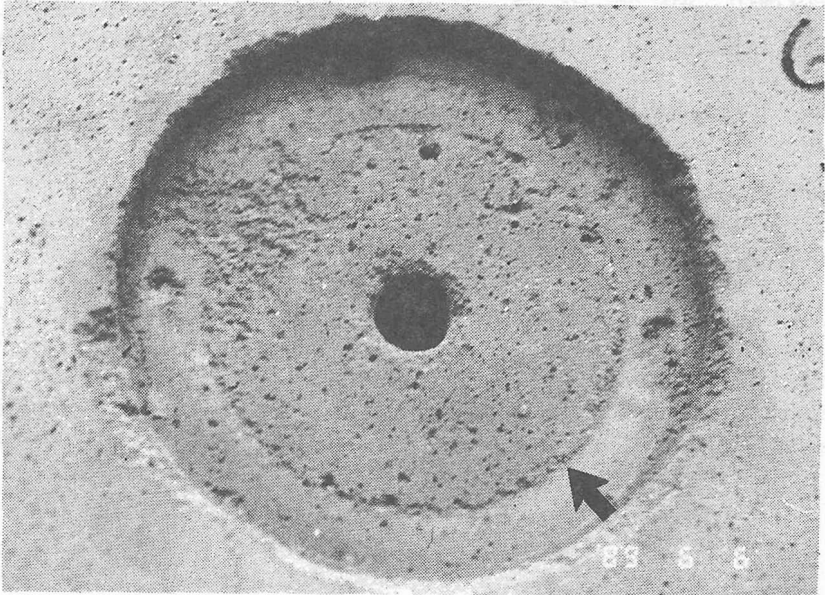
LOK-test and CAPO-test failure modes

As mentioned in chapter 4 it is important for the reliability of the LOK-test and the CAPO-test results that the pull-out failures are regular without radial cracking or spalling of the concrete outside the circular crack left by the 55 mm in diameter counterpressure.

LOK-test failures

Figure 56 and 57 illustrates the appearance of ideal LOK-test failures when the pull-out has been performed exactly and only to failure of the concrete (figure 56), and when the pull-out cone is fully dislodged (figure 57). Note that no radial cracking or spalling is visible while the 55 mm counterpressure circle is clearly visible or sharp. In both the illustrations, the L-40 insert has been used where the basic insert is attached to a watertight masonite plate nailed to wooden shutters. This explains the 80 mm in diameter imprint of the concrete

Figure 56. Appearance of a correct performed LOK-test using L-40 insert after completed testing exactly and only to failure. The pull-out cone (arrow) is lifted 0.1mm from the testing surface. There is no sign of other cracks, radially or spalling.



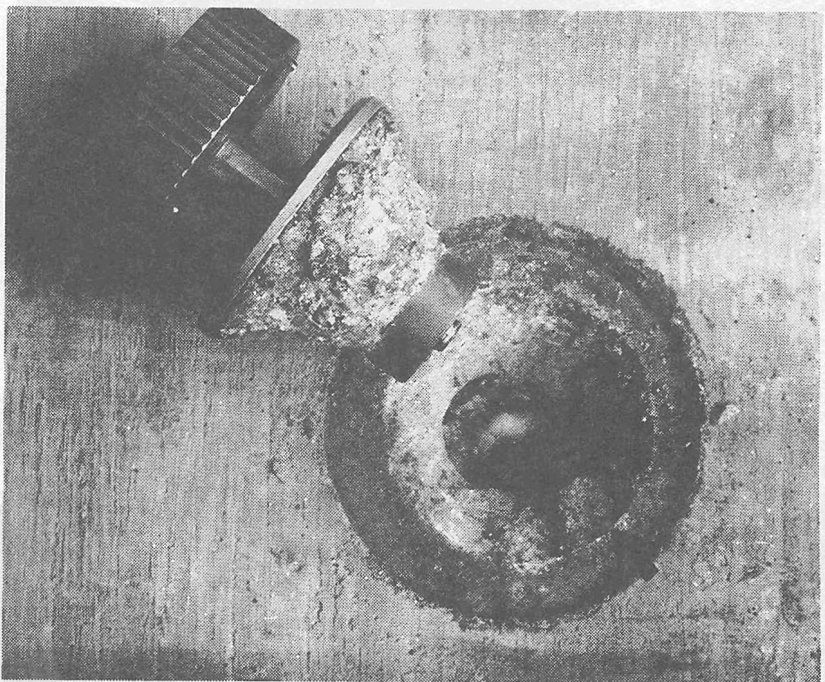
3 mm high outside the 55 mm counterpressure crack. The imprint is not caused by the testing itself!

Should radial cracking or spalling occur outside the 55 mm circle crack, the test is rejected. Such cracking is typically caused by neglecting the minimum distance requirements to edges/corners or between two adjacent LOK-test's; if the centerline of the inserts has not been perpendicular to the surface or if the surface has not been sufficient smooth and plane.

CAPO-test failures

The CAPO-test pull-out cone is always fully dislodged since the pullbolt has to be reused. Again it is important that the cone failure towards the surface is limited by a sharp 55 mm circular edge as illustrated in figure 58, arrow. Also with CAPO-test no other visible radial cracking or spalling of the concrete must be visible.

Figure 57. Fully dislodged LOK-test cone with attachments using L-40 insert. Note the sharp edge left by the 55 mm inner diameter of the counterpressure (arrow).



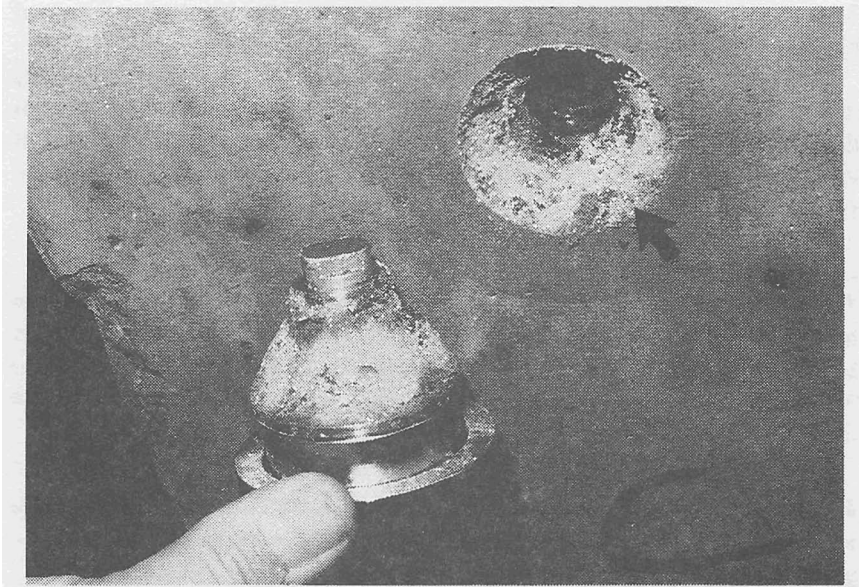


Figure 58. CAPO-test failure. The CAPO-test pull-out cone is always fully dislodged. Note the sharp edge (arrow) at the concrete surface left by the 55 mm inner circle of the counterpressure.

Figure 59. Detail of the CAPO-test pull-out cone.



Radial cracking or spalling of the concrete occurs typically if the required minimum distances to edges or corners (100 mm) or in between two tests (200 mm) have not been met, or if the surface has not been planned with the diamond wheel, or if the centerline of the expanded CAPO-test insert has not been pulled perpendicular to the surface. Another cause for an incomplete test may be if the preparation of the CAPO-test hole and recess have been made insufficient or the expandable ring has not been fully expanded inside the concrete before pull-out. ■

Appendix 9. Summary

Pull-out testing by LOK-test and CAPO-test

The previous chapters and appendixes have in detail dealt with how to perform the pull-out testing on The Great Belt Link. The following appendix gives a summary of pull-out testing performed in-situ with LOK-test and CAPO-test.

The review is founded on the The Great Belt Link's SAB requirements. Special assumptions related to the amount and the speed of production applies to the project. Thus, the review can not directly be transferred to any smaller concrete structure in Denmark.

Applications

The Great Belt Link has chosen to inspect the compressive strength of the concrete in-place and not only trust the inspection of the potential strength combined with the visual inspection of the casting, the compaction and the curing conditions.

Pull-out testing by means of LOK-test

LOK-test is used for:

Checking the quality of the compressive strength in-place according to the requirements of the SAB and its General Note for the inspection section in question.

Timing of early loading operations as early form stripping, pulling of reshores, cutting of strands or tension operations.

Governing the curing of the concrete. A pre-determined strength level has to be kept constant during production. The strength level is determined at a controlled and documented pre-testing and trial casting.

In the first and the last case the usual statistical approach is *inspection by sample testing*, only for small inspection sections the *total inspection* will be applied.

The size of the inspection section, when measurement of early strength is the issue, is decided upon by the contractor in cooperation with the supervision. Usually *total inspection* is used since the inspection sections are small.

Pull-out testing by means of CAPO-test

The CAPO-test applications are the following:

- Supplementary testing if the in-place concrete of an inspection section has been rejected by means of LOK-test.
- Supplementary testing if LOK-test inserts have been installed incorrectly in an inspection section.
Supplementary testing if the properties of the concrete or the production conditions in an inspection section has changed so that the control section in fact consists of two or more sections and the needed amounts of observations established by means of LOK-test are not available compared to the number of batches.
- Supplementary testing if the concrete is only evaluated by means of cylinders and there is a substantiated reason for mistrusting the curing conditions applied.

Pull-off testing by means of BOND-test

The SAB is not specifying the BOND-test. This test method is, however, usefull for applications such as:

- Measurement of the in-place tensile strength of the concrete to detect defects of the coverlayer other than cracking perpendicular to the surface
- Checking if the bond between a parent concrete and a newly applied concrete patch, mortar, epoxy, bitumeneous layer or paint is in compliance with a specified bond-strength and the testing has to be performed in-situ.

Choosing the size of the inspection section

Any type of concrete inspection and control testing according to DS 411 and DS 423.1 is founded on splitting up of the structure into a number of inspection sections. This methodology also applies for the SAB.

General comments

For control testing of the concrete strength in relation to a required quality assurance, the structural engineer normally divides the structure into inspection sections. For The Great Belt Link project this is not the case.

The contractor may always chose to subdivide a control section, but it is prohibited to add more control sections into one.

Batches

One inspection section consists of a number of batches. One batch is the amount of concrete supplied in a truck-load, or otherwise homogeneous amount of concrete.

Size of an inspection Section

The limits of an inspection section is fixed by means of the following criterions:

- The material property and other characteristics have to be the same from batch to batch.
An inspection section must not contain more than 200 batches.
One inspection section has to be cast continuously. No change in production or transition to other mix materials, e.g. additives, is allowed.
- One inspection section should as a general rule not consist of different types of structural elements.
- The size chosen of the inspection section has to be related to the consequence of rejection (the contractor may sub-divide one inspection section). In this respect it is important to distinguish between the inspection of the strength and the durability property.

Positioning of the LOK-test and the CAPO-test inserts

The following regulations have to be observed:

At least 6 test locations have to be placed at random throughout the inspection section.

The test results from one and the same batch is averaged and is considered as one observation.

One observation is consisting of minimum two LOK-tests and/or two CAPO-tests.

LOK-test or CAPO-test inserts in one batch have to be placed at the same horizontal layer.

- Inserts have to be placed minimum 100 mm from edges and corners. The distance from the failure surface after testing to the closest reinforcement has to be the minimum size of the coverlayer.
- The distance between two inserts within the same observation has to be minimum 200 mm, maximum 300 mm.
- Foreign bodies as thermal wires etc. have to be outside the failure cone.

Observations

One observation is related to the testing of one batch and is the average of all test results within the batch placed. Usually two or more inserts are tested.

Minimum Sample Size

If the number of observations are smaller than the number of batches the number of observations are called *the sample size of the inspection section*.

The minimum sample size of the inspection section is depending on the number of batches of the inspection section. Unless other requirements are stated in the concrete working conditions for the control section, the minimum sample size has to be as given in DS 423.1, cf table 13 below.

The Great Belt Link's SAB has for this purpose adopted the following simple regulation:

»At least two observations have to be made for each 100 cubic meter of concrete, but minimum 3 observations for each inspection section«.

Needed maturity

At the time of testing with LOK-test and CAPO-test the maturity of the concrete needs to be as follows:

In relation to quality assurance the SAB states the required strength of an inspection section to be achieved 28 maturity days after casting, disregarded the type of cement to be used.

The SAB allows, however, the pull-out testing to be performed one or two days later as long as the measured strength is transformed to 28 maturity days. Therefore, the strength development of the concrete in relation to the maturity has to be measured with sufficient accuracy during the trial casting.

The maturity is measured close to the LOK-test inserts or where the CAPO-tests have to be performed, e.g. 25 mm below the concrete surface and 200 mm apart from the test location.

Table 13. Minimum sample size of an inspection section in dependance of the number of batches of the inspection section according to DS 423.1.

<i>Number of batches</i>	<i>Minimum sample size</i>	<i>Number of batches</i>	<i>Minimum sample size</i>
1-3	Total inspection	88-96	14
4-15	3	97-105	15
16-21	4	106-114	16
22-27	5	115-123	17
28-33	6	124-132	18
34-40	7	133-141	19
41-47	8	142-150	20
48-54	9	151-160	21
55-62	10	161-170	22
63-70	11	171-180	23
71-78	12	181-190	24
79-87	13	191-200	25

Common requirements

The General Note of the SAB specifies the strength requirement for each of the types of structures in question. Normally in Denmark, the minimum requirement of the concrete is depending on the so-called »class of environment« as stated in DS 411 and/or the Danish »BBB« (the Basic Concrete Specification, by the National Building Agency; in Danish: »BasisBetonBeskrivelsen«). However, for The Great Belt Link, the concrete strength will always be higher than strictly needed from environmental considerations.

Characteristic Strength

The required characteristic strength f_{ck} as measured on standard cylinders (DS 423.23 and interpreted according to DS 411) is given in the SAB's General Note.

Two-sided control testing

The SAB requires the in-place concrete to be uniform. This is stated as a tolerance with upper and lower limits for the in-place strength to fall within. In this manner the control testing is limited to the establishment of »yes« and »no« statements, so-called *inspection by attributes*, as far as the durability aspect is concerned.

In-situ testing

DS 411 states the strength requirement to be fulfilled if at least 80 per cent of the required potential strength of the concrete as measured on cylinders is achieved in-place. SAB follows this requirement.

Transformation equations

For concretes with a maximum aggregate size of less than 38 mm and for other aggregates than lightweight or pure mortar, the relation between the LOK-test and the CAPO-test pull-out force in kN-units and the compression strength of 150 mm×300 mm cylinders in MPa-units is the following (verified by means of 2693 pull-out and cylinder tests on different concrete mixtures):

$$F_u = 0,96 \cdot f_c + 1,00 \quad \text{for } 2 \text{ kN} \leq F_u \leq 25 \text{ kN}$$

$$F_u = 0,80 \cdot f_c + 5,00 \quad \text{for } 25 \text{ kN} \leq F_u \leq 60 \text{ kN}$$

Interpretation by total inspection

According to DS 423.1 the evaluation of the observations is different depending on how many of an inspection sections batches are being tested.

Definition

Every batch is controlled if the interpretation is said to be performed by *total inspection*. The pull-out forces measured within one batch are averaged and is considered as *one observation*.

Rule of decision

At total inspection all batches within an inspection section are evaluated. The concrete of one batch is accepted if the observation of the batch is minimum 80 per cent of the required cylinder strength. An inspection section is only accepted if all batches within the inspection section are accepted in this manner.

Choosing of total inspection

Inspection sections with three or less batches have to be inspected by total inspection.

The contractor may choose to conduct total inspection instead of inspection by sample testing, if so desired.

The structural engineer may also choose to require total inspection, e.g. of important structural elements. Such a requirement has to be stated clearly in the concrete specification and its general note.

Interpretation of inspection by sample testing

Inspection by sample testing may be performed as *inspection by variables* or as *inspection by attributes*.

Rule of decision if inspection by variables is applied

At inspection by sample testing the number of pull-out observations are less than the number of batches, but at least the minimum sample size as shown in table 13.

The rule of decision of DS 411 clause 8.1.1 is used as follows:

- The strength requirement f_{ck} has to be fulfilled according to the SAB's General Note.
- The minimum sample size has to be as stated in the SAB (table 13).
- pull-out testing is made as stated in DS 423.31 and the SAB-Amendment to DS 423.31.
- The observations of the pull-out forces in kN-units are transformed to cylinder compressive strength f_c as stated in the above mentioned relationship.
- The sample size n and the average f_c of the n observations is calculated.
- The un-documented coefficient of variation is taken from table 7 in relation to the required characteristic strength f_{ck} or calculated from:

$$\delta = 0,22 \quad \text{for } 5 \leq f_{ck} \leq 10 \text{ MPa}$$

$$\delta = 0,23 - 0,002 \cdot f_{ck} \quad \text{for } 15 \leq f_{ck} \leq 35 \text{ MPa}$$

$$\delta = 0,14 \quad \text{for } 40 \leq f_{ck} \leq 50 \text{ MPa}$$

- The k_n -factor is taken from table 8 for the un-documented coefficient of variation and number of observations in question or calculated from:

$$k_n = \exp \left[\left(2,28 + \frac{1}{\sqrt{n}} \right) \cdot \delta - 0,1875 \right]$$

If the measured average strength \bar{f}_c is greater than or equal to $0,8 \times k_n \times f_{ck}$, the concrete of the inspection section is accepted; otherwise it is rejected.

Rule of decision if inspection by attributes is applied

Inspection by attributes produces »yes« or »no« statements. This may be the case in the following situations:

The LOK-test insert is only loaded to a required strength level. The test result is a »yes« if the concrete is not failing, and a »no« if it does. This methodology is not allowed according to the SAB since the SAB also requires an upper limit to be observed.

When using BOND-test the requirement may be that the failure happens in the parent material, not in the adhesion zone or in the applied overlay. A failure of the parent material is then a »yes« statement, otherwise it is a »no«.

- At two-sided control as when the pull-out forces have to be placed within a lower and an upper limit, inspection by attributes is desirable. Inspections by variables may be made, but this methodology is not included in the Danish Standards.

If control in total is applied, no observations is allowed to be rejected. Using inspection by sample testing, the sample size has to be minimum as stated in table 13 and the maximum number of defects as indicated in table 14.

Ekstreme observations

During testing the technicians have to evaluate wheater or not a test result is acceptable. Ekstreme values may be caused by:

- Weak concrete due to locally insufficient compaction or curing conditions.
- Faulty installed LOK-test inserts or incorrect performed CAPO-test.
- Unacceptable types of LOK-test and CAPO-test.
- Foreign bodies appearing in the pull-out cone or failure surface.

Applied random sample	Max. no. of defects
3-12	0
13-19	1
20-29	2
30-39	3
40-49	4
50-64	5

Applied random sample	Max. no. of defects
65-79	6
80-94	7
95-109	8
110-124	9
125-145	10
—	—

Table 14. Approval criteria for inspection by attributes as a function of the applied random sample according to DS 423.1 edition 2.

Supplementary testing

Ekstreme value are only allowed to be excluded of the statistical interpretation if a testing error is documented. DS 423.1 gives guidelines for the interpretation of ekstreme values.

Supplementary testing with CAPO-test has to be made to substitute rejected observations.

Petrographic Analyses

If supplementary testing by CAPO-test still rejects the concrete investigated, the reason for non-compliance has to be found, e.g. by means of petrographic analyses, i.e. thin-section analyses.

Report

The issued testing report has to contain all information required by the SAB, e.g. concerning the concrete, the test equipment, the technician, the positioning of the tests in relation to the inspection section and its batches together with all relevant data collected during the testing including the weather condition. ■

Appendix 10. List of references

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