BOND BETWEEN REINFORCEMENT AND CONCRETE IN VACUUM TREATED ZONES

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ABSTRACT

At vacuum treatment of concrete the lowering of the top concrete might cause cavities under the top reinforcing bars and disturb the bond. This investigation has shown that the vacuum treatment does not affect the bond negatively. A lowering of the top concrete face with 3.0 mm has not resulted in any cavities under the top bar. Movement of reinforcing bars at the vacuum treated concrete front by walking on the reinforcement results in cavities below the bars going into the concrete up to 200 mm. The bond strength and stiffness is affected negatively by any reinforcement movements.

INTRODUCTION

Concrete bridges are severely affected by de-icing agents and the freezing of water in the pores of the concrete. In addition to air entraining agents vacuum treatment of the upper surface of the concrete slab is used to increase the durability of the concrete.

At vacuum treatment it is possible that the concrete surface is pressed down due to sucking out of water. This lowering of the concrete is resisted by usually rigid reinforcement and might therefore cause cavities in the concrete below the upper reinforcing bars. A reduction of the bond capacity for the bars might be the result.

Another reason for deterioration of bond of reinforcement at vacuum treatment of concrete might be the walking on the assembled reinforcement when working. The bending deformations of the bars caused by walking people, and the springing back of the bars might give rise to cavities in the concrete around the bars, where this reinforcement goes into recently casted and vacuum treated concrete.

OBJECT OF THE INVESTIGATION

The aim with the investigation is to determine if cavities appear under the reinforcing bars at vacuum treatment of the concrete surface and if these cavities affect the bond between the reinforcement and concrete.

Another object of the investigation is to observe if cavities appear in the concrete at casting front caused by movements of the reinforcing bars, when walking and working on them and if the bond is affected by these cavities.

The determination of the increased risk for corrosion of the reinforcement which the possible cavities might give rise to is not the subject of this investigation.

The main object of the investigation is to determine if the ultimate bond capacity is reduced by the vacuum treatment and the working on the reinforcement

THE PLANNING OF TESTS AND TEST SPECIMENS

The tests should analyse the situation in bridge concrete slabs. Therefore representative and frequent slab dimensions should be chosen for the test specimens.

The bond strength can be determined in pull-out tests with the height representing the thickness of the concrete slab of the bridge deck. The reinforcing bar is then situated in the upper part of the pull-out specimen according to fig. 1. The upper surface of the pull-out specimen can be vacuum treated.

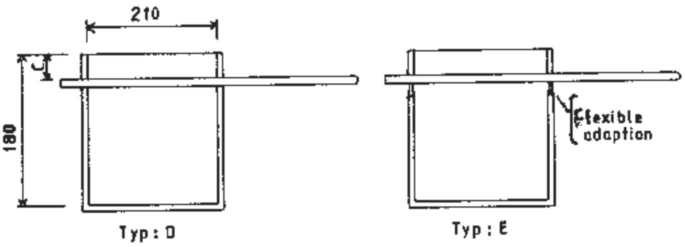

FIG. 1. Pull-out specimen. The diameter of the cylindrical specimen is 210 mm.

The diameter of the reinforcing bars in the investigation is chosen to be 16 mm, because this diameter is the most frequently used. The pull-out specimens are chosen as cylinders with the bars orientated along the diameter in the upper part of the cylinders with appropriate concrete covers, c. The height of the cylinders is chosen to be 180 mm to correspond to the thickness of the most frequent slabs in bridges. The bond length is chosen so the bond failure will govern in most cases. Two types of concrete, Swedish K20 and K40 and two types of reinforcement, Swedish Ks400 and Ks600 should be tested.

The cylinder form for the pull-out specimens is chosen because it is easy to arrange the vacuum suction from the circular surface without having corner effects. The moulds can easily be manufactured from plastic pipes.

The possible cavities at vacuum treatment can be obtained using the specimen, FIG. 1. For reason of comparison, tests should be performed on specimens with flexible adaptation of the reinforcement which should not cause disturbance in concrete at vacuum treatment. Corresponding tests should also be performed with specimens not treated with vacuum .

In the investigation to determine the influence of the reinforcement movements on the bond capacity and arrangement at casting of the specimens is made according to FIG. 2.

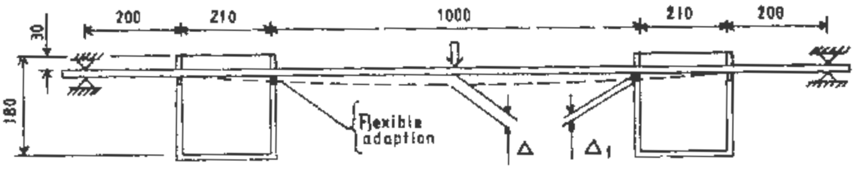

FIG. 2. Test arrangement for movements of bars at casting of the concrete.

The bars are pressed down by a load. Then the bars are let to spring back into the original position. The arisen cavities can be studied and their influence on the bond can be determined in the pull-out tests. Comparison should be done with specimens, where the reinforcement has not been moved.

The following measurements should be made:

- Sucked out amount of water at vacuum treatment.
- Existence of any cavities in the concrete below the reinforcing bars.
- Bond capacity and stiffness of the bond.

TEST PROGRAM

The test program is formed with the concepts stated at planning of the tests.

TABLE I Pull-out tests with vacuum treated concrete and reference tests with concrete not treated with vacuum. Type of test refers to FIG.1.

No. Vacuum treated	No. Not vacuum treated	Concrete batch	Concrete strength K-value	f_{cc} MPa	$\overline{\sigma}$ MPa	Reinforcement quality	Concrete cover c, mm	Type of test
1 - 3	49 - 51	1	K20	30.4	1.6	Ks400	15	D
4 - 6	52 - 54	"					30	D
7 - 9	55 - 57	"					15	E
10 - 12	58 - 60	"					30	E
13 - 15	61 - 63	2	K20	29.4	1.4	Ks600	15	D
16 - 18	64 - 66	"					30	D
19 - 21	67 - 69	"					15	E
22 - 24	70 - 72	"					30	E
25 - 27	73 - 75	3	K40	48.9	1.6	Ks400	15	D
29 - 31	76 - 78	"					30	D
31 - 33	79 - 81	"					15	E
34 - 36	82 - 84	"					30	E
37 - 39	85 - 87	4	K40	41.1	1.1	Ks600	15	D
40 - 42	88 - 90	"					30	D
43 - 45	91 - 93	"					15	E
46 - 48	94 - 96	"					30	E

D = rigid fastening of reinforcement. E = elastic fastening of reinforcement.

TABLE II Pull out tests with vacuum treated concrete and imposed deflection, FIG. 2. Reference tests without vacuum treatment and deflection.

Vacuum treated No.	Not vacuum treated No.	Concr. batch	Concrete strength K-value	f_{cc} MPa	$\bar{\sigma}$ MPa	Reinforcement quality	Concr. cover c, mm	Deflection mm	Deflection at concr. face mm
97- 98		5						11	4
99-100		"	K20	29.0	1.0	Ks400	15	22	8
	113-114	"						0	0
101-102		6						10	3
103-104		"	K40	49.8	1.2	Ks400	15	19	6
	115-116							0	0
105-106		7						13	4
107-108		"	K20	24.3	1.5	Ks600	15	24	8
	117-118	"						0	0
109-110		8						10	4
111-112		"	K40	46.3	1.5	Ks600	15	21	8
	119-120	"						0	0

The following measurements are performed:

- The amount of water sucked out at vacuum treatment.
- The depth influenced by vacuum treatment.
- The "load-free bar end displacement curve" for the pull-out tests.
- The load on the pull-out specimens, when the concrete cover cracks along the bar P_{crack}.
- The ultimate load on the pull-out specimens, P_{um}.
- Inspection of cavities in the concrete close to the bars.

THE QUALITIES OF THE CONCRETE

The concrete was composed according to Swedish standard methods /1/. The composition of the concrete is given in TABLE III.

TABLE III

Type of concrete. Swedish:	K20	K40
Standard Portland cement	232 kg/m^3	370 kg/m^3
Siliceous sand, fineness modulus M = 3.10	1180 kg/m^3	1180 kg/m^3
Cubical crushed granite fineness modulus M = 6.50 maximum size 16 mm	680 kg/m^3	495 kg/m^3
Admixture Sika A40 % of cement weight	3	3
W/c ratio	0.71	0.51
Air content %	6-7	6-7
Consistence	4 VB	4 VB

The specimens were made out of 8 batches of concrete. In addition to the pull-out specimens 6 standard cubes with the side length 150 mm were casted from every batch. The cubes were stored together with the pull-out specimens and tested at the same time. The obtained concrete mean compressive strengths and standard deviations, are given in TABLES I and II. The time of storage from casting to testing was 48 days. The test specimens were stored at 20°C and r.h. 50% .

THE QUALITIES OF THE REINFORCEMENT

Two types of Swedish standard reinforcement was used in the tests. The reinforcement is hot rolled and has the following yield stress and ultimate strength:

Ks400 $f_{sy} = 424\ \mathrm{N/mm^2}$, $\bar{\sigma} = 2.9\ \mathrm{N/mm^2}$; $f_{su} = 640\ \mathrm{N/mm^2}$.

Ks600 $f_{sy} = 652\ \mathrm{N/mm^2}$, $\bar{\sigma} = 3.6\ \mathrm{N/mm^2}$; $f_{su} = 885\ \mathrm{N/mm^2}$.

CASTING AND VACUUM TREATMENT OF THE TEST SPECIMENS

The moulds for the pull-out specimens were made of a circular plastic pipe with an inner diameter of 210 mm, FIG. 3. Plastic covers were made for the vacuum treated specimens with individual manometers. The covers were made airtight with a rubber strip which enabled vertical movement for the plastic cover. For the specimens which had flexible adaptation of the reinforcing bar, this was achieved by letting the rubber strip hold the bar in position in the vertical slots of the plastic mould during casting. The fixation in the rubber strip is not stronger than it yields at vacuum treatment.

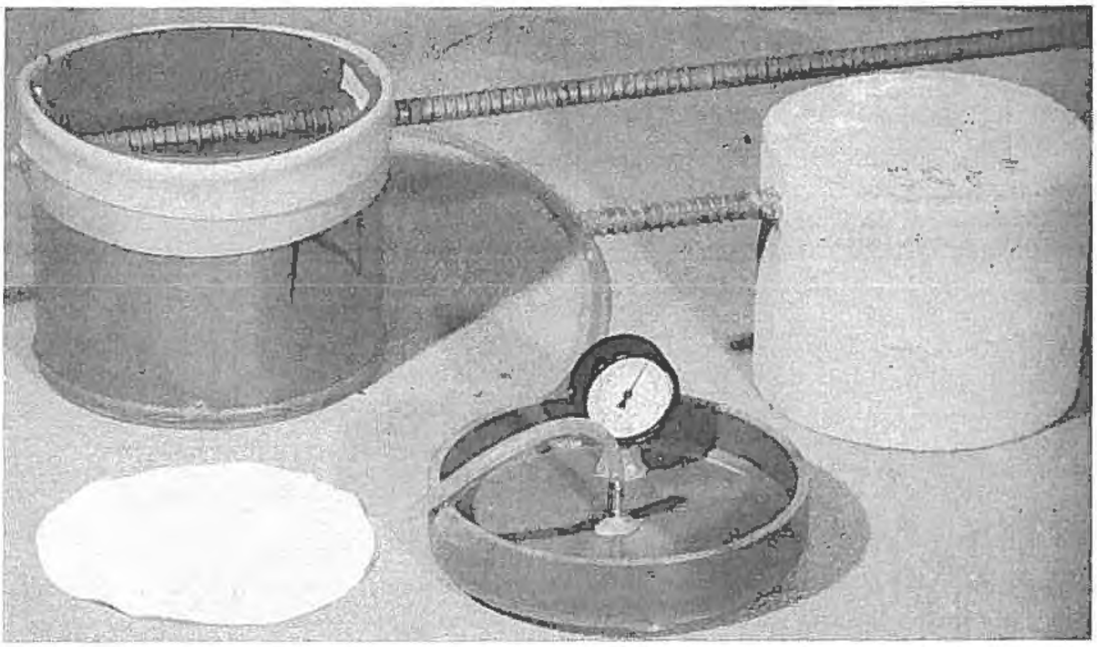

FIG. 3. A mould with plastic cover for vacuum suction and a casted pull-out specimen.

The casting was arranged in groups of vacuum treated and reference pull-out specimens at the same time from one batch of concrete. The grouping of the specimens is shown in FIG. 4. The concrete was vibrated with a poker vibrator with a diameter of 35 mm. The vacuum was applied through a central body. The sucked amount of water was measured as an average for all specimens. The lowering of the plastic covers for specimens was registered as an average of 3 measurements.

The arrangement of the moulds at casting of the specimens with reinforcement movements is shown in FIG. 5. Two pull-out specimens are interconnected by a common reinforcing bar. This bar was supported and bent down slowly by a load at mid span according to FIG. 2 and then slowly unloaded so it could spring back into original position. The mid span deflections correspond about to those observed under a walking person and give the deflections Δ_1 at the face of the concrete. After hardening, the two with the bar interconnected specimens were cut apart at mid span and the cavities around the bars were studied after demoulding.

FIG. 4. Arrangement of vacuum treated and reference moulds just before casting.

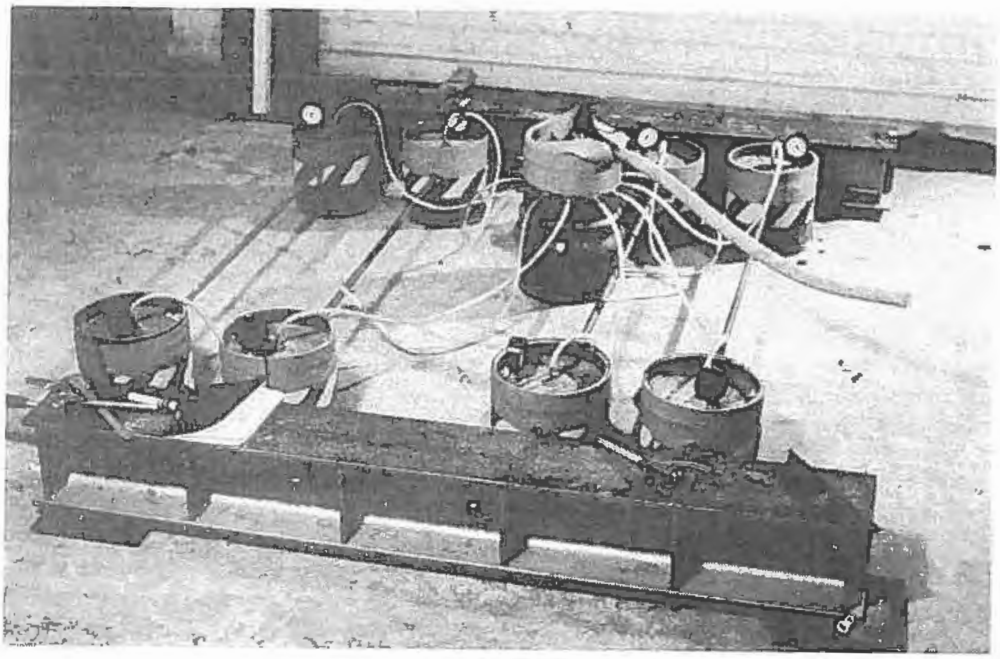

FIG. 5. Arrangement of vacuum treated moulds with reinforcement which is moved by bending.

At vacuum treatment 0.6 vacuum (0.4 atmospheric pressure) was applied during 5 min and 0.7 during 20 minutes at the concrete surface. The lowering of the concrete surface at vacuum suction was determined for two specimens in every casting arrangement and is presented in TABLE IV together with the amount of sucked out water. It can be stated that the concrete surface went down about 0.5 mm more for the concrete K20 in comparison with that of the concrete K40. The sucked out amount of water was about the same for both types of concrete. The depth of penetration of the vacuum was about 100 mm for all specimens.

TABLE IV

Concrete batch	Concrete quality	Lowering of concrete surface mm	Sucked out water		
			ℓ/m^2	ℓ/m^3	% of total
1	K20	2.85	2.9	16.0	9.3
2	K20	2.83	3.2	17.6	10.7
3	K40	2.38	3.5	19.2	10.3
4	K40	2.10	2.9	16.0	8.6
5	K20	-	2.9	16.0	9.8
6	K40	-	3.5	19.2	10.3
7	K20	-	3.5	19.2	11.7
8	K40	-	3.5	19.2	10.3

PULL-OUT TESTS

The pull-out tests were performed with an 750 kN mechanical testing machine with constant rate of deformation. The load was applied continuously to failure and the "load-free bar end displacement relative to the concrete" curve was plotted for every specimen. The testing arrangement is shown in FIG. 6. A special device was made to support the cylindrical pull-out specimen with the not symmetrically positioned bar.

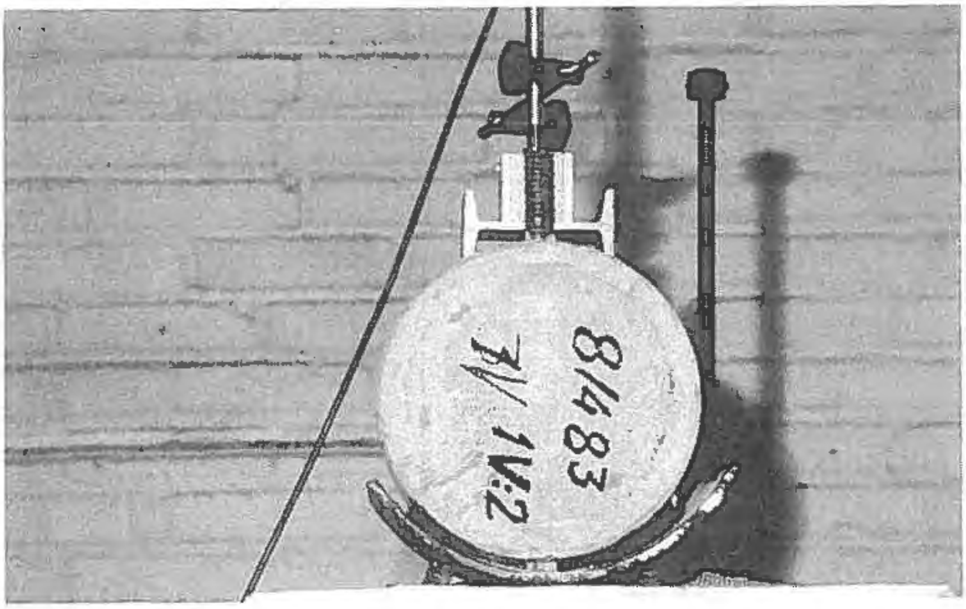

FIG. 6. Testing arrangement for pull-out tests.

Tests according to TABLE I

A typical "load-free bar end displacement" curve is shown in FIG. 7. At the load P_{crack} there is a sudden increase in displacement, when the concrete cover cracks along the bar. The ultimate load P_{um} is also registered.

The bond stress τ related to fct at P_{crack} can be calculated with a theory for thick concrete ring around the bar according to /2/ and /3/. For the concrete ring in a partly cracked plastic stage

$$\frac{\tau}{f_{ct}} = \frac{(C + \varnothing/2)}{1.664 \cdot \varnothing} \qquad (1)$$

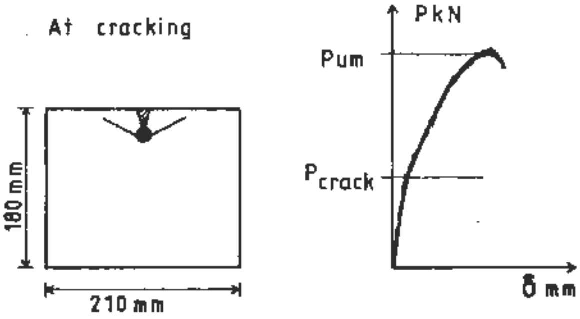

FIG. 7. A typical "load free bar end displacement" curve with P_{crack} when concrete cover along the bar cracks and P_{um} when the cover splits off.

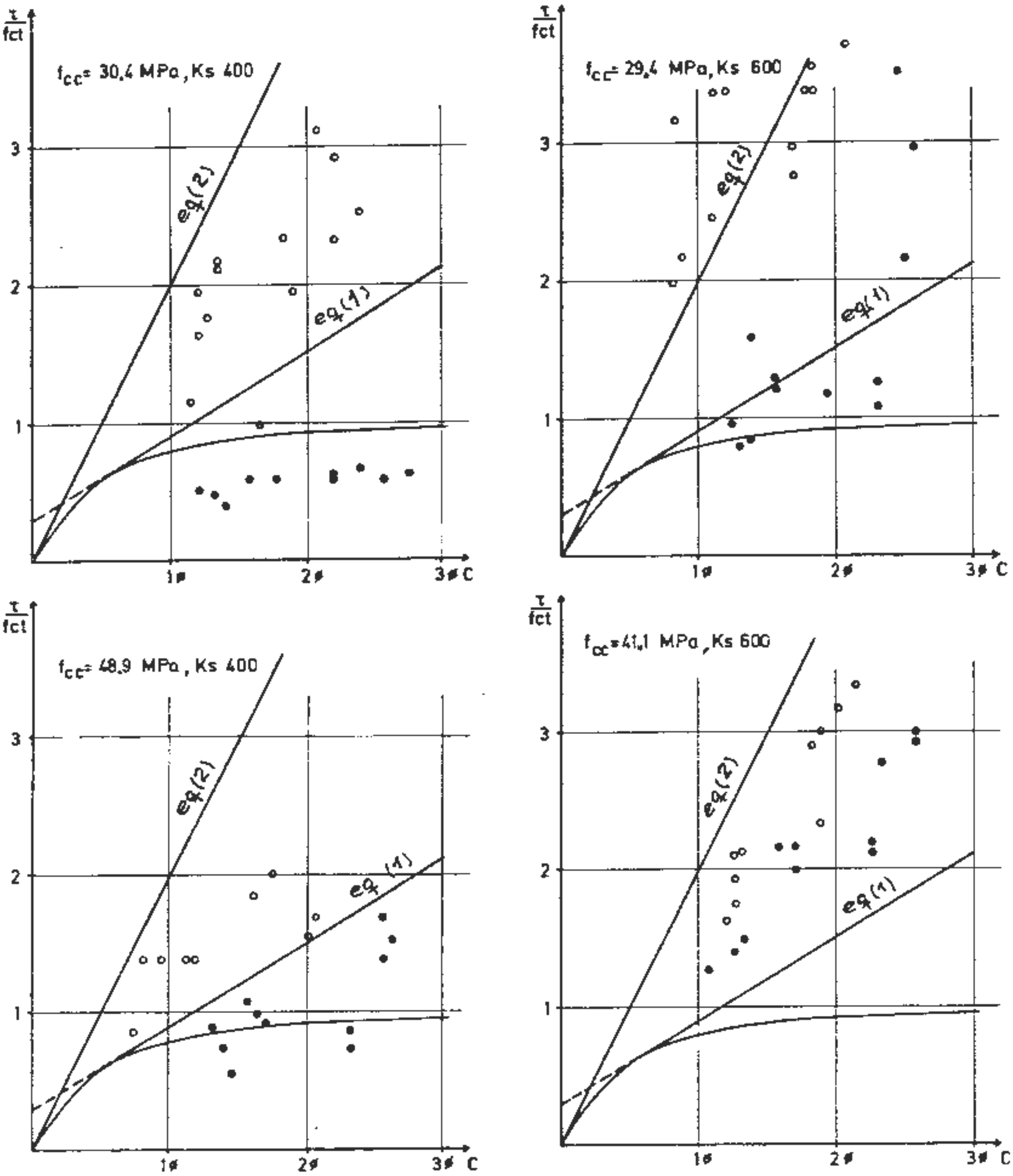

FIG. 8. Bond stress at P_{crack} related to f_{ct} for the specimens with different concrete covers. ○ vacuum treated specimens. ● not vacuum treated specimens.

and in a fully plastic stage

$$\frac{\tau}{f_{ct}} = 2\,\frac{c}{\emptyset} \tag{2}$$

where

$$f_{ct} = 0.443\sqrt{f_{cc}} \tag{3}$$

The eqs (1) and (2) are represented by straight lines in the diagrams in FIG. 8. The third curved line, the concrete ring strength P_{crack} in a not cracked elastic stage, is not of importance here.

As the concrete has a certain plasticity the measured concrete cover cracking loads should fall in between the two straight lines according to /3/.

In FIG. 8 the four categories of test results are plotted and compared with theoretical lines for the two stages, eqs (1,2). It can be stated, that the results from the vacuum treated specimens fall in between the two lines, while the not vacuum treated specimens have too low cover cracking load due to "top bar" effect. Vacuum treatment increases the concrete compressive strength in the upper part of the specimen with $\gtrsim$ 7.5 MPa according to /4/ and rises the P_{crack} value.

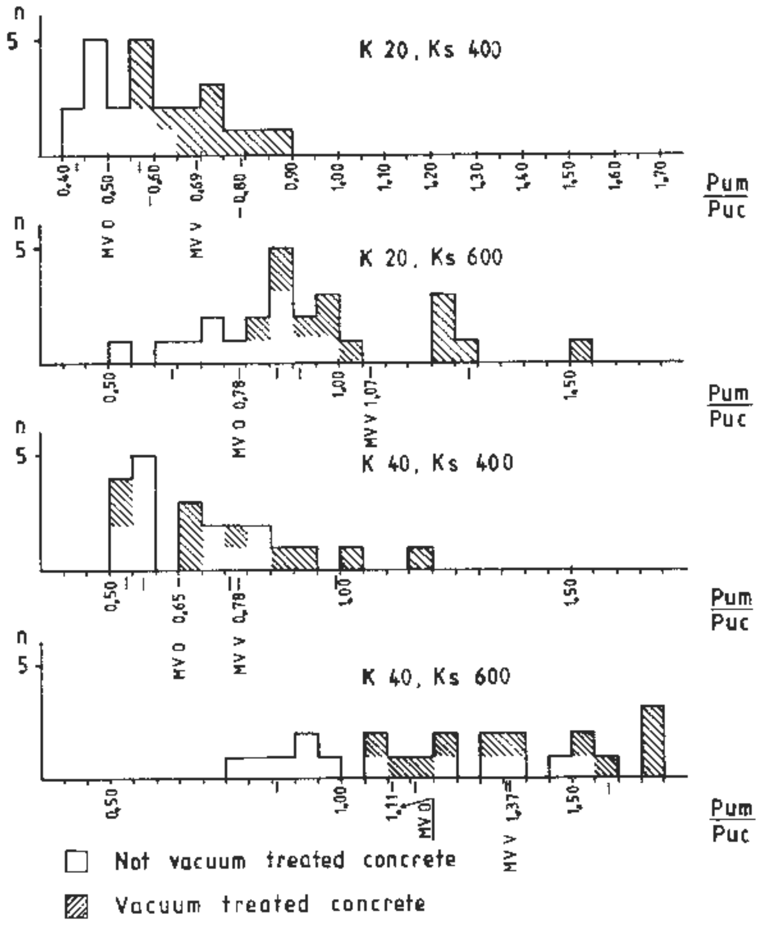

FIG. 9. Histogram for the relation between measured and calculated load at bond failure, P_{um}/P_{uc}.

The ultimate load P_{uc} when the concrete cover is split off by the pressure from the bond forces can be calculated according to /2/ with

$$P_{uc} = 2\pi\, l \cdot (C + \frac{Ø}{2}) \cdot f_{ct} \tag{4}$$

The measured load is compared with the calculated one and shown in histograms in FIG. 9 for the individual specimens. It appears that vacuum treated specimens have higher P_{um}/P_{uc} than those not treated with vacuum. The latter have the total mean $P_{um}/P_{uc} = 0.76$, $\bar{\sigma} = 0.27$ which about corresponds to the usual reduction of bond in codes with 30% for the top bar effect. Obviously the vacuum treatment with the total mean $P_{um}/P_{uc} = 0.96$, $\bar{\sigma} = 0.33$ does not affect the bond negatively.

No cavities have been detected below the reinforcing bars, not even for the vacuum treated specimens with rigidly fixed bars. The apprehended effects from vacuum treatment obviously are not forthcoming. For vacuum treated specimens with flexible reinforcement the mean $P_{um}/P_{uc} = 0.93$, $\bar{\sigma} = 0.34$ and for specimens with fixed reinforcement the mean $P_{um}/P_{uc} = 0.99$, $\bar{\sigma} = 0.33$. Thus the bond has not become affected negatively by rigid reinforcing bars at vacuum treatment.

Tests according to TABLE II

Typical measured "load-free bar end displacement relative concrete" curves are shown in FIG 10. Obviously movements of the reinforcing bars at the concrete front after vacuum treatment increase the deformability and decrease strength of the bond. Inspection has detected cavities under the bars going in up to full bond length 210 mm with a mean value of 104 mm from the concrete face.

The measured ultimate load at bond failure P_{um} is compared with the calculated one P_{uc} with eq (4) and shown in histogram FIG. 11. The specimens not treated with vacuum have mean $P_{um}/P_{uc} = 0,62$, $\bar{\sigma} = 0,06$ due to top bar effect. The vacuum treated specimens should have P_{um}/P_{uc} increased but show only 0,57, $\bar{\sigma} = 0.17$ due to the cavities. Thus bar movements after vacuum treatment affects the bond negatively and results in cavities where the reinforcement also might corrode.

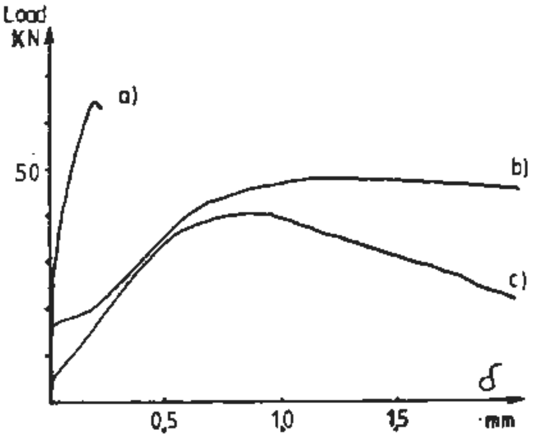

FIG. 10. Typical "load-free bar end displacement relative concrete" curves
a) Not vacuum treated. Displacement at concrete face = 0 mm
b) Vacuum treated. Displacement at concrete face = 4 mm
c) Vacuum treated. Displacement at concrete face = 8 mm

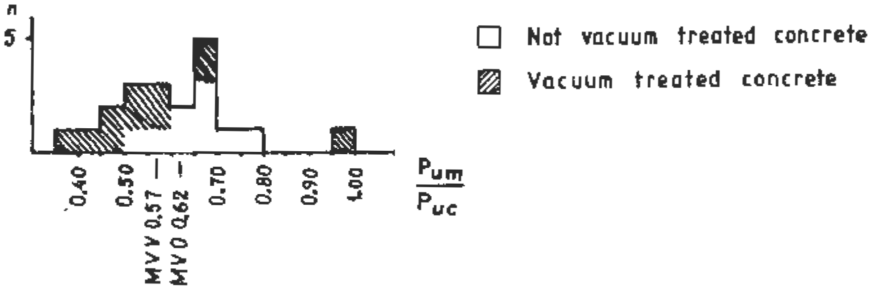

FIG. 11. Histogram for the relation between measured and calculated load at bond failure, P_{um}/P_{uc}. The reinforcement has been moved after the vacuum treatment.

CONCLUSIONS

- Vacuum treatment of the concrete surface increases the strength of the concrete in the upper part of the structure and thus the bond strength for the top reinforcement.

- No cavities have been detected at vacuum treatment under the top bars even when the bars are fixed in position and the lowering of the upper concrete face is up to 3.0 mm.

- Movement of the reinforcing bars at the vacuum treated concrete face results in cavities going in to the concrete up to 200 mm and increases the deformability and decreases the strength of bond. The cavities might give rise to corrosion of the reinforcement. Working when standing on the reinforcement should not be done at concreting and vacuum treatment.

NOTATIONS

P_{crack} = load when the concrete cover of the pull-out specimen cracks along the bar.
P_{uc} = calculated ultimate pull-out load
P_{um} = measured ultimate pull-out load
c = concrete cover depth
l = bond length
f_{cc} = concrete compressive strength
f_{ct} = concrete tensile strength
δ = free bar end displacement relative to the concrete in pull-out specimen
Ø = diameter of the reinforcing bar
$\bar{\sigma}$ = standard deviation
τ = bond stress at cover cracking along the bar.

ACKNOWLEDGEMENT

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