LOK-TEST and CAPO-TEST Literature

Organized by year of publication

August 1st, 2019

1. **Kiekegaard-Hansen, P..: "Lok-Strength", Nordisk Betong 3-1975**
   The initial development of a pullout test is described, the desire being to design a reliable, physical test for testing the compressive in-place instead of relying on laboratory cast and cured standard cylinders, only. The paper describe the development from 1962 to 1975 conducted at the Danish Technical University. A cast-in disc 25 mm in diameter was positioned at a 25 mm depth and pulled out through a counter pressure on the surface with varying inner diameters. The depth of the disk 25 mm was chosen for the critical cover layer of a structure to be tested. Varying inner diameters of the counter pressure was researched, and it was found that for 55 mm inner diameter the relationship to standard cylinder strength was a straight line, with a slope of almost 45^0. The test was named "LOK-TEST", "LOK" being the Danish name for "Punching".

2. **Jensen, B.C. & Bræstrup, M.W.: "Lok-Test determine the compressive strength of concrete", Nordisk Betong 2-1976**
   Plasticity analysis is applied to determine the load-carrying capacity of a concrete embedded disc which is pulled out under application of a counter pressure (LOK-TEST). It is shown that when the angle between the direction of deformation and the failure surface is equal to the angle of friction for the concrete, then the pull-out force is proportional to the concrete compressive strength.

3. **Kierkegaard-Hansen, P.: "LOK-TEST until today Oct. 1978, Historical background", Danish Engineering Academy, 1978**
   The main results from 5 independent major Danish calibration trials made until today can be summarized in one single correlation $L=5 + 0.8\, f_c$ where L is the Lok-Test pullout force in (kN) and f_c is the cylinder compressive strength in (MPa) from 10 MPa to 70 MPa.
   Furthermore, it documented by testing on square columns that the coefficient of correlation for LOK-TEST is 0.96, for cores 0.92, for standard cylinders 0.84, for UPV 0.53 and for the rebound hammer 0.50

4. **Ottosen, N.S.: "Influence on pullout strength in relation to change in depth for the LOK-TEST and the CAPO TEST", Copenhagen, Denmark, 1978**
   The analytical approach in ref. 2 is used to evaluate the influence of the depth of the disk/ring in relation to the change in pullout force in a LOK-TEST and CAPO-TEST. It is found that a depth of 24 mm (instead of the prescribed 25 mm) will cause a loss of 6% in the pullout force, and 12% if the depth is 23 mm

5. **Kierkegaard-Hansen, P. & Bickley, J.A.: "In-situ strength evaluation of concrete by the LOK-TEST system", ACI Fall Convention, Nov. 3rd, 1978**
   The development of the LOK-TEST system and the method of test is discussed. Details are given of the research programs carried out by various academic and research institutes.
   The use of the system on three major projects is described. Site test data and experience is given together with the practical aspects of the use of the test method.
   The economics , costs and benefits are reviewed, and the technical questions solved and raised by in-place concrete testing are summarized

6. **Trow Group: "Special Mix, Fast Test Speed Building Job", Heavy Construction News, Oct 1978**
   A specially designed fast-set/early-high strength concrete mix – combined with a new system for compressive strength of in-place concrete – to speed up occupancy by five months and to yield substantial dollars savings on a 15-storey apartment building in Mississauga, Ontario, Canada is described in the paper

7. **Drinkgern, G.: "Neuartige Erhärtungsprüfung an Bauteilen aus Beton", Fertigteile Beton Werkstein, Sonderdruck Heft 2/78 (in German)**
   The LOK-TEST is described. Reference is made to the German standard DIN 1048, Teil2, where a requirement of minimum 85% of the laboratory cast and cured cubes is stated for testing of structures in-situ. Furthermore, it is noticed that there are constant rising costs for QA/QC in Germany using laboratory

specimens, including the cube inflation experienced, "Würfelinflation", could be reduced by testing the structure itself with LOK-TEST.

8. **Bickley, J.A.: "Sample proposal for the use of Lok-Test on a project", University of Liverpool, Dec., 2000**
A detailed technical proposal for conducting an "accelerated program" for new in-situ cast structures is given, including testing in-place with pullout, concrete costs and savings (reduction in financing costs, earlier rental, owners overhead and credits from contractor)

9. **Petersen, C.G.: "CAPO-TEST", Nordisk Betong, 5-6, 1980**
The paper outline the development of the CAPO-TEST, (CutAndPullOut test), allowing pullout tests where LOK-TEST has been prepared by casting-in an insert. Initial comparison to LOK-TEST showed identical correlation to cylinder strength in the range from 10 MPa to 70 MPa

10. **Ottosen, N.S.: "Nonlinear Finite Element Analysis of Pull-Out Test", Journal of the Structural Division, ASCE, Vol. 107, No. ST4, April 1981**
A specific pull-out test used to determine in-situ concrete compressive strength is analyzed. This test consists of a steel disc that is extracted from the structure. The finite element analysis considers cracking as well as the strain hardening and softening in the pre- and post-failure region, respectively. The aim is to attain a clear insight into structural behavior. Special attention is given to the failure mode. Severe cracking occurs and the stress distribution is very inhomogeneous. However, large compressive forces run from the disc in a rather narrow band towards the support and this constitutes the load-carrying mechanism. The failure is caused by the crushing of the concrete in this region, and not be cracking

11. **Bickley, J.A. & Fasullo, S.: "Analysis of pull-out test data from Construction sites", Transportation Research Board, Washington, USA, Jan 1981**
Test-data from eighteen construction sites, together with relevant calibration/correlation results, are analyzed. The data is further examined in the perspective of a series of tests which attempt to determine the true in-test variation of the pull-out tests. It is shown that the pull-out test used has the same order of in-test variation as standard cylinders. It is therefore possible to measure the in-place strength of concrete and the variation of its strength. From this, the minimum strength of concrete in a pour can be calculated to a high degree of confidence

12. **Krenchel, H.: "LOK-Styrkeprøvning og CAPO-Styrkeprøvning af Betons Trykstyrke", Department of Structural Engineering, Technical University of Denmark, Serie I, No 71, 1982 (in Danish)**
30 different mixes were tested with LOK-TEST and CAPO-TEST and compared to standard cylinder strength. The pullout testing was conducted centrally placed on the vertical faces of 200 mm cubes compacted and cured identical to the cylinders. The conclusion is that the LOK-TEST correlation is identical to the CAPO-TEST´s and that the previous researched general correlation is confirmed for both the test systems. The average coefficient of variation for cylinders was found to be 3.5%, for the LOK-TEST 7.9% and for the CAPO-TEST 7.8%

13. **Bickley, J.A.: "The Variability of Pullout Tests and In-Place Concrete Strength", Concrete International, April 1982**
The development of pullout testing is reviewed briefly. Test data from 18 construction sites together with relevant correlation results are analyzed. The data are further examined in the perspective of a series of tests which attempt to determine the true in-test variation of the pullout test. It is shown that the pullout test used has the same order of in-test variation as the standard cylinder. It is, therefore, possible to measure the in-place strength of concrete and the variation of its strength. From this, the minimum strength of concrete in a placement can be calculated by standard statistical methods to a high degree of confidence.

14. **Hubler, R.L.: "Developer Saves Time, Reduce Interest Costs with New Concrete Testing System", Canadian Building Magazine, Jan. 1982**
Capitalizing on the cost reductions made possible by using the new LOK-TEST system to determine early concrete strengths, Oxford Development Group Ltd, Toronto, recently chopped a month off the construction of its Toronto Place Phase II office building, saving 600.00 dollars, and was able to advance the occupancy date.

15. **Bickley, J.A.: “The Evaluation and Acceptance of Concrete Quality by In-Place Testing”, SP 82-6, ACI**
The standard method of determining the queslity of hardened concrete is the cylinder test. Unless test results fail to meet specified values, and other test procedures are called into play, the standard cylinder test is usually the only quantitative measure of the quality of concrete in a structure. Analysis of test results to ACI 214 enables assessment of this quality to be made.
On two large projects in Toronto, horizontal elements were extensively tested by in-place testing for form removal, termination of shoring, and confirmation of specified 28-day strength. Permission to waive standard cylinder testing for these elements was obtained from the City Building Department

16. **Bellander, U.: “Kvalitetskontroll av Betonkonstruktioner”, Nordisk Betong 3-4 1983 (in Swedish)**
The regression between standard cube strength and the LOK-TEST and CAPO-TEST was investigated for different concrete mixes ranging from 5 MPa to 85 MPa cube strength in sets of 75 comparisons. The correlations were investigated for 18 mm and 38 mm maximum aggregate size. No significant difference was found for different aggregate sizes and the LOK-TEST correlation matched the CAPO-TEST´s following the general correlation for cubes

17. **Petersen, C.G.: ”LOK-test and CAPO-Test development and their applications”, Proc. Inst´n Civ. Engrs, Part 1, Vol 76, May 1984**
Calibration data from 19 major projects in Denmark, Sweden, Norway, the Netherlands, USA and Canada are presented totaling 4774 pullouts and 4202 compression tests (cylinders or cubes). Based on the experience so far, general relationships are recommended for normal concrete with maximum aggregate size not greater than 38 mm. Variations in the pullout tests is shown to be in the same order as for the standard cylinder or the standard cube

18. **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 for Civil Engineers and National Bureau of Standards, Ottawa, Canada, Oct 2-5, 1984**
Summary of 3,431 LOK-TEST´s from 86 structures tested for QA/QC together with obtained standard variations and coefficient of variations from each of the projects are presented.
A total of 24 correlations to cylinder and cube strength are illustrated leading to the conclusion that general correlations can be used no matter what concrete parameter is considered (up to 38 mm max aggregate size) except for the use of lightweight aggregates.
Variations from lab testing on cylinders, cubes and pullouts are given as well as from testing on-site with pullout (beams and columns, slabs, walls and foundations, shotcrete and dubious structures)

19. **Bickley, J.A.: “Trinity Square: Commentary on Concrete”, Cement and Concrete Aggregates, ASTM, 1984**
The building, Trinity Square, is the new head office for Bell Canada in Toronto, Canada. The structural frame was completed late in 1981 and used 53,000 m3 of concrete. The main purpose of the paper is to show in-place testing can be used alone to determine the strength of concrete in a structure eliminating the normal statutory requirement for standard concrete test cylinders

20. **Bickley, J.A.: “Cost Effectiveness of In-Situ Testing”, CANMET/ACI Intnl. Conference on In-Situ/Non-Destructive Testing of Concrete, Ottawa, Oct 2, 1984**
This paper illustrates by way of a case study how in-situ testing can be applied to accelerate a construction program and summarizes the cost benefits that result

21. **Krenchel, H. & Mossing, P.: “LOK-Styrkeprøvning af Beton, Brudmekanisk Analyse”, Department of Structural Engineering, Technical University of Denmark, Serie R, No 198, 1985 (in Danish)**
The load-displacement curve during a LOK-TEST is analyzed. The cracking starts out with circumferential crack in an open angle of at about 30%, where the linearity is lost, then a band of compression forces are created between the disc and the counter pressure causing parallel micro cracking in this band causing the primary parallel crack pattern in the strut, all the way up on the load-displacement curve until the peak load is reached, followed finally by formation of the secondary crack pattern producing the pullout cone

22. **Krenchel, H. & Shah, S.P.: "Fracture Analysis of the Pull-Out Test", RILEM, Materials and Structures, November-December 1985, No 108**
Pullout tests are increasingly being used to determine the in-situ strength of concrete. Several studies have shown that a close correlation exists between the maximum pullout load and compression strength of concrete. However, the failure mechanism is yet not understood. Conflicting theories have been forwarded to analyze the pullout.
In this study, progressive internal micro cracking was examined during the pullout testing. A commercial available equipment was modified to enable monitoring the pullout load vs. relative displacement relationship. Specimens were loaded and unloaded from predetermined fractions of the ultimate load. Acoustic activity was measured during testing. Unloaded specimens were sectioned and examined for micro cracking.
Results indicate a two-stage cracking process. A stable cracking system dominate for loads up to the peak load. A different cracking pattern develops near the peak load and governs the shape of the finally extracted cone.

23. **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**
A survey of the different pullout systems developed for controlling concrete strength is given together with an examination of stress- and strain-distribution inside the concrete at peak load for the Scandinavian pullout testing system.
Calibration tests based on 128 compression tests (cylinders 150 mm diameter x 300 mm), 240 LOK-TEST´s and 234 CAPO-TEST´s are shown. Variations as stated in ref.12, for cylinders 3.5%, for LOK-TEST 7.9% and for CAPO-TEST 7.8%
The three different stages of internal cracking in the concrete during pull-out loading are illustrated

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**
This paper discusses the use of pullout testing to achieve safety and economy in construction. The test is more suitable as a construction tool than the traditional 28 days cylinder test. Collapses have resulted from unrecognized low in-place strength and this test solves this problem
The procedure as per ASTM C 900 is illustrated.
The development of specifications and interpretation are discussed, A model specification is presented and suitable interpretation criteria suggested.
Because of the possibility of excessive deflection in concrete structures loaded at an early age, creep and curing factors are reviewed. The stress-strength ratio is seen to be critical.
The benefits of accelerating construction schedules are reviewed and illustrated by an example showing the financial savings which can be achieved

25. **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**
The influence of stresses standing in a structure on the pullout force was investigated. 200 mm cubes were prepared in 4 strength classes, 5 MPa, 10 MPa, 28 MPa and 40 MPa with LOK-TEST inserts cast-in the vertical faces. The cubes were loaded in a laboratory testing machine up to about 60% of the failure load. At the various load levels LOK-TEST´s were performed on the free surface while the cubes were under load.
The stresses standing in the cubes loaded were found to have no influence on the pullout force

26. **Stone, W.C., Carino, N.J. & Reeve, C.P.: "Statistical Methods for In-Place Strength Predictions by the Pullout Test", ACI Journal, Technical Paper, Sept – Oct 1986**
Pullout tests and companion cylinder tests were conducted to examine the variations in ultimate load with respect to concrete strength, and provide experimental data for the development of a new statistical procedure for predicting in-place compressive strength from the pullout test. The coefficients of variation were found to be relatively constant with average values of 4% for cylinder tests and approximately 10% for pullout tests in concrete with hard coarse aggregates. Pullout tests in lightweight concrete exhibited coefficients of variation of only 6%. Two test series were conducted with river gravel aggregate using apex angles of 54 and 74 deg. Both geometries produced coefficients of variation of 10%. A statistical procedure is developed for

determining the correlation equation which accounts for: 1) the constant coefficients of variation in ultimate load, and 2) the X-variable (pullout load) error. A procedure is also developed to predict the in-place characteristic strength to any desired confidence level. A method is presented to determine the appropriate number of in-place tests to be performed for a given concrete placement. A recommended minimum number of 8 to 12 pullout tests per 76 m^3 (100 cubic yards) is proposed

27. **Carino, N.J.: "Statistical Methods to Evaluate In-Place Test Results", RILEM, Testing during concrete construction, Proceedings, Chapman and Hall, 1990**
In-place testing is used to estimate the compressive strength of concrete in a structure by measuring another property related to compressive strength. Statistical methods are needed for reliable estimates of in-place strength. Such methods should account for the uncertainly in the measured property, thr uncertainty of the correlation relationship and the variability of the in-place concrete. Standard statistical procedures have not yet been adopted in North America practice. Recommendations are provided for development of the correlation relationship, and a reliable, easy-to-use approach is presented to estimate in-place characteristic strength

28. **Yun, C.H., Choi, K.R., Kim, S.Y. and Song, Y.C.: "Comparative Evaluation of Nondestructive Test Methods for In-Place Strength Determination", Special Publication SP 112, American Concrete Institute, 1990**
This paper presents an investigation to determine the within-test variability of various nondestructive test (NDT) methods and the correlation between NDT test results and the corresponding compressive strength of cores.. The size effect of coarse aggregate on the variability and correlation was also evaluated. The NDT test methods evaluated in the test series include rebound hammer, pulse velocity, probe penetration, pullout (LOK-TEST) and the CAPO (Cut And Pullout). Companion tests of field-cured standard cylinders and cores were also made. The tests were performed on plain concrete slabs, 1000 mm x 1000 mm x 300 mm, at the ages of 1, 3, 7, 14, 28 and 90 days. The test variables include the size of coarse aggregate (sand only, 25 mm and 40 mm), and the compressive strength of concrete (21 MPa, 28 MPa and 35 MPa).
The test results show that the within-test variability of the in-situ tests, herein reported, except for the UPV, is 2-5 times higher than that of the corresponding standard compression test, and is affected significantly by the amount of coarse aggregate and its size. In general, the highest degree of correlation is for pullout test (LOK-TEST), followed by that for CAPO-TEST, and rebound test, probe penetration and UPV

29. **Worthers, P.H.: "In-Situ Compressive Strength Testing of Precast Concrete Tunnel Lining Segments using CAPO-TEST", Translink Joint Venture, Construction Materials Management, November 1990**
Production of French-British tunnel elements for the Translink Joint Venture was made in heating tunnels. Adjacent to the elements were cast standard cubes tested for compressive strength. Over a period the cube strength dropped, and the elements were quarantined. These elements were tested, at a later age, with CAPO-TEST. First a calibration was performed, and the general correlation confirmed. Secondly, the quarantined elements were tested, 3 CAPO-TEST in each. The strength was found to be adequate, and the quarantined elements released for erection in the tunnel.
The reason for the drop experienced in the strength of the production cured cubes was identified subsequently, the cement produced had changed the gypsum component of the cement.

30. **Petersen, C.G.: In-Place Testing for Quality Assurance and Early Loading Operations with Pullout Testing and Maturity Measurements", in Testing during Concrete Construction, Chapman and Hall, RILEM Workshop, Mainz, March 1990.**
Pullout testing systems and maturity measurements for quality assurance and early loading operations are briefly reviewed. Correlation data and variability of pullout testing is stated. Present applications are illustrated by a number of test cases based on the statistical evaluation procedure in the Danish Concrete Code DS 411 from 1984 and the Danish Standard for Evaluation of Test Results DS 423.1 from 1985 with particular reference to pullout testing in-situ

31. **Petersen, C.G. & Poulsen, E.: "Pull-Out Testing by LOK-TEST and CAPO-TEST with particular reference to the Great Belt Link, Danish Concrete Institute, 1993**
Instructional booklet on the LOK-TEST and CAPO-TEST outlining the equipment and testing procedures and the specified correlation between standard cylinders and pullout for the Great Belt Link. Statistics are stated in detail.

32. **Great Belt Link: "LOK and CAPO Tests, The experience of pull-out testing during The Great Belt Link (Storebælt) project in Denmark, Storebæltsforbindelsen, Denmark, 1999**
The project of 1.1 million m^3 of concrete required 100 years of service life against chloride penetration. Pretesting of the concrete selected was made in the lab to make sure this requirement could be met. Large trial specimens were cast on-site and tested for chloride penetration as well, and with LOK-TEST / CAPO-TEST at different maturities to establish acceptable limits for the pullouts testing the defect intensity of the cover layer. Approximately 40,000 pullouts were conducted throughout the project
The general correlation was confirmed for the East Tunnel and East Bridge, while the West Bridge used a separate correlation.
The relative strength of the cover layer with LOK / CAPO-TEST compared to laboratory cylinders giving the potential strength was found to be 0.78 for the East Tunnel, 0.98-0.0.99 for the East Bridge and 0.90-0.93 for the West Bridge

33. **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, March 20, 1994**
This paper demonstrates how the author´s approach can form part of a logical plan which facilitates speed of construction, ensure high quality, and results in significant cost savings
The economic needs of today dictate that many projects shall be built to a fast-track schedule. Recent developments in cementitious materials and admixtures have provided unlimited scope for the formulation of concrete mixes. Early age and later age high strength requirements can be met with the same mix. The safe removal of formwork from structural components can be accomplished at ages less than 24 hours. Post-tensioning, reshoring and curing in cold weather can be controlled to optimum economic cycles. These economic benefits can be achieved by the use of selected in-place testing procedures which allow a fast track approach with safety.

34. **Bishr, A.M., Al-Armoudi, O.S.B, Basanbul, I. & Al-Sulalmani, G.: "Assessment of concrete compressive strength using the Lok-Test", Construction and Building Materials 1995, Vol. 9, No 4.**
This paper reports the results of a comprehensive investigation to assess the accuracy and predictability of the LOK-TEST for estimation of the in-situ compressive strength of concrete made with: (i) three water-to-cement ratios, (ii) two cement contents, and (iii) two types of local carbonate aggregates from eastern Saudi Arabia. The compressive strength of both cast and cored cylindrical specimens was statistically correlated with the LOK-TEST force. Based on a regression analysis of the generated data, the influence of the above mixture design variables on the compressive strength, the LOK-TEST force correlation was assessed. The results of the statistical analysis compared well with those reported in the international literature. Among the linear, bi-linear, quadratic and cubic models used, the results indicate that the linear relationship between the compressive strength and the LOK-TEST force was very significant and totally independent on all the mixture design variables. Hence, the LOK-TEST can be used in estimating the in-situ compressive strength with a high degree of reliability

35. **Petersen, C.G.: "LOK-TEST and CAPO-TEST pullout testing, Twenty Years Experience", British Insitute of Non-Destructive Testing, Non-Destructive Testing in Civil Engineering Conference in Liverpool, April 8-11, 1997**
26 major correlations are presented leading to the conclusion that general correlations to cylinder and cube strength exist between LOK-TEST / CAPO-TEST and reference specimens. The relationships are illustrated by straight lines. Test series are presented from testing in USA, Denmark, Luxembourg, UK and Sweden comparing the data to the general correlations.
LOK-TEST results are compared to CAPO-TEST and found to be identical
The variability from on-site testing with the two systems is given for slabs, beams and columns, walls and foundations as well as dubious structures, comprising a total of 9,197 LOK-TEST and 4,961 CAPO-TEST.

36. **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 enclosed Strength Development Monitoring Case Studies**
A full scale seven-storey in-situ advanced reinforced building frame designed to Eurocode 2 by Buro Happold was constructed in the Building Research Establishment´s Cardington laboratory encompassing a range of different concrete mixes and construction techniques. This provided an opportunity to use in-situ non-destructive test methods, namely the LOK-TEST and the CAPO-TEST, on a systematic basis during the construction of the building. They were used in conjunction with both standard and temperature-matched cube specimens to assess their practicality and their individual capabilities under field conditions

Six different mixtures were used ranging from 37MPa to 85 MPa in strength
The combined correlation for all mixtures is surprisingly very close to the manufacturers general correlation. Correlations were developed in the same manner for LOK-TEST and for CAPO-TEST. It is concluded that one strength correlation can be used for both systems.
It is furthermore concluded that there are definite advantages in being able to rely on the manufacturers recommended strength correlation, as is the case with the LOK-TEST and the CAPO-TEST in absence of a specific strength correlation

37. **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**
This guide provides recommendations for determining the strength of concrete on site at early ages using pullout

38. **Moczko, A.: "Comparison between compressive strength tests from cores, Capo-Test and Schmidt Hammer", Department of Civil Engineering, Wroclaw University, Poland, 2008**
Testing for strength of 10 bridges is reported using cores, CAPO-TEST and the rebound hammer. Strength ranged from 19.6 MPa to 42.0 MPa.
In relation to core strength, the CAPO-TEST, using the general correlation, exhibited in average 2.1% higher strength, the rebound hammer on-site 71.0% and the rebound hammer tested on the cores in the lab 35.5% higher strength than the cores

39. **Bickley, J.A.: "A Brief History of Pullout Testing: With Particular Reference to Canada, A Personal Journey", International Conference on Non-Destructive Testing, ACI, Seville, Spain, Oct 2009**
From the 1930´s to the 1970´s a number of researchers in Russia, the US and Canada worked on the development of a reliable pullout tests. In Denmark Kierkegaard-Hansen´s research first established pullout insert dimensions that resulted in a straight line relationship between the pullout force and compressive strength. This led to the development by Germann Petersen of s portable tester suitable for site use. Subsequently the procedure proved effective in assuring safe form removal times at early ages in the acceleration of construction schedules. Experience worldwide over the last 30 years has established the usefulness of the test and it has been standardized in many countries

40. **Thun, H., Ohlsson, U. & Elfgren, L.: "Determination of Concrete Compressive Strength with Pullout Tests", Structural Concrete Journal of the fib, Thomas Telford 2009**
Conclusions. The studies in this paper indicate that a pullout method, the pullout test for concrete strength assessment in new structures (Lok-Test) can also be used to estimate the in-place concrete strength in old structures such as bridges (Capo-Test)
It has been found that the power function relating the compressive strength f_c (MPa) and the pullout force F (kN) by Capo-Test given by the manufacturer $f_c=0.76\ F^{1,16}$give conservative values of the compressive strength f_c. For that reason an improved function is proposed, $f_{core}=0.98\ F^{1.14}$for the interval 11 to 105 MPa. The proposal is based on eight bridges build between 1965 and 1980, on laboratory tests on a one year old concrete slab and data from Rockström and Molin from six read bridges, which were aged up to 54 years. The results have also been used to analyze the strength of 37 bridges built between 1953 and 1980.
When the pullout test is performed on an old concrete surface, for example an old bridge, caution must be used because there is a risk of a big difference in aggregate size, which could affect the result. In this case more tests should be performed in order to obtain a reliable result
(The cores 100 mm x 100 mm were before testing air-cured three days in the lab
It is uncertain if the planning of the surface before CAPO-TEST´ing was performed)

41. **Moczko, A., Carino, N.J. & Petersen, C.G.: "CAPO-TEST to Estimate Concrete Strength in Bridges", ACI Materials Journal, Technical Paper, No 113-M76, November – December 2016**
This paper addresses whether carbonation in existing concrete structures affects the compressive strength estimated using the CAPO-TEST, a post-installed, pullout test conforming to ASTM C900 and EN 12504-3. Fifteen bridges, ranging from 25 to 52 years of age at the time of testing, were investigated. For each bridge, average values of core strengths and CAPO pullout strengths were obtained. Carbonation depth, which varied from 2 to 35 mm (0.08 to 1.4 in.), was measured using chemical staining methods.

It was anticipated that, as the depth of carbonation increased, the pullout strength would increase for the same underlying concrete strength. Thus, the in-place compressive strength estimated on the basis of the manufacturer's general correlation would be expected to systematically exceed the strength measured by the cores. It was found that, on average, the compressive strength estimated from the CAPO-TEST and the general correlation was only 2.8% greater than the measured core strength. More importantly, there was no correlation between depth of carbonation and the relative error of the estimated strength based on the CAPO-TEST.
The correlation between core (100 mm x 100 mm) compressive strength f_{core} *(MPa) and the Capo-Test pullout force F in kN was found to be* $f_{core}=0.77F^{1.15}$
This correlation match closely the manufacturers correlation for cubes $f_{cube}=0.76F^{1.16}$
The 100 mm x 100 mm cores is assumed to give the same strength as 150 mm cubes.
(The cores in this study were before testing cured 4 days in the lab)

42. **Zhengqi, Li, Desai, J. & Wesley B.: "In-Place Estimation of Concrete Compressive Strength Using Postinstalled Pullout Tets – A Case Study", Journal of Testing and Evaluation, ASTM, August31, 2018**
It was proposed that a 16-story steel framing structure be built on top of an existing 12-year-old 1-story reinforced-concrete structure. The in-place concrete compressive strength of 3 footings and 29 plinths was estimated using a post-installed pullout test (CAPO-TEST) and a core compressive strength test. The influence of different length-to-diameter ratios of the cores and different diameters of cores and the correlation between maximum pullout force and core compressive strength were investigated. The results of the pullout test and core strength test indicate that the concrete compressive strength of footings and plinths was considered structurally adequate as per the acceptance criteria for tested core strength and estimated core strength given by ACI 318, Building Code Requirements for Structural Concrete and Commentary, and ACI 228.1R: In-Place Methods to Estimate Concrete Strength, respectively. maximum pullout force had a strong correlation with the core compressive strength. The influence of the different length-to-diameter ratio of cores on the strength correlation was not significant if the raw results of the compressive strength tests were corrected by multiplying the corresponding correction factors for the length-to-diameter ratio given by ASTM C42: Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete. The mixed use of the test results of 3.20 and 3.74-in.(81-mm and 95-mm) cores resulted in a decrease in the R of the correlation model, compared to that of the correlation model based on 3.74-in. (95-mm) cores. This was attributed to the potentially increased testing error as the diameter of the cores decreased. Recommendations for successfully performing post-installed pullout tests in the field were proposed. With the use of pullout tests, the project team was able to determine that the existing structural members had sufficient capacity. A delay in the project schedule was avoided.
(The cores were cured prior to testing as prescribed by ASTM C42, that is stored in water tight containers for at least 5 days after last being wetted. If the ends of cores have to cut with a water cooled saw, then 5 days iafter the cutting)

Miscellaneous:

43. **Poulsen, E.: "Note on the determination of Characteristic Value of Observations", Copenhagen, Denmark, 2001**

44. **Correlation procedure for establishing the relation of pullout force versus cylinder compressive strength,** Extract from LOK/CAPO on the Great Belt Link booklet, p. 85-100

Standards:

45. **ASTM C 900-15: "Standard Method for Pullout Strength of Hardened Concrete", ASTM Committee on Standards, 1916 Race Street, Philadelphia, Pa. 19103, USA**

46. **British Standard BS 1881: Part 207, "Testing concrete, recommendations for the assessment of concrete strength by near-to-surface tests", British Standard Institution, 2 Park Street, London W1A 2BS, U.K.**

47. **EN 12504-3 European Standard: "Testing concrete in structures- Part 3: Determination of pull-out force", , European Committee for Standardization, Central Secretariat, rue de Stassart 36, B- 1050 Brussels, Belgium**

48. **CSA Group: "Concrete Materials and methods of concrete construction / Test methods and standard practices for concrete", A23.1-14 / A23.2 -14**

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