INVESTIGATION OF CONCRETE STRENGTH

Two series of tests have been performed. The first series is a field study of eight concrete trough bridges. Here the Capo-tests are compared to drilled core tests. In the second series, a laboratory study is conducted.

Field survey of eight railway bridges

In order to get reference material regarding the relationship between the concrete compressive strength of drilled cores and the pullout forces from the Capo-test, the concrete compressive strength was examined for eight railway bridges (road underpasses) during the late 1990s. The bridges were built between 1965 and 1980 with the Swedish concrete class K400 (in most cases), with a mean concrete compressive strength of approximately 45-47 MPa tested on 150 mm cubes after 28 days (maximum aggregate size of 32 mm).

In **Table 1** a summary is presented of the results from the tests. Eq. (1) and (2), see **Fig. 2**, are used to calculate the compressive strength obtained with the Capo-test. The mean concrete core compressive strength varies between 61.3 and 85.3 MPa and the mean compressive strength calculated from the pullout strength varies between 51.6 and 76.9 MPa. These values are substantially lower than the ones from the concrete cores and indicate that the relationship between the pullout load, F, and the concrete compressive strength, f_c, ought to be improved for old concrete. In order to check this a laboratory study was initiated.

Table 1 - Concrete compressive and tensile strengths for eight trough bridges determined with drilled cores and Capo-tests. The cores are obtained from the longitudinal beams if nothing else is said (drilled vertically from above in most cases). The Capo-test compressive strength is evaluated with Eq. (1) and (2), see Fig. 2.

INCOMPLETE

Bridge No. [a)]	Type of Strength/Force		Individual Values								m	s	CoV
1	Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	--	34.9	45.6	46.5	33.4	**40.1**	**5.4**	**0.13**
	Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	--	46.3	61.5	62.6	44.2	**53.6**	**8.4**	**0.16**
	Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	--	--	--	--	68.4	78.7	71.9	**73.0**	**4.3**	**0.06**
2	Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	--	48.8	46.7	50.3	54.3	**50.0**	**2.5**	**0.05**
	Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	--	65.9	62.9	70.3	76.6	**68.9**	**5.2**	**0.07**
	Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	--	--	--	--	88.3	77.3	84.5	**83.4**	**4.6**	**0.05**
3	Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	--	42.7	41.2	41.7	46.4	**43.0**	**2.0**	**0.05**
	Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	--	57.3	55.2	55.9	62.5	**57.7**	**2.8**	**0.05**
	Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	--	--	--	--	74.0	77.0	69.7	**73.6**	**3.0**	**0.04**
4	Pull-out force from Capo-Test, [kN]	$F=$	48.7	45.0	36.6	33.8	42.1	31.2	32.3	39.5	**38.7**	**5.9**	**0.15**
	Compressive strength Capo-test [b)], [MPa]	$f'_c=$	65.8	60.6	48.7	44.7	56.5	41.2	42.7	52.7	**51.6**	**8.3**	**0.16**
	Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	65.7	71.1	64.2	58.7	54.7	65.0	60.4	**62.8**	**5.0**	**0.08**
5	Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	--	49.1	52.4	52.9	38.5	**48.3**	**5.2**	**0.11**
	Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	--	66.3	73.7	74.5	51.5	**66.5**	**9.3**	**0.14**
	Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	--	--	--	--	77.0	86.0	75.4	**79.5**	**4.7**	**0.06**
6	Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	--	--	58.3	46.5	45.1	**50.0**	**5.1**	**0.10**
	Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	--	--	83.1	62.6	60.8	**68.8**	**10.1**	**0.15**
	Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	--	--	71.7	61.5	63.8	53.9	55.6	**61.3**	**6.4**	**0.10**
7	Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	--	42.6	49.2	35.6	45.5	**43.2**	**4.5**	**0.10**
	Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	--	57.2	66.5	47.3	61.3	**58.1**	**7.0**	**0.12**
	Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	--	--	--	--	71.2	65.5	59.1	**65.3**	**4.9**	**0.08**
8	1:Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	54.6	54.3	52.4	51.8	59.0	**54.4**	**2.3**	**0.04**
	1:Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	77.1	76.6	73.7	72.7	84.2	**76.9**	**4.0**	**0.05**
	1:Compressive strength drilled cores, [MPa]	$f_{cc}=$	--	--	80.3	83.4	86.4	83.9	88.3	89.2	**85.3**	**3.4**	**0.04**
	2:Pull-out force from Capo-Test, [kN]	$F=$	--	--	--	--	--	--	53.8	50.7	**52.2**	**1.2**	**0.02**
	2:Compressive strength Capo-test [b)], [MPa]	$f'_c=$	--	--	--	--	--	--	75.8	71.0	**73.4**	**2.4**	**0.03**
	2:Compressive strength drilled cores, [MPa]	$f_{cc}=$	69.9	70.8	78.2	66.5	69.3	74.1	74.0	77.8	**72.6**	**4.2**	**0.06**

m = mean value, s = standard deviation, CoV = coefficient of variation.
a) Bridge No. 1 = Boden C (year of construction 1971), 2 = Garnisonsgatan (1970), 3 = Gammelstad (1970), 4 = Luossajokk (1965), 5 = Haparandavägen (1980), 6 = Kallkällevägen (1966), 7= Bensbyvägen (1965) and 8= Lautajokki (1967, 2= long. beam and 1 = slab).
b) Compression strength according to Eqs. (1) or (2).

Laboratory study

In order to check the difference obtained in the filed study of eight bridges, a simple laboratory test was performed. In it we would like to check the sensitivity to what kind of surface the Capo-test was performed on. First, a reinforced slab with the dimensions 0.35×0.70×1.4 m was cast and vibrated with a handheld stick vibrator in the laboratory, see **Fig. 4**. The idea was then to cut the slab into two beams, dimensions 0.35×0.35×1.4 m, by using a water-cooled hydraulic saw with a diamond blade and perform the Capo-test on both the cut surface and the mould surface. Between these two surfaces cores were to be drilled so a comparison could be made between the Capo-test and the drilled cores. The slab was cast on the ground as shown in **Fig. 4**. The following concrete mixture was used (1m^3): Cem I 42.5 BV/SR/LA: 432 kg/m^3, Fine aggregate 0-8 mm: 910 kg/m^3, Coarse aggregate 8-16 mm: 945 kg/m^3, Silica fume: 39 kg/m^3, Super-plasticizer: 1.1%, Water reducing agent: 0.5%, Water-to-cement ratio: 0.29, Water-to-binder content: 0.27. The mixture was tested in connection with casting and the slump was 120 mm and the air content was 1.7%.

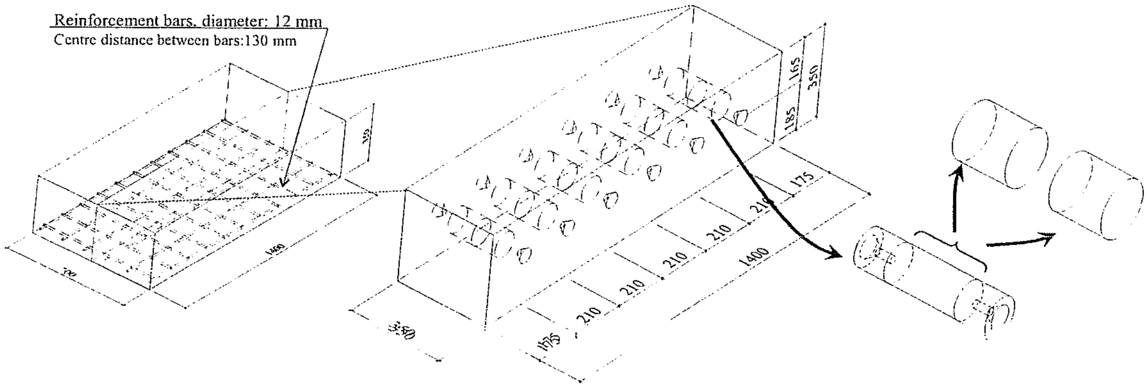

Fig. 4 - Dimensions of slab cast in the laboratory.

After the slab was cast it was stored for three days in the laboratory at room temperature. After these 3 days it was placed in a water tank with a water temperature of approximately +20°C. 36 days after casting it was cut and the two "beams" were again placed in the water tank, where they remained until the day the tests were performed, i.e. 398 days after casting. The Capo-test was performed according to the manufacturer's directions, which recommended corner/end distance of minimum 100 mm and 200-300 mm between each Capo-test on the same horizontal level (the tests were performed during a period of about 2 weeks due to problems with the equipment). A total of twelve Capo-tests on each type of surface could be performed and twelve cores, containing 24 specimens, could be extracted (diameter of about 100 mm, height and diameter ratio of 1.0). In **Fig. 5** the results from the Capo-test and the drilled cores are presented visually.

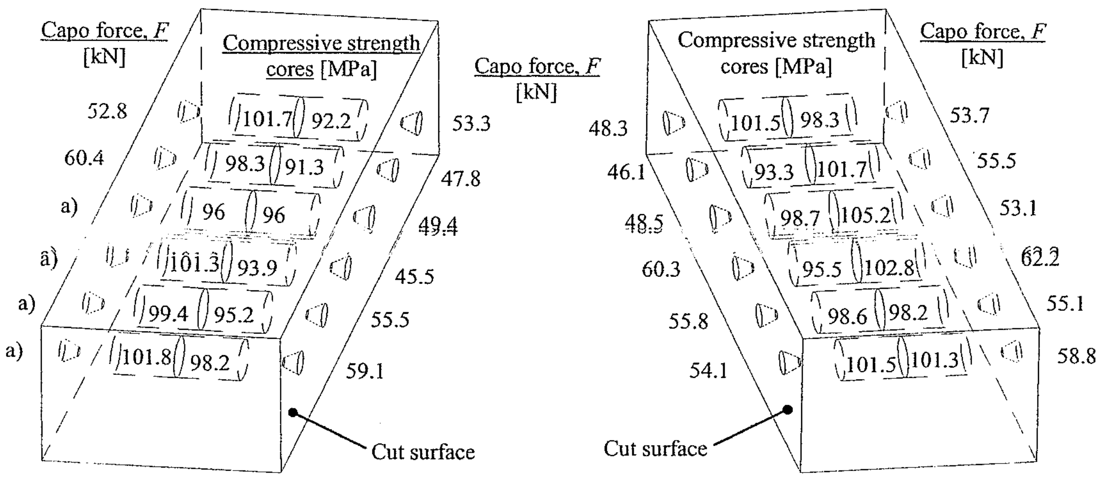

Fig. 5 - Figure showing results from performed tests. [a)] For four locations no result from the Capo-test could be presented due to human errors.

At the same time as the drilled cores were tested, six 150 mm standard cubes were also tested for compressive strength together with three 150 mm standard cubes that were exposed to tensile splitting test. The mean concrete compressive strength was 97.4 MPa (the standard deviation is 2.7 MPa and the coefficient of variation is 0.03) for these six specimens and the mean splitting tensile strength was 5.7 MPa (the standard deviation is 0.3 MPa and the coefficient of variation is 0.05). The 28-day 150 mm standard cube compressive strength was 81.4 MPa (cube compressive strength, mean values of three cubes, for 1-day = 20 MPa, 7-days = 52.9 MPa, 14-days = 65.2 MPa).

DISCUSSION AND ANALYSIS

Field survey of eight railway bridges

In Table 1 it can be seen for bridge 8 that the compressive strength is higher in the slab (Test 1) than in the longitudinal beams (Test 2). The Capo-test gives in fact a higher value of the concrete compressive strength for the slab than the drilled cores from the slab. One explanation could be that the slab contains micro cracks in the tension zone (as the bridge has earlier been exposed to a fatigue test, see Paulsson et al. [3,4]) which are reflected in the cores partly taken from this zone, but not in the Capo-test since it has been performed on the top surface – the compression zone. Another explanation might be that too few Capo-tests are performed on the slab, they are also performed vertically. According to Germann Petersen & Poulsen[1] testing the upper side of a slab gives a higher standard deviation than testing on a vertical surface.

In **Table 1** only two bridges (bridges no. 6 and no. 8) have higher Capo-test concrete compressive strength values than the core strength values. One reason for this could be that only three tests have been performed on these bridges, i.e too few in comparison with the recommended four. For bridges no. 7 and 8 there is a difference between the Capo-test and the core strength of about 8 MPa, but for the other bridges Eqs. (1) and (2) give very low concrete compressive strengths compared with the drilled core compressive strength. It is almost a difference of 20 MPa.

Laboratory study

When the values of the Capo-force presented in **Fig. 5** are studied it can be seen that the Capo-forces for the cut surface is lower than the Capo-forces for the mould surface. The mean pullout force for the cut surface is 52 kN (the standard deviation is 5 MPa and the coefficient of variation is 0.1). The mean pullout force for the mould surface is 56 MPa (the standard deviation is 3.5 MPa and the coefficient of variation is 0.06).

Statistical hypothesis test - A way to confirm or deny the difference statistically is to compare the mean values obtained on the two different surfaces. One approach to evaluating this is to perform a so-called statistical hypothesis test which could be found in e.g. Montgomery[23] or Coladarci et al. [24]. In this case a method called two-sample *t*-test can be performed where the mean values of two groups are analysed if they are statistically different from each other. But, to be able to perform this test the following conditions must be fulfilled, firstly: both samples are drawn from independent populations that can be described by a normal distribution, secondly: the observations are independent random variables and thirdly: the standard deviation or variances of both populations are equal. In the laboratory study there are too few tests that have been conducted on each type of surface, so it is difficult to decide if all three conditions are fulfilled.

But, if it is assumed that the conditions above are fulfilled a two-sample *t*-test could be performed with the null-hypothesis (H_0) that the mean values are equal (i.e the Capo-test is not sensitive to what surface it is performed on) and with the alternative hypothesis (H_1) that the mean values are not equal. If the level of significance is chosen to 0.05 (α) a calculation analysis with the software Statgraphics (by Statistical Graphics Corp.) leads to rejection of the null-hypothesis at the 95% confidence level since the p-value is less than 0.05, i.e. 0.044. The confidence interval for the difference between the means extends from 0.13 to 8.81. Since the interval does not contain the value 0.0, there is a statistically significant difference between the means of the two samples at the 95% confidence level.

Thus, we can reject the null-hypothesis in favour of the alternative, i.e. the Capo-test gives different results for the two types of tested surfaces. But, as mentioned earlier, if any of the assumptions made is not correct, the result is uncertain and in this case more studies should be made since the *p*-value is very close to the level of significance which indicates that the result could be discussed (a bit more explicit result would have been wanted).

Now an interesting question arises; why does the Capo-test give higher values when performed on the mould surface? The spontaneous guess is that it would be higher on a cut surface since there is probably more ballast involved in the test volume. One reason for the lower values on the cut surface could be that micro cracks have formed when the surface was cut with the diamond blade, but this is something for future studies. Another explanation could be that there is a difference of moisture content between the two surfaces. As mentioned earlier a reduction of the strength for the cut surface occurs during the cutting process since the cut surface is moistened by water, see Möller et al. [8]. However, since the two cut halves are placed in a water tank for more than a year before the test was performed, this difference in moisture content between the mould surface and the cut surface has most likely been levelled out. Nevertheless, a difference in moisture content between the different capo-test spots arise though during the actual testing period since it takes some time between the first and last test. Efforts have been made to reduce this by keeping the specimens wet and as sealed as possible until all the tests were done.

If the conclusion above is accepted, i.e. the Capo-test is sensitive to the surface, how does it influence the pullout force from an old concrete surface, e.g. an old concrete bridge? We have seen that Eqs. (1) and (2) give lower strengths than the tested cores. If the reason for this difference is only because the Capo-test is performed on an old surface, it seems realistic that a lower pullout force is obtained when the Capo-test is performed on an old surface (even though the concrete compressive strength is high a bit further in the structure e.g. at the level where a core is obtained which is often a few centimetres inwards). Since the surface of an old concrete bridge has often been exposed to environmental degradation over the years e.g. carbonation (i.e. the reaction between the hydrated cement and carbon dioxide) which could reduce the concrete strength. Maybe more grinding is needed of the surface in the preparation phase of a Capo-test when the Capo-test is performed on an old concrete surface.

There could of course also be an actual variation of concrete compressive strength between the cover-layer and the interior mass. In **Fig. 5** it could be seen that the concrete core compressive strength varies even if the cores are lying next to each other and as pointed out by Stone & Carino[21] or Germann Petersen[11] the Capo-test only measures the concrete compressive strength of the cover-layer and not the interior of the concrete structure.

Revised strength relationship for cores with the diameter and the height of about 100 mm

In order to establish a strength relationship between the pullout force from the Capo-test and the compressive strength of a drilled core with the diameter and the height of about 100 mm, the following has been done:

- Field survey of eight bridges - The result from the tests on the eight railway bridges is used, i.e. the mean pullout forces are plotted versus the mean compressive strengths from Table 2 – see the crosses in **Fig. 6**. Unfortunately it is not possible to use all the data obtained in this study. Thus it is not possible to connect the pullout force from a Capo-test to a certain core. This is due to the fact that several companies have performed the tests and there is no record of core numbers (the cores were taken prior to this study). So it is only possible to connect the pullout force from the Capo-tests to the concrete core compressive strength for a whole bridge. In **Fig. 6** two values for very old bridges are also presented, the ones with a circle. As the cores from these bridges showed that the concrete used in the bridges was composed of a few very big aggregates (approximately 70 mm) and the rest were small ones (approximately 8 mm) combined with mortar, they are not included in the regression analysis. As one can see in **Fig. 6** these two bridges give somewhat dif-