BOND-TEST OF CONCRETE AND OVERLAYS

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ABSTRACT

The Bond-Test system developed in Denmark is presented. A testing case illustrates its use compared with incorrect testing of the adhesion strength. A finite element analysis is applied for a normal and a high strength concrete to compare the theoretical uniaxial tensile strength with the strength measured by the Bond-Test performed at the surface and with a drill depth of partial coring at 75mm. The effect of the drill depth is further investigated in an experimental program for two types of concrete mixes. The Bond-Tests are compared with the tensile strength of drilled-out cores and with the compressive strength measured by Lok-Test by Capo-Test. The results are compared with other experimental findings.

1. *THE BOND-TEST*

The Bond-Test evaluates in-place the adhesion strength between a concrete substrate and an applied overlay (epoxy, mortar, fiber concrete, shotcrete, etc.). Prior to the application of the new layer, it is recommended to evaluate the soundness of the parent material with the test after the surface preparation has been completed, e.g. by jack hammering, diamond cutting, sandblasting or water jetting.

The test configurations are as shown in Fig.1 and Fig.2.

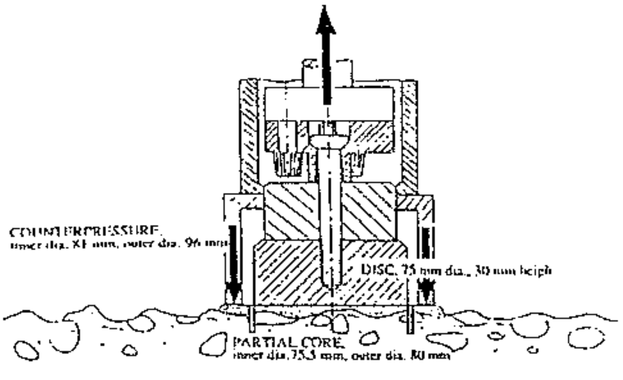

Figure 1. Testing of the substrate prior to the application of a new layer

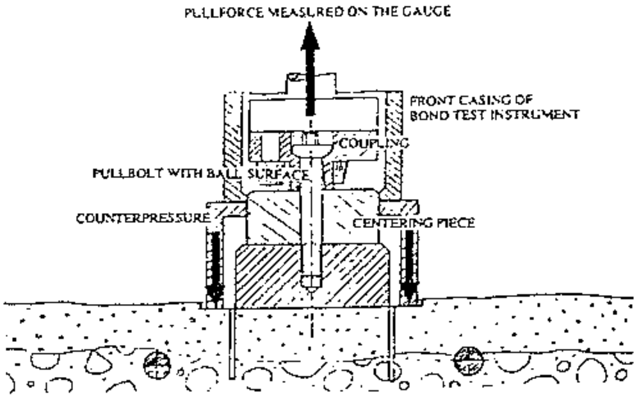

Figure 2. Testing of the adhesion strength

The Bond-Test utilizes a 75 mm diameter steel disc, 30 mm high, that is glued on the surface. The steps of testing involve planing of the surface, gluing on of the disc, partial coring around the disc perpendicular to the planed surface and pulling the disc against a centered counterpressure resting on the planed surface, using a calibrated hydraulic pullmachine with constant and uniform loading rate. The equipment developed and the recommended test procedures are described in detail in Ref. (1) and Ref. (2).

The Bond-Test equipment and test procedure ensures the following criterions for testing are met:

1.1 The disc is glued on a dry, clean and plane surface with a strain gauge epoxy, producing a strong contact between the faces (min. 8 MPa tensile strength)

1.2 The centerline of the disc will coincide with the centerline of the partially drilled core within a tolerance of plus/minus 0.25 mm

1.3 The coring will not cause cracking in the partially drilled core and the core will be drilled perfectly straight and perpendicular to the planed surface

1.4 The pull-off is performed immediately after the partial coring has been terminated and the loading will be uniform and constant (3 seconds for each kN)

1.5 A test procedure, from start to end, well within 15 minutes for a trained technician

2. *TESTING CASE*

The following case illustrates the possible differences that may be encountered when testing the same materials for adhesion strength inappropriately and appropriately. The testing was performed on horizontal and vertical faces of repaired box girders.

The surface preparation was made by water jetting. A 10 to 30 mm fiber concrete was applied as overlay. Trial castings and trial tests were not performed and no testing of the substrate was made prior to the application of the new layer. The specified adhesion strength was minimum 1.5 MPa for an average of three adhesion tests, positioned in a triangle with an internal distance of 40 cm between the test.

The contractor who was responsible for the testing, tested the adhesion strength using the following procedure: First, 60 mm in diameter cores were drilled to a depth of 40 to 50 mm using ordinary coring equipment. Secondly, one day after, irregularities on the surface were removed with a cup stone mounted on a grinding machine. Thirdly, after another day, the surface of the partially cut core was brushed with a steel brush and a steel disc was glued on centrally, in most cases held in position by adhesive tape. After hardening of the glue, pull-off was made with a calibrated hydraulic loading jack resting against a centered counterpressure on the surface.The test results are reproduced in Table 1, labelled "Contr. AHT".

The sections mentioned were rejected by the consulting engineer. Bond-Tests were subsequently conducted in the same areas with test results as shown below for comparison.

Pos. No.	Contr. AHT			BOND-TEST		
	(kN)	failure type	Ave. (MPa)	(kN)	failure type	Ave. (MPa)
1	4.0	N/A	1.4	6.9	(1)	1.8
	3.5	N/A		8.5	(3)	
	4.0	N/A		8.1	(3)	
2	6.0	N/A	1.4	10.0	(3)	2.0
	4.0	N/A		8.6	(3)	
	2.0	N/A		8.4	(2)	
3	3.5	N/A	0.7	7.6	(2)	1.5
	2.0	N/A		6.1	(1)	
	0.5	N/A		6.3	(2)	
4	4.5	N/A	1.3	7.5	(3)	1.8
	3.0	N/A		8.3	(3)	
	3.5	N/A		8.2	(3)	
5	9.0	N/A	1.2	8.0	(3)	1.7
	0.5	N/A		7.0	(3)	
	0.5	N/A		7.5	(3)	
6	3.0	N/A	1.4	6.2	(1)	1.6
	3.0	N/A		6.3	(2)	
	6.0	N/A		9.0	(3)	
7	4.0	N/A	1.4	9.3	(3)	1.8
	5.5	N/A		7.8	(3)	
	2.0	N/A		7.5	(3)	
8	4.0	N/A	0.1	9.3	(3)	1.8
	0.5	N/A		7.2	(3)	
	0.5	N/A		7.5	(3)	

Failure type: (1) overlay, (2) adhesion layer, (3) parent material, (N/A) not available

Table 1: Test results from testing of the adhesion strength of repairs of box girders, the results of the adhesion tests made by the contractor ("Contr. AHT") compared to Bond-Tests

The difference between the test results is believed to be caused by the contractor´s lack of compliance with the criterions for correctly performed testing as stated on page 1.

3. *PURPOSE OF THE INVESTIGATION CONDUCTED*

The purpose of the present paper is to attempt to answer the following two questions often raised in relation to the testing with Bond-Test:

3.1 " Is the Bond-Strength (max. pullforce divided by the area of 4476 mm^2) comparable to the *uniaxial tensile strength* of concrete?"

3.2 "Is the *depth of the partial coring* having an influence on the Bond-Strength?"

The stiffness of the disc is known to be critical for the measurement of the tensile property of the concrete. For steel, the height of the disc has to be minimum 40% of the disc diameter, Ref. (3). Otherwise, the disc may "curve" during pull-off and produce a failure right below the disc at a lower pullforce. The height of the Bond-Test steel disc is 30 mm.

4. *METHODOLOGIES USED*

To answer the two questions, the following courses of action have been applied:

4.1 Investigation of the Bond-Test failure mechanism by means of a finite element analysis and to compare the theoretical uniaxial tensile strength of two concretes, normal-strength and high-strength, to the Bond-Strength for a disc pulled off at the surface and after a 75mm deep partial core has been cut.

4.2 To conduct an experimental program on normal and high-strengh homogeneous concrete to measure the actual influence of the partial coring drill depth on the Bond-Strength and to compare the Bond-Strength to tensile tests performed on drilled out cores. Furthermore, to measure the concrete compressive strength with Lok-Test and Capo-Test to make comparisons to recent published data relating the tensile strength to the compressive strength of normal and high-strength concretes.

The finite element study was carried out at the Division of Structural Mechanics, Lund University of Technology, Lund University, Sweden.

The tensile tests were performed at the laboratory of the Danish Enginering Academy in Lyngby, Denmark, Ref. (7).

The concrete slabs were produced from mixes supplied to the building site at Novo Nordisk, Maaløv, Denmark (the normal type) and for the Great Belt Link´s tunnel lining elements at Halskov, Denmark (the high-strength type). All the testing of the slabs was conducted by a certified technician from In-Situ Testing of Copenhagen, specialized in testing in-place, Ref. (8).

5. *FINITE ELEMENT ANALYSIS OF BOND-TEST OF CONCRETE*

5.1 *Description of material behaviour*

Assuming isotropy, the elastic strain rate $\dot{\epsilon}$ is related to the stress rate $\dot{\sigma}$ by the expression

$$\dot{\epsilon}_{ij} = C^{e}_{ijkm} \ \dot{\sigma}_{km} \tag{1}$$

where C^e is the compliance tensor, given by

$$C^{e}_{ijkm} = \rho_e \, \delta_{ij} \, \delta_{km} + \kappa_e(\delta_{ik} \, \delta_{jm} + \delta_{im}\delta_{jk}) \tag{2}$$

in which δ_{ij} is Kronecker's delta and ρ_e and κ_e are parameters related to the elastic modulus E and Poisson's ratio ν by the expressions

$$\rho_e = \frac{\nu}{E} \ ; \ \kappa_e = \frac{1+\nu}{2E} \tag{3}$$

The fictitious crack model according to Hillerborg et al. [4] is based on the fact that fracture is localized to a thin zone. The fracture in that zone is modelled by a fictitious crack, whose width represents the total fracture in the zone. A smeared crack approach based on the fictitious crack model has been proposed by Ottosen and Dahlblom [5][6].

Crack development is assumed to start when the maximum principal stress reaches the tensile strength f_t.

The fracture energy G_F necessary to produce one unit area of crack is given by the integral

$$G_F = \int_0^{w_c} \bar{\sigma}_{11} \ dw_{11} \tag{4}$$

where σ_{11} is the stress normal to the crack plane, expressed in a local coordinate system, w_{11} is the crack width, and w_c is the crack width when $\bar{s}_{11}$ has dropped to zero.

In the present model a linear relation between $\bar{\sigma}_{11}$ and w_{11} is assumed, i.e.

$$\bar{\sigma}_{11} = f_t - \frac{f_t^2}{2G_F} \, w_{11} \tag{5}$$

The mean fracturing strain $\bar{\epsilon}^{f}_{11}$ in some region which includes the crack is defined

$$\bar{\epsilon}^{f}_{11} = \frac{w_{11}}{L_1} \tag{6}$$

where L_1 is an equivalent length related to the size and shape of the finite element where the crack develops. In the present work the equivalent length is defined as in Ref. [6].

Crack development will reduce the ability to transfer shear stresses across the crack plane. In the analysis of fracture it is important to use a reasonable expression for the shear behaviour. In Ref. [6], the shear displacement was assumed to be proportional to the shear stress and to the crack width. To avoid having a non-symmetric system of equations, it is in the present work instead assumed that the rate of the shear displacement is proportional to the rate of the shear stress and to the crack width, i.e.

$$\dot{w}_{12}= \frac{w_{11}}{G_S}\ \bar{\sigma}_{12} \tag{7}$$

where G_S is the so-called slip modulus.

As in the case of fracture normal to the crack plane, a fracturing strain component is defined for shear displacement. The fracturing shear strain is defined by

$$\bar{\epsilon}^{f}_{12}= \frac{1}{2}(\frac{w_{12}}{L_1} + \frac{w_{21}}{L_2}) \tag{8}$$

The strain rate $\dot{\epsilon}$ is assumed to be the sum of the elastic strain rate and the fracturing strain rate, as described above, i.e.

$$\dot{\epsilon}_{ij}=\dot{\epsilon}^{e}_{ij} + \dot{\epsilon}^{f}_{ij} \tag{9}$$

Substitution of the above expression for ϵ^{e}_{ij} and ϵ^{f}_{ij}, expressed in a global coordinate system, into Eq. (9) yields a relation between $\dot{\sigma}$ and $\dot{\epsilon}$ which can be expressed as

$$\dot{\sigma}= D_{ijkm}\ \dot{\epsilon}_{km} \tag{10}$$

5.2 *Finite element results*

The theory proposed has been implemented into a finite element program. The behaviour of a bond test performed on a plane surface as well as with a drill depth of 75 mm is simulated using an eight node isoparametric element. Two different qualities of concrete are used. The high quality concrete has the material properties $E = 40\ GPa$, $\nu = 0.25$, $f_t = 4.0\ MPa$, $G_F = 100\ N/m$ and $G_S = 40\ kPa$ and the normal quality concrete has the properties $E = 30\ GPa$, $\nu = 0.25$, $f_t = 2.5\ MPa$, $G_F = 75\ N/m$ and $G_S = 30\ kPa$. The steel has the material properties $E = 210\ GPa$ and $\nu = 0.25$. The test simulated and the finite element mesh used are illustrated in Fig. 3

The behaviour of the specimen when an increasing displacement is applied at the centre of the steel plate is simulated. In Fig. 4 the total vertical force applied at the steel plate is shown as a function of the vertical displacement. It may be observed that initially the force is proportional to the displacement and that the curve is steeper for a plane surface than for a drilled core. This is due to elastic deformation of the core. In addition it may be noted that the peak value is somewhat higher for a plane surface than for a drilled core. This is caused by the more uniform stress distribution occurring for a plane surface. The maximum value of the force is in this case predicted to be 17.2 kN and 10.9 kN for high and normal quality concrete, respectively. This corresponds to the mean stress 3.88 MPa and 2.47 MPa, which may be compared to the tensile strength 4.0 MPa and 2.5 MPa, respectively. For a drilled core the peak values are predicted to be 15.8 kN and 10.2 kN, which corresponds to the mean stress 3.58 MPa and 2.32 MPa, respectively.

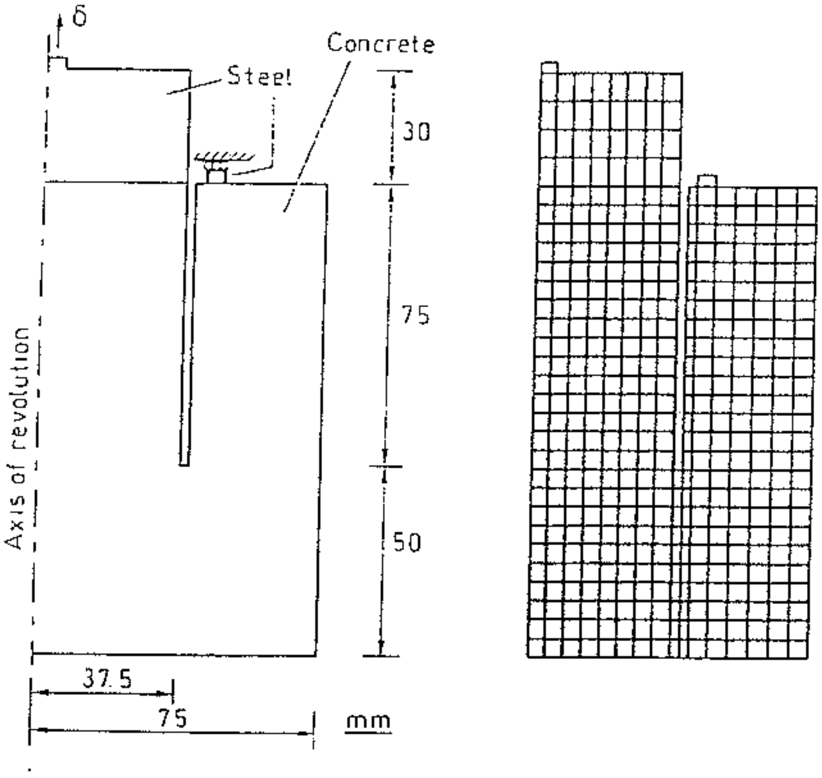

Figure 3: *Test simulated and finite element mesh used*

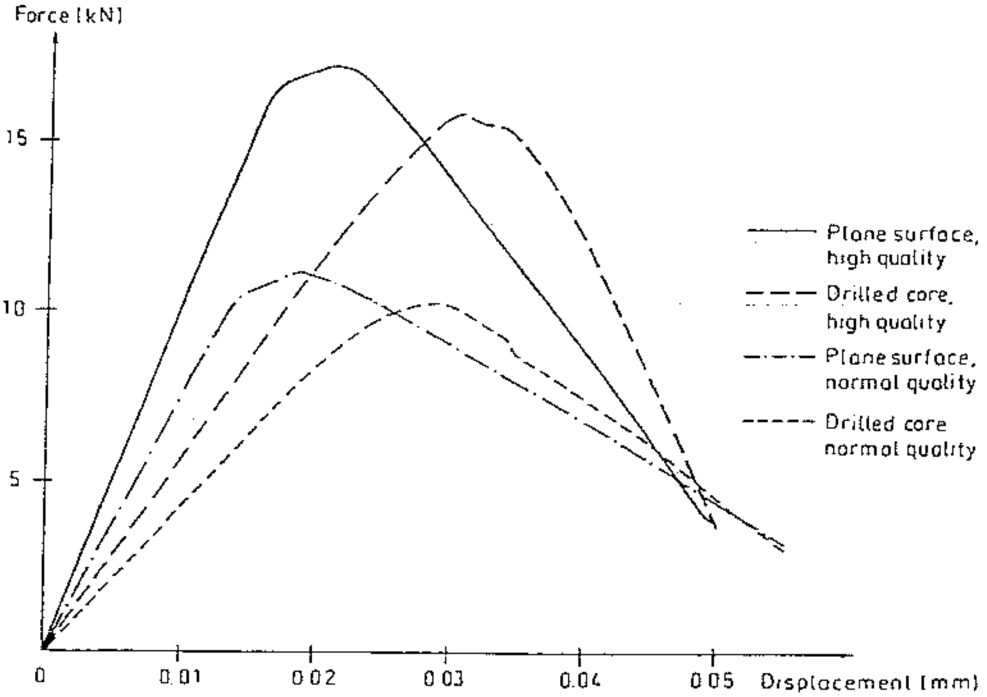

Figure 4: *Predicted force-displacement relation.*

6. *EXPERIMENTAL PROGRAM*

The designs of the concrete mixes used are given in table 2. For the first mix sea gravel was used as aggregates, and for the second mix, granite, in both cases with a maximum aggregate size of 32 mm.

	Mix 1 Normal-Strength (kg/m^3)	Mix 2 High-Strength (kg/m^3)
Water	149.0	124.7
Cement (PC)	335.0	314.4
Silica	0.0	20.0
Fly-ash	0.0	59.9
Sand	708.0	570.8
Aggregates	1100.0	1247.4
Admix.	2.5	7.4
Aircontent	7%	6%

Table 2. Mix designs of the concretes tested

The 28 day cylinder strength of the normal-strength mix was 38 MPa and of the high-strength 54 MPa, in average.

Two slabs were cast, dimensions 1000 mm x 600 mm, 100 mm in thickness, in wooden formwork, vibrated and covered with plastic. The formwork was removed after 36 hours and the specimens were cured in water one week. Then, the slabs were covered with airtight plastic/insulation and stored. The following testing was performed at an age of two months for the normal-strength concrete and twenty months for the high-strength:

6.1 *Four Lok-Tests* from the bottom of the slabs (for compressive strength)

6.2 *Four Capo-Tests* from the top of the slabs (for compressive strength)

6.3 *Twenty Bond-Tests* from the bottom of the slabs. The tests were conducted at random, four after brushing of the surface and the remaining sixteen after removal of the "skin" of the concrete to a depth of 2 mm with the diamond surface planer and brushing the surface. Of the sixteen tests, four were tested without prior partial coring, four after 20 mm deep, four after 40 mm deep and four after 75 mm deep partial coring

6.4 *Five drilled-out cores*, 75 mm in diameter, 100 mm long, for laboratory tensile testing. Three cores were cured in water 3 days before testing and the remaining two were air-cured 6 days. Prior to the tensile testing, the cores were saw-cut at a depth of 5-10 mm at both ends and dried at the end faces with a hairdryer. Discs similar to the Bond-Test discs were glued centrally on to the faces with the same epoxy. The cores were pulled to failure in a calibrated, class 1, 0-40 kN hydraulic, stationary pullmachine. Specimens displaying failure in the glue was disregarded.

The test results are summarized in table 3 and table 4 on the following page.

NORMAL-STRENGTH CONCRETE

1. COMPRESSIVE STRENGTH

	Lok-Test (bottom) (kN)	Capo-Test (top) (kN)
	35.0	36.0
	37.5	38.5
	38.0	35.0
	36.5	39.0
Ave./var.:	36.8 kN (v=3.6%)	37.1 kN (v=5.2%)
Total average: 37.0 kN eqv. to 40.1 MPa cyl. strength		

2. TENSILE STRENGTH OF DRILLED-OUT CORES

Water cured 3 days (MPa)	failure type	Air cured 6 days (MPa)	failure type
2.44	(a)	1.00	(a)
(1.72)	(b)	1.20	(a)
2.62	(a)		
Average: 2.53 MPa tensile str.		1.10 MPa tensile str.	
Failure type: (a) pure tensile failure, (b) partly glue failure			

3. BOND-STRENGTH

After surface brushing		After 2 mm deep surface planing & brushing							
		without coring		20 mm deep coring		40 mm deep coring		75 mm deep coring	
(kN)	failure type	(kN)	failure type	(kN)	failure type	(kN)	failure type	(kN)	failure type
6.2	(1)	11.6	(3)	10.1	(5)	13.5	(4)	9.3	(4)
5.8	(1)	12.1	(3)	12.6	(4)	9.6	(4)	13.7	(4)
10.1	(2)	13.1	(3)	13.4	(4)	13.4	(4)	11.9	(4)
8.4	(2)	12.2	(3)	12.5	(4)	11.5	(5)	11.6	(4)
Ave/var.: 7.6 kN (v=53%)		12.3 kN (v=5.4%)		12.1 kN (v=11.8%)		12.0 kN (v=15.4%)		11.4 kN (v=17.6%)	
		Total ave. after 2 mm surf. planning: 12.0 kN eqv. to 2.68 MPa BOND-Strength (v=3.3%)							
Failure type: (1) mortar, (2) mortar & 5-10% aggregates, (3) concrete failure, (4) bottom failure, (5) failure half way down									

Table 3. Test results from testing of the normal-strength concrete slab

HIGH-STRENGTH CONCRETE

1. COMPRESSIVE STRENGTH

	Lok-Test (bottom) (kN)	Capo-Test (top) (kN)
	79.0	71.0
	73.5	75.5
	78.0	77.0
	76.5	70.0
Ave./var.:	76.8 kN (v=3.1%)	73.4 kN (v=4.8%)
Total average: 75.1 kN eqv. to 87.6 MPa cyl.strength		

2. TENSILE STRENGTH OF DRILLED-OUT CORES

Water cured 3 days (MPa)	failure type	Air cured 6 days (MPa)	failure type
4.51	(a)	3.82	(a)
3.46	(a)	3.50	(a)
(3.59)	(b)		
Average: 3.99 MPa tensile str.		3.66 MPa tensile str.	
Failure type: (a) pure tensile failure, (b) partly glue failure			

3. BOND-STRENGTH

After surface brushing		After 2 mm deep surface planing & brushing							
		without coring		20 mm deep coring		40 mm deep coring		75 mm deep coring	
(kN)	failure type	(kN)	failure type	(kN)	failure type	(kN)	failure type	(kN)	failure type
24.2	(1)	20.1	(3)	18.9	(5)	20.3	(4)	17.2	(5)
26.5	(1)	21.9	(3)	21.1	(4)	23.7	(5)	21.3	(4)
27.3	(1)	21.5	(3)	20.6	(5)	18.4	(5)	20.2	(4)
26.1	(2)	18.5	(3)	22.4	(4)	21.1	(4)	19.3	(4)
Ave/var.: 26.0 kN (v=5.1%)		20.5 kN (v=7.5%)		20.8 kN (v=5.8%)		20.9 kN (v=10.5%)		19.5 kN (v=9.0%)	
		Total ave. after 2 mm surf. planning: 20.4 kN eqv. to 4.58 MPa BOND-Strength (v=3.1%)							
Failure type: (1) mortar, (2) mortar & 5-10% aggregates, (3) concrete failure, (4) bottom failure, (5) failure half way down									

Table 4. Test results from testing of the high-strength concrete slab

6.5 *Comparison to litterature findings*

Experimental studies comparing the tensile strength to compressive strength of cast cylinders (dia. 100 mm, length 200 mm) have recently been published in Ref. 10, also for high-strength concrete. The findings are reproduced in Fig. 5. For comparison to the test results measured in the present investigation, the Lok-Test and the Capo-Test pullout force was transformed to 150 mm x 300 mm cylinder compressive strength using the correlation given in Ref. (9). The values of the average Bond-Strength (●) and the tensile strength (0) measured on the cores relative to cylinder compressive strength are plotted in the figure (dotted lines) for comparison.

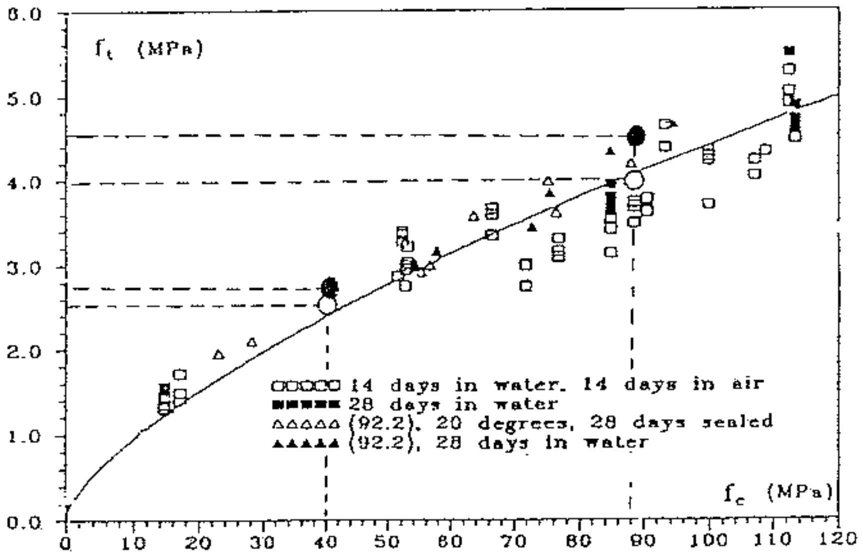

Figure 5. The experimental results of this investigation relating Bond-Strength (●) and the tensile strength measured on drilled-out cores (0) to standard cylinder compressive strength (measured by Lok/Capo-Test) compared to findings published in Ref. (10).

7. CONCLUSIONS

7.1 *"Is the Bond-Strength comparable to the uniaxial strength of concrete?"*

The finite element analysis performed, show the Bond-Strength to be 1.2% lower for a concrete with a theoretical tensile strength of 2.5 MPa, and 3.0% lower for a tensile strength of 4.0 MPa. This is if the Bond-Test is performed at the surface.

The experimental program conducted and the comparison to other experimental findings indicates the Bond-Strength to be slightly higher than the tensile strength as measured on drilled-out cores (dia. 75 mm, length 90 mm) or on cast cylinders (dia. 100 mm, length 200 mm). For a normal-strength concrete with a compressive strength of 40.1 MPa, the Bond-Strength was found to be 6.0% higher than the tensile strength measured. For the high-strength concrete with compressive strength of 87.6 MPa, the difference was found to be 14%. More data is needed to substantiate this preliminary finding. The difference cannot be explained, furthermore, before a finite element study has been made to investigate the failure mechanism in an experimentally performed "uniaxial" tensile test.

7.2 *"Is the depth of the partial coring having an influence on the Bond-Strength?"*

For a tensile strength of 2.5 MPa the finite element analysis show a 7.2% decrease in the Bond-Strength if the partial coring is made at a depth of 75 mm. For a tensile strength of 4.0 MPa, the decrease is 10.5%. The difference from testing at the surface is caused by the elastic deformation of the core.

The experimental program indicates a similar trend, although less significant, as well as an increase in the variation with the depth, in general. This tendency may also be explained by instrument-related inaccuracies and/or concrete inhomogeneousness. However, it has been demonstrated that the "skin"-property of plain concrete has a significant influence on the Bond-Strength. For the concrete investigated having a compressive strength of 40.1 MPa, the Bond-Strength was 37% *lower* at the surface than if 2 mm was removed prior to testing. For the concrete with a 87.6 MPa compressive strength the Bond-Strength of the skin was 28% *higher* than at a depth of 2 mm.

In conclusion, based on the present investigation, the Bond-Test compares favorably to the uniaxial tensile strength of concrete for practical testing purposes if the drill depth of the partial coring is kept within smaller dimensions, 10-20 mm. When testing the tensile strength of plain concrete with Bond-Test, the top surface should be removed by surface planning to a depth of 2 mm for the glue to reach the aggregates.

7.3 *FURTHER CONCLUSIONS*

From the laboratory testing for tensile strength of drilled-out cores it has been demonstrated that if the cores are allowed to dry out six days, the tensile strength will decrease with 50% for normal concrete, and 10% for high-strength concrete. This finding was expected, although not that prominent, and only stresses the need of performing the pull-off shortly after the partial coring has been completed, especially on vertical faces where the water will flow away from the drilled-out groove after coring. In the testing case illustrated on page 2 the rather low test results measured by the contactor may be explained partly by such drying-out effects of the partially drilled core left standing in the concrete.

8. *ACKNOWLEDGEMENTS*

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