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## CAPO-TEST to Estimate Concrete Strength in Bridges

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*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.*

**Keywords:** CAPO-TEST; carbonation; core strength; correlation; existing structures; in-place strength; pullout test.

### INTRODUCTION

The aging of concrete bridges in combination with increased service loads and high replacement costs increases the need for assessment, maintenance, and, if needed, strengthening of these existing structures. One of the key parameters in any structural assessment is the in-place compressive strength of the concrete.

Traditionally, the in-place compressive strength has been evaluated by taking and testing cores. With this method, cores are drilled out, shipped carefully to the laboratory, saw cut to the proper length, moisture-conditioned, ends capped (or ground), and tested in the laboratory using a calibrated compression testing machine. The strength obtained depends on many factors such as core size, aggregate size, location of core, direction of coring, moisture condition at time of testing, length-diameter ratio, end preparation, and presence of embedded steel. The taking of cores leaves holes in the structure that must be repaired and the entire process of drilling, specimen preparation, and testing is time-consuming and costly.

Alternative methods for assessing the in-place compressive strength may include the rebound hammer, measuring ultrasonic pulse velocity, or the CAPO-TEST.<sup>1</sup> These are indirect methods that require the use of an empirical correlation to estimate the in-place compressive strength from the parameter measured by the test method.

Rebound hammer measurements on old, carbonated structures have shown increases of rebound numbers of up to 50% compared with non-carbonated concrete of the same strength.<sup>2,3</sup> The same phenomenon has been observed by one

of the authors<sup>4</sup> in a comparison of strengths estimated by rebound hammer compared with measured core strengths. Despite the use of a recommended "aging reduction factor" of 0.7 to account for carbonation, the estimated compressive strength from rebound values was found to be, on average, approximately 25% higher than the core strengths.<sup>4</sup> Without applying this "aging reduction factor," the strength estimate would have been, on average, approximately 80% higher than the core strengths. There is no general correlation between rebound number and compressive strength. Therefore, each structure has to be evaluated based on a correlation developed with cores from that structure.

Another popular technique is measuring the speed of a pulse of ultrasonic stress waves, typically called the ultrasonic pulse velocity (UPV). For a given concrete strength, there are several factors that will affect the UPV of the concrete, such as aggregate type, aggregate content, and moisture content.<sup>3</sup> In mature concrete, small differences in UPV can correspond to large differences in compressive strength, that is, UPV is relatively insensitive to changes in concrete strength. In addition, in reinforced concrete, the presence of reinforcement can lead to inaccurate values of UPV. While UPV is not known to be influenced by surface carbonation, the UPV method is not a good choice for obtaining reliable estimates of in-place compressive strength; the method is more appropriate for assessing the uniformity of the concrete in a structure.

The CAPO-TEST<sup>1</sup> is a post-installed pullout test conforming to the requirements of ASTM C900<sup>5</sup> and EN 12504-3.<sup>6</sup> The term "post-installed" means that the CAPO-TEST does not require preplacing inserts in fresh concrete. The test can be performed on an existing structure at any accessible location. In the CAPO-TEST, concrete strength is assessed within a 25 mm (1 in.) deep region. The CAPO-TEST will be described in detail.

This paper focuses on the correlation between CAPO-TEST results and the compressive strength of companion cores taken from 15 existing concrete bridges with varying carbonation depth. This correlation is compared to the general correlation established previously based on a series of independent studies for noncarbonated concrete. For practical field testing, it will be interesting to examine if the general correlation is reliable for estimating in-place concrete strength in old structures with a carbonated surface layer.

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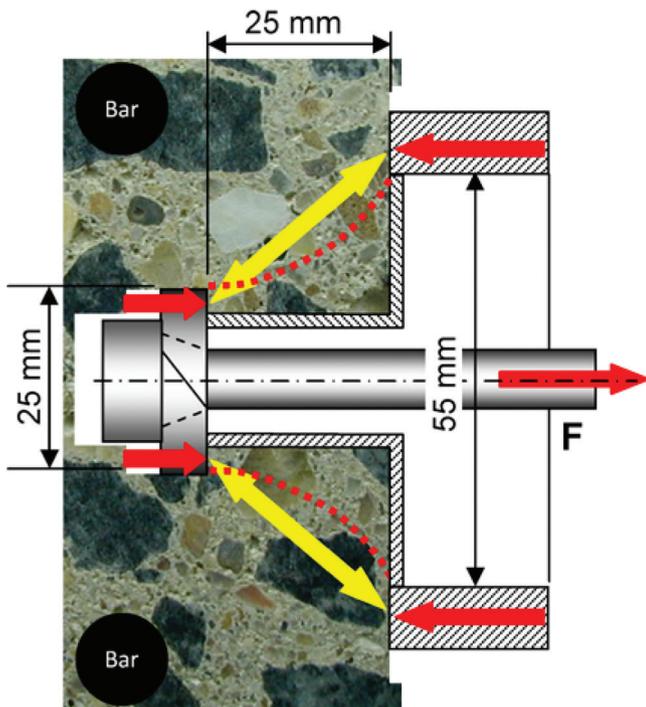


Fig. 1—Cross section view of CAPO-TEST. (Note: 1 mm = 0.0394 in.)

The testing that forms the basis of this paper was carried out as part of a national program in Poland to evaluate and upgrade old concrete bridges.

### RESEARCH SIGNIFICANCE

A problem in interpreting the results of in-place tests for evaluating concrete strength in old structures is the influence of carbonation on the reliability of the estimated strengths. The results of some surface in-place tests are known to be influenced by the depth of carbonation. In this field evaluation, which involved 15 concrete bridges with carbonation depths varying from a few millimeters to more than 25 mm (1 in.), it is shown that the compressive strengths estimated by the CAPO-TEST were not influenced by the depth of carbonation. Thus, the CAPO-TEST offers the potential for economical and reliable estimates of the in-place concrete strength in existing structures.

### CAPO-TEST AND LOK-TEST

#### Background

A schematic cross-section of the CAPO-TEST (Cut And PullOut Test) is shown in Fig. 1. As mentioned, the CAPO-TEST allows performing a pullout test conforming to ASTM C900<sup>5</sup> or EN 12504-3<sup>6</sup> without having to embed hardware into fresh concrete. Figure 2 is a schematic of the LOK-TEST, in which inserts are cast into the fresh concrete. The LOK-TEST is designed for testing the strength of the cover layer in new construction to assess curing efficiency, or for timing of early and safe loading operations.<sup>7-9</sup> A key feature of these pullout tests is the bearing ring used to provide counter pressure to the applied tensile load. As will be discussed, the bearing ring constrains the concrete to fail in a consistent and well-defined manner.

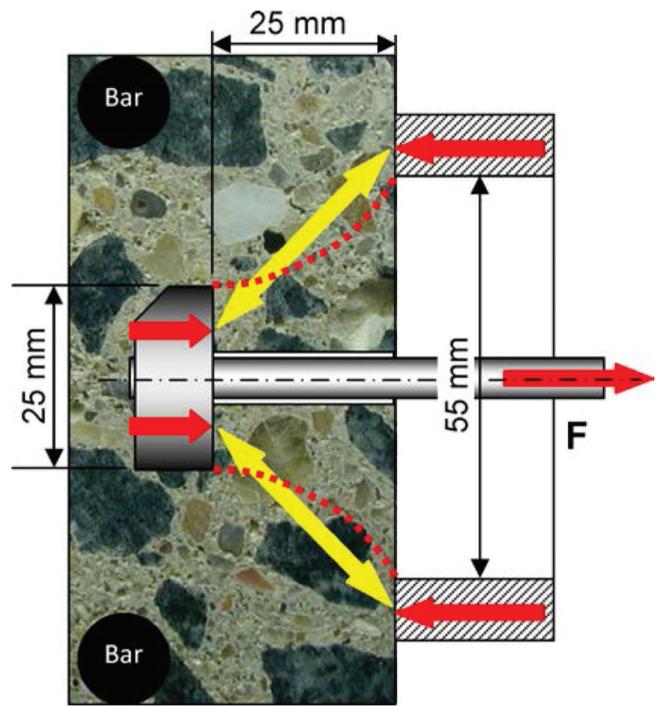


Fig. 2—Cross section view of LOK-TEST. (Note: 1 mm = 0.0394 in.)

To perform a CAPO-TEST, the reinforcement is located first using a cover meter, and the location for the CAPO-TEST is chosen so that the reinforcing steel is outside of the failure zone. An 18 mm (0.71 in.) diameter hole is cored perpendicular to the surface and to a depth of 65 mm (2.6 in.) using a coring drill. The surface is made flat to a depth of approximately 3 mm (0.1 in.) using a diamond-impregnated surface planer. A 25 mm (1 in.) diameter recess is cut at a depth of 25 mm (1 in.) using a diamond-impregnated grinding wheel. A split ring that has been coiled to fit into the cored center hole is inserted in the hole. The ring is expanded to a diameter of 25 mm (1 in.) using special hardware so it fits into the recess. Finally, the expanded ring is pulled out using a tension jack reacting against the counter pressure ring with an inside diameter of 55 mm (2.17 in.). As indicated in Fig. 1, the counter pressure ring causes the concrete to behave as a compression strut between the expanded ring and the counter pressure (bearing) ring. Thus, although a tension load is being applied, the concrete between the expanded ring and the bearing ring is subjected to a large compression force. Hence, as will be explained, the measured pullout force correlates well to the compressive strength of the concrete within a depth of 25 mm (1 in.).

Having a flat surface beneath the bearing ring is essential to obtain a valid CAPO-TEST result. Otherwise, the measured maximum pullout force may be reduced because the concrete between the expanded ring and the counter pressure will not be stressed uniformly. An example of an acceptable CAPO-TEST failure is shown in Fig. 3, while Fig. 4 shows an unacceptable failure because the test surface was not flat. Detailed procedure manuals for the CAPO-TEST are available.<sup>7,10</sup>

It takes approximately 20 minutes for a trained operator to perform one CAPO-TEST and repair the surface after



Fig. 3—Example of acceptable CAPO-TEST with complete ring at surface.



Fig. 4—Example of unacceptable CAPO-TEST; surface was not flat and a complete ring was not formed at surface.

extraction of the fragment. The surface damage to the structure is minimal, and the test result is available immediately. A core test, on the other hand, takes approximately 2 hours of cumulative time to drill the core, repair the hole, ship the core to the laboratory, prepare the test specimen, and measure compressive strength. It may take 1 to 2 weeks to obtain a report of the test results, depending on the moisture conditioning regimen that was used.

#### Equivalence of CAPO-TEST and LOK-TEST results

More correlations of pullout force versus concrete strength have been performed with the LOK-TEST compared with the CAPO-TEST. Thus, an important issue that needs to be addressed is whether the pullout force measured using a

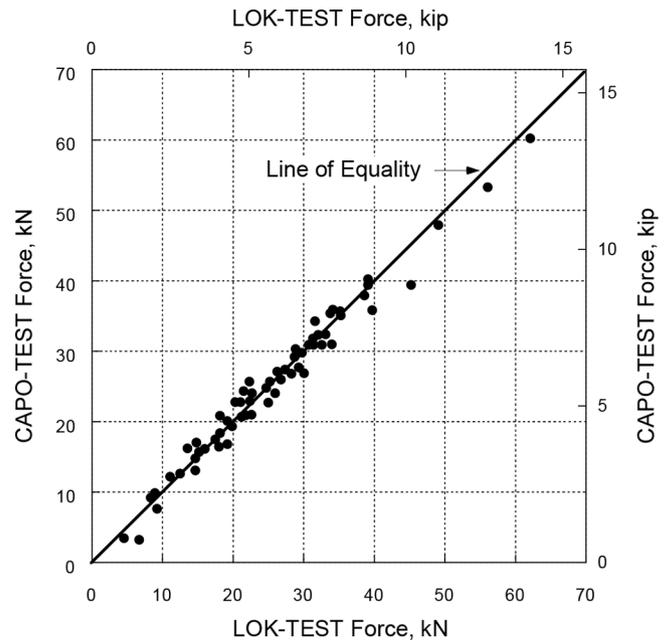


Fig. 5—Comparison of pullout forces for CAPO-TEST and LOK-TEST on the same concrete.<sup>11</sup>

CAPO-TEST is the same as for a LOK-TEST for the same concrete. Petersen<sup>11</sup> compiled data from different independent investigations aimed at establishing whether the two test techniques result in the same pullout force for the same concrete. Figure 5 shows Petersen's compiled data. The closeness of the data to the line of equality indicates that for the same concrete strength, the two techniques would result in the same pullout force. Thus, correlations obtained using the LOK-TEST would be expected to be applicable to the CAPO-TEST.

#### Correlations

Approaches for correlating CAPO-TEST (or LOK-TEST) results to compressive strength of standard specimens are described in various references.<sup>7,9,11-13</sup> It is important to perform the CAPO-TEST or LOK-TEST and the standard compressive strength tests on companion specimens of similar concrete in terms of having the same compaction, curing conditions, and maturity at time of testing. It is also important to avoid radial cracking while performing the pullout tests on laboratory specimens. Thus, the edge of the insert or expanded ring needs to be at least 3.5 times the insert diameter from the edge of the specimen.<sup>5</sup>

During the period from 1987 to 2014, 30 major independent studies were performed to develop empirical correlations between the CAPO-TEST or LOK-TEST and standard compressive strength. The studies were performed by various laboratories in Denmark, Sweden, Norway, Holland, Canada, the United States, Poland, and England.<sup>11,12</sup> Figure 6 shows the best-fit correlations between the compressive strength of 150 x 300 mm (6 x 12 in.) cylinders and pullout force, which was measured generally on the sides faces of 200 mm (8 in.) cubes. The best-fit curve to the 18 correlations is shown in Fig. 6 and is given by Eq. (1)

$$f_{cyl} = 0.69F^{1.12} \quad (1)$$

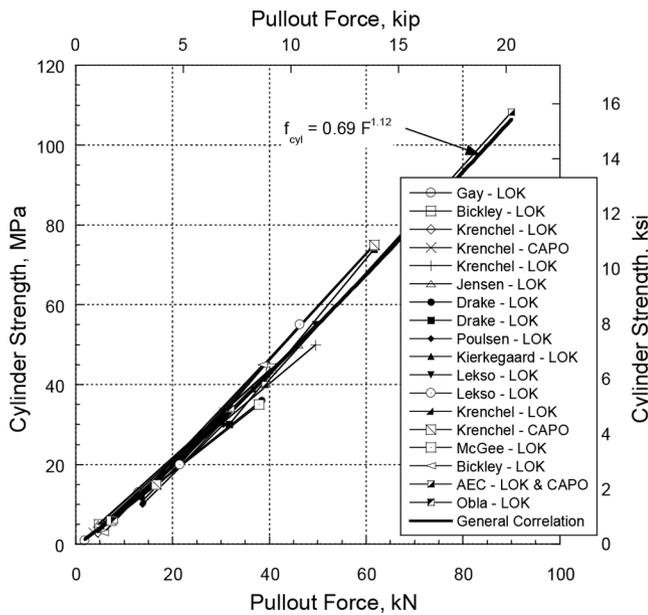


Fig. 6—Eighteen correlations between pullout force (LOK-TEST or CAPO-TEST) and compressive strength of 150 x 300 mm (6 x 12 in.) cylinders (equation is for SI units).

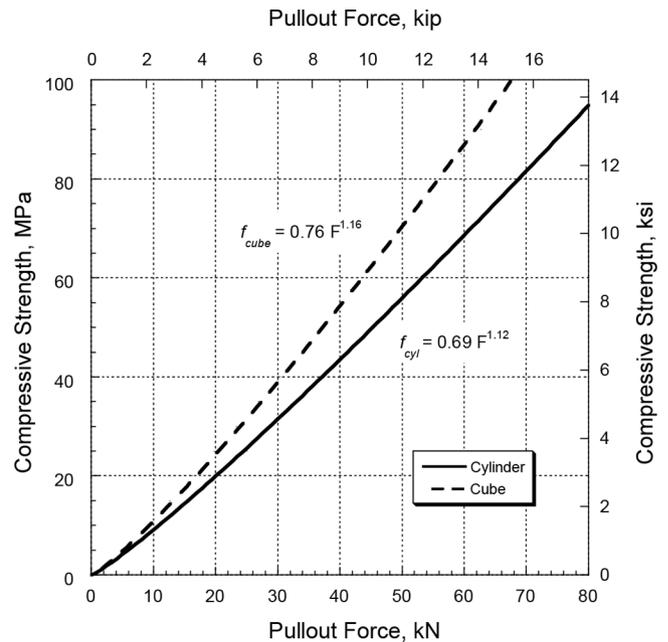


Fig. 8—General correlations for estimating compressive strength based on pullout testing using CAPO-TEST or LOK-TEST (equations are for SI units).

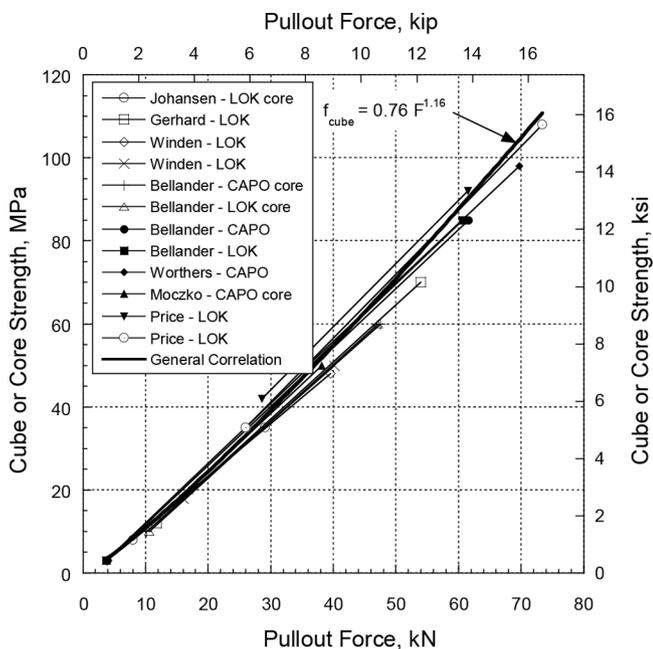


Fig. 7—Twelve correlations between pullout force (LOK-TEST or CAPO-TEST) and compressive strength of 150 mm (6 in.) cubes (equation is for SI units).

where  $f_{cyl}$  is the cylinder compressive strength, in MPa; and  $F$  is the maximum pullout force, in kN. (Note: Commercial test systems measure pullout force in kN. To avoid confusion, correlation equations in inch-pound units are not provided.)

Figure 7 shows correlations between compressive strength of 150 mm (6 in.) cubes and pullout force. Some of the correlations in Fig. 7 are between the compressive strength of 100 x 100 mm (4 x 4 in.) cores and pullout force. In practice, it is assumed that the compressive strength of a 100 x 100 mm (4 x 4 in.) core is equivalent to the compressive

strength of a 150 mm (6 in.) cube.<sup>14</sup> The best-fit curve to the 12 correlations is given by Eq. (2).

$$f_{cube} = 0.76F^{1.16} \quad (2)$$

where  $f_{cube}$  is the cube compressive strength, in MPa; and  $F$  is the pullout force, in kN.

Other correlations have been established, such as the large project at the University of Liverpool aimed at methods for assessing early-age strength.<sup>15</sup> These efforts led to a best practice guide by the British Cement Association<sup>8</sup> in which the pullout test is recommended for assessing early-age strength in new construction. In these British investigations, the general correlation between LOK-TEST and 150 mm (6 in.) cube strength given by Eq. (2) was confirmed for the normal-density concrete mixtures investigated.

Figure 8 summarizes the general correlations for estimating cylinder or cube compressive strength on the basis of pullout tests. It has been shown that these general correlations are not affected by types of cementitious materials, water-cementitious materials ratio ( $w/cm$ ), maturity, use of self-consolidating concrete, presence of fibers, air entrainment, use of admixtures, curing conditions, stresses in the structure, rigidity of the member, as well as shape, type, and size of aggregate up to 40 mm (1.6 in.).<sup>11,12,16</sup> Only if lightweight aggregates are used will there be a significantly different correlation between compressive strength and pullout force.

The coefficient of variation of replicate pullout tests is normally 7 to 8% in the laboratory and 8 to 12% in the field, depending mainly on the maximum size of the aggregates and testing locations in the structures.<sup>11,12</sup> If higher variabilities are encountered in practice, it is likely that concrete strength at the pullout test locations is not uniform.

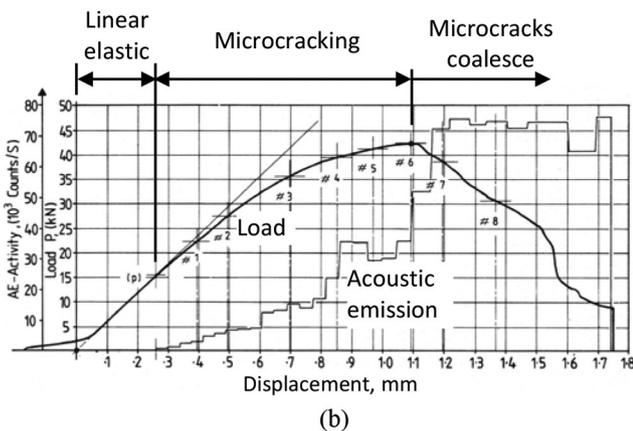
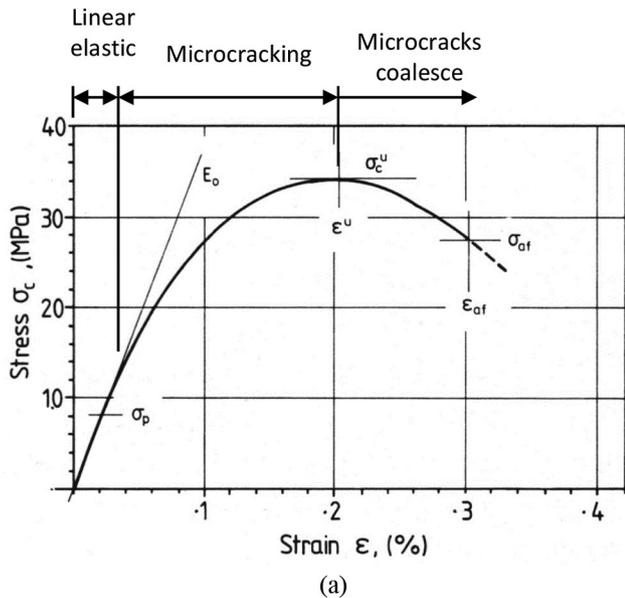


Fig. 9—(a) Stress-strain curve from uniaxial compressive strength test; and (b) load-displacement curve and acoustic emission activity for LOK-TEST.<sup>18</sup> (Note: 1 MPa = 145 psi; 1 mm = 0.0394 in.)

### Why the good correlation with compressive strength?

Among the many methods for estimating in-place compressive strength, the pullout test in accordance with ASTM C900 or EN 12504-3 has been shown to have one of the most robust correlations. The reason for this is discussed in this section. Carino<sup>17</sup> provides a review of some of the proposed failure mechanism of the pullout test.

Figure 9(a) shows the stress-strain curve for a cylinder loaded in compression compared to a load-displacement curve for a LOK-TEST shown in Fig. 9(b).<sup>18</sup> The displacement refers to the movement of the bolt used to pull out the insert. As can be seen, the curves have similar shapes, clearly showing three distinctive regions related to the failure process: the initial linear-elastic region; the nonlinear region corresponding to the formation and growth of microcracks; and the ultimate load followed by a descending branch corresponding to the coalescence of microcracks and softening plasticity.

Also shown in Fig. 9(b) is the rate of acoustic emissions measured while performing the LOK-TEST. Acoustic emis-

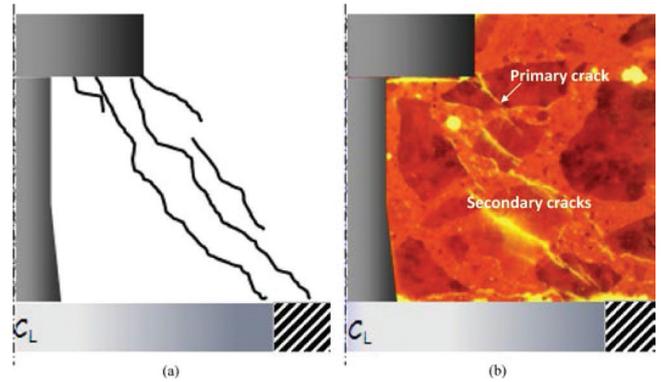


Fig. 10—(a) Cracking at 98% of ultimate load in LOK-TEST based on finite element analysis by Ottosen<sup>19</sup>; and (b) experimentally observed cracking at ultimate pullout load.<sup>20</sup>

sions are the result of sudden release of strain energy due to cracking. It is seen that the initiation of acoustic emissions corresponds to the end of the linear-elastic region, indicating the initiation of microcracks. With increasing load, more microcracks develop and the rate of acoustic emissions increases. As the ultimate load is reached, the rate of acoustic emission increases suddenly and remains at a high value as microcracks join together to form the conic frustum that is extracted from the concrete.

There have been two major contributions to help understand the failure mechanism during a pullout test. The first was a study by Ottosen,<sup>19</sup> in which a nonlinear finite element analysis was conducted to predict crack formation in the LOK-TEST. The second was an experimental study of crack formation conducted by Krenchel and colleagues.<sup>18,20</sup> In the latter study, the failure process was monitored by loading LOK-TEST specimens to various fractions of their anticipated pullout strength. The unloaded specimens were impregnated with fluorescent epoxy, sectioned, and the cracks were observed under ultraviolet light and low-power magnification.

Figure 10(a) shows the cracking pattern predicted from the finite element analysis at 98% of the ultimate load. Ottosen<sup>19</sup> summarized the findings of the analytical study as follows:

It has been shown that large compressive forces run from the disc in a rather narrow band towards the support, and this constitutes the load-carrying mechanism. Moreover, the failure in a LOK-TEST is caused by crushing of the concrete and not by cracking. Therefore, the force required to extract the embedded steel disc is directly dependent on the compressive strength of the concrete.

Figure 10(b) shows the experimental cracking observed at peak load for a LOK-TEST.<sup>20</sup> It is evident that there are parallel cracks in a band running from the insert to the counter pressure ring, which is consistent with Ottosen's analytical study. From the experimental studies,<sup>18,20</sup> Krenchel developed this description of the failure process in the LOK-TEST. At approximately 30% of the ultimate load, a primary circumferential tensile crack develops at the edge of the disc and propagates into the concrete at a



Fig. 11—Dislodged conical fragment from LOK-TEST, with debris at bottom of hole due to multiple microcracks within compression band.

flat angle. This corresponds to the end of linearity in the load-displacement curve shown in Fig. 9(b). The primary crack stops as it enters a region of low tensile stress. From thereon, multiple parallel microcracks develop in a compression band between the disc and the counter pressure ring. This secondary cracking is similar to the system of parallel cracks that develop in a uniaxial compression test. Beyond the ultimate load, the secondary microcracks coalesce to form the trumpet-shaped cone between the outer edge of the disc and the inner edge of the counter pressure ring. With additional applied displacement, the conical fragment is dislodged from the concrete mass, as shown in Fig. 11. The formation of numerous parallel cracks in the region between the insert and the counter pressure ring is evidenced by the debris observed in Fig. 11 at the bottom of the hole.

## IN-PLACE TESTING

### Structures tested

Fifteen bridges were tested by performing CAPO-TESTS and removing cores from critical zones where compressive strength was critical.<sup>4</sup> Most of the tests were performed on beams, but for two bridges, columns were tested. At time of testing, the bridges ranged in age from 25 to 52 years and the depth of carbonation varied from 2 to 35 mm (0.08 to 1.37 in.). The core strength ranged from 20 to 46 MPa (2900 to 6680 psi). Figure 12(a) shows one of the concrete bridges that was tested, and Fig. 12(b) shows the measurement of the pullout force for the CAPO-TEST. The objective of this study is to examine the differences between measured cores strengths and the compressive strengths estimated using the manufacturer's general correlation for the CAPO-TEST. In addition, it was desired to determine if the depth of carbonation had a systematic effect on the CAPO-TEST results.

### Testing for carbonation

Carbonation involves a chemical reaction in which carbon dioxide (CO<sub>2</sub>) in air diffuses into hardened concrete through the capillary pores and reacts with calcium hydroxide (Ca(OH)<sub>2</sub>) present in the hardened cement paste. The prod-



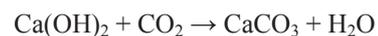
(a)



(b)

Fig. 12—(a) Example of bridge being tested; and (b) CAPO-TEST being performed.

ucts of the reaction are calcium carbonate (CaCO<sub>3</sub>) and water as summarized in the following chemical equation



As a result of the reaction, hydroxide ions are consumed and the pH of the pore solution decreases from above 12 to less than 9, rendering embedded reinforcing steel susceptible to corrosion in the presence of moisture and oxygen.

The calcite (CaCO<sub>3</sub>) and other alkali-carbonate products resulting from the carbonation reaction are less soluble than calcium hydroxide and densify the concrete paste by precipitating in the available pores within the carbonated zone near the surface. As a result, carbonation increases the density of the cement paste and increases concrete strength.<sup>21</sup>

Carbonation begins at the outer surface of the concrete and progresses inward with time. The rate of penetration of the carbonation front depends on several factors, such as the porosity of the paste, the moisture content, and the atmospheric concentration of carbon dioxide. The rate of carbonation is low in dry concrete and in saturated concrete.

In this study, the depth of carbonation was measured on cores, or alternatively on the surface of the holes created by the CAPO-TEST or on the 18 mm (0.71 in.) cores extracted in preparation for the CAPO-TEST. The depth of carbonation

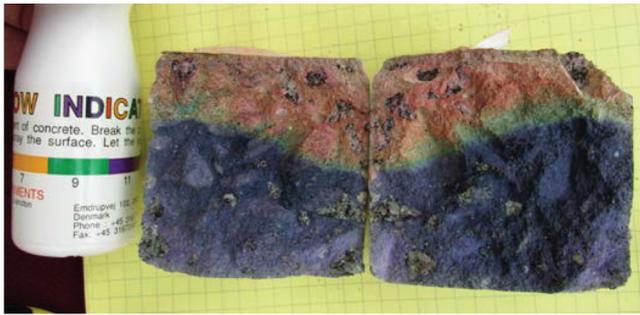


Fig. 13—Example of measuring depth of carbonation on split core using pH indicator solution sprayed on freshly broken surface.

was measured using a pH indicator solution<sup>22</sup> sprayed on a freshly cut or broken surface, as shown in Fig. 13. The particular pH indicator solution that was used turns green at a pH of approximately 9 and turns blue at a pH above about 11. Thus, for the example in Fig. 13, the depth of carbonation is approximately at the boundary between the light and dark region.

### Coring and core testing

Cores with a diameter of 100 mm (4 in.) were drilled to a depth of 300 to 400 mm (12 to 16 in.) using a water-cooled coring rig. Cores were drilled adjacent to CAPO-TEST locations, placed in sealable plastic bags, and shipped carefully to the laboratory. They were cut using a water-cooled saw with a diamond blade to a length of 100 mm (4 in.) within the noncarbonated concrete, and stored in laboratory air for 4 days before being tested for compressive strength. The ends of the cores were capped using a “sand-box” capping system in accordance with EN 12390-3.<sup>23</sup> Figure 14 shows a capped core being tested in a calibrated compression testing machine. In accordance with EN 13791,<sup>14</sup> it is assumed that the compressive strength of a 100 x 100 mm (4 x 4 in.) core is equivalent to the compressive strength of a molded 150 mm (6 in.) cube of the same concrete.

### Test results

Table 1 lists the bridges investigated, the elements tested, and the individual measured core strengths and CAPO pullout forces. To present all data for each structure in a compact format, Columns 4 and 5 in Table 1 show the individual test results separated by a space. Table 2 shows the age of the bridges; the average depth of carbonation; the average core strength, in MPa (average of three to 14 cores); the coefficient of variation (COV) of core strengths; the average pullout force, in kN, from the CAPO-TEST (average of five to 20 tests); and the COV of the CAPO pullout forces. The bridges are listed in order of increasing carbonation depth. The average COV of the core strengths was 7.4% and the average COV of the CAPO-TEST pullout forces was 8.9%.

### DATA ANALYSIS

In Fig. 15, the average core strengths in Table 2 are plotted versus the corresponding average CAPO-TEST pullout force. The best-fit, power-function equation (solid line) to the data is

$$f_{core} = 0.77F^{1.15} \quad (3)$$



Fig. 14—Core being tested for compressive strength using “sand box” caps described in EN 12390-3.<sup>23</sup>

The residual standard deviation of the best-fit equation is 2.1 MPa (300 psi). Figure 15 also shows the 95% confidence limits of the average core strength that would be estimated using this correlation. Finally, Fig. 15 shows the general correlation for estimating cube strength (refer to Fig. 8). It is seen that the general correlation for 150 mm (6 in.) cube strength,  $f_{cube} = 0.76F^{1.16}$  (bold dashed line), falls within the confidence limits for the correlation based on the core strengths from the bridges.

In comparing the correlations in Fig. 15, it has been assumed that the strength of 100 x 100 mm (4 x 4 in.) cores is equivalent to the strength of 150 mm (6 in.) cubes. Figure 16 shows correlation data for 150 mm (6 in.) cube strength versus pullout strength obtained by Bellander<sup>24</sup> and from a project on the French-British Channel Tunnel.<sup>25</sup> Also shown are the core strength versus CAPO-TEST results from this study (Fig. 15). It appears that the correlation using cores is conservative—that is, it underestimates the cube strength compared with the correlation based on the two sets of 150 mm (6 in.) cube data. Also shown in Fig. 16 is the general correlation for cube strength, which as has been shown in Fig. 15 is similar to the core strength correlation from this study.

The results in Fig. 15 show that there is a minor difference between the correlation obtained from the cores strengths and CAPO-TEST performed on carbonated concrete in the 15 bridges and the general correlation for cube strength. This similarity suggests that the presence of a layer carbonation may not have a significant influence on the application of the CAPO-TEST for estimating in-place compressive strength. To examine this further, an analysis was made of the difference between estimated concrete strength based on the CAPO-TEST using the general correlation and the measured core strength. The relative error  $\alpha_{CT}$  is used for this purpose, which is defined as follows

$$\alpha_{CT} = \frac{f_{CAPO} - C_{core}}{C_{core}} \times 100\% \quad (4)$$

**Table 1—Bridges evaluated and test results**

No.	Name	Element	Core strength, MPa	CAPO pullout force, kN
1	Zyrow	Beams	36.4 31.5 34.7	30.0 28.0 26.6 30.6 25.2
2	Dobrut	Beams	25.6 24.2 23.2 24.3 26.1	21.4 20.8 21.7 24.4 18.9 21.2
3	Wizna	Beams	44.7 48.0 46.0 43.8 47.4 48.6	38.1 39.0 35.5 33.8 37.2 32.5 38.4 34.2 40.1 39.6 39.5 40.0
4	Jablonica	Beams	36.8 35.1 30.7	29.4 30.0 26.6 29.6 27.7
5	Kamion	Beams	36.0 33.6 41.8	24.4 27.0 25.8 26.7 32.5 28.4 29.1 27.1 26.2
6	Modlin	Beams	41.4 38.9 46.0 42.7 41.0	26.5 34.4 31.2 25.3 33.2 30.0 27.4 34.0 29.3
7	Modlin	Columns	38.5 38.0 36.4 36.9	27.8 32.0 33.1 26.3 29.3 27.5 31.2 26.5
8	Jablonica II	Beams	35.0 36.9 34.3	29.5 26.5 28.6 29.1 27.8
9	Leszno	Beams	43.7 36.9 38.9 45.5 41.7 47.5	29.6 33.4 31.9 30.5 30.9 30.0 32.2 33.4 30.1 28.6 30.9 25.3
10	Wierzbica	Beams	34.5 33.5 31.8 33.4	26.9 27.3 27.5 25.8 26.2 24.1 23.3 22.3 22.5 24.5 26.1 22.5
11	Zyrow	Columns	30.5 26.6 27.6 34.2	27.5 25.0 25.7 21.4 24.2 21.5 26.7
12	Zofka	Beams	26.4 29.0 28.5 29.2 27.6 30.5	20.0 26.1 27.8 22.9 19.9 25.0 26.4 27.0 24.0
13	Zglobice	Beams	33.6 31.6 31.3 31.0 32.5 40.0 32.9 29.7 33.2 25.2 25.8 26.5 36.2 34.2	25.5 27.8 28.1 25.2 25.5 21.7 29.7 28.1 29.4 24.6 24.2 22.3 30.3 21.8 26.1 24.6 25.0 28.3 27.4 25.9
14	Terespol	Beams	36.6 34.6 29.9 25.6 31.7	25.0 24.7 23.0 29.6 30.3
15	Minsk	Beams	19.1 20.9 21.3 18.1 19.5 18.9	14.7 15.3 16.5 20.6 14.8 16.5

Notes: 1 MPa = 145 psi; 1 kN = 224.8 lb.

**Table 2—Summary of bridges evaluated and test results**

Bridge No.	Age of bridge, years	Carbonation depth, mm	Average core strength $C_{core}$ , MPa	COV of core strength, %	Average CAPO-TEST $F_c$ , kN	COV of CAPO force, %
1	30	2	34.2	7.3	28.1	8.1
2	50	4	24.7	4.7	21.4	8.3
3	35	5	46.4	4.1	37.3	7.1
4	41	5	34.2	9.2	28.7	5.0
5	52	7	37.1	11.4	27.5	8.5
6	48	7	42.0	6.2	30.1	11.0
7	48	7	37.5	2.6	29.2	8.9
8	41	8	35.4	3.8	28.3	4.2
9	25	10	42.4	9.5	30.6	7.2
10	42	19	33.3	3.4	24.9	7.9
11	30	20	29.7	11.5	24.6	9.7
12	34	20	28.5	5.0	24.3	12.0
13	32	22	31.7	12.7	26.1	9.7
14	49	26	31.7	13.5	26.5	12.2
15	27	35	19.6	6.3	16.4	13.4

Notes: 1 mm = 0.039 in.; 1 MPa = 145 psi; 1 kN = 224.8 lb.

where  $\alpha_{CT}$  is the relative error between estimated and measured concrete strength;  $f_{CAPO}$  is the concrete cube strength estimated from the average of the CAPO-TEST results using the general cube-strength correlation given by Eq. (2); and  $C_{core}$  is the measured average core strength. The values of these relative errors for the 15 bridges are shown in the last column of Table 3.

In Fig. 17, the relative error in the estimated in-place cube strength is plotted as a function of the depth of carbonation. The value of the correlation coefficient for a straight-line fit

to the data is 0.06. The slope of the line is  $-0.03$  and the standard deviation of the estimated slope is 0.16. Because of the high standard deviation, the slope is not statistically significant, and it is clear that there is no relationship between depth of carbonation and the differences between estimated strength and measured core strength. On average, the strength estimated by the CAPO-TEST using the general cube strength correlation is approximately 2.8% greater than the measured core strength. It is felt that this bias is of no practical significance for the purpose of a structural evaluation.

## CONCLUSIONS

This paper summarizes the results of an investigation into the in-place compressive strength of concrete in 15 existing concrete bridges. The strength of 100 x 100 mm (4 x 4 in.) cores was compared with the cube strength estimated from CAPO-TEST results using the general correlation for cube strength. The CAPO-TEST measures the pullout strength of the outer 25 mm (1 in.) of concrete, while the cores were prepared to provide a measure of the interior concrete strength. One of the concerns addressed by this study is whether the presence of carbonation in the outer portion of a concrete member would result in a significant bias in the strength estimated by the CAPO-TEST.

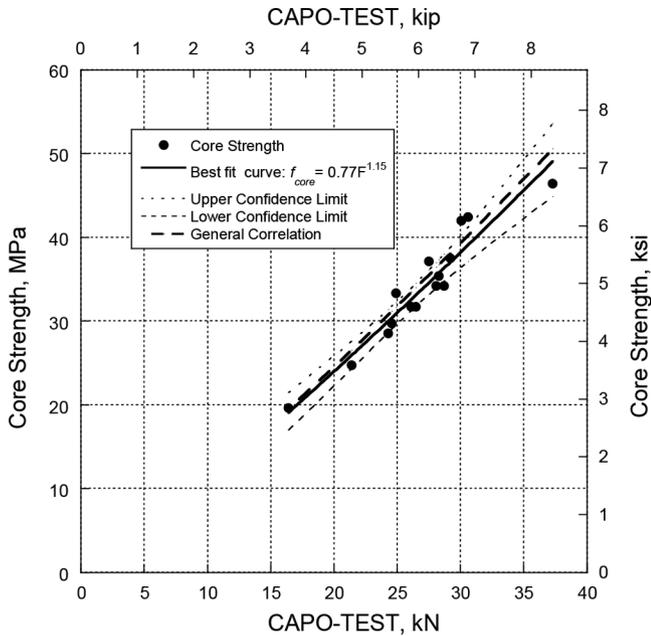


Fig. 15—Correlation between average core strength and average CAPO-TEST results (equation is for SI units).

The following conclusions can be stated on the basis of the analysis presented in this paper:

1. The general correlation for estimating concrete strength on the basis of the CAPO-TEST provides a reliable estimate of the in-place compressive strength. On average, the estimated in-place cube compressive strength was approximately 2.8% greater than the strength measured from 100 x 100 mm (4 in.) cores. This small average bias is believed to be of no practical significance for the purpose of strength evaluation of an existing structure.
2. There is no correlation between the relative error in estimated in-place strength based on the CAPO-TEST and depth

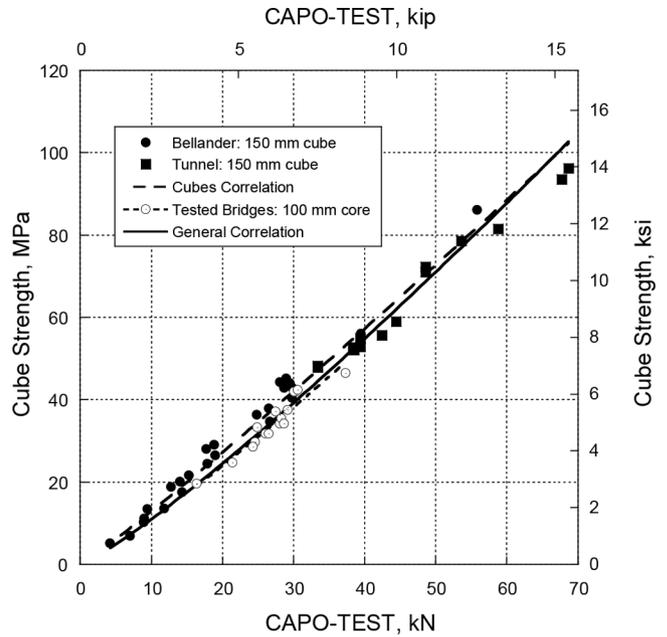


Fig. 16—Correlation between 150 mm (6 in.) cube strength and CAPO-TEST compared with 100 x 100 mm (4 x 4 in.) core strength correlation in this study. (Note: 1 mm = 0.0394 in.)

Table 3—Relative error in estimated concrete strength based on CAPO-TEST

Bridge No.	Name	Carbonation depth, mm	Average core strength $C_{cores}$ , MPa	Average CAPO-TEST $F$ , kN	Estimated compressive strength $f_{CAPO}$ ,* MPa	Relative error $\alpha_{CT}$ , %
1	Zyrow	2	34.2	28.1	36.4	6.4
2	Dobrut	4	24.7	21.4	26.6	7.7
3	Wizna	5	46.4	37.3	50.6	9.1
4	Jablonica	5	34.2	28.7	37.3	9.1
5	Kamion	7	37.1	27.5	35.5	-4.3
6	Modlin	7	42.0	30.1	39.4	-6.2
7	Modlin	7	37.5	29.2	38.1	1.6
8	Jablonica II	8	35.4	28.3	36.7	3.7
9	Leszno	10	42.4	30.6	40.2	-5.2
10	Wierzbica	19	33.3	24.9	31.7	-4.8
11	Zyrow	20	29.7	24.6	31.2	5.1
12	Zofka	20	28.5	24.3	30.8	8.1
13	Zglobice	22	31.7	26.1	33.4	5.4
14	Terespol	26	31.7	26.5	34.0	7.3
15	Minsk	35	19.6	16.4	19.5	-0.5

\*Based on general correlation for cube strength;  $f_{CAPO} = 0.76F^{1.16}$ .

Notes: 1 mm = 0.0394 in.; 1 MPa = 145 psi; 1 kN = 224.8 lb.

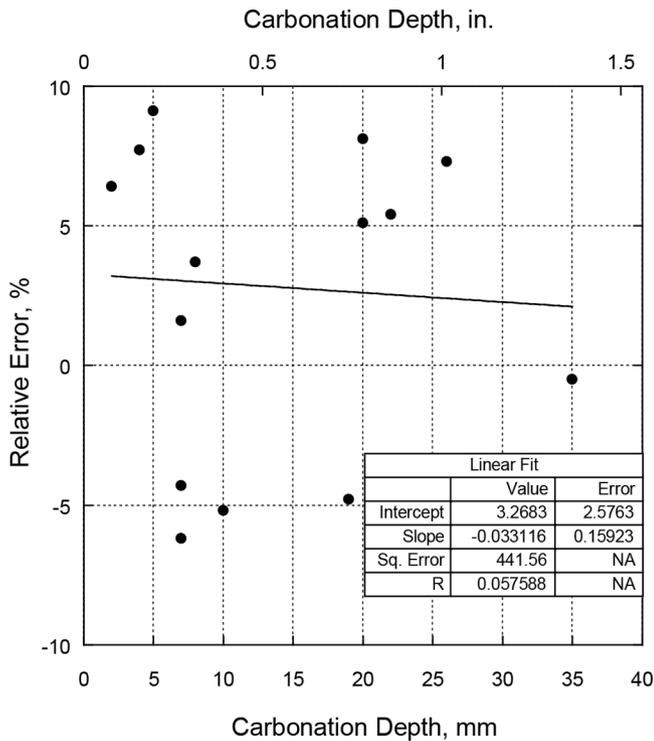


Fig. 17—Relative error in estimated in-place strength as function of depth of carbonation.

of carbonation. Thus, it appears that the CAPO-TEST will provide reliable estimates of the in-place strength of the interior concrete in structures with an exterior layer of carbonation.

3. The results of this investigation support the applicability of the general correlation for estimating in-place strength based on the CAPO-TEST.

The authors believe that the CAPO-TEST is a viable complement to testing cores, provided the concrete in the 25 mm (1 in.) cover layer is representative of the interior concrete. This opens up the possibility to test existing concrete structures with the CAPO-TEST at a much higher testing frequency than using cores alone. Compared with core testing, testing costs can be reduced, test results are immediate, and there is little damage to the structure that has to be repaired. It is recommended, however, that a limited numbers of cores should be always taken to confirm that the correlation being used is applicable to the concrete in the structure.

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