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INFLUENCE ON THE LOAD-DISPLACEMENT BEHAVIOUR OF STEEL-TO-CONCRETE CONNECTIONS WITH POST-INSTALLED ADHESIVE ANCHORS

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Abstract. *Designing frame structures requires knowing the behaviour of each member of the frame (beam, column, joint, etc.) regarding the axial forces, shear forces, and bending moments. Furthermore, the ductility of the structure under seismic loading is essential in earthquake regions. Nowadays, structural frames are built from different materials such as concrete and steel, to achieve better performance. Therefore, the behaviour of the connections between steel and concrete is essential. The steel-to-concrete joints were the focus of the INFASO project, where joint solutions with easy fabrication, quick assembly, applicability in old structures, sufficient ductility, and high loading capacity were developed. They proposed the use of anchor plates with welded studs or post-installed fasteners such as adhesive anchors to connect the steel and concrete members. This paper focuses on the performance of post-installed adhesive anchors. During their service life, post-installed anchors are subjected to monotonic, constant, and seismic loading. Each of these loading approaches is described in the current standards. Seismic and constant loading tests are of importance to the long-term behaviour of the anchors. Seismic loading tests are carried out using a predefined cycle pattern. According to TR049, seismic tests of category C1 (tension and shear) are performed with 140 load cycles, where the load amplitude decreases after 10, 30, and 100 cycles. On the contrary, C2 category tests increase the amplitude within 75 or 59 cycles, depending on the test. Constant loading tests apply when the anchors are installed in cracked concrete. In contrast to the mentioned patterns, this study observes the behaviour of the adhesive anchors when the amplitude of each cycle is increased by 5 % until the anchor fails. Standard short-term pull-out tests are carried out to determine the load increments. Various parameters such as the embedment depth, bond line thickness, hole cleaning, wet concrete, and elevated temperatures are studied. Confined and unconfined tests are performed. Overall, the reference short-term failure loads are higher than those in the tests with incremental and cyclic loading. The anchors installed with reduced hole cleaning, in wet concrete or subjected to elevated temperatures have a lower failure load compared to the reference series. Two additional bond line thicknesses are used for comparison. The increase in the thickness influenced the failure load differently for confined and unconfined test setups.*

1 INTRODUCTION

Knowing the behaviour of each member of a frame structure is important especially in earthquake regions [1]. One of these members is the connection between steel and concrete. In recent years, there has been a significant advance in the research of these type of joints. The project INFASO focused on the joint solution with easy fabrication and applicability using anchor plates with headed studs or post-installed fasteners such as adhesive anchors [2].

Adhesive anchors are classified as capsule systems and injection systems [8]. This classification is based on their method of placement in concrete. They consist of two parts, the resin and the steel component which is either a threaded rod or a reinforcing bar. The resins can be vinyl ester, epoxy or unsaturated

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polyester resin. The load is transferred through micro-keying and adhesion (chemical interlock) [9]. The behaviour of adhesive anchors is influence by different factors such as embedment depth, concrete condition, hole cleaning, temperature (installation and when testing), bond line thickness, anchor diameter, support diameter, long-term loading, etc. [10].

During their service life, adhesive anchors are subjected to different types of loading (monotonic, constant, and seismic). Different standards describe the testing procedure to evaluate the performance of adhesive anchors [3,4,5,6]. Figure 1 illustrates the different types of loadings. Anchors subjected to short-term loading follow mostly the monotonic loading pattern. Constant and seismic loading are used to investigate the long-term performance of anchors [6,7]. According to TR049, there are two categories to test the performance of post-installed anchors in concrete, namely C1 category and C2 category. Both categories consist of pulsating or alternating tension and shear loads using the sinusoidal pattern. The main difference between them is that the cyclic loading in the C1 category decreases within 140 cycles, whereas in the C2 category, the load increases within 75 or 59 cycles. The applied load is decreased or increased in a predefined number of cycles which are specified in the standard. Within each cycle group, the load is kept constant [6].

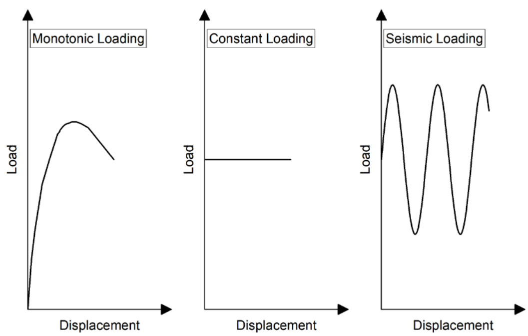

Figure 1. Types of anchor loading.

This paper is part of a research project at the Institute of Construction Materials [11]. The objective of this paper is to investigate the behaviour of adhesive anchors subjected to incremental loading in non-cracked low-strength concrete using confined and unconfined test setups. The loading pattern investigated is described in section 2.2.

2 TESTING PROGRAM

Concrete of the class C20/25 was used as anchorage ground. The cubic compressive strength of the specimen was 32.31 MPa. The compressive strength was tested on three concrete cubes with dimensions 150 x 150 x 150 mm. The adhesive anchor tested was a two-component epoxy resin. The components were mixed through a mixing nozzle with the help of an application gun. Threaded rod M12 with steel strength 12.9 served as a fastener.

Table 1 summarizes the range of the parameters used in this test program. Short-term and incremental loading tests using confined and unconfined setup were performed. The first column describes the test series name, followed by the type of test carried out (R - reference test, ShT - short-term test, IL - incremental loading test). The third and fourth columns show the embedment depth and the drilling diameter. The fifth column describes the concrete condition, whereas the sixth column the hole cleaning (HP - hand pumping, MB - machine brushing). The last two columns display the temperature when testing and the test support used to test the anchors.

Table 1: Testing program.

Test Series [-]	Type of Test [-]	Embedment depth [mm]	Drilling diameter [mm]	Concrete Condition [-]	Hole Cleaning [-]	Testing temperature [C]	Support [-]
D028	R-ShT	60	14	dry	HPxMBxHP	20	confined
D029	R-IL	60	14	dry	HPxMBxHP	20	confined
D030	R-ShT	60	14	dry	HPxMBxHP	20	unconfined
D031-D032	R-IL	60	14	dry	HPxMBxHP	20	unconfined
D033	IL	60	14	dry	1xHP	20	confined
D034	ShT	60	14	dry	1xHP	20	confined
D035	IL	60	14	dry	1xHP	20	unconfined
D036	ShT	60	14	dry	1xHP	20	unconfined
D037	IL	60	16	dry	HPxMBxHP	20	confined
D038	IL	60	16	dry	HPxMBxHP	20	unconfined
D039	IL	60	20	dry	HPxMBxHP	20	confined
D040	IL	60	20	dry	HPxMBxHP	20	unconfined
D041-D042	R-ShT	80	14	dry	HPxMBxHP	20	unconfined
D043	R-IL	80	14	dry	HPxMBxHP	20	unconfined
D044	IL	80	14	dry	1xHP	20	unconfined
D045	IL	80	16	dry	HPxMBxHP	20	unconfined
D046	IL	80	20	dry	HPxMBxHP	20	unconfined
D047	IL	60	14	wet	HPxMBxHP	20	unconfined
D048	IL	60	14	wet	HPxMBxHP	20	confined
D049	IL	60	14	dry	HPxMBxHP	43	confined
D050	IL	60	14	dry	HPxMBxHP	43	unconfined
D051	IL	80	14	dry	HPxMBxHP	43	unconfined
D065	IL	60	14	dry	1xHP	43	confined
D066	IL	60	20	dry	HPxMBxHP	43	confined
D067	IL	80	14	dry	HPxMBxHP	43	confined
D068	IL	60	20	dry	HPxMBxHP	43	unconfined
D069	IL	80	20	dry	HPxMBxHP	43	unconfined
D070	R-ShT	80	14	dry	HPxMBxHP	20	confined
D071	R-ShT	105	14	dry	HPxMBxHP	20	unconfined
D072	R-IL	105	14	dry	HPxMBxHP	20	unconfined
D073	IL	105	14	dry	HPxMBxHP	20	unconfined
D074	R-IL	80	14	dry	HPxMBxHP	20	confined
D075	IL	80	14	dry	1xHP	20	confined
D076	IL	80	20	dry	HPxMBxHP	20	confined

2.1 Specimen preparation

The holes were drilled using a hammer drilling system mounted on a drill stand to ensure perpendicularity on the concrete slab. Three drill bit diameters d_{cut} were used: 14 mm (standard drill bit diameter according to the manufacturers' printed instructions MPII), 16 mm, and 20 mm. After drilling the holes were cleaned as described in table 1. The fasteners were then installed at room temperature. The mortar was pressed in the hole and the steel component was inserted. The anchors were cured at room temperature for 24 to 48 hours.

The anchors in wet concrete were installed similarly. However, before drilling, the concrete specimens were stored underwater for a minimum of 28 days.

2.2 Testing

A total of 36 series (D028-D051 and D065-D076) were tested. Six parameters were changed throughout the program: the embedment depth, the bond line thickness, hole cleaning, hole saturation, temperatures when tested, and the test support width. The reference tests were drilled with a drill bit diameter of 14 mm and cleaned according to the MPII cleaning procedure: hand pumping to remove dust, machine brushing, and hand pumping.

The anchors were installed at room temperature at three embedment depths, 60 mm, 80 mm, and 105 mm. The bond line thickness investigated were 1 mm (d_{cut}= 14 mm), 2 mm (d_{cut}= 16 mm) and 4 mm (d_{cut}= 20 mm). Besides the standard cleaning procedure, a reduced cleaning effort was investigated (only hand pumping). The anchors were tested at 20°C and 43°C using a confined and unconfined test setup.

The anchors in the short-term tests were loaded to failure with a constant loading rate within 3 minutes. The anchors subjected to incremental loading were loaded and unloaded with 5 % load increments within 5 minutes. The increments were calculated using the reference short-term failure loads. Figure 2 illustrates a typical loading curve for short-term and for incremental loading tests.

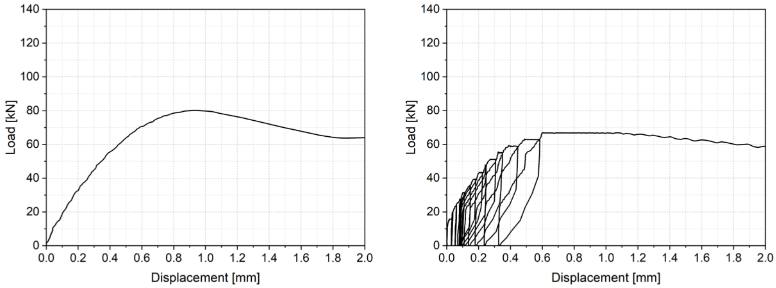

Figure 2. Illustration of load vs displacement curves for short-term and incremental loading tests.

The fastener was axially loaded with the help of a hydraulic cylinder. The load was transmitted from the cylinder to the fixture using a steel rod. Figure 3 illustrates the test setups used. The clearance hole of the fixture for confined tests had a diameter of 24 mm. The diameter of the support for the unconfined test was chosen such that its diameter was more than four times the embedment depth. Thus, for an embedment depth of 60 mm a 240 mm support was used, and for 80 mm and 105 mm, a diameter of 350 mm. The load was measured using a load cell, whereas the displacement using a displacement transducer. The measurements were recorded using commercial software.

Figure 3. Confined and unconfined test setup.

3 RESULTS

The results of the tests are listed in table 2. The first three columns are the same as in table 1. The fourth and the fifth columns give the mean failure load and standard deviation for each test series.

The anchors exhibited the following failure modes: 12 % pull-out failure, 25 % pull-out with mortar failure, 11 % combined pull-out and pull-out with mortar failure, 17 % concrete failure, and 35 % mixed concrete and pull-out failure.

Table 2: Test results.

Test Series [-]	Type of Test [-]	Embedment depth [mm]	Mean Load $N_{u,m}$ [kN]	Standard deviation [kN]	Support [-]
D028	R-ShT	60	78.62	2.34	confined
D029	R-IL	60	68.71	2.27	confined
D030	R-ShT	60	39.22	3.30	unconfined
D031-D032	R-IL	60	33.94	2.61	unconfined
D033	IL	60	42.13	2.36	confined
D034	ShT	60	47.00	4.62	confined
D035	IL	60	30.86	2.28	unconfined
D036	ShT	60	35.86	2.19	unconfined
D037	IL	60	80.16	8.24	unconfined
D038	IL	60	39.38	0.07	confined
D039	IL	60	77.62	2.42	unconfined
D040	IL	60	39.02	4.45	confined
D041-D042	R-ShT	80	57.87	3.25	unconfined
D043	R-IL	80	46.99	3.17	unconfined
D044	IL	80	41.53	4.50	unconfined
D045	IL	80	58.26	0.41	unconfined
D046	IL	80	57.08	3.42	unconfined
D047	IL	60	32.83	1.20	unconfined
D048	IL	60	65.06	5.15	confined
D049	IL	60	56.68	2.48	confined
D050	IL	60	31.42	2.19	unconfined
D051	IL	80	45.63	3.27	unconfined
D065	IL	60	45.92	8.23	confined
D066	IL	60	65.8	2.32	confined
D067	IL	80	81.56	8.69	confined
D068	IL	60	33.98	1.75	unconfined
D069	IL	80	49.44	2.97	unconfined
D070	R-ShT	80	118.23	2.35	confined
D071	R-ShT	105	89.99	12.92	unconfined
D072	R-IL	105	81.58	4.64	unconfined
D073	IL	105	90.22	4.41	unconfined
D074	R-IL	80	100.77	5.93	confined
D075	IL	80	61.88	2.01	confined
D076	IL	80	110.95	3.47	confined

3.1 Influence of incremental loading

The influence of incremental loading was observed on a total of ten test series. Table 3 lists the reference test series and the series with incremental loading. Figure 4 illustrates the results for the confined setup tests (left figure) and unconfined tests (right figure). The difference between short-term tests and incremental loading tests was more apparent in the confined tests. The anchors installed at 60 mm embedment depth had a 12 % lower failure load because of incremental loading. Similarly, with an increase in the embedment depth to 80 mm, the failure load reduced by 17 %. The test series with reduced cleaning effort (D034 and D033) had a 10 % drop in failure load, due to incremental loading.

Table 3: Influence of incremental loading.

Confined		Unconfined	
reference	incremental	reference	incremental
D028	D029	D030	D031/D032
D034	D033	D036	D035
D070	D074	D041/D042	D043
		D071	D072

The series tested with an unconfined setup and incremental loading had a drop in the loads between 10 % and 19 % for the three embedment depths and the reduced cleaning effort tests.

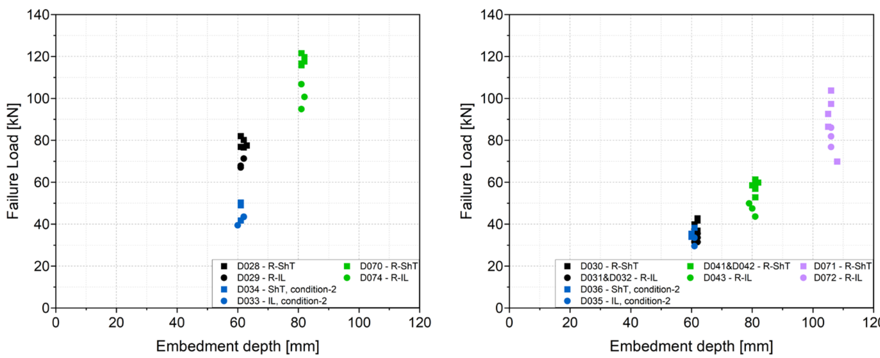

Figure 4. Failure load vs embedment depth curves - influence of the type of loading.

3.2 Influence of hole cleaning

The influence of hole cleaning was observed on two embedment depths for both support widths. Table 4 summarizes the series which were considered.

Table 4: Influence of hole cleaning.

Confined		Unconfined	
reference	hole cleaning	reference	hole cleaning
D028	D034	D030	D036
D029	D033	D031/D032	D035
D049	D065	D043	D044
D074	D075		

The comparison was carried not only on the incremental loading tests but also in the short-term tests. As it can be seen in figure 5, the short-term tests with reduced cleaning effort had 40 % (confined setup) and 9 % (unconfined setup) lower failure load compared to the reference short-term tests with the standard cleaning procedure.

The incremental loading tests under confined setup at room temperature displayed a drop in the carrying capacity of 39 % at both embedment depths, whereas the tests at elevated temperature (43°C) dropped only 19 % in the load.

The unconfined tests revealed the same pattern, for the embedment depth 60 mm, the load reduced by approximately 9 % and for the 80 mm depth tests 12 %.

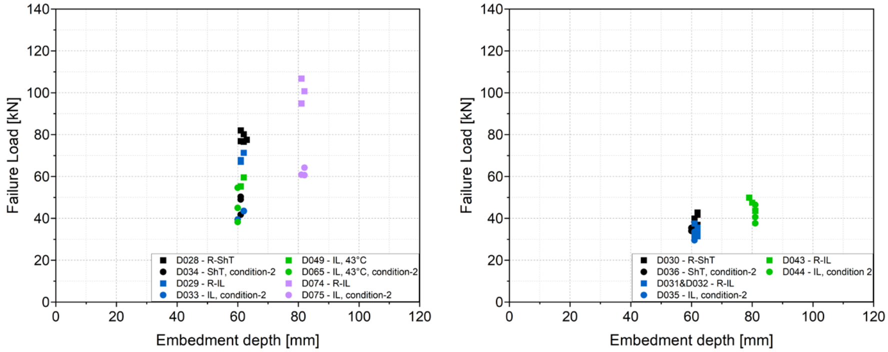

Figure 5. Failure load vs embedment depth curves - influence of the hole cleaning.

3.3 Influence of bond line thickness

The bond line thicknesses of 1 mm (standard), 2 mm (RS2), and 4 mm (RS4) were investigated. All the anchors were tested at both temperatures. A summary of the test series is given in table 5.

Table 5: Influence of bond line thickness.

Confined		Unconfined	
reference	bond line thickness	reference	bond line thickness
D029	D037, D039	D031/D032	D038, D040
D049	D066	D043	D045, D046
D074	D076	D050	D068
		D051	D069
		D072	D073

Figure 6 illustrates the failure loads for confined and unconfined setups. As it can be seen, the tests with embedment depth 60 mm at 20°C had an increase in the failure load of 17 % for bond line thickness RS2, however only 13 % for RS4. At a higher embedment depth, 80 mm, the load of the tests with 4 mm bond line thickness was 10 % higher compared to its reference series. Furthermore, the anchors at elevated temperature, also revealed an increase in the failure load when drilling with a larger drill bit (16 % rise in load).

A similar behaviour pattern exhibited in the unconfined tests. The results of the tests at room temperature with 2 mm bond line thickness at the embedment depths 60 mm and 80 mm, failed at 16 % and 24 % higher loads compared to the reference tests with 1 mm bond line thickness. A further increase to 4 mm bond line thickness, also showed an increase of the load compared to the reference tests, however a slight decrease compared to the RS2 tests. The tests at 43°C and RS4 bond line thickness revealed 16 % and 8 % higher loads (60 mm and 80 mm depth respectively) compared to the tests with 1 mm bond line thickness. Lastly, the anchors installed at 105 mm and RS4 thickness had a rise of 11 % in the failure load.

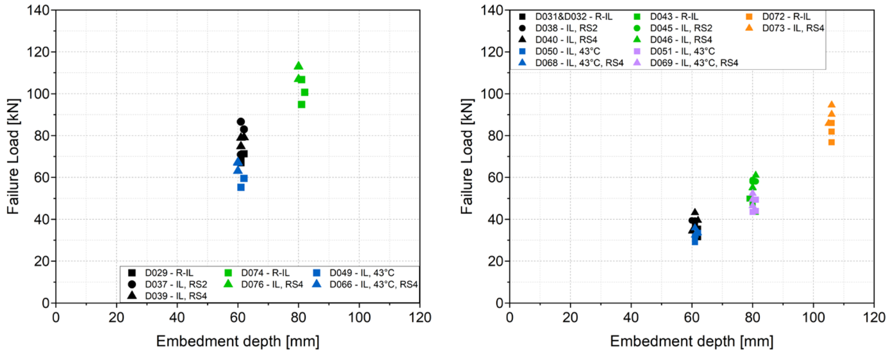

Figure 6. Failure load vs embedment depth curves - influence of the bond line thickness.

3.4 Influence of wet concrete

The influence of wet concrete was observed only on four test series at 60 mm embedment depth with confined and unconfined setups. Figure 7 displays the results of these tests. As expected, the failure loads for confined tests were higher compared to the unconfined tests. The carrying capacity of the anchor was influenced minimally by the condition of the concrete. For the confined tests, the anchors installed in wet concrete had a 5 % lower failure load, whereas the unconfined tests only 3 % lower load compared to the reference tests in dry concrete.

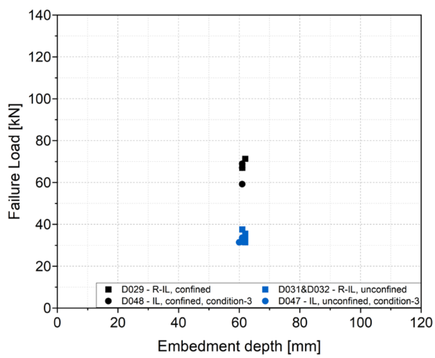

Figure 7. Failure load vs embedment depth curves - influence of the wet concrete.

3.4 Influence of temperature

Table 6 lists the test series where the influence of the temperature when testing was observed. For each support width, four test series were considered. Aside from the temperature, the embedment depth, hole cleaning procedure, and bond line thickness were varied.

Figure 8 illustrates the results of the tests. The results showed an influence of the temperature on the carrying capacity of the anchors. At the embedment depth of 60 mm, the load decreased approximately 18 \% for confined tests and 7 % for unconfined tests with an increase in the testing temperature to 43°C. At a higher embedment depth (80 mm), the same trend was observed, 19 % and 3 % lower failure loads for confined and unconfined tests.

Table 6: Influence of temperature when testing.

Confined		Unconfined	
reference	temperature	reference	temperature
D029	D049	D031/D032	D050
D033	D065	D040	D068
D039	D066	D043	D051
D067	D074	D046	D069

The next parameter taken into consideration was the bond line thickness of 4 mm or RS4. The confined tests at 60 mm had 15 % lower residual capacity at increased temperature compared to the room temperature tests. Similarly, for unconfined tests, the loads had a 13 % drop for both embedment depths.

The last parameter tested was the hole cleaning procedure, however only for confined setup at 60 mm embedment depth. The high testing temperature and reduced cleaning effort influenced positively the residual capacity of the anchors; the mean failure load increased from 42.13 kN for reference tests to 45.92 kN (9 % load increase).

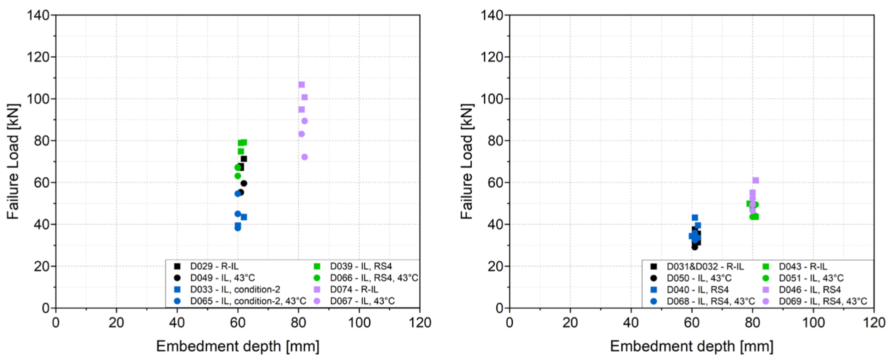

Figure 8. Failure load vs embedment depth curves - influence of the temperature.

3.5 Bond strength

Except the failure loads, the bond strengths of each series were investigated. According to EAD 330499, the bond strength is calculated as follows:

$$\tau = \frac{N_u}{h_{ef} \times d \times \pi} \quad (1)$$

where: τ is the bond strength in N/mm², N_u is the failure load in kN, d is the diameter of the fastener in mm and h_{ef} is the embedment depth [4].

Figure 9 summarizes the bond strength for each test. In this figure, the values are grouped according to the embedment depth and the support width. The mean bond strengths and their standard deviation are plotted. The bond strength of the anchors installed at 60 mm depth and tested with confined setup varied from 18.21 N/mm² (the tests with reduced cleaning effort) to 34.66 N/mm² (the tests with bond line thickness 2 mm). The bond strength increased by approximately 10 % with an increase in the embedment depth to 80mm.

Similarly, the unconfined tests, exhibited lower bond strengths at 60 mm (13.42 - 17.27 N/mm²) compared to 80 mm (13.60 - 19.24 N/mm²) and 105 mm (20.42 - 22.65 N/mm²).

The trend of the results illustrated that the bond strength of the anchors was the lowest for the anchors installed with reduced cleaning effort and the highest for the increased bond line thickness tests (both cases).

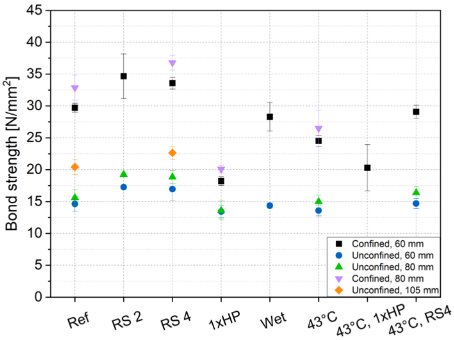

Figure 9. Summary of the mean bond strength for each embedment depth and parameter.

4 CONCLUSIONS

The conclusions of this work are drawn together and presented in this section. The focus of this paper was the behaviour of adhesive anchors under short-term and incremental loading. Aside from the influence of the type of loading, the influence of hole cleaning, bond line thickness, concrete condition, and increased temperature when testing were investigated.

Firstly, the influence of the type of loading was investigated. As expected, the anchors subjected to incremental loading failed before the anchors tested within 3 minutes. The failure loads for confined and unconfined setups were in the range of 10 % to 20 % lower than the reference short-term tests.

Secondly, the influence of hole cleaning was observed. The anchors were installed in holes with the cleaning procedure as described in the manufacturer's printed instructions and in holes with a reduced cleaning effort (only one hand pump to blow out the concrete dust). This influence was more obvious in the confined tests where the load was approximately 40 % lower compared to the reference tests. An exception were the anchors installed at 60 mm and tested at 43°C with a 19 % lower failure loads. For the confined tests, the failure loads dropped by a maximum of 12 % than the reference tests.

Another investigated parameter was the bond line thickness. The results demonstrated an increase of the failure load with the increase of the bond line thickness. The anchors installed in the holes drilled with d_{cut} = 16 mm (RS2 or 2 mm bond line thickness) had higher failure loads than the reference incremental loading tests, between 16 % to 24 % for both confinements. Drilling with a larger diameter d_{cut} = 20 mm (4 mm thickness), increased the failure load compared to the reference tests (8 – 21 % higher loads) despite the loads being slightly lower than those tested with 2 mm thickness.

The results showed a small influence of the hole saturation in the carrying capacity of the anchors. The failure loads were 5 % lower than the reference incremental loading tests.

Lastly, the influence of increased testing temperature was observed. Overall, the increase of the temperature lowered the residual capacity of the anchors. The failure loads for confined tests were 15 % to 19 % lower and for unconfined tests between 3 % and 13 % lower than their reference loads. An exception was the confined tests at 60 mm with a reduced hole cleaning, where the load increased with 9 % with an increase of the testing temperature.

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