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Laboratory Tests of Adhesion of Steel Bars to Ordinary and Frozen Concrete

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Abstract. The issue of adhesion of steel to concrete is one of decisive features characterising reinforced concrete. Adhesion constraints to concrete are simplistically presented with shear stress evenly distributed on the side surface of reinforcement. However, an exact value of this stress depends on many factors and its estimation is very complicated. There is a lot of laboratory methods aimed at testing adhesion of the reinforcement to concrete but they frequently give different results. Sometimes, they are even contrary.
In this paper, the state of knowledge on the steel-concrete adhesion, mechanism of its loss, and factors influencing it were reviewed. Own tests were conducted with two methods, pull-out and push-on, aimed at reflecting the operation of reinforced concrete structure and specifying the chemical adhesion, as well as the friction force of the reinforcement to concrete. The impact of the freeze-thaw cycle on this process was also studied. The interfacial transition zone on the steel-concrete boundary was analysed as well. The structure of boundary layer around the reinforcement in concrete is very similar to the zone of aggregate separation from paste. In the Polish and foreign literature, the thickness of the transition zone is estimated as 50-100 μm but only 10-20 μm of this zone has variable mechanical properties. The microstructure of the boundary line depends on the kind of concrete and reinforcement, presence and kind of additions, conditions of curing, and many other factors. In order to describe this phenomenon more precisely, own tests of the steel-concrete interfacial transition zone involving analysis of SEM images and identification of chemical composition of this EDS area were conducted.

1. Introduction

The morphology of the cement paste-aggregate boundary line or the cement paste-steel reinforcement boundary line significantly affects the mechanical properties of concrete and reinforced concrete. Much attention has been paid to the cement paste-aggregate interfacial transition zone so far [1,2]. By analogies to the coarse aggregate, one must suppose that a regular but weakened boundary line forms around steel (in the form of steel fibres with the diameter of up to 1 mm distributed in a matrix or the concrete cased steel bars with the diameter of up to 24 mm) located along the bar, around its entire perimeter [3-5].

In structural concrete, the steel bars, both in the tensioned and compressed zones, are exposed to very large shear forces causing shear between the concrete paste and the steel. The safety (loss of stability) limit of a reinforced concrete component depends on the volume of external loads, which must be transferred in the compressed zone through the concrete and the steel bars, and in the tensioned one – mainly through the steel bars. The steel bars operate effectively until the interfacial transition zone between the concrete paste and the concrete is destroyed. However, the steel-concrete interfacial transition zone is not set only by mechanical features of the concrete and steel, but also by the nature of the mortar shaped by the effect of chemical admixtures and mineral additives [6-8], by environmental conditions, and – which is the subject of these tests – compressive or tensile forces influencing the steel-concrete system. Because of this, recognition of the phenomenon, to which the literature paid far less attention than to the paste-aggregate interfacial transition zone, is extremely important for the structure reliability.

2. Mechanisms affecting the adhesions of steel bars to concrete and methods of their determination

2.1. Factors determining the adhesion

The phenomenon of adhesion between reinforcing steel and concrete is characteristic for reinforced concrete structures. The steel's adhesion constraints to concrete depend on many factors. However, the industry literature lists a few of the most important ones affecting significantly this phenomenon. These are: concrete and steel strength, reinforcing steel yield strength, spacing, and position of the bars during concreting, their corrosion degree, the reinforcement's geometry, concrete covering's thickness, and the length of anchoring in the concrete. The multitude of these factors indicates the complexity of the issue of testing concrete and reinforcing steel's adhesion in the reinforced concrete components.

The cooperation between these materials is ensured by the ability to counteract their mutual displacement. The industry literature highlights three main mechanisms influencing the adhesion. These are:

- chemical adhesion, on which the classic adhesion concept was based. This is a mutual, chemical reaction of adjacent concrete and reinforced layers that generates some level of this connection's shear strength. The adhesion is lost even at very small slip of a rebar in relation to the covering. In non-cracked concrete, the bond stresses emerge because of chemical adhesion between the reinforcing steel and the concrete – this condition was marked on figure 1 as point A. The chemical adhesion fades because of two reasons: the rebar's slip in relation to the concrete and as a result of internal microcracks of concrete adjacent to the bar surface [9,12];

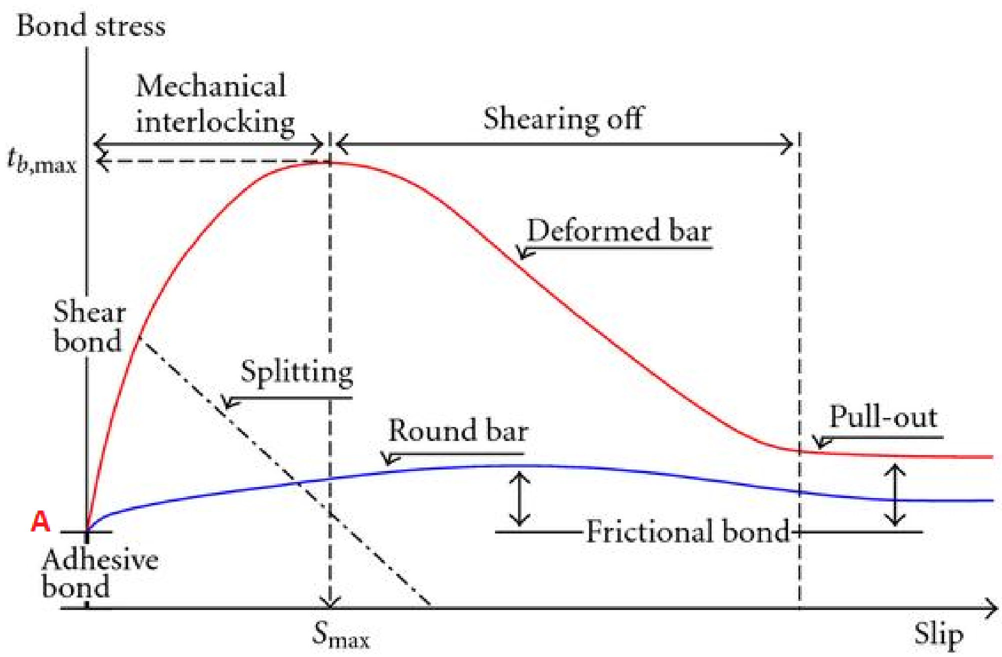

Figure 1. Typical bond stress-slip relationship [9]

- frictional resistance, which depends greatly on the bar's geometry and side surface. It is estimated that the share of friction may be even 35% of the final biding strength. The frictional resistances for smooth and ribbed bars were marked on figure 1 [9];
- mechanical interlocking – a gradual mechanism of adhesion's destruction. The loss of adhesion may be described with two mechanisms: concrete splitting and pulling the bar out of the concrete. For the smooth bars, the destruction mechanism is related to the loss of chemical adhesion and friction. Then, influenced by placing the increasing tensile force, the continuity of both materials' deformations is interrupted and mutual slip appears [9,12].

2.2. Adopted test methods

2.2.1. Methods of testing the adhesion of the reinforcement to the concrete.

Because of a great number of parameters influencing the cooperation of the reinforcing steel with the concrete, the test methodology of this phenomenon is complex. Among many methods of testing the adhesion of the rebars to the concrete, the most applied one is the so-called pull-out method involving pulling the bar out from the concrete block (figure 2a). This method can be applied only in comparison tests of concretes with different properties or in assessment of the joint quality of concrete and rebars with different anchoring length and surface. The restrictions of applying this method result from different state of stresses prevailing in a given sample and the actual structure. In a laboratory pull-out test, the concrete is compressed and the bar is tensioned, whereas, in actual reinforced concrete structures, the bar and concrete are subjected to the same stresses. Another method of testing the adhesion constraints of the steel to the concrete is the push-on method (figure 2b). The method involving pushing the bar on a concrete block is similar to the pull-out method. The difference is that both materials are subjected to compressive stresses. Figure 2c shows tests of pulling the bar out and lap tests. These methods are applied in testing the adhesion of anchoring areas and overlap joints [12].

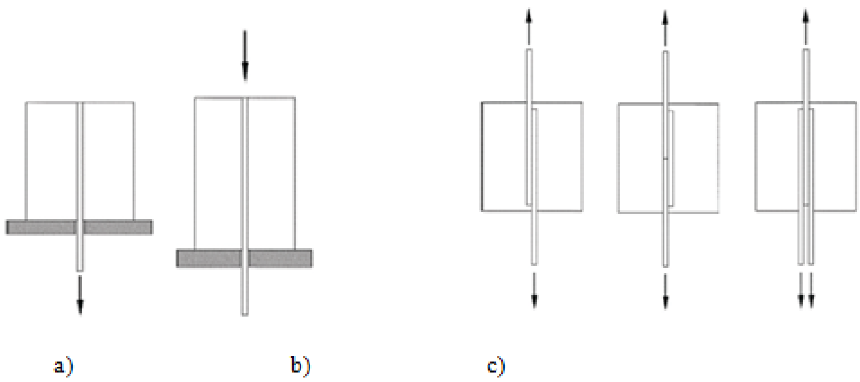

Figure 2. Method of testing the adhesion of steel bars to concrete: a) pull-out, b) push-on, c) lap test [12]

2.2.2. SEM tests

The contact zone between the steel and the concrete was assessed using the VEGA 3 scanning electron microscope with available accelerating voltage of 0.3-20 kV, 50-300000x magnification, resolution of 10 nm, and maximum sample sizes of 100×25×25 mm. Because of such small sizes of the samples, they were cut out from the control sample with a laser, exposing a steel bar and a 5-mm concrete band around the bar. The ordinary and the cyclically frozen samples were analysed with SEM (micrographs) and EDS (identification of chemical elements contained in the tested material).

3. Own tests of the adhesion of smooth bars to bridge concrete with pull-out and push-on methods

3.1. Preparation of samples and marking basic strength characteristics

In 2016, tests aimed at determining adhesion forces of reinforcing steel to bridge concrete, describing the interfacial transition zone of these materials, and studying the impact of cyclic freezing on this phenomenon were conducted. Typical bridge concrete class C35/45 with the mix design as in Table 1 was adapted. In order to execute samples, twelve previously prepared, cylindrical PCV moulds with internal diameter of 10 cm and height of 16 cm (figure 3a) with an axially positioned, smooth rebar with the diameter of 10 mm were used. The cylindrical forms were filled with a concrete mix (figure 3b) with the mix design as in Table 1, were subjected to compaction on a shake table. On the next day, the samples were taken out of the moulds and put away for 28-day seasoning in a water environment.

Table 1. Mix design of the concrete mix

Component	Amount
Cement 42,5 HSR NA	370 kg
Water	167 l
W/C ratio	0.45
Sand	699 kg/m^3
Gravel	599 kg/m^3
Chippings 8/11	438 kg/m^3
Chippings 8/16	399 kg/m^3
Chippings 11/16	300 kg/m^3
Plasticizer	0.80 %

a) b)

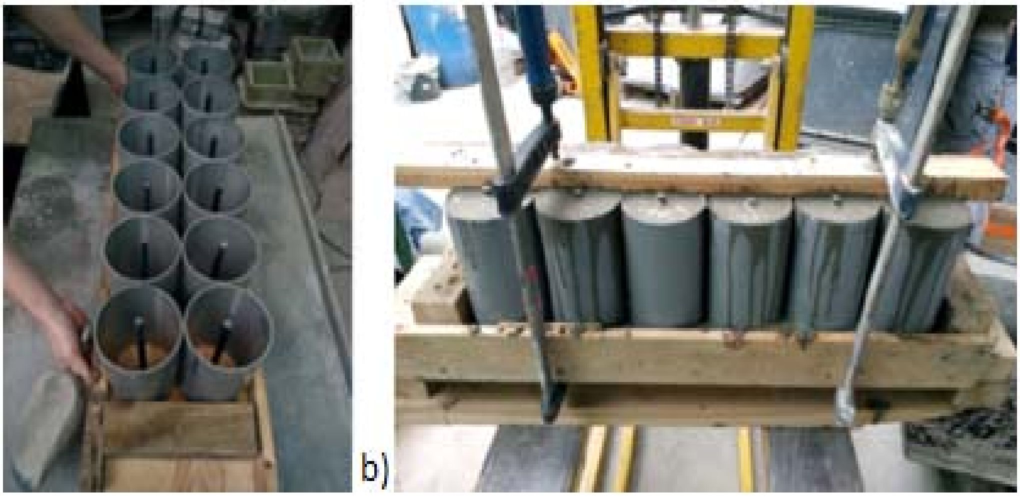

Figure 3. a) Moulds for executing the moulds for pull-out and push-on tests, b) Concreted cylindrical moulds with an axially positioned rebar

Fourteen cubic, standard samples with sides' dimensions of 15 x 15 x 15 cm for the test of concrete compressive strength were also prepared. After 28-days of seasoning, all the cylindrical samples were cut into two pieces to the length of 8 cm. The piece with a protruding bar was for a pull-out test, and the other was for a push-on test. In order to test the impact of freeze on the adhesion of the reinforcement to concrete of twelve cylindrical samples (six of them for the pull-out and six for the push-on) and seven cubic samples were subject to 150 cycles of freeze-thaw, whereas the remaining reference samples were seasoned in water at temperature of 20°C. The cubic samples, both the reference and the cyclically frozen ones, were subjected to the compressive strength tests, and the results are shown on figure 4.

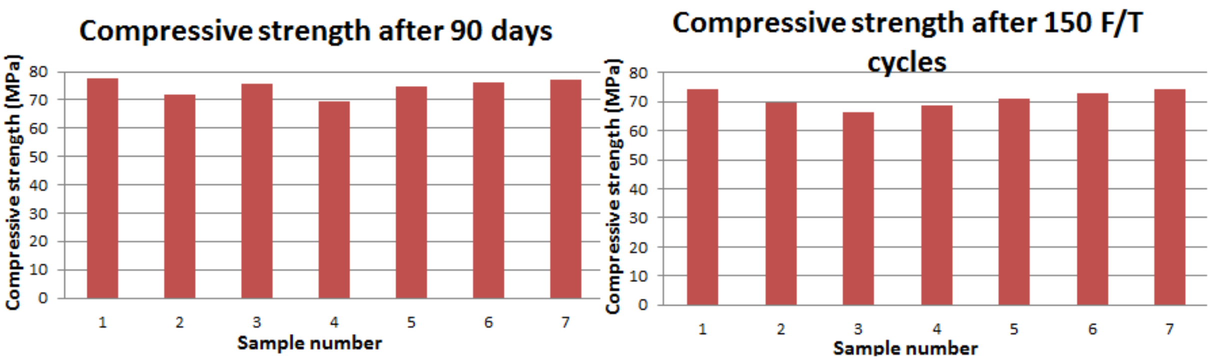

Figure 4. Compressive strength of the reference samples after 28 days and 150 cycles of freeze-thaw.

The average concrete compressive strength of non-frozen concretes was 74.65 MPa, and after 150 cycles of freezing – 71.05 MPa, which means the decrease by 4.82% allows to qualify concrete as frost-resistant in light of the PN/B - 06250 Polish standard.

3.2. Tests of the adhesion of a rebar to concrete with the pull-out method

Twelve previously prepared samples, of which six were seasoned in water and six were cyclically frozen and thawed, were subjected to the test of pulling smooth bars out from a concrete cylinder. The INSTRON 300DX machine with a specially prepared unit was used (figure 5a). The steel bar was pulled out axially from the concrete cylinder at constant speed of 0.05 mm/s according to the diagram shown in figure 2a. The pull-out test was finished at the moment of achieving the displacement of the bar in relation to the initial state by 10 mm. During the test, three values were measured: force, displacement and energy at the maximum load. Tables 2 and 3 and figure 6 show the results of testing reference and frozen samples.

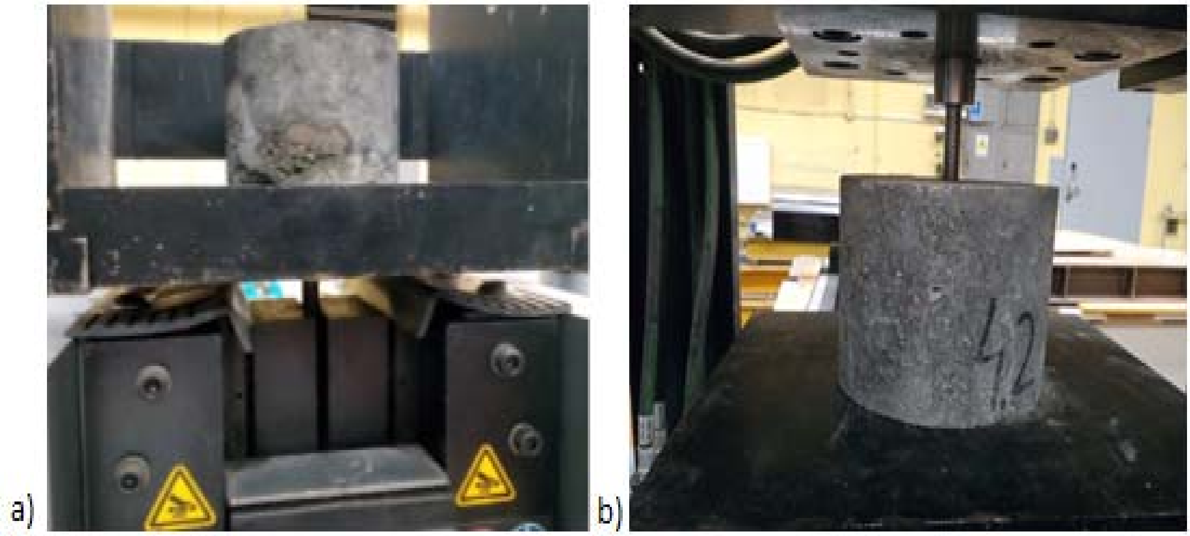

Figure 5. The unit for a) pull-out (pulling the bar out) test, b) push-on (pushing the bar on) test

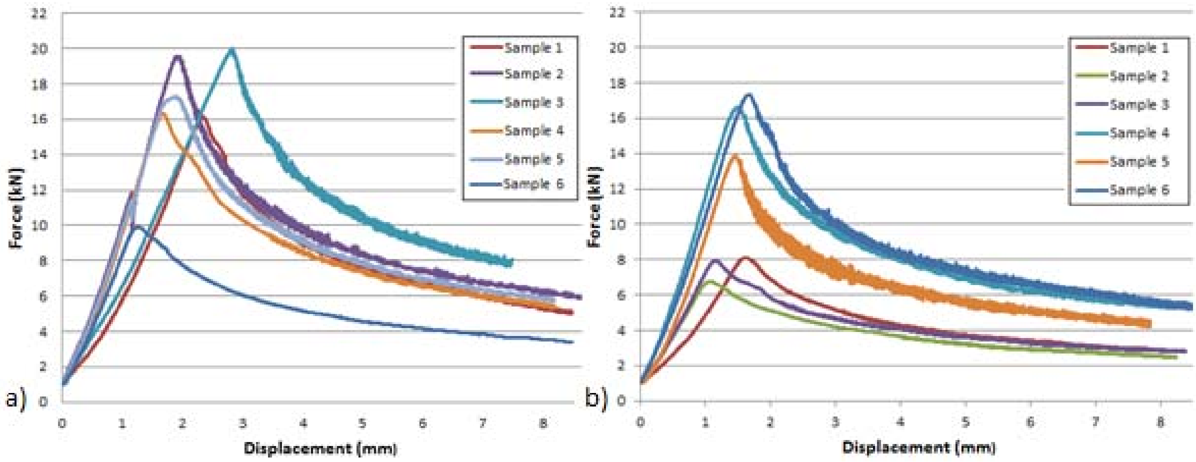

Figure 6. Diagram of the relationship between force and displacement for the pull-out test
a) reference samples, b) frozen samples

Table 2. Results of testing the reference samples – the pull-out method

Sample's label	Tensile displacement at maximum load (mm)	Maximum load (kN)	Shear stress (MPa)	Energy at maximum load (J)
Smooth control 1	2.33	16.16	6.42	18.49
Smooth control 2	2.02	9.90	3.94	7.41
Smooth control 3	2.91	17.62	7.01	18.02
Smooth control 4	1.69	19.64	7.81	19.95
Smooth control 5	2.00	20.02	7.97	29.13
Smooth control 6	1.26	16.33	6.50	14.78
Standard deviation	0.56	3.66	1.46	7.08
Average	2.04	16.61	6.61	17.96

Table 3. Results of testing the cyclically frozen samples – the pull-out method

Sample's label	Tensile displacement at maximum load (mm)	Maximum load (kN)	Shear stress (MPa)	Energy at maximum load (J)
Smooth frozen 1	1.78	6.75	6.75	4.94
Smooth frozen 2	1.07	13.84	13.84	10.80
Smooth frozen 3	1.16	17.34	17.34	15.62
Smooth frozen 4	1.44	8.10	8.10	7.58
Smooth frozen 5	1.40	16.61	16.61	13.67
Smooth frozen 6	1.65	7.90	7.90	5.77
Standard deviation	0.27	4.74	4.74	4.35
Average	1.42	11.76	11.76	9.73

3.3. Tests of the adhesion of a rebar to concrete with the push-on method

For the push-on tests, the twelve remaining cylindrical samples, of which six were cyclically frozen, were used. For the test, as in the case of the pull-out method, the INSTRON 300DX machine with the unit specially prepared for this method was used (figure 5b). The steel bars were pushed out axially from the concrete cylinder at constant speed of 0.05 mm/s according to the diagram shown in figure 2b. The push-on test was finished at the moment of achieving the displacement of the bar in relation to the initial state by 10 mm. As in the pull-out method, three variables were measured: force, displacement, and energy at the maximum load. Tables 4 and 5 and figure 7 show the experiment results.

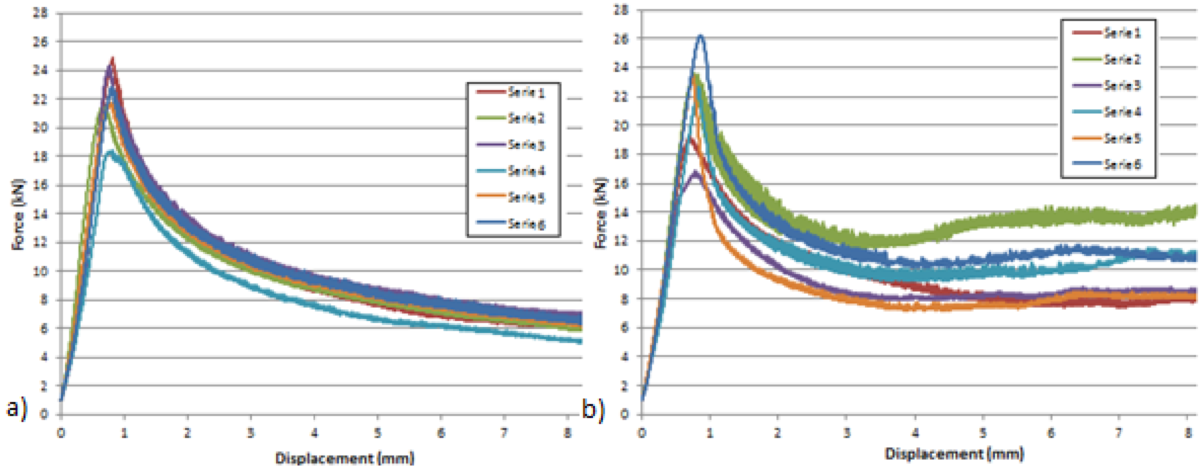

Figure 7. Diagram of the relationship between force and displacement for the push-on test a) reference samples, b) frozen samples

Table 4. Results of testing the reference samples – the push-on method

Sample's label	Tensile displacement at maximum load (mm)	Maximum load (kN)	Shear stress (MPa)	Energy at maximum load (J)
Smooth control 1	0.88	24.82	9.88	11.49
Smooth control 2	0.75	22.84	9.09	9.51
Smooth control 3	0.86	18.35	7.30	8.49
Smooth control 4	0.83	24.31	9.67	9.45
Smooth control 5	0.72	21.40	8.52	8.47
Smooth control 6	0.77	23.02	9.16	9.32
Standard deviation	0.06	4.74	0.93	4.35
Average	0.80	22.46	8.94	9.73

The results of testing the mechanical features of the ordinary and cyclically frozen concretes indicate that the value of shear stress τ depends both on the method of testing this process (the steel bars pulled out or pushed on the concrete) and the impacts of multiple freezing in the temperature range from +18 °C to -18 °C.

Table 5. Results of testing the cyclically frozen samples – the push-on method

Sample's label	Tensile displacement at maximum load (mm)	Maximum load (kN)	Shear stress (MPa)	Energy at maximum load (J)
Smooth frozen 1	0.71	26.22	10.43	12.03
Smooth frozen 2	0.78	23.45	9.33	9.10
Smooth frozen 3	0.70	22.64	9.01	9.81
Smooth frozen 4	0.67	16.90	6.73	8.26
Smooth frozen 5	0.63	23.61	9.39	9.54
Smooth frozen 6	0.79	19.25	7.66	7.79
Standard deviation	0.06	3.36	1.34	1.49
Average	0.71	22.01	8.76	9.42

The average values $\boldsymbol{\tau}$ for the pulled-out bars are:
-6.61 MPa for ordinary concretes;
-4.68 MPa for cyclically frozen concretes;
and for the pushed-on bars, respectively 8.94 MPa and 8.76 MPa, which indicates the decrease in the adhesion by 29% in the case of pulling the bars out and only by 2% in the case of the pushed-on bars. The relationship between $\boldsymbol{\tau}_{\text{pulled-out}}$ and $\boldsymbol{\tau}_{\text{pushed-on}}$ is equal to 0.74 for the ordinary concretes, and for the frozen ones – 0.53.

4. Analyses of SEM images and identification of the chemical composition of the interfacial transition zone

The diverse values of adhesion forces encouraged the authors to execute detailed tests of the steel-concrete contact zone by means of microscope scanning analysis. The contact layers of ordinary and cyclically frozen samples were tested. SEM (figures 8 and 10) and EDS (figures 9 and 11) analyses were conducted.

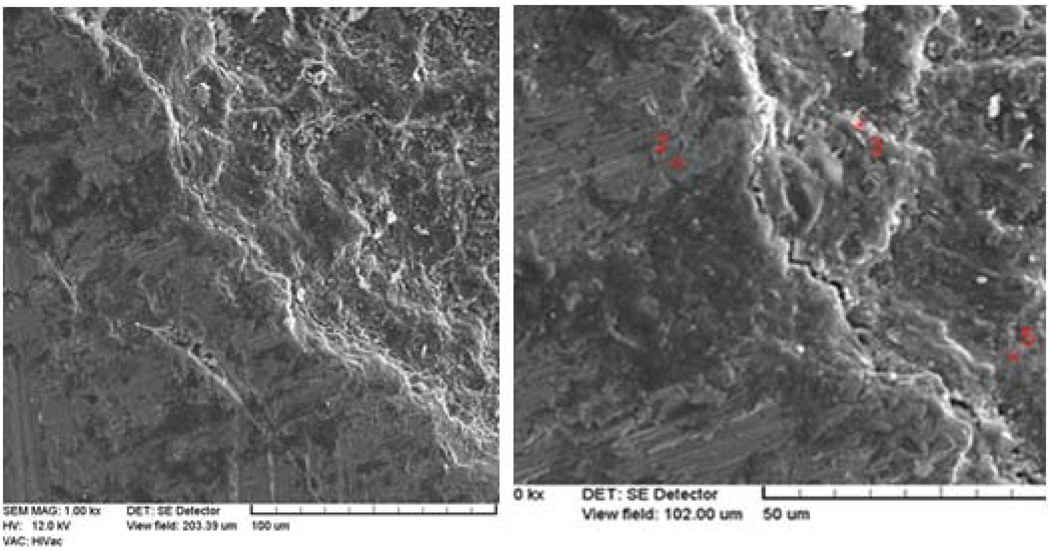

Figure 8. Micrograph of a steel-concrete joint. A visible microscratch on the zones' border. Chemical analysis executed for point 5.

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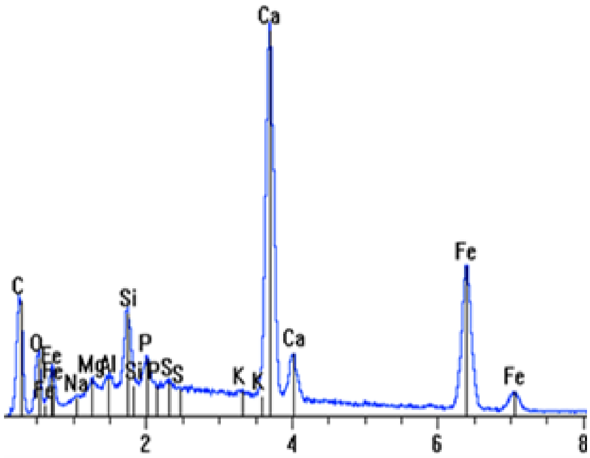


Element	Line	Wt%	At%
O	KA1	7,82	9,43
Na	KA1	0,12	0,10
Mg	KA1	0,46	0,37
Al	KA1	0,50	0,36
Si	KA1	2,06	1,42
Ca	KA1	17,15	8,26
Fe	KA1	27,17	9,39
P	KA1	0,99	0,61
K	KA1	0,00	0,00
C	KA1	43,53	69,95
S	KA1	0,20	0,12
Total		**100,00**	**100,00**

Figure 9. Elements distribution at the distance of 70 µm from the steel bar.

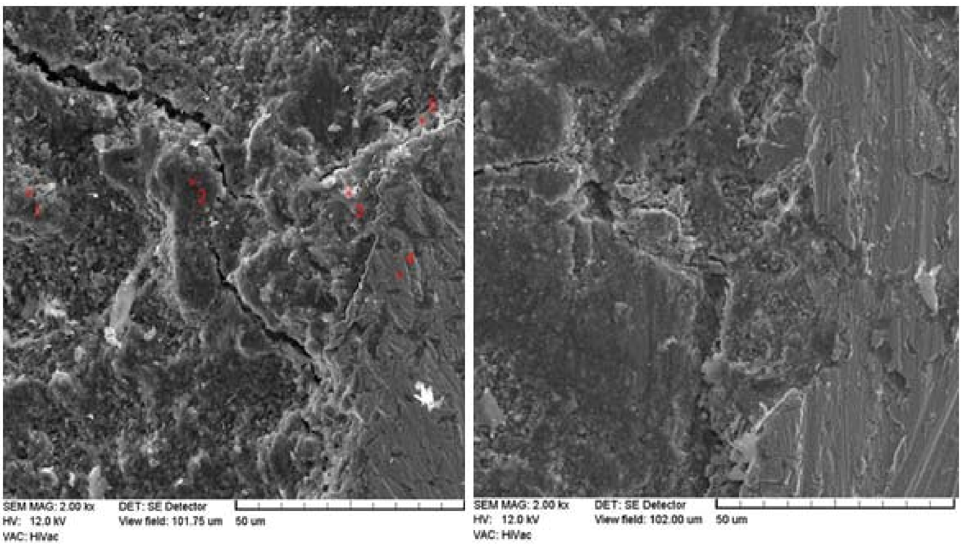
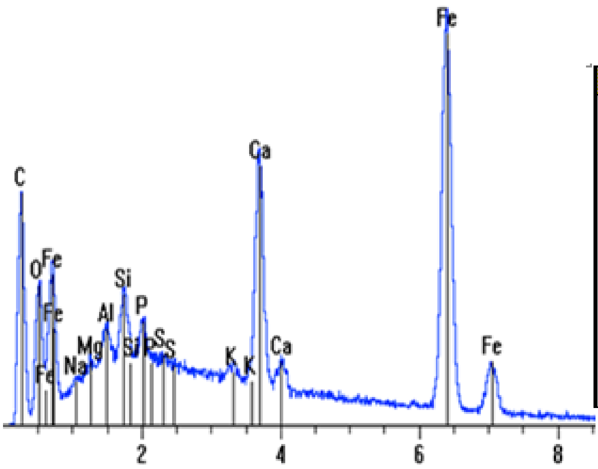


Figure 10. Cyclically frozen concrete. Visible microscratches (2 µm) perpendicular to the bar and loosened concrete structure. Chemical analysis executed for point 3.



Element	Line	Wt%	At%
O	KA1	7,13	8,43
Na	KA1	0,14	0,11
Mg	KA1	0,27	0,21
Al	KA1	0,73	0,51
Si	KA1	1,12	0,75
Ca	KA1	5,34	2,52
Fe	KA1	36,89	12,48
P	KA1	0,80	0,49
K	KA1	0,26	0,13
C	KA1	47,20	74,30
S	KA1	0,12	0,07
Total		**100,00**	**100,00**

Figure 11. Elements distribution at the distance of 50 µm from the steel bar. A noticeably greater iron content in the contact zone.

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5. Conclusions analysis

The tests' results presented in the article concern mainly mechanical characteristics of the steel-concrete contact zone in the reinforced concrete. However, it was stated that the mechanical characteristics depend directly on the environmental conditions, which shape the space around the bar differently. The conducted SEM and EDS analyses prove this.

The values of shear stresses obtained by means of an experiment in the shear test and given in Tables from 2 to 5 are average values. In the engineering practice [11], the computational values obtained by means of statistical estimation of extreme values, adopted as a 5% quantile assuming the normal distribution of the likelihood of the estimated values are used. The shear values depend only on the concrete class and they are respectively: C20/25 – 1.4 MPa, C30/37 – 2.2 MPa, C35/45 – 2.6 MPa, C50/60 – 3.0 MPa.

As results from Tables from 2 to 5, the actual values characteristic for many cases of structure load are significantly higher, and for C35/45 class concretes, they are 4.1 MPa (ordinary concrete) and 1.56 MPa (frozen concrete) for the pull-out test, and 7.4 MPa (ordinary concrete) and 6.6 MPa (frozen concrete) for the push-on test.

The attention is also paid to the mutual relationships of these tests' results: the relationship between τ pulled out and τ pushed on is equal to 0.74 for ordinary concretes and 0.53 for frozen concretes.

The knowledge of these parameters will allow designers to design a structure with an optimal amount of reinforcement and ensuring its safe operation under negative environmental conditions.

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