LOK-TEST and CAPO-TEST for in-situ compressive strength

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ABSTRACT: Among the test systems for in-place strength available today, two measure the in-place physical strength, pullout and cores. Both systems are dealt with in detail in this paper, the pullout systems named LOK-TEST / CAPO-TEST (ASTM C900-19) and coring (ASTM C42/42M-18). Six testing cases with emphasis on pullout and cores are illustrating different applications:

Case 1. Production testing at the Great Belt Link, Denmark.
Case 2. Service life of bridge pier, Great Belt Link, Denmark.
Case 3. Curing of the cover layer evaluated by pullout and conductivity, Denmark.
Case 4. Strength testing with CAPO-TEST for further loading of old bridges, Poland.
Case 5. In-Situ compressive strength testing of quarantined precast concrete tunnel lining segments using CAPO-TEST, UK.
Case 6. Safe and early loading with LOK-TEST, Canada.
Other cases are given on www.NDTitans.com

INTRODUCTION

Proper strength testing in-situ is important for purposes such as QC and QA of in-situ concrete not only relying on the potential lab strength, revealing effects of changed mixes, transportation, pumping, casting, consolidation and curing.

Furthermore, it is important for documentation of unknown strength, upgrading of structures, for additional loading, for durability and for documentation of doubtful structures in cases where questions are raised in relation to compliance with code specifications, and finally and not at least, for timing of safe and early loading of maturing members.

Among the test systems for evaluating in-situ compressive strength – detailed in ACI 228,1R-19 “Report on Methods for Estimating In-Place Concrete Strength” [1] – is pullout testing with LOK-TEST / CAPO-TEST (ASTM C-900-19) [45] measuring directly the physical compressive strength at a depth of 25 mm wherever required, usually of the cover layer, or if needed, deeper in the structure.

Cores (ASTM C42/C42M-18) [49] also measure the physical strength, but not of the cover layer which is essential for durability in relation to ingress of harmful substances such as chlorides, CO_2 and moist causing corrosion of the reinforcement.

Concerning the rebound hammer and pulse-velocity, reference [1] states “Use of the rebound hammer in accordance with ASTM C805/C805M or the pulse-velocity in accordance with ASTM C597 may be specified by Architect/Engineer to evaluate uniformity of in-place concrete to select areas to be cored. These methods shall not be used to evaluate in-place strength”.

The LOK-TEST and the CAPO-TEST are presented in detail in this paper with their theoretical analysis background, a fracture analysis and correlations from 30 major studies worldwide, showing robust general correlations with regression coefficients >0.95 between pullout force and cylinder or cube/core strength, no matter what concrete parameter is considered.

The correlations are stated together with the COV of the systems in the lab and on-site on a wide range of mixes and structures comprising more than 12,000 tests.

These general, robust correlations of the LOK-TEST and CAPO-TEST are the backbone and the essence of the two systems, offering a viable alternative to cores, giving results directly on-site, quickly, not needing any laboratory compression machine, more reliable, less complicated, more economic, and causing less damage to the structure, if any at all - as with the LOK-TEST loaded exactly to failure or only to a required strength by which the test is a truly NDT method.

A special feature of the pullout systems is testing of the cover layer for durability, the “Peel” of new structure protecting the reinforcement. Proper concrete quality, compaction and curing of this “Peel” is essential on new structures in terms of durability and service life, especially if chlorides are present from de-icing salts, from the sea water or airborne chlorides close to the ocean. Pullouts in combination with conductivity is presented for service life estimation.

In addition, the two pullout systems can advantageously be used on slender structures where cores may weaken the elements, and on structures with dense reinforcement, without cutting the rebars.

The testing depth of the pullouts is 25 mm. If needed, deeper embedment can be made, for the LOK-TEST as instructed in the Canadian Standard [46], and for the CAPO-TEST by surface planning to a required depth to starting out the test.

1. THE PULLOUT SYSTEMS

Invented at the Danish Technical University (DTU) in the late 1960’s and 1970’s [2, 3, 4, 5, 6, 7], the LOK-TEST (the Danish name for “Punch-Test”) uses a disc cast into the fresh concrete, and the CAPO-TEST (Cut And Pull Out- Test) a ring expanded in an undercut recess in existing concrete. Pullout is made through a counterpressure, dimensions as shown in Figure 1 and Figure 2, producing compression forces between the imbedded disc or ring and the counterpressure, hence the pullout force is a direct measure of the compressive strength.

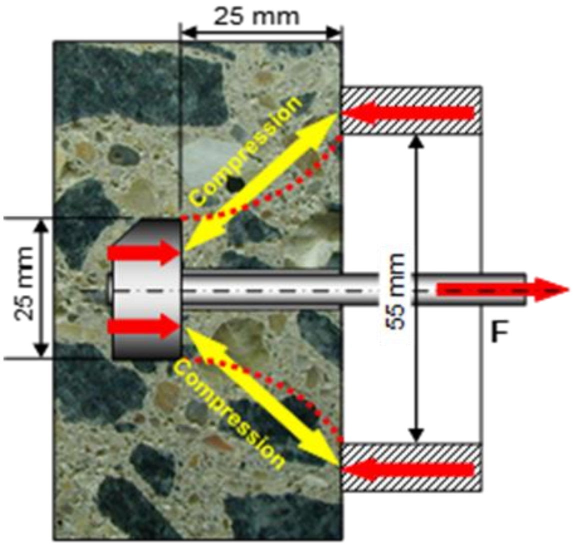

Figure 1. LOK-TEST

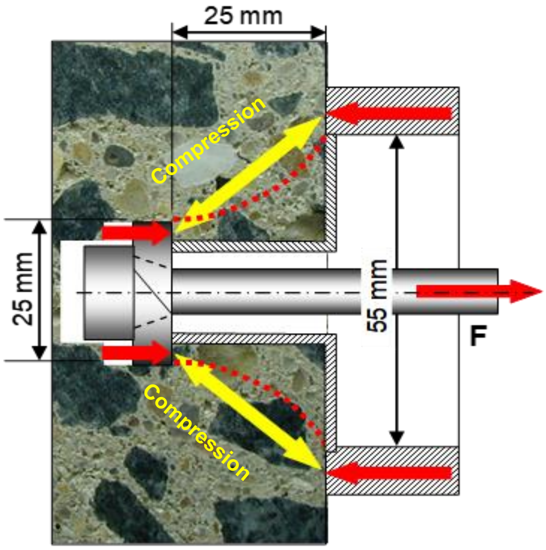

Figure 2. CAPO-TEST

2. THEORETICAL ANALYSIS

Two major analyses were produced, one by plasticity theory and one by finite elements analysis. The plasticity analysis of the failure by Jensen, B. C. & Bræstrup, M. W. was published in 1976 [8], and the comprehensive finite element analysis was published in 1981 [9] by Ottosen, N. S., concluding that the failure is caused by crushing of the concrete in the “strut” between the disc and the counterpressure (Figure 7).

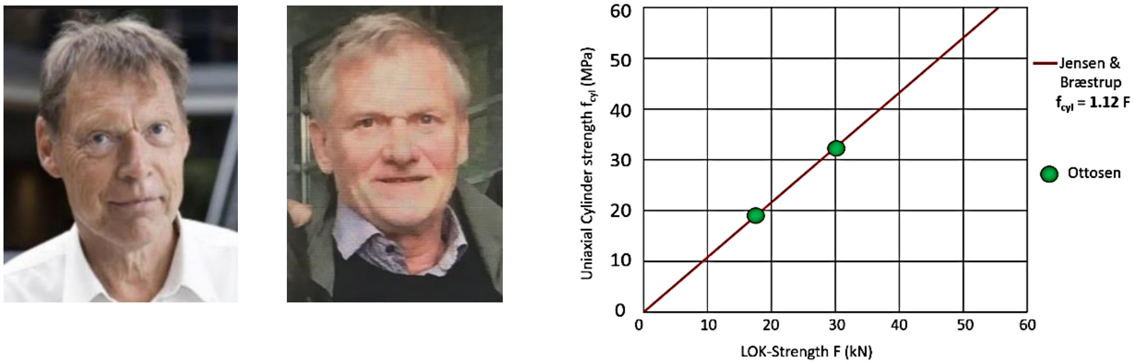

Figure 3. Left, Lich. Tech. M. W. Bræstrup; middle, Professor N. S. Ottosen; right, theoretical found relations between pullout force in kN and uniaxial compressive strength in MPa.

3. FRACTURE ANALYSIS

To substantiate Ottosen’s crack development found in his finite element analysis, Professor Herbert Krenchel (DTU, Denmark) conducted in 1985 a comprehensive physical trial program [10] loading pullout in specimens to various levels on the load-displacement curve, slicing the specimens, polishing the surfaces and impregnating them with fluorescence-dye for documentation of the cracking. The fracture analysis revealed, at about 30% of the top-load, that a circumferential crack develops at an open angle running from the outer edge of the disc. This is where the linearity is lost. From thereon, a band of parallel multiple microcracks is developed in a compression “strut” between the disc and the counterpressure, carrying the compression load (Figure 4).

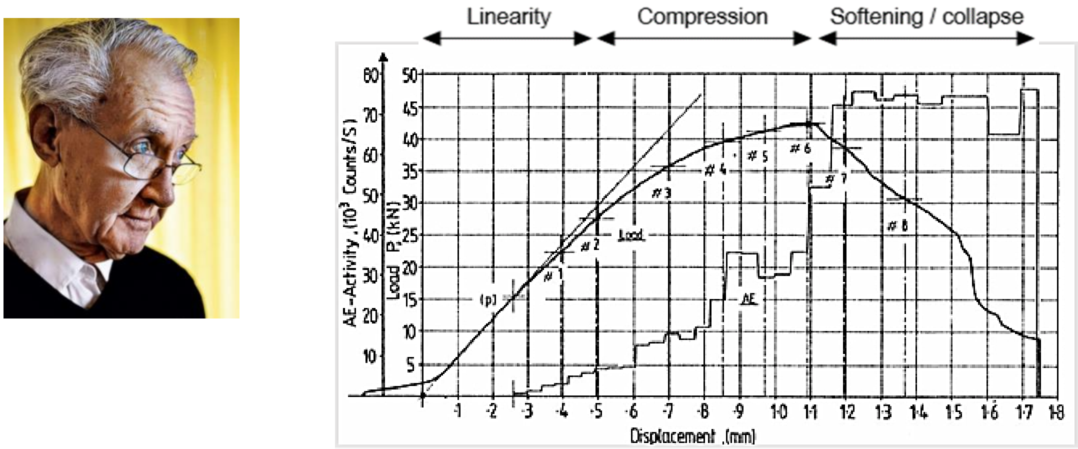

Figure 4. Left, Prof. Herbert Krenchel; right, load-displacement curve for a pullout test.

The circumferential crack developed at 30% of the load is important also (fig. 7), as it releases stresses by which the test results are not influenced by inherent stresses [12]. A collapse happens from the top-point in the softening regime at increased loading, forming the final pullout cone, if loaded past failure (Figure 6).

In this manner LOK-TEST and CAPO-TEST measure the compressive strength of concrete (in the 2nd crack pattern, the strut). This constitutes the load-carrying mechanism, hence the pullout force is a direct measure of the compressive strength between the disc and the counter pressure.

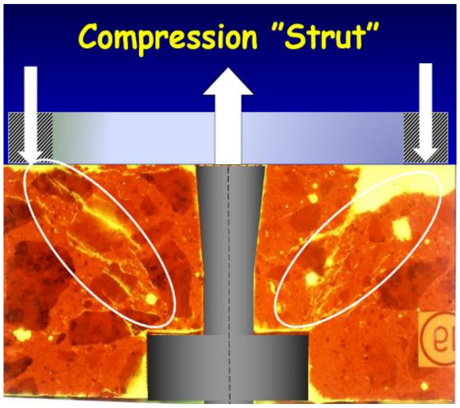

Figure 5. Parallel microcracking in the “strut”.

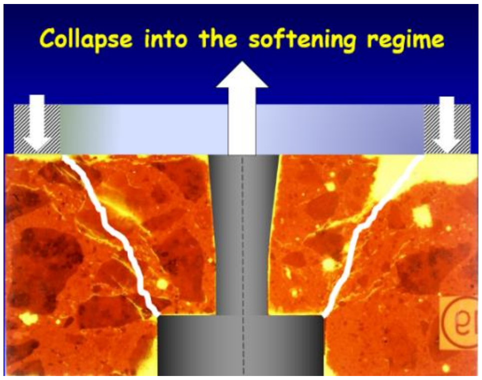

Figure 6. Pullout cone intersecting the “strut”.

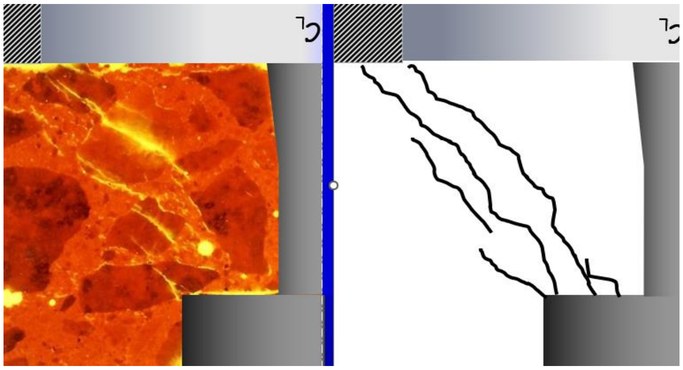

Figure 7. 2nd stage cracking in the “strut”, Krenchel (left). and Ottosen (right)

The width of the cracks in the strut was measured by Krenchel in a microscope to be 1/200 mm, confirmed by Ottosen´s in his finite element analyses.

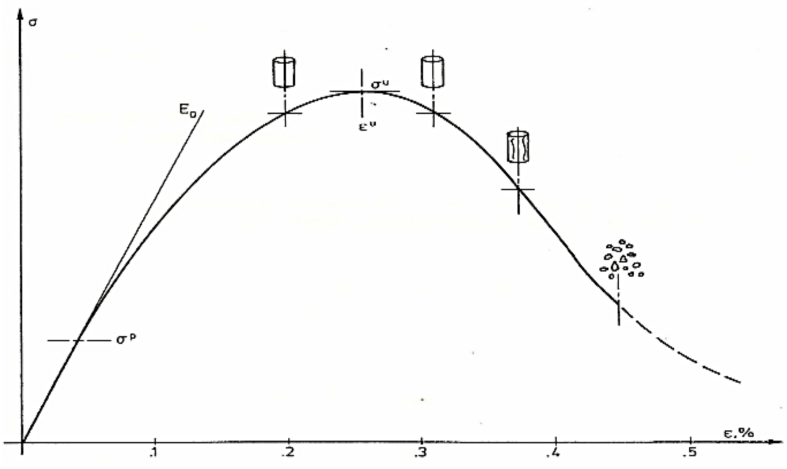

Figure 8. Load-displacement curve for a standard cylinder.

It is worth noticing that the load-displacement curve shown in Figure 4 is identical to a 150 mm x 300 mm standard cylinder’s curve (Figure 8).

And, most importantly, the stress in the “strut” is similar to the uniaxial stress in the middle of a cylinder (Figure 9).

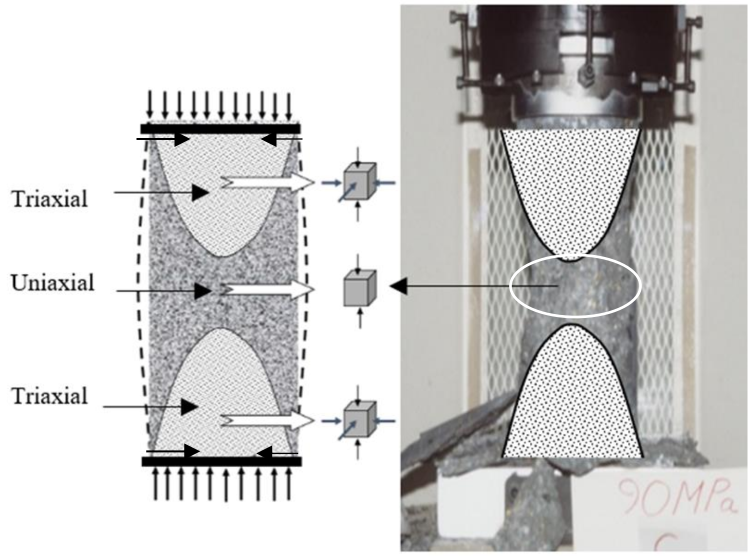

Figure 9. Stresses in a standard cylinder during loading.

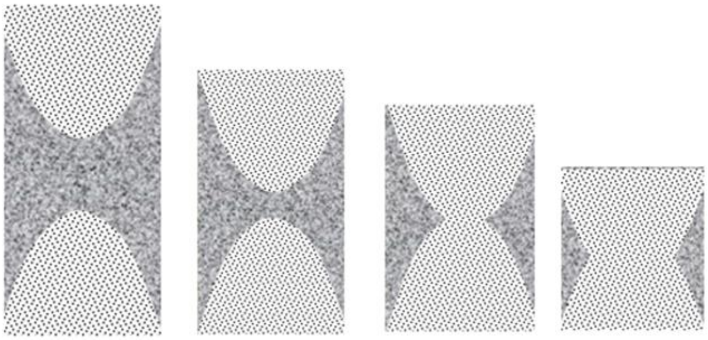

Figure 10. Strength increases as L/D decreases.

As the cylinder gets shorter, for the same diameter, the specimen will be in a triaxial state of stress (fig. 10), hence the strength of a standard cube or a 100 mm x 100 mm core is higher than that of a 150 mm x 300 mm standard cylinder as the triaxial stress produce a higher strength than the uniaxial.

In general, the strength of a standard cube 150 mm x 150 mm x 150 mm is equivalent to the strength of a core 100 mm x 100 mm, both in triaxial stress during compression.

For design calculations it is the uniaxial strength that is important, that is the strength obtained by 150 mm x 300 mm standard cylinders, as used e.g. in e.g. Denmark, USA and Canada.

BS and some EU codes, e.g. Sweden, Poland, UK, Holland and Germany, propose to use 150 mm x 150 mm x 150 mm cubes, equivalent to 100 mm x 100 mm cores, which produce a 20 to 30% higher strength than cylinders cast from the same concrete batch.

4. CORRELATIONS

Following the analyses, the first major experimental correlations were made in Denmark at DTU, and in Sweden at CBI (Figures 11 and 12).

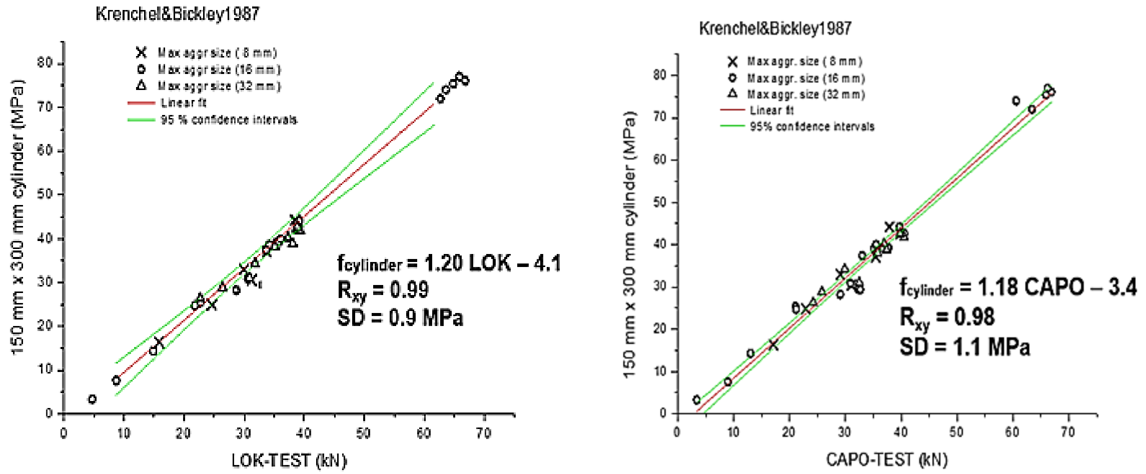

Figure 11. Correlations to cylinders made at DTU, Denmark [10, 15]: LOK-TEST to cylinders (left) and CAPO-TEST to cylinders (right).

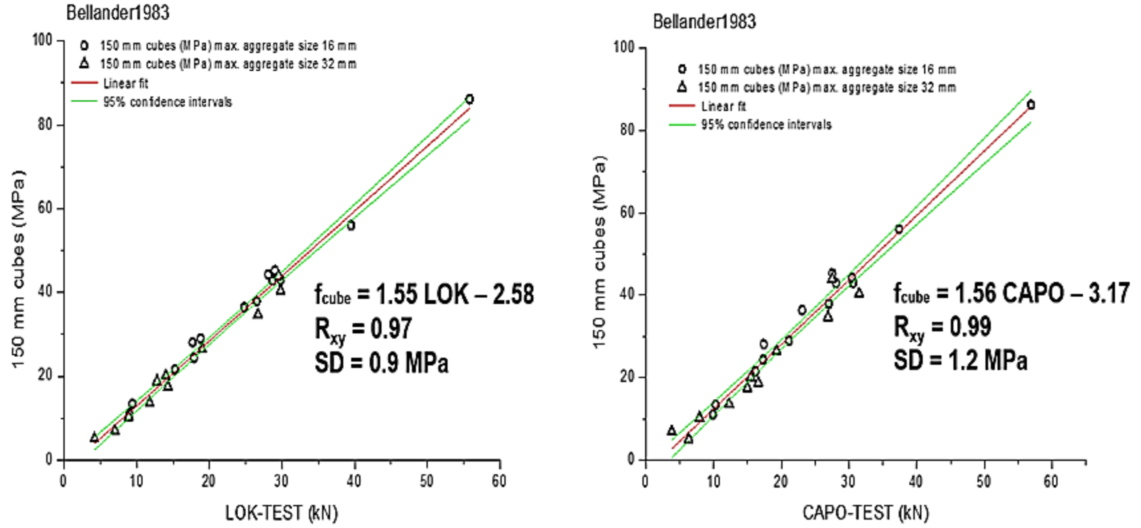

Figure 12. Correlations to cubes made at CBI, Sweden, [13, 14]: LOK-TEST to cubes (left) and CAPO-TEST to cubes (right).

In the years to follow, further major correlations were performed (fig. 13 and 14) by testing authorities in Denmark, Sweden, Norway, Holland, Canada, USA, Poland, England and KSA, investigating the influence on the correlations for the following parameters:

- types of cementitious materials
- water-cementitious materials ratio (w/cm)
- age
- air entrainment
- use of admixtures,
- curing conditions
- stresses in the structure

- stiffness of the members
- carbonation,
- shape, type, and maximum nominal size of aggregate up to 40 mm

SUMMARY

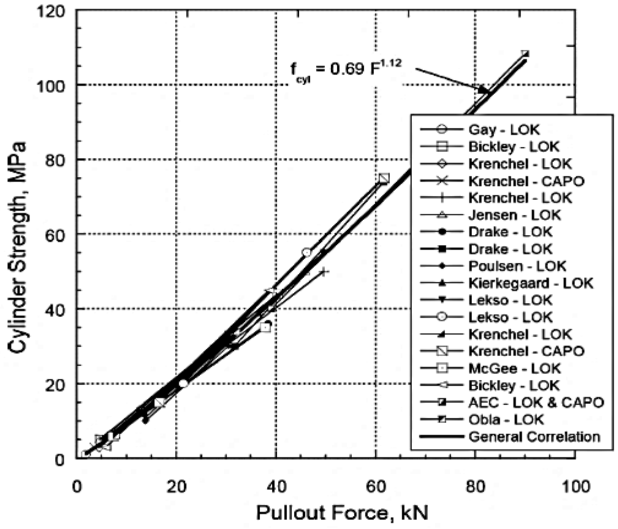

Figure 13. Summary of the eighteen correlations [18] to standard 150 x 300 mm cylinder compressive strength.

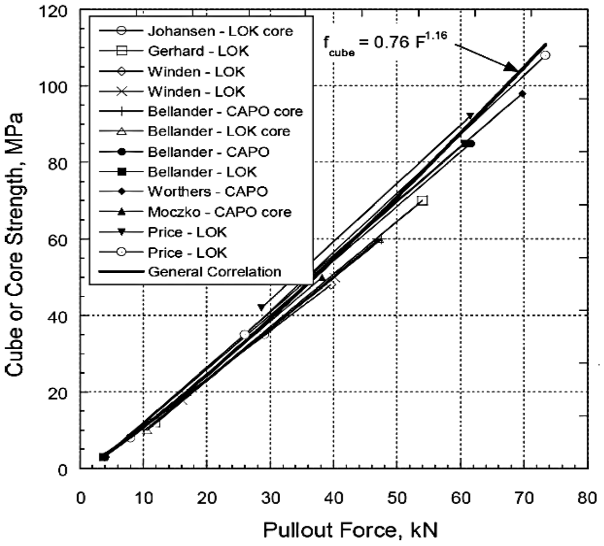

Figure 14. Summary of the twelve correlations [18] to standard cubes (or cores) compressive strength.

In average, the correlation between pullout force F in kN (LOK or CAPO) and 150 mm x 300 mm cylinder strength f_{cyl} in MPa was found to be, fig 13:

$$\mathbf{f_{cyl} = 0.69\ F^{1.12}}$$

with a maximum deviation from this general correlation of about 2 MPa, despite the correlations are produced using different laboratory testing machines.

And in average, the correlation between pullout force F in kN (LOK or CAPO) and 150 mm x 150 mm x 150 mm cube or 100 mm x 100 mm core strength $f_{cube/core}$ in MPa was found to be, fig.14

$$\mathbf{f_{cube/core} = 0.76\ F^{1.16}}$$

What is also interesting is that the uniaxial cylinder correlation shown in fig. 13, follows closely the analytical theoretical results shown in Figure 3, see fig. 15.

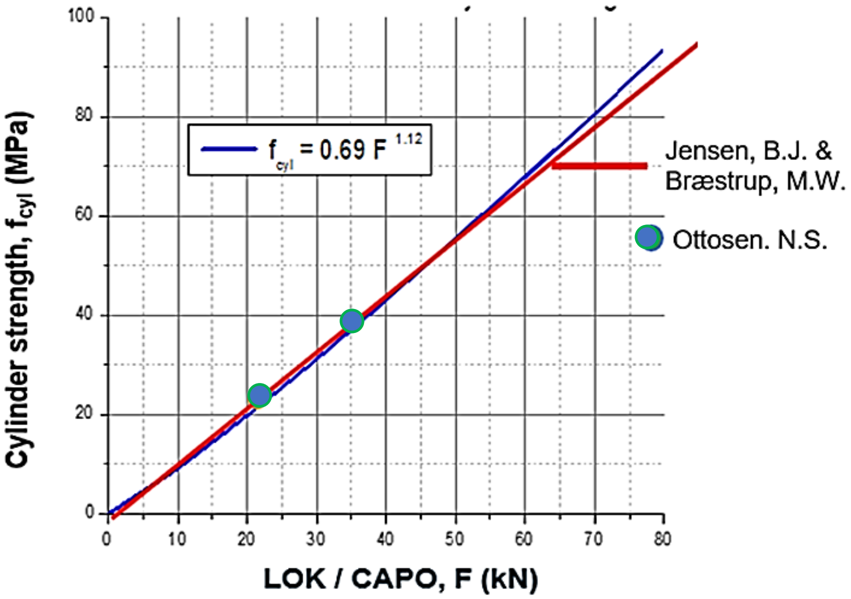

Figure 15. The experimentally found correlation $f_{cyl} = 0.69\ F^{1.12}$ for cylinders compared to the findings of the theoretical analysis by Jensen/Bræstrup and Ottosen.

LOK-TEST COMPARED TO CAPO-TEST

In fig. 16, seven major comparisons are presented between LOK-TEST force and CAPO-TEST force, both in kN, showing a 1:1 relationship, meaning that the general robust correlations in fig. 17 are applicable for both pullout systems.

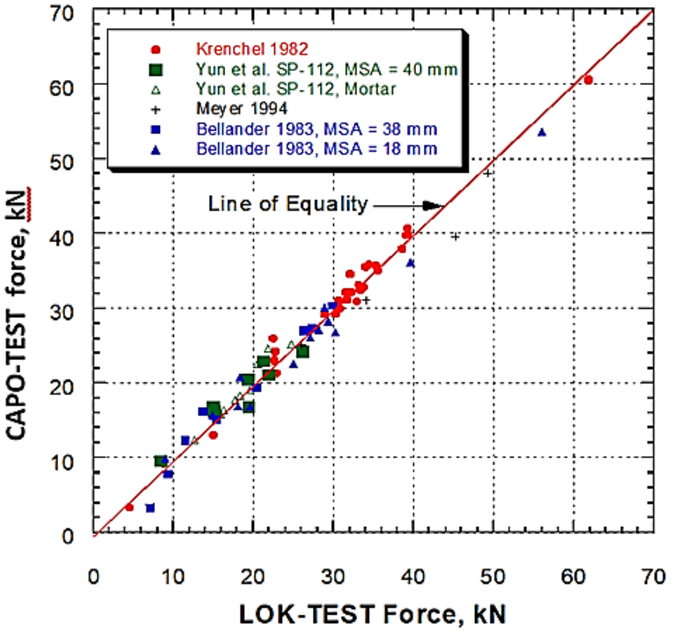

Figure 16. Comparison between LOK-TEST and CAPO-TEST.

5. THE GENERAL ROBUST CORRELATIONS

The two general robust correlations are presented together in fig. 17. For the same pullout load, cubes/cores produce 20% to 30% higher strength than the cylinder depending on the strength level as explained in fig. 9 and 10.

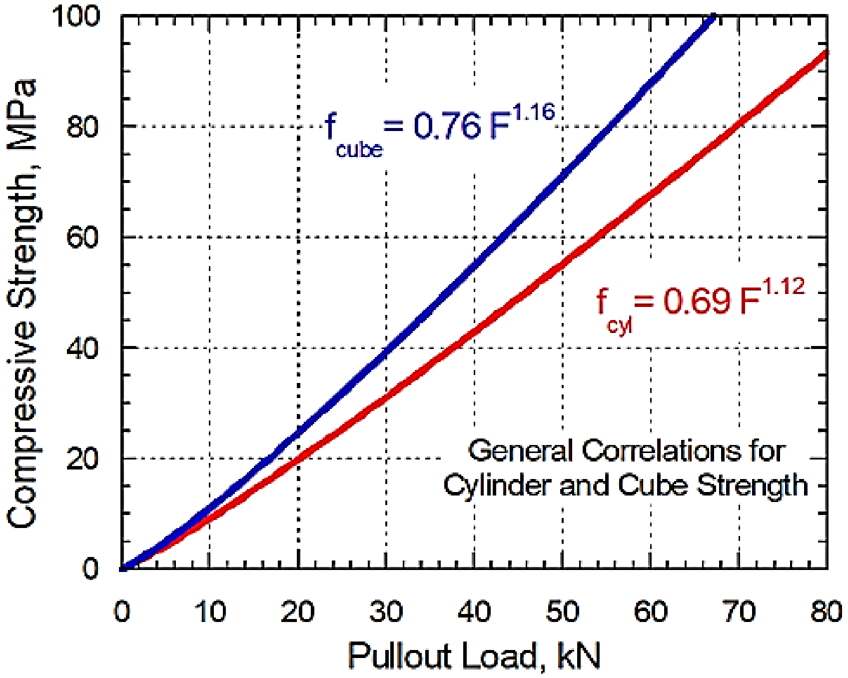

Figure 17. The general robust correlations between pullout force by LOK or CAPO-TEST to standard cylinder or standard cube/core strength.

6. VARIATIONS

Variations were reported in large scale in 1984 [15, 16]. Table 1 shows the results in laboratory conditions and Table 2 are from testing on-site

Table 1. Laboratory variations.

Procedure / Laboratory	Standard specimen		Pullout	
	COV	Nos	COV	Nos
Danish	4.3%	1177	9.4%	2188
North American	6.4%	994	7.5%	994
Swedish/ Dutch/UK	6.2%	963	6.8%	1180

Danish: 150 x 300 mm standard cylinders, and 200 mm cubes for pullout, centrally placed in the vertical faces, two LOK-TEST and two CAPO-TEST in each cube

North American: 150 x 300 mm standard cylinders and accompanying cylinders with LOK-TEST in the bottom.

Swedish/Dutch/UK: 150 mm cubes and accompanying cubes for pullout, one LOK-TEST and one CAPO-TEST

Table 2. Variations on-site.

Structure	LOK-TEST		CAPO-TEST	
	COV	Nos	COV	Nos
Shotcrete			3.2%	820
Slabs, bottom	10.5%	5320	7.1%	35
Slabs, top	12.9%	955	9.3%	623
Beams & Columns	8.1%	677	8.0%	434
Walls & Foundations	10.1%	1020	10.4%	534
Dubious Structures[a)]	14.7%	1225	15.3%	3334

[a)] Dubious structures: ASR reacted, non-uniform concrete, insufficient consolidation and curing, changed mixes, fire damaged structures and frozen concrete.

Normal practice on-site is to use an average of two pullouts as one observation.

7. PRECISION

As shown in Figure 18, LOK- TEST and CAPO-TEST have an overall precision of about 3 MPa for one single test, 2.0 MPa for two tests and 1.5 MPa for four tests. The precision is calculated based on correlations made by Krenchel (Figure 19) and Bisr (Figure 20) which also match the general robust correlations.

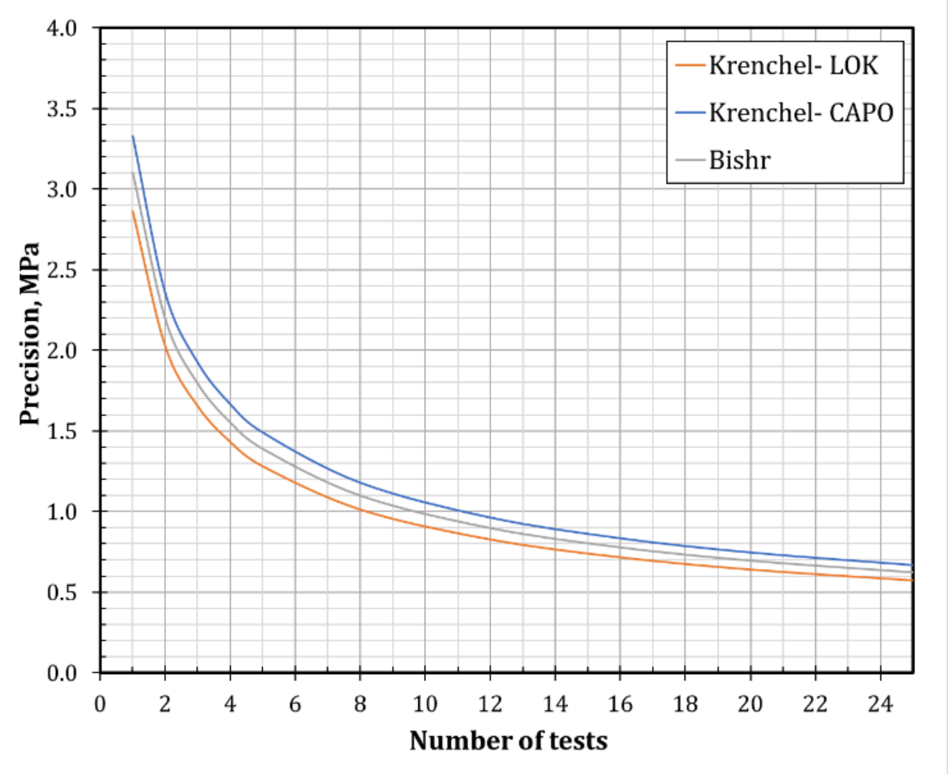

Figure 18. The calculated precision in MPa of LOK-TEST and CAPO-TEST in dependence of the number of tests.

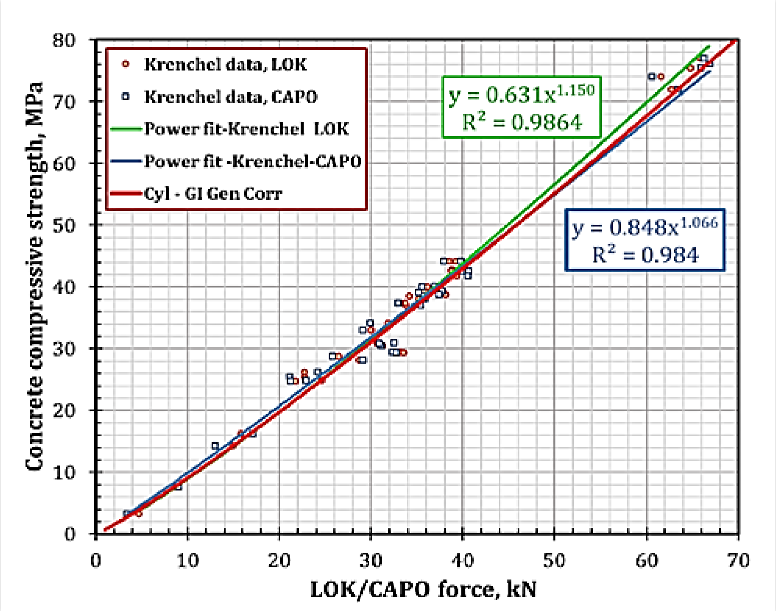

Figure 19. Data by Krenchel for calculation of precision [21].

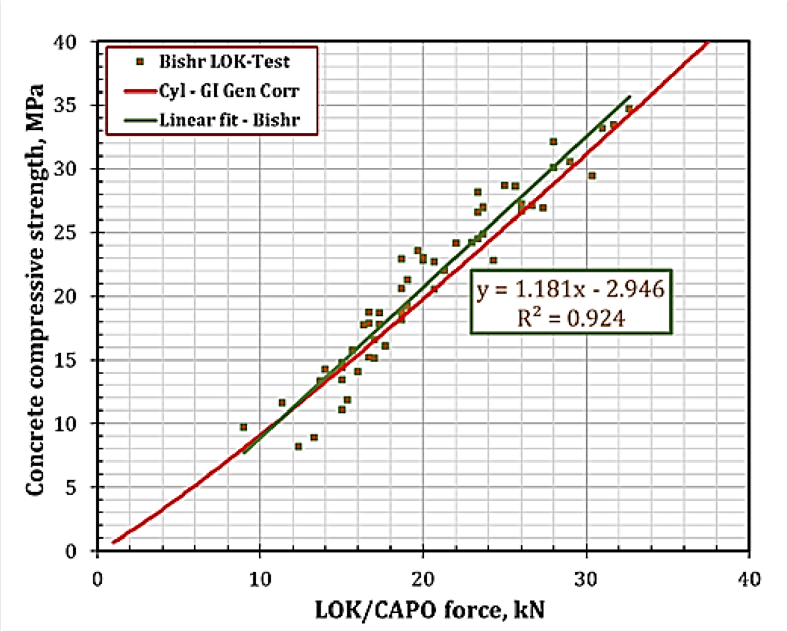

Figure 20. Data by Bishr for calculation of precision [17].

$$P = \frac{z \cdot C_v}{\sqrt{n}} \quad ; \quad C_v = \frac{s_p}{\bar{x}} \quad ; \quad s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \cdots + (n_m - 1)s_m^2}{n_1 + n_2 + \cdots + n_m - m}}$$

where:

P, Precision is the maximum error between the in-situ obtained sample average of pull-out force and the true average under a certain confidence level (ACI 437R, ASTM E122),

Z, factor of the normal distribution = 1.96 for a 95% confidence level,

n, sample size, number of in-situ Lok/Capo tests,
C_v, coefficient of variation of the data sets,
x, mean of the data sets,
s_p = Pooled standard deviation of the data sets,
$n_{i \cdots m}$ = number of tests per set, and
m = number of sets.

8. CANADIAN LOK-TEST EXPERIENCE

Figure 21. John A. Bickley, D.Sc. Honoris Causa P.Eng., FICE, FCSCE, CEO of Trow Group Inc. in Toronto, Canada, until he formed his own consulting engineering company, John A. Bickley Associates Ltd.

During cooperation with Professor Herbert Krenchel of DTU, Denmark [21], Dr.John A. Bickley (fig. 21) introduced the LOK-TEST in Canada, concentrating on reducing construction schedules of high-rise structures for safe and early loading, of which he became a champion, as illustrated in case 12.6.

Dr. John A. Bickley stated to the Author several times: “*Claus, you are selling instruments, I am selling money*.”

Dr. John A. Bickley published many papers related to this concept as well as other applications, data and variations of the LOK-TEST [22, 23, 24, 25, 26, 27, 28 and 29].

In [27 and 29] are described cases where only LOK-TEST was used for QC on large projects, wavering the standard laboratory cylinders and the use of laboratory testing machines on remote sites.

One of his conclusions is mentioned in [4], as early as in 1978: “*The LOK-TEST system of pullout tests offers a simple, reliable, economic and non-destructive way of determining the actual in-place strength in a practical statistically valid manner*”.

-Non-Destructive- is performed by only loading the LOK-TEST right to the top-point on the load displacement curve, or to a required strength without failing the concrete.

In Dr. John A. Bickley´s autobiography “Anecdotes of My Life” p. 177, he appoints the LOK-TEST to be “*The Holy Grail of Concrete Testing*”, as it is “beautifully engineered and fit into a brief case, the pullout test specimen is 25 mm in diameter and the same distance inside the concrete making it practical for thin structural members like slabs, and the correlation between pullout and compressive strength is a straight line”.

9. BRITISH PULL-OUT EXPERIENCE

Professor John Bungey (Figure 22) tested LOK-TEST and CAPO-TEST systematically in conjunction with standard and temperature-matched cubes [30, 31, 32, 33 and 34], concluding that "*the combined correlation is surprisingly very close to the manufacturers correlation*" and "*one strength correlation can be used for both the LOK- and the CAPO-TEST*".

The systems were subsequently recommended as "Best Practice Guides for In-Situ Concrete Frame Building" [35].

Figure 22. John Bungey, Emeritus Professor of Civil Engineering at the University of Liverpool, UK. In charge of the project "Early age strength assessment of concrete on-site".

10. CORES AND/OR PULLOUT. USA

Figure 23. Dr Nicholas J Carino joined NIST in the US for 25 years. Today he is an independent consultant, internationally recognized, expert and teacher on NDT and standard methods. Multiple times awarded from ACI and ASTM for his work in research and standards development. Honorary member of ACI and a Fellow of ASTM. Main teacher at the NDTitans NDT workshops. www.NDTitans.com

Dr. Carino (fig.23) is an excellent teacher in all essential NDT methods. In one of his presentations ("Core Testing"), he outlines that for cores, the strength depends on a number of factors:

- Core size
- Location of core
- Direction of coring
- Moisture conditioning
- Length to diameter ratio
- End preparation
- Embedded steel

Most importantly is Dr Carino´s presentation "In-Place Strength Without testing cores."

11. CASES

11.1 Production testing at the Great Belt Link, Denmark

For production testing the pullout was specified on the Great Belt Link, Denmark [6], not only for strength and durability but also for uniformity of the in-place concrete.

The Great Belt Fixed Link (Figure 24) runs between the Danish islands of Sjælland and Fyn (eastern and western Denmark). The 18 km long project consists of three structures: a road suspension bridge and a railway tunnel between Sjælland and the small island Sprogø located in the middle of the Great Belt; and a box girder bridge for both road and rail traffic between Sprogø and Fyn. The "Great Belt Bridge" (Danish: “Storebæltsbroen”) commonly refers to the suspension bridge, officially known as the East Bridge, which has one of the world's longest main span (1.6 km). The construction work took place between 1988 and 1998 and because of its size and importance, implied that aspects of durability were studied in an unprecedented scale in Denmark to keep the risk level at a minimum for a 100-year service life design period. One important objective was therefore to specify the requirements to prevent deterioration from alkali-silica reactions, frost attack, and reinforcement corrosion due to chloride ingress. In total, the project comprised 1.1 million m^3 of concrete.

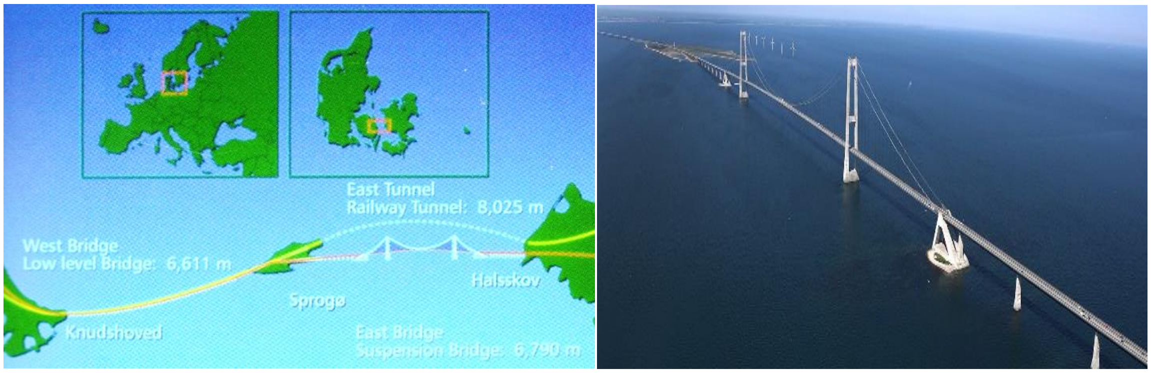

Figure 24. The Great Belt Fixed Link.

Table 3. The main characteristics of the concrete mixes tested with LOK or CAPO

Structure	East Tunnel	East Bridge		West Bridge	
Concrete ID	A1 $^{a)}$	A	B	A	B $^{b)}$
28-day f'_c, MPa $^{c)}$	76	56	53	58	57
w/c	0.33	0.34	0.37	0.34	0.36
Fly ash, %	10	12	13	10	17
Microsilica, %	5	5	5	5	5
Density, kg/m^3	2,485	2,340	2,348	2,323	2,280
D_{max}, mm	16	25	25	32	32
Air content, %	0.8	1.4	1	6	6
Superplast. kg/m^3	1.8	7.6	6	8.8	5.7

a) segments b) caissons c) from standard cylinders

Both concrete strength and durability are influenced by the curing conditions. Inspection of potential compressive strength with companion well cured lab specimens, however, gives no guarantee of safety against failure of the concrete structure or quality of the cover layer, therefore, it was of major importance to specified that, in addition, the achieved characteristic compressive strength at the cover layer was controlled using in-situ testing with LOK and CAPO tests.

The decision rule for acceptance in an inspection section was: $\{fc\} \geq 0.8\ k_n\ f_{ck}$, where {fc} is the mean value of the strengths measured, and k_n is a factor that depends on the number of tests and the coefficient of variation.

During full-scale trial castings of the caissons of the West Bridge, it was realized that the in-situ CAPO strengths determined by the general correlation produced significantly lower results. The contractor produced hereafter his own correlations as shown in Figure 25, to achieve acceptance.

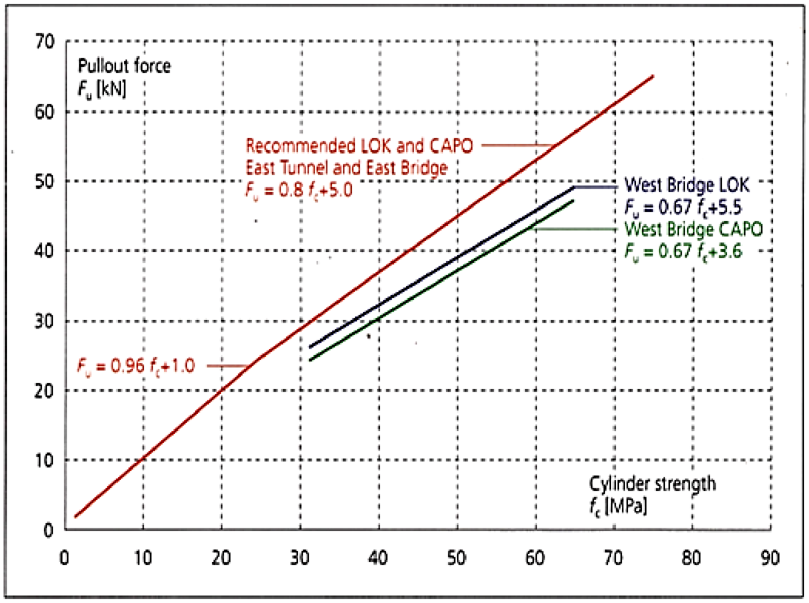

Figure 25. The correlations applied on the Great Belt Link project.

The reasons for the lower CAPO-TEST strength in the West Bridge caisson’s cover layer was later found to be related to the slipform casting procedure (Figure 26):

“*Petrographic results showed cracks, porosities and separation in the cement paste of the cover concrete. In particular many surface parallel defects could be observed*” [30, p. 211]., fig. 26;

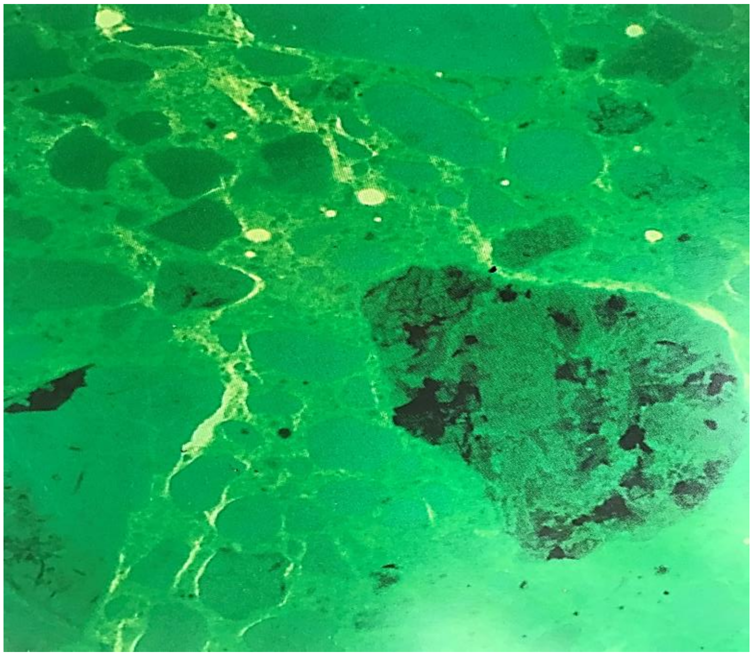

Fig. 26 Petrographic testing showing paste separation and separation paste – aggregates.

"Investigations showed that the defect could not be avoided, They were caused by the filling of the small slip, that occurred between the concrete and the steel form each time the form was lifted", "Also. An investigation was made on other slipformed structures in Denmark. All these structures showed similar defects" [31, p. 129].

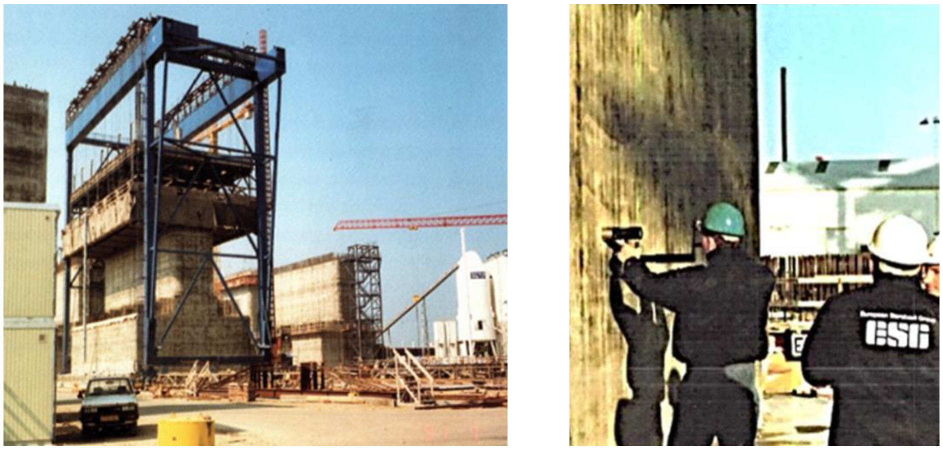

Figure 27. Steel slipform used for the caissons (left), and CAPO-Testing (right).

"At the time, where the problems were discovered, it was no longer possible to change the slipforming concept without causing serious delays to the whole project, and it was decided to proceed with the slipforming concept" [31, p. 130].

"In conclusion, the defects appeared to be an inherent part of the slipforming concept, and could not be avoided unless the production concept was changed, which was not practically and economically possible" [30, p. 212].

"To remedy the effects observed in the petrographic testing, is was decided to install cathodic protection systems on all the West Bridge´s caissons" [30, p. 215].

For pullout testing the structures were subdivided into inspection sections, each of which was accepted or rejected after thorough statistical evaluation [38], The main quantities and number of required strength tests for one of the inspection sections are presented in Table 4 for the West Bridge.

Table 4. Figures per inspection section in the West Bridge

	Concrete, m^3	No. of LOK/CAPO tests	No. of test cylinders
Caissons (walls)	2,500 - 2,900	100 - 116	50 - 58
Pier shafts	700 - 1,200	28 - 48	14 - 36
Road girder	2,300	92	46
Rail girders	1,700	84	34

An example is shown in Figure 28 for the West Bridge rail girder inspection sections by LOK-TEST compared to lab cylinders.

As will be seen, in the beginning of the test period the cylinder and in-situ strengths with LOK-TEST were almost identical until November 1991. From there on, the LOK-strength was lower because of poorer concrete in the concrete cover, Why? The Author don't know.

The final results of the comprehensive statistical evaluation of the major part of the project (Table 5) shows the differences between the strength and coefficient of variation, CV, obtained under lab conditions (cylinders) and under in-situ conditions, which in turn, evidence how important the control of transport, casting, compaction, and curing is in order to maintain a proper level of quality. Without quantitative monitoring the structure, the works would have run in blind.

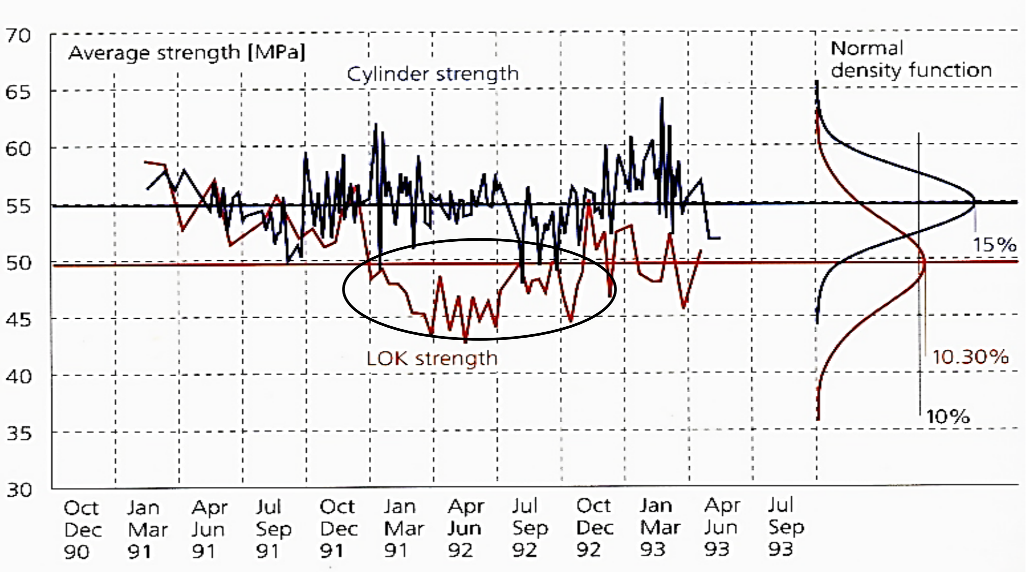

Figure 28. Results of laboratory cylinders and in-situ LOK-TEST performed on the West Bridge´s rail girder section. The reason for the drop in LOK-TEST, highlighted, is unknown by the Author.

Table 5. Results of the comprehensive statistical evaluation

	28-d LOK/CAPO strength, $\mathbf{f_{L/C}}$		28-d cylinder strength, $\mathbf{f_c}$		Ratio
Structure / Concrete ID	Avg., MPa	CV, %	Avg., MPa	CV, %	$\mathbf{f_{L/C}/f_c}$
East Tunnel A1	58.2^{C}	16.3	76.4	6.0	0.78
East Bridge A	55.4^{L}	11.6	55.8	7.6	0.99
B	51.8^{L}	13.3	53.0	6.9	0.98
West Bridge A	53.7^{L}	9.7	57.6	4.9	0.93
B	51.9^{C}	19.5	57.4	4.9	0.90

In-situ strength testing had never before been used production tests in Denmark, but on the Great Belt Link LOK-test inserts were used for all structures (in average 1 test for every 25 m^3) except the slip-formed caisson walls (West Bridge) and the tunnel lining segments, where CAPO-TESTS were used at the time of testing.

Well-planned pretesting and trial castings for the actual work methods, and prior certified training of the workforce, was a key aspect. Training and technical follow-up during all this Danish iconic project (fig. 29).

Figure 29. Trial testing for chloride migration and pullout (left) for the specified concrete, and Certification Course in testing with LOK-TEST and CAPO-TEST (right). Diploma was awarded if the technician could complete 4 LOK-TEST´s and 4 CAPO-TEST´s within 2 hours.

The conclusions by the Great Belt Link concerning using LOK-TEST and CAPO-TEST) for production testing [36, p.270]:

“*Regarding the use of pull-out testing (LOK and CAPO tests),* ***it is a primary recommendation for production testing****, provided that problems relating to training test operators, placing test bolts, and statistical evaluation of results are solved.*

However, despite first class materials and mix proportions being optimized to secure durability, strength and uniformity, inadequate casting, vibration, compaction, and curing can completely destroy the quality of the final structure.

Experience from the Great Belt Link shows that high performance concrete requires thorough pretesting of the fresh concrete properties to determine adequate work procedures and to train site staff in these before start of work.”

11.2 Service life of bridge pier, Great Belt Link, Denmark

The East Bridge of the Great Belt Link project was finished in 1991 (Figure 30). In 1998 and again in 2005, chloride ion content profiles were obtained from various locations to evaluate the service life on the pier, D1 being in the splash zone.

Figure 30. The Great Belt Link´s suspension bridge and one of its piers selected for testing for service life. The pier was constructed using plywood form kept on for 3-5 days before stripping. LOK-TEST performed met the requirements.

Based on a cover layer thickness of 75 mm and a threshold chloride ion content concentration of 0.10 % by concrete weight, the estimated time for the initiation of chloride-induced corrosion at different elevations of the bridge piers were calculated using a simplified model of diffusion theory [40, 41, see Figures 31 and 32.

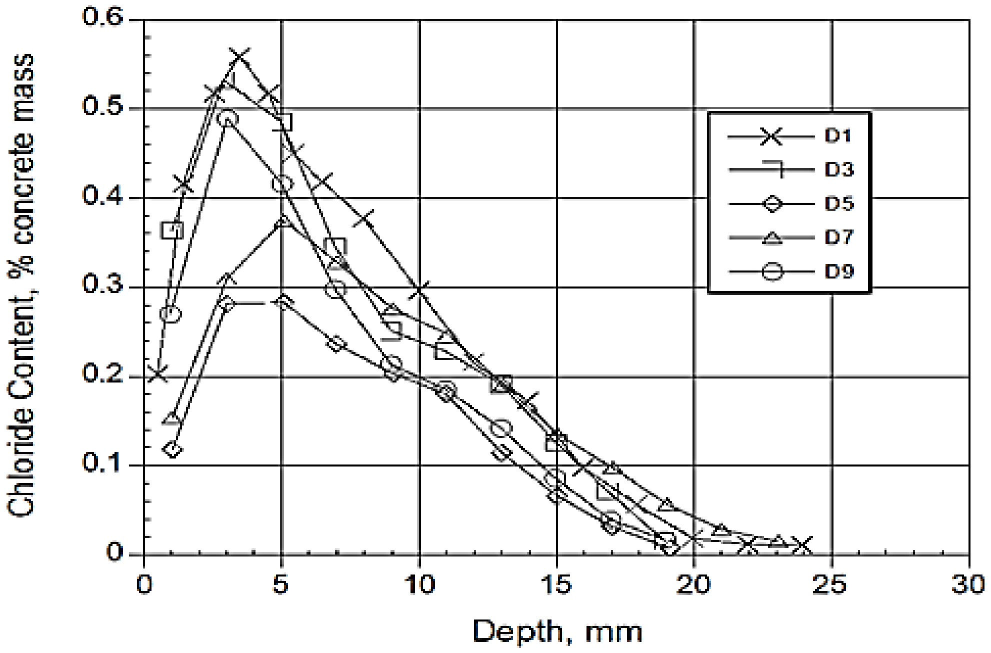

Figure 31. Chloride profiles obtained in 1998 at different locations on the pier.

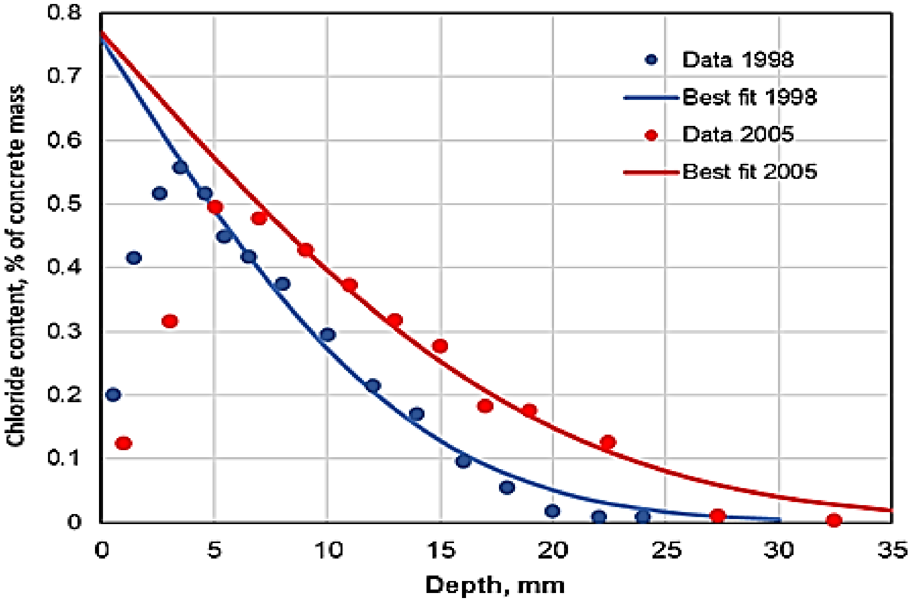

Figure 32. Repeated measurements made in 2005 compared to the 1998 data for the pier in the splash zone.

The final results of these calculations, in relation to remaining service life, are shown in Figure 33 based on a simplified model using Fick´s Second Law of diffusion.

In the splash zone the estimated remaining service life is about 100 years, as required by the specifiers of the high performance concrete. e.g. Professor Ervin Poulsen, DTU, Denmark. [38, 40]:

The very long service life (>500 years) above elevation +5 is attributed to the lower moisture content compared with the splash zone at elevation -1 to +1, where the concrete capillary pores are fully saturated.

The longer service life below sea level, compared with the splash zone, is attributed to the reduced oxygen content in submerged concrete.

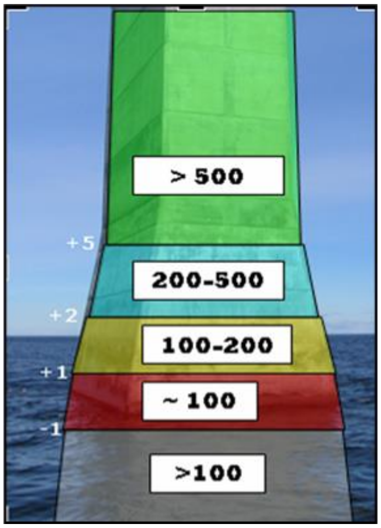

Figure 33. Service life in years calculated at different levels on the pier.

11.3 Curing of the cover layer evaluated by pullout and conductivity.

For resistance to chlorides from, e.g., the sea or deicing salts, the cover layer is the “Peel of the Orange”, Figure 34, protecting the reinforcement against corrosion. Similar with carbonation. This “PEEL” is the essential part of a new structure when it comes to durability, not the interior. To achieve a good, durable cover layer, the right mix has to be used, it has to be well compacted, have a sufficient thickness and be well cured. Optimal curing is providing water or keeping the formwork in place during hydration, alternatively, using internal curing with LW fine aggregates or water absorbent polymers, while less efficient curing is achieved if curing compounds, or plastic sheets are applied.

Figure 34. The cover layer is the “peel of the orange” for concrete.

No curing has significant detrimental effects, as does exposure to high temperature and wind (mis-curing). Early Danish research in 1969 at DTU showed a 31% reduction in LOK-TEST pullout strength for a w/c-ratio of 0.36, and 40% for a w/c-ratio of 0.50 when concrete is mis-cured compared to water curing at 20^{o}C. But how about the resistance to chlorides?

Recently, a comparison between LOK-TEST pullout strength and bulk conductivity has been performed for estimating the chloride diffusivity and service life for wet cured concrete and air cured, for simplicity.

The two standards applied were: ASTM C900-19: “Standard Test Method for Pullout Strength of Hardened Concrete” [45]. (LOK-TEST, Figure 35) and ASTM C1876-19: “Standard Test Method For Bulk Electrical Resistivity or Bulk Conductivity of Concrete” (using the MERLIN device, Figure 36), ref [44], performed on slices of cores, estimating the chloride diffusion coefficient and the service life, defined here as the estimated time it takes to build up a critical chloride content at the depth of the steel reinforcement.

Figure 35. LOK-TEST pullout force in kN, testing depth 25 mm.

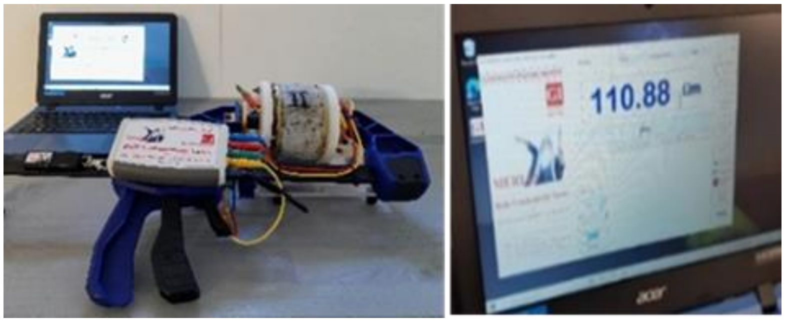

Fig. 36. Bulk resistivity in Ω·m of saturated 50 mm core from the cover layer measured with the Merlin.

The concrete used was a C40/C50 class concrete (f'_c 40 MPa on cylinders, 50 Mpa on cubes) which was tested after 56 days. The average results from testing of three sets of specimens (wet and air cured) are shown in Table 6.

The LOK-TEST showed a 23% compressive strength reduction. The bulk resistivity testing with the MERLIN device on the 50 mm cover layer resulted in 166 Ω·m for wet curing and 111 Ω·m for air curing, which represents a 33% reduction. With simplified assumptions, these resistivity values can be transformed to a chloride diffusion coefficient, D_a, using the Nernst-Einstein relation. This way, wet curing would correspond to a chloride diffusion coefficient of 27.2 mm^2/y and air curing to 41.5 mm^2/y.

By means of the Life 365TM Software (free available at www.life-365.org), based on Fick’s second law of diffusion, the expected service life in years, t, can then be estimated for a given cover layer and exposure condition. For a 50 mm cover layer and sea water splash exposure condition, the estimation shows a 40% reduction of the service life regardless of the critical limit for corrosion of the reinforcement is considered to be 0.050% Cl- or 0.100% Cl- by concrete mass (Table 7 and Figure 37). For very mis-cured concrete (wind and higher temperature), the reduction would be much larger.

Table 6. Results of pullout and resistivity.

Curing	LOK-TEST	Resistivity
Wet cured	42.7 kN	166 Ω·m
Air cured	33.0 kN	111 Ω·m

Table 7. Estimated service life.

Critical chloride level	Wet curing	Air curing
0.05 % Cl^-/mass	66 years	37 years
0.1 % Cl^-/mass	92 years	56 years

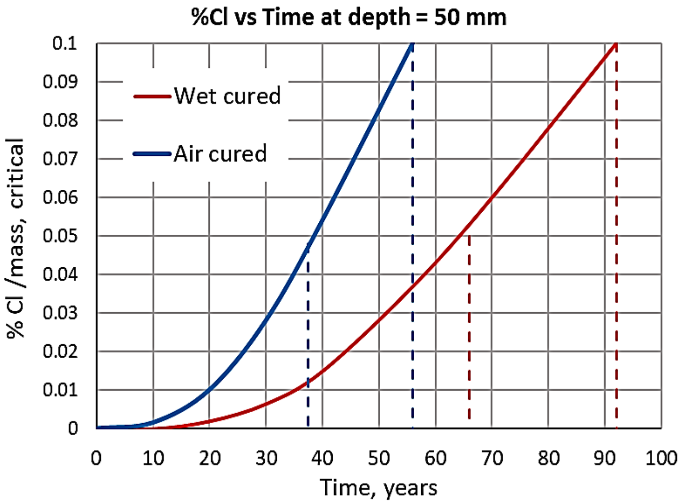

Figure 37. Chloride ingress, wet and air cured concrete specimens.

Other testing examples

Figure 38. Left: Great Belt Link, Denmark, 40,000 pullouts were made. The strength by pullout was accepted if the strength was minimum 80% of the potential lab strength [16]. Center: supporting sea wall, Copenhagen. Minimal curing compound applied. Pullout strength = 70% of lab strength. Right: Garage parking structure, UK. Concrete covered by heavy plastic sheet and wet mats. Pullout matched the lab strength.

In this manner, a quick on-site strength test, the LOK-TEST or the CAPO-TEST, will immediately indicate the cover layer quality.

If lower than expected, cores may be drilled out from the cover layer, sliced and water saturated for further testing with the MERLIN for bulk resistivity (or its inverse, conductivity) and estimating the remaining service life in chloride environment.

More examples of pullout used for cover layer quality are shown in fig. 38.

11.4 Strength testing with CAPO-TEST for further loading of old bridges in Poland.

As part of strength testing of 50 old bridges to be upgraded (Figure 39), for increased loading from army tanks, fifteen bridges, ranging in age from 25 to 52 years, were investigated initially, to establishing a correlation curve between 100 mm x 100 mm cores and the CAPO-TEST (ASTM C-900 and EN 12504-3), with special focus on the effect on carbonation. The depth of carbonation varied from 2 mm to 35 mm on the bridges. The strength of the bridges ranged from 20 MPa to 50 MPa.

The number of 100 mm x 100 mm cores and CAPO-TEST´s for each bridge are reported in the referenced ACI publication [18]. The average values are plotted in Figure 40.

Figure 39. Examples of Polish bridges tested for upgrading –higher loading– shown with CAPO-TEST

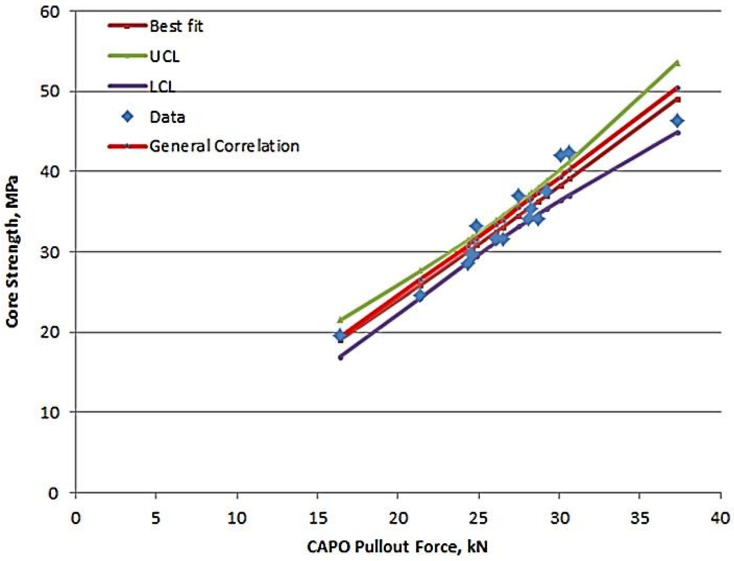

Figure 40. The correlation obtained from the Polish bridges.

It can be seen that the best fit curve (purple) matches the robust general correlation for cubes (red): $f_{cube} = 0.76\ F^{1.16}$ with a COV on the cores of 7.4% and 8.8% on the CAPO-TEST, in average.

Most interestingly, the effect of carbonation is only minimal on the CAPO-TEST and there is no correlation between the depth of carbonation and the relative error of the estimate based on the CAPO-TEST.

Schmidt Hammer testing was also performed. The estimated strength from this test showed about 80% higher strength than cores, using the correlation recommended by the manufacturer of the Schmidt Hammer.

Subsequently testing of the remaining bridges was performed by CAPO-TEST, only.

Another example of testing with CAPO-TEST before additional loading is applied to the structure is given in ref. [39] from Houston, USA

11.5 In-Situ compressive strength testing of quarantined precast concrete tunnel lining segments using CAPO-TEST, UK

Tunnel elements were produced at the Translink Joint Venture, on the Isle of Grain, UK, and hardened in a heating tunnel on a moving conveyer belt. For strength estimation, cubes were placed alongside. The production took place in large numbers, automatically. The cube strength, after heating, was specified to be 60 MPa. During a period, the cube strength dropped, but production continued until the drop was realized.

All the elements produced in that period were quarantined. Scrutinizing, it was later established that the reason for the drop was a change in the cement used in the mix; the gypsum component in the cement had been changed.

To test the final strength of the quarantined elements, two systems were selected as candidates, coring or CAPO-TEST. Testing with cores was too time-consuming, uncertain and costly, and considered to cause too much destruction. CAPO-TEST was selected, also due to the minimal damage by which the element tested could be used.

A calibration program was conducted in relation to cube strength ranging from 35 MPa to 100 MPa, partly between production cured cubes and CAPO-TEST, and partly between standard cured cubes and CAPO-TEST (Figure 41). Testing was made in relation to maturity at 4, 7, 28, 154 and 329 actual days.

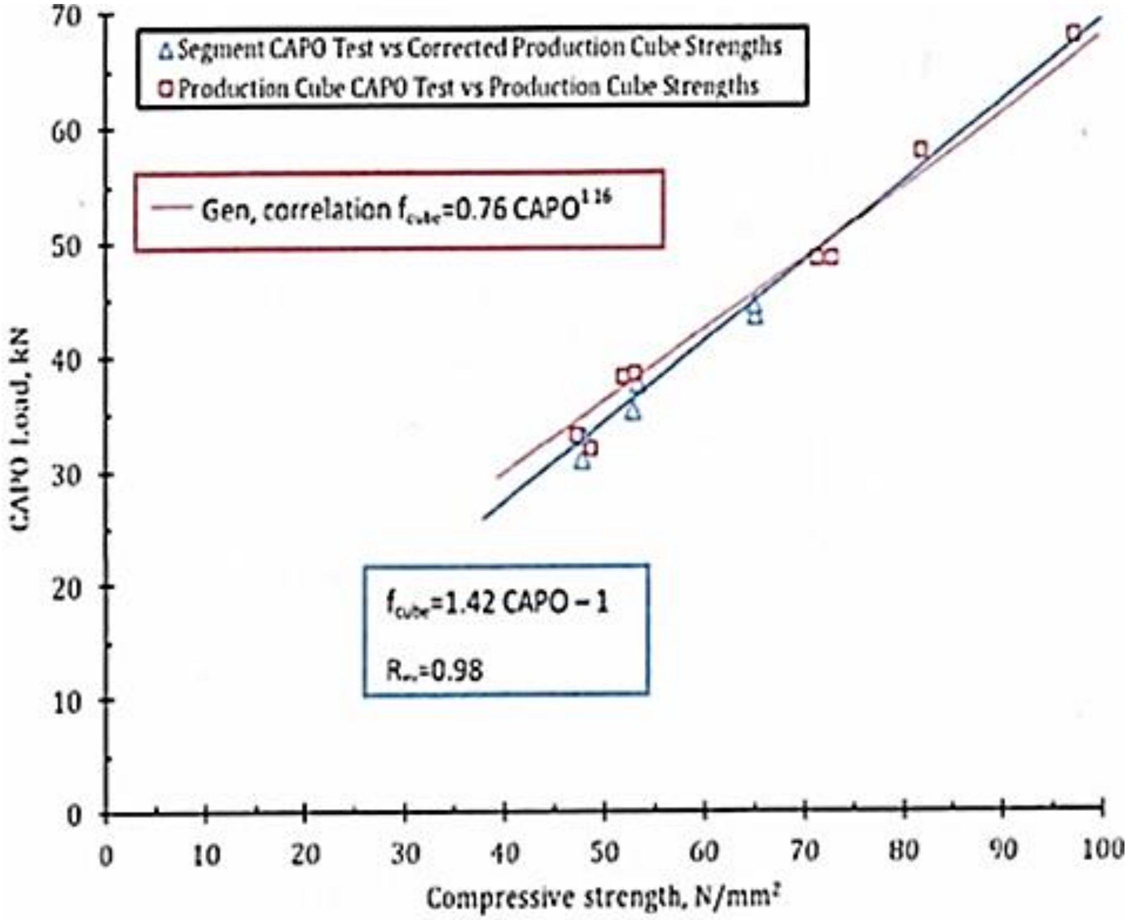

Figure 41. Correlation obtained between CAPO-TEST and standard cubes.

Subsequently, the quarantined elements were tested at random in a statistical valid manner with three CAPO-TEST´s in each element as shown in Figure 42.

Figure 42. CAPO-TEST in progress. Three CAPO-TESTs in each quarantined element were performed.
Photo shows certified CAPO-TEST technician Mr. Henrik Kristensen in action.
Well organized. a two-man trained testing crew can perform 30-40 CAPO-TEST´s a day, depending on accessibility.

All the quarantined elements older than 150 days old were accepted for erection in the tunnel, as the strength with CAPO-TEST related to cube strength showed strength over 60 MPa from 150 days and onwards.

The correlation obtained (blue), matched perfectly the general one between CAPO-TEST and cube strength (red) and was used for evaluation of the in-situ strength.

Variation in the CAPO-TEST was on average 9.6%, ranging from 7.9% to 11.5% for all the elements. Testing on each element lasted about 1 hour for each set of 3 CAPO-TESTs.

11.6 Safe and early loading with LOK-TEST, Canada

Not only for accelerating construction schedules, but also for safety, the LOK-TEST pullout system is used extensively for testing the strength of slabs during construction on high rise residential and office structures in Canada.

The test system is used in conjunction with optimized concrete mixes, by which a scheduled time of construction can be reduced, saving interest, costs on formworks, reshoring, winter heating and earlier rental [22, 28, 29].

Figure 43. LOK-TEST being performed by CET Sal Fasullo, Toronto, Canada, for safe and early form stripping in a high-rise building.

In a 100 m^3 slab pour, 10 to 15 LOK-TEST inserts are installed equally distributed on the bottom of the slab through prepared port holes in the flying form systems. Inserts can also be installed as floating inserts on the top, but the bottom installation is preferred due to simplicity and Speed.

Inserts can also be installed as floating inserts on the top, but the bottom installation is preferred due to simplicity and speed. Experience has shown that top installment of inserts produce about 10% lower strength at the top compared to the buttom, due to better compaction and curing at the bottom, [25].

At the time of testing a couple of inserts are tested, and if meeting the expectations, the remaining inserts are tested. 10 inserts can be tested in about 1 hour. The LOK-TEST pullout forces are converted to equivalent cylinder strength in MPa by means of a pre-established relationship following closely the general, robust correlation.

The standard deviation is calculated, followed by calculation of the “Minimum in-place strength” as: Average Strength less a k-factor times the Standard Deviation. The “k” factor relates to the 10% fractile of the T-distribution. If the “Minimum in-place strength” is higher than 75%

of the f'c, stripping/reshoring takes place, otherwise, testing of remaining inserts is performed later, e.g., after another 6 hours, and the "Minimum in-place strength" is recalculated.

This procedure has been adhered to in many cases for safe and early loading of slabs in high rises as the Scotia Plaza in Toronto (Figure 44), Canada, where earnings due to speeding up construction schedule was reported to be 1.5 million dollars.

Optimized concrete mixes were used, allowing forms to be removed as quickly as after 1.5 actual days, even in cold winter conditions. On the other hand, in the substructure, strength is not needed that quickly. Here e.g., fly-ash, slag cement, or other supplementary materials is used in the mix, reducing the costs of the concrete mix.

Figure 44. Scotia Plaza, Toronto, Canada

Full descriptions, including documented correlations, variability and reports from 18 projects are referenced in [11, 12, 13, 14].

On projects as reported in Trinity Square [13], the building officials allowed elimination of the usual mandatory standard cylinder tests, only relying on Lok-Test for in-place strength.

The Canadian Standard CSA-A23.2-15C [18], outlines in detail the procedure for performing the LOK-TEST properly.

12. CONCLUSIONS

Pullout testing is a physical test, like compression testing of standard cylinders, standard cubes or cores. In pullout, the compression and crushing of the concrete happens between the cast-in disc (LOK-TEST) or the expanded ring in a recess (CAPO-TEST and the counterpressure on the testing surface. Robust correlations between pullout force and standard cylinders, or standard cubes/cores exist, and can be used with great confidence without further correlations involving traditional laboratory testing.

In this manner, only s portable compression machine, the hydraulic LOK-TEST and CAPO-TEST pull machine, needs to be brought along to the site for testing the structure avoiding bundles of lab specimens. This obviates the need for traditional laboratory testing equipment, e.g., as reported in [27, 29] or on remote sites where the lab compression machine was too troublesome to bring along. Examples are from construction of the harbor piers at the island Tristan da Cunha in the Atlantic Ocean, and the construction at the Federal Research Base 6 hours flight north of Montreal, resulting in reduced casting time from 14 days to 7 days and with considerable savings [29],

If needed, for potential strength assessment 200 mm cubes, with inserts installed centrally in the vertical faces, can be cast, compacted, water cured and tested at specific time intervals and using the general correlations for transforming the pullout force´s to MPa´s of cylinders or cubes, eliminating the need of the traditional compression machine in the laboratory.

This paper illustrates the successful use of pullout for testing of dubious structures, for testing of old structures before further loading, for safe and early loading of structures involving use of optimized mixes and for evaluation of the curing of the cover layer protecting the reinforcement against aggressive environment to maximize the service life.

The precision of pullout testing is on a 95% confidence level 2 MPa for an average of 2 tests in the testing range to 80 MPa. In Ref [4] statistics are detailed for production testing in relation to number of batches in a placement and the coefficient of variation

CAPO-TEST has proven to be a useful inspection tool in condition evaluation of old structures, not at least when the reinforcement is densely installed and cutting of reinforcement (for example on highly loaded columns) has to be avoided. Also, on slim columns where coring can weaken the column, CAPO-TEST has been preferred.

Pullout testing can for durability be an efficient indicator of the cover layers quality followed by conductivity measurements of sliced cores for service life estimation.

CAPO-TEST can substitute cores, they are quicker, (15-20 minutes per test for a trained technician), giving immediate reliable results, more economic, cause less intrusion and eliminate the factors affecting the core (e.g. core size, L/D, moist, coring direction and end preparation).

13. USEFUL LINKS

- Section 1: Theoretical Analysis, Fracture Mechanism and Correlations
- Section 2: Rationale and testing cases, Standards.
- Section 3: Hardware, Testing Procedures and Instruments.
- Development of CAPO-TEST 1974
- ACI publication: CAPO-TEST to Estimate Concrete Strength in Bridges.
- In-Place Strength Without testing cores.
- Core Testing
- CAPO-TEST Video
- Publications

14. REFERENCES

1. ACI 228.1R-19 : "Report on Methods for Estimating In-Place Concrete Strength ", Reported by ACI Committees 228, American Concrete Instirute, Jan 2019, ISBN : 1-64195-050-3
2. Krenchel, H.: "Lok-Strength testing of concrete, Report No. S/69", Structural Research Laboratory, Danish Technical University, DTU, 197
3. Kierkegaard-Hansen, P.: "Lok-Strength", Nordisk Betong, No.3, 1975
4. Kierkegaard-Hansen, P. & Bickley, J.A.: "In-situ strength evaluation of concrete by the LOK-TEST system", ACI Fall Convention, Nov. 3rd, 1978
5. Kierkegaard-Hansen, "LOK-TEST until today", Danish Engineering Academy (DIAB), Copenhagen, Denmark, Oct. 1978
6. Petersen, C.G.: "CAPO-TEST", Nordisk Betong, No. 5-6, 1980
7. Petersen, C.G.: "Development of the CAPO-TEST,Strength testing at the Hestetorvet slab, Roskilde,Denmark, NDTitan case EC-1, 1975
8. Jensen, B.C. & Bræstrup, M.W.: "Lok-Test determine the compressive strength of concrete", Nordisk Betong, No.2, 1976
9. Ottosen, N.S.: "Nonlinear Finite Element Analysis of Pull-Out Test", Journal of the Structural Division, ASCE, Vol.107, No. ST4, April 1981
10. Krenchel, H. & Shah, S.P.: "Fracture analysis of the pullout test", Dept. of Structural Engineering, Technical University of Denmark, RILEM, Materials and Structures, Dunod, Nov-Dec. 1985 no 108
11. Krenchel, H. & Mossing, P.: "LOK-Styrkeprøvning af Beton, Brudmekanisk Analyse", Department of Structural Engineering, Technical University of Denmark, Serie R, No 198, 1985
12. Jensen, J.Kr.J., "Influence of Stresses in a Structure on the LOK-TEST Pullout Force", Department of Building Technology and Structural Engineering, AUC, Denmark, 1987
13. Bellander, U, "Strength in Concrete structures", Swedish Cement and Concrete Research institute, CBI Report Ra 1:78, Stockholm 1978, 15 pp
14. Bellander, U.: "Kvalitetskontroll av Betonkonstruktioner", Nordisk Betong 3-4 198322. Krenchel, H.: "LOK-Styrkeprøvning og CAPO-Styrkeprøvning af Betons Trykstyrke", Department of Structural Engineering, Technical University of Denmark, Serie I, No 71, 1982
15. Krenchel, H. & Petersen, C.G.: "In-Situ Pullout Testing with Lok-Test, Ten Years Experience", Int. Conf. on In-Situ / Non-Destructive Testing of Concrete, CANMET, ACI, Canadian Society of Civil Engineers and National Bureau of Standards, Canada, Oct, 1984
16. Petersen, C.G.: " Lok-Test and Capo-Test pullout testing, Twenty Years Experience", British Institute of Non-Destructive Testing in Civil Enginering Conference at Liverpool, April, 1997
17. Bishr, H.A.M.: "Assessment of Concrete Strength by Lok and Capo Tests", Thesis, Faculty of the College of Graduate Studies, King Fahd University of Petroleum & Minerals, Dharan, Saudi Arabia, June, 1990, 214 pages
18. Moczko.A, Carino, N. J. and Petersen, C.G.: "CAPO-TEST to Estimate Concrete Strength in Bridges" ACI Materials Journal, Nov. Dec. 2016, Technical Paper, title no. 113-M76
19. Petersen, C.G. : "Practical cases in the application of the pullout method (LOK-TEST and CAPO-TEST) for in-place compressive strength, Conrete Solution Conference 361, 0 (2022)
20. Carino, N. J.: "In-Place Strength Without Testing Cores: The Pullout Test", 6th International Seminar on Advances in Cement & Concrete Technology for Sustainable Development, 2012
21. Krenchel, H. & Bickley, J.A.: "Pullout Testing of Concrete, Historical Background and Scientific Level Today", Nordic Concrete Research, The Nordic Concrete Federation, Publication No. 6, 1987
22. Bickley, J.A.: "Concrete Optimization", Concrete International, Vol 4, No 6, June 1982
23. Bickley, J.A.: "The Evaluation and Acceptance of Concrete Quality by In-Place Testing", SP 82-6, ACI, 1982
24. Bickley, J.A.: "Achieving Safety and Economy in High Rise Concrete Structures through the use of In-Place Testing", Third International Conference on Tall Buildings, Chicago, USA, Jan. 1986
25. Bickley, J.A. & Fasullo, S.: "Analysis of Pull-Out Test Data from Construction Sites", TRB, Washington, USA, Jan. 1981

26. Bickley, J.A.: “The Variability of Pullout Tests and In-Place Concrete Strength”, Concrete International, April 1982
27. Bickley, J.A.: “Trinity Square: Commentary on concrete test date, Cement, Concrete, and Aggregate, CCAGDP, Vol 6, No.1, 1984, pp 28-32
28. Bickley, J.A. & Hindo, K.R.: “How to Build Faster for Less – The Role of In-Place Testing in Fast Track Construction”, ACI, Spring Convention, San Francisco, USA, 1994
29. Bickley, J.A.: “A Brief Historien of Pullout Testing: With Particular Reference to Canada, A Personal Journey”, International Conference on Non-Destructive Testing, ACI, Seville, Spain, Oct 2009
30. Bungey, J.H.: “Monitoring Concrete Early Age Strength Development”, Non-Destructive Testing (Proc. 12th), Elsevier Science Publishers, The Netherlands, 1997
31. Bungey, J.H.: “Assessment of insitu concrete strength, overview of test procedures”, Department of Civil Engineering, University of Liverpool, UK, 1998
32. Bungey, J.H.: “Strength Development Monitoring, Case Studies”, Department of Civil Engineering, University of Liverpool, UK, 1999
33. Soutsos, M.N., Bungey, J.H. & Long, A.E.: “In-Situ Strength Assessment of Concrete, The European Concrete Frame Building Project”, Department of Civil Engineering, University of Liverpool, UK, 1999
34. Bungey, J.H. & Soutsos, M.N.: “Reliability of Partially Destructive Tests to Assess the Strength of Concrete On Site”, Department of Civil Engineering, University of Liverpool, UK, 1999
35. BCA, BRE, Construct, Reinforced Concrete Counsil & DETR: “Early age strength assessment of concrete on site”, Best Practice Guides for In-Situ Concrete Frame Buildings, J.H. Bungey, A.E.Long, M.N. Soutsos & G.D. Henderson, BRE Report 387, CRC Ltd, UK, 2000
36. Great Belt Link: “Concrete Technology” Edited by Niels J. Gimsing, Copenhagen, Denmark, 1999, A/S Storebæltsforbindelsen, ISBN 87-89366-92-3
37. Great Belt Link : “West Bridge“, Edited by Aksel G. Frandsen and Niels Gimsing, Copenhagen, Denmark, 1997, A/S Storebæltsforbindelsen, ISBN 87-89366- 1
38. Petersen, C.G. & Poulsen, E.: “Pullout testing by Lok-Test and Capo-Test with particular reference to the in-place concrete of the Great Belt Link”, Dansk Betoninstitut A/S, Birkerød, Denmark, 1991
39. Zhengqi, Li, Desai, J. & Wesley B.: “In-Place Estimation of Concrete Compressive Strength Using Postinstalled Pullout Test – A Case Study”, Journal of Testing and Evaluation, ASTM, August 31, 2018
40. Poulsen, E. and Mejlbro. L., Diffusion of Chlorides in Concrete, Theory and Application, Modern Concrete Technology Series, Taylor and Francis, 2006, ISBN13: 9-78-0-419-25300-6
41. Petersen, C.G. & Orozco, H.D.: “Service Life Evaluated by Chloride Profiling”, XII International Conference on Structural Repair and Rehabilitation, 26-29th October, 2016, Porto, Portugal
42. Germann Instruments: “RCT, Instruction and Maintenance Manual”, March 2023, Germann Instruments A/S, Emdrupvej 102, DK-2400 Copenhagen NV, Denmark
43. Germann Instruments: “Profile Grinder”, March 2023, Germann Instruments A/S, Emdrupvej 102, DK-2400 Copenhagen NV, Denmark
44. Ministry of Transportation: “Method of test for determination of electrical resistivity of concrete”, Test Method LS-444, Ontario, Canada

Standards

45. ASTM C900 – 19: “Standard Test Method for Pullout Strength of Hardened Concrete” ASTM, Philadelphia, USA
46. Canadian Standard CSA A23.2-15C: “Evaluation of concrete strength in place using the pullout test”, 2014 CSA Group, Canada
47. EN 12504-3: “Testing concrete in structures – Part 3; Determination of pull-out force”, European Committee for Standardization, Brussels, Belgium
48. ASTM C1876-19: “Standard Test Method For Bulk Electrical Resistivity or Bulk Conductivity of Concrete”, ASTM, Philadelphia, USA
49. ASTM C42/C42M-18 “Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete”, ASTM, Philadelphia, USA