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EFFECT OF CONCRETE ADDITION OF SELECTED MICRO-FIBERS ON THE REINFORCING BARS CORROSION IN THE REINFORCED CONCRETE SPECIMENS

ABSTRACT

The micro-fibers increase the consistency and uniformity of concrete, which can improve the protective properties of concrete cover and thus should reduce the corrosion of the reinforcement bars in the reinforced concrete elements. The article presents a study which main objective was to specify the effect on concrete mix the addition of steel or polypropylene micro-reinforcement fibers on the reinforcing bars corrosion process. The research included measuring the reinforcement corrosion progress caused by the chloride impact as well as cyclical freezing and thawing specimens test. To measure the electrochemical corrosion progress the non-destructive i.e. galvanostatic pulse method was used. The results were used to conduct a comparative analysis.

Key words: *concrete, reinforced concrete, steel fibers, polypropylene fibers, chloride corrosion*

INTRODUCTION

Randomly scattered the micro-fibers added to the concrete mix increase the concrete consistency and homogeneity [1,2]. The most commonly fibers used in the construction (both the advantageous properties as well as price) are steel and polypropylene fibers. These fibers "merge" the concrete matrix and prevent from the large pores formation in the concrete mix as well as reduce the appearance and spread of shrinkage cracks formed during the concrete setting and hardening. Additionally, the steel fiber increase the concrete mechanical and strength properties [3,4,5] and reduce scratching from the mechanical load. Thanks to the micro-fibers the concrete cover is sealed [2,6], which should positively effects the reinforcement protection, including the limitation of the reinforcement bars corrosion processes.

A common reinforced elements concrete corrosion cause (apart from carbonation) is so called chloride corrosion. Most exposed to it there are bridges elements, tunnels and garages (exposure class XD and XF by Eurocode 2 [7]), due to the use of de-icing substances containing chlorides in the winter, while weakening the concrete due to freezing and thawing [8, 9,10,11]. Due to the chloride penetration ions into the deep concrete coating zone and the physical - chemical processes taking place, the corrosion formation on the rebar surface appear as well as the reinforcement corrosion process development [8,9,11,12,13].

The article publishes the study results which aimed to assess the effect of the steel and polypropylene fibers addition to the concrete on the main reinforcement bars process corrosion. Compared the study results carried out for the three specimens series of the reinforced concrete: concrete specimens without fibers (Series A), specimens in which to the concrete mix the short steel fibers are added (Series B) and specimens in which polypropylene fibers are added to the concrete mix (C series).

EXPERIMENTAL STUDIES

Research Material

There were 18 specimens prepared for testing reinforced concrete pieces with the measurements 100×228×210 mm in three different series:

a) Series A: specimens without the fiber addition (reference specimens) – 6 pieces (name: con_1 ÷ con_6)
b) Series B: specimens with the steel fibers addition – 6 pieces (name: sfc_1 ÷ sfc_6)
c) Series C: specimens with the polypropylene fibers addition – 6 pieces (name: pfc_1 ÷ pfc_6)

All specimens (regardless of the fibers addition) were reinforced. In each specimen there were two parallel ribbed bars placed with a diameter of ϕ8 mm stainless BST 500 arranged in a row distance of 70 mm from the specimen side edge; concrete cover was 25 mm.

All specimens were made according to a formula as for concrete class C30/37, the consistency K-5, w/c = 0.43 as per [14]. The following amounts of ingredients on 1m^3: CEM I cement (CEM I 42.5 N-IAS/NA) - 384 kg, sand - 680 kg, gravel 2 to 8 mm - 600 kg, gravel 8 to 16 mm - 650 kg, water - 166 l, a plasticizer (0.6%), aerator (0.1%). A series specimens were made of concrete without the fibers addition. In specimens B series short steel fibers were added to the concrete mix BauMix 60/1 in an amount of 1% relatively to the mixture volume; Fiber parameters - length l_w = 60 mm, diameter $\varnothing$ = 1.0 mm; shape - straight fibers with hooked ending. In specimens C series polypropylene fibers were added to the concrete mix BauCon in an amount of 0.9 kg/m^3 with the following parameters: length $l_w \approx 12$ mm, diameter $\varnothing \approx 38$ μm, shape - straight fibers.

The concrete mix consolidation took place on the vibrating table. All specimens were made in a laboratory hall with identical thermal conditions and humidity. All the specimens were removed from the molds the next day after concreting and stored in water for seven days. After removal from the water specimens were stored in a air-dried laboratory.

In addition, the accompanied studies have been made in order to the state the concrete class in accordance with [15, 22]. For each series 3 cubic specimens were prepared 150x150x150 mm on which the concrete compressive strength was tested and the average strength was calculated as well as standard deviation and variation coefficient. On this basis, each specimen series were made of concrete class C35/45, i.e. a class higher than assumed.

Galvanostatic pulse method

There was used the measuring galvanostatic pulse method was used to assess the degree of the rebar corrosion risk [16,17,18,19]. This is the electrochemical non-destructive test method that has been developed taking into account that the reinforcement corrosion process in concrete is an electrochemical process. The basis for this method development is the assumption that the concrete with pores filled with alkaline liquid is the electrolyte and the steel rod placed in it is the electrode. Using the appropriate equipment for measuring some electric quantities (which changes result from the corrosion process course) can indirectly (by reference theses values to the criterion limit value) assess the reinforcement corrosion process progress in concrete. In the studies described for the measurements GP-5000 GalvaPulse^{TM} set was used [19,20,21]. The set main equipment is a device to control and record (Psion) Silver-Chloride reference electrode. Set GP-5000 allows you to perform two types of measurements:

a) basic measurements that allow to evaluate the conducive conditions for the corrosion of the concrete tested surface based on two parameters measurements: reinforcement stationary potential - E_{st} and concrete cover resistivity - Θ,
b) extended measurements, which not only allow you to specify the conditions for corrosion, but also allow you to estimate the reinforcement corrosion activity on the basis of measuring the corrosion current density - i_{cor}.

The value obtained from the analysis should be referred to the criterion limit [20,21], which allows a determination of the corrosion occurrence probability in the study area and forecasting its activity over time. Table 1 lists the criteria to assess the reinforcement corrosion risk degree on the basis of three parameters measured [21].

Table 1. *Criteria listed to assess the reinforcement corrosion risk degree according [21]*

Criteria to assess the reinforcement corrosion risk degree			
On the basis of the current corrosion density value	i_{cor} [$\mu A/cm^2$]	< 0.5	not forecast corrosion activity
		0.5 ÷2.0	irrelevant corrosion activity
		2.0 ÷ 5.0	low corrosion activity
		5.0 ÷ 15.0	moderate corrosion activity
		> 15.0	high corrosion activity
On the basis of the stationary potential	E_{st} [mV]	< -350	95% corrosion probability
		-350 ÷ -200	50% corrosion probability
		> -200	5% corrosion probability
On the basis of the concrete cover resistivity	Θ [kΩ·cm]	≤ 10	high corrosion probability
		10 ÷ 20	moderate corrosion probability
		≥ 20	low corrosion probability

Measuring ways

In tests carried out, in order to initiate corrosive processes on the reinforcement bars, the specimens were subjected to 120 cycles of freezing and thawing in 3% sodium chloride solution (NaCl). The study of the reinforcement corrosion progress was made by measuring the galvanostatic pulse using a set of GP-5000 GalvaPulse^{TM} using extended measurements. All specimens in each series measurements were made in two phases: phase I - initial measurements (reference), stage II - after completed measurement cycles of freezing and thawing.

The measurements were made according to the manual that came with this device GP-5000 GalvaPulse^{TM} [21]. On the surface of each specimen four grid points were marked 70mmx70 mm (two points above each bar). At the time of measurement at each designated point three parameters values were recorded: corrosion current density (i_{cor}), reinforcement stationary potential (E_{st}) and concrete cover resistivity (Θ) (Fig.1). During the measurements the concrete surface was strongly hydrated with water to obtain adequate electrical conductivity. The results were archived in the created database.

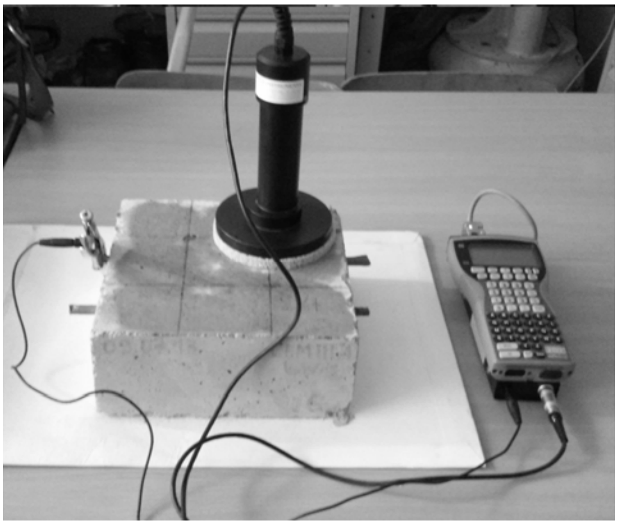

Fig. 1. Measurement using a set GP-5000 GalvaPulse^{TM}

The research results are presented in three tables separately for all recorded parameters (respectively: Tab. 2 ÷ 4). Each table contains the parameter value measured in designated points (P1 ÷ P4) for all tested specimens series (A, B, C) in both measurements stages (I - before freezing, II - after cycles of freezing). Bold values indicate the greatest reinforcement corrosion risk in a given specimen.

Table 2. *Summary of corrosion current density measurements results*

series	specimen number	corrosion current density, i_{cor} [$\mu A/cm^2$]							
		measurement point (coordinates)							
		P1 (1, 1)		P2 (1, 2)		P3 (2, 1)		P4 (2, 2)	
		stage I	stage II	stage I	stage II	stage I	stage II	stage I	stage II
A	con_1	0.58	**10.19**	0.85	6.96	0.57	8.31	0.79	6.67
	con_2	0.66	9.85	0.55	**11.96**	0.69	7.85	0.55	10.17
	con_3	0.83	**12.82**	0.71	9.27	0.87	12.42	0.73	7.59
	con_4	1.08	4.27	1.07	4.22	1.25	**4.86**	1.19	3.63
	con_5	1.74	6.37	1.17	**6.59**	1.48	6.12	0.96	6.37
	con_6	1.31	**6.78**	1.16	5.00	1.20	6.54	0.98	4.90
B	sfc_1	0.85	2.79	0.75	2.54	0.92	2.64	0.71	**2.86**
	sfc_2	1.12	2.63	1.13	2.71	1.04	**2.87**	1.19	2.70
	sfc_3	1.01	2.87	0.92	3.04	0.99	2.37	1.15	**3.55**
	sfc_4	0.75	3.02	0.72	2.92	0.71	2.81	0.87	**3.14**
	sfc_5	0.88	2.75	0.93	2.12	0.95	**2.93**	0.90	2.37
	sfc_6	0.30	2.82	0.33	2.43	0.33	**2.90**	0.32	2.67
C	pfc_1	2.71	**4.84**	2.05	4.33	2.41	3.67	2.36	4.40
	pfc_2	1.43	3.39	2.09	4.19	2.59	**4.21**	2.27	3.83
	pfc_3	2.07	4.93	1.84	3.68	2.29	4.80	2.20	**5.92**
	pfc_4	2.65	4.27	1.94	3.38	1.98	**8.51**	2.10	3.24
	pfc_5	2.30	**5.10**	2.19	3.07	2.16	4.40	2.15	3.55
	pfc_6	2.04	**5.80**	2.30	3.43	2.72	4.55	2.39	3.50

Table 3. *Summary of the reinforcement stationary potential measurements results*

series	specimen number	reinforcement stationary potential, E_{st} [mV]							
		measurement point (coordinates)							
		P1 (1, 1)		P2 (1, 2)		P3 (2, 1)		P4 (2, 2)	
		stage I	stage II	stage I	stage II	stage I	stage II	stage I	stage II
A	con_1	-155	**-256**	-199	-217	-132	-250	-211	-225
	con_2	-131	-280	-138	**-350**	-114	-265	-125	-298
	con_3	-213	-283	-163	-283	-222	**-305**	-152	-271
	con_4	-168	**-224**	-194	-220	-165	-221	-212	-222
	con_5	-150	-282	-257	-288	-155	**-341**	-249	-334
	con_6	-174	-266	-246	**-271**	-180	-254	-247	-252
B	sfc_1	-52	**-363**	-70	-333	-57	-352	-77	-317
	sfc_2	-38	-352	-71	**-360**	-37	-358	-46	-348
	sfc_3	-26	-364	-69	-346	-40	**-370**	-56	-309
	sfc_4	-57	-372	-93	-373	-57	-280	-85	**-379**
	sfc_5	-54	-336	-88	-302	-53	**-340**	-87	-288
	sfc_6	-41	**-360**	-85	-334	-62	-344	-73	-330
C	pfc_1	-42	-279	-61	-285	-43	**-299**	-53	-296
	pfc_2	-86	**-333**	-87	-306	-63	-240	-65	-267
	pfc_3	-40	**-349**	-104	-329	-45	-218	-89	-294
	pfc_4	-77	-211	-84	**-340**	-64	-288	-61	-334
	pfc_5	-40	-285	-65	**-344**	-48	-304	-84	-339
	pfc_6	-67	-282	-76	**-336**	-79	-299	-84	-331

Table 4. *Summary of the concrete cover resistivity measurements results*

series	specimen number	concrete cover resistivity, Θ [kΩ·cm]							
		measurement point (coordinates)							
		P1 (1, 1)		P2 (1, 2)		P3 (2, 1)		P4 (2, 2)	
		stage I	stage II	stage I	stage II	stage I	stage II	stage I	stage II
A	con_1	1.70	**1.30**	1.50	1.40	1.70	1.30	1.60	1.60
	con_2	1.70	1.20	1.60	**0.90**	1.70	1.30	1.40	1.00
	con_3	1.60	**1.10**	1.60	1.20	1.50	1.10	1.60	1.20
	con_4	1.20	1.90	1.10	1.80	1.20	**1.80**	1.10	2.40
	con_5	1.20	**1.30**	1.20	1.40	1.30	1.40	1.30	1.50
	con_6	1.40	1.50	1.30	1.60	1.40	**1.40**	1.20	1.70
B	sfc_1	1.50	0.60	1.80	**0.50**	1.80	0.60	1.90	0.60
	sfc_2	1.40	0.60	1.40	**0.60**	1.30	0.70	1.30	0.60
	sfc_3	1.10	0.60	1.00	0.70	1.30	0.60	1.10	**0.50**
	sfc_4	1.70	**0.50**	1.30	0.60	1.50	0.60	1.40	0.60
	sfc_5	2.00	0.70	1.90	0.80	1.50	**0.60**	1.40	0.70
	sfc_6	3.20	0.60	3.00	0.60	2.80	**0.50**	2.60	0.60
C	pfc_1	2.20	0.80	2.00	0.80	2.60	0.70	2.50	**0.60**
	pfc_2	3.10	0.70	3.20	0.80	3.20	**0.70**	3.40	0.80
	pfc_3	1.80	0.80	1.90	**0.80**	1.90	0.90	1.80	0.80
	pfc_4	3.40	0.90	3.40	**0.80**	3.40	0.90	3.20	0.80
	pfc_5	2.40	0.80	2.00	0.80	2.00	**0.60**	1.80	0.80
	pfc_6	3.30	**0.70**	2.90	0.80	3.00	0.80	2.90	0.80

RESULTS ANALYSIS

The three parameters measurements results, i.e. reinforcement corrosion current density, reinforcement stationary potential and concrete cover resistivity are in the references to the criterion limit [21] in the table 1. From these parameters the corrosion current density is the most reliable measurement result performed directly on the tested rod which defines its corrosion activity. The two other parameters results, i.e. reinforcement stationary potential and concrete cover resistivity are less important because they only specify the corrosion conducive conditions on the tested concrete surface in a probability wide range [16,17,11,18].

On the reinforcement corrosion current density measurements (Tab. 2) basis referenced to listed in table 1 criterion, it can be seen that the Series A specimens (without fiber addition) reinforcement corrosion activity increased between measurements stage I and II from the irrelevant ($i_{cor} < 2 \mu A/cm^2$) to the moderate one ($i_{cor} \sim 5 \div 11.96\ \mu A/cm^2$). The same parameter measurements in the series B specimens (with the short steel fibers addition), demonstrated a significantly lower reinforcement corrosion activity between measurement stage I and II – from the negligible one ($i_{cor} < 2\ \mu A/cm^2$) to low ($i_{cor} = 2.86 \div 3.55\ \mu A/cm^2$). In the Series C specimens (with the polypropylene fibers addition) the reinforcement corrosion current density measurements between the measurements stage I and II of showed an increase in the reinforcement corrosion activity from irrelevant or low ($i_{cor} = 1.43 \div 3.55\ \mu A/cm^2$) to low or moderate ($i_{cor} = 4.21 \div 8.51\ \mu A/cm^2$). The specimens three series results comparison in the second measurements phase suggests that the lowest reinforcement corrosion activity the Series B specimens reveal (with the steel fibers) and the highest series A specimens (without added fiber). The Series C specimens (with polypropylene fiber) the reinforcement is characterized by lower corrosion activity than the Series A specimens, but higher than in series B specimens. Taking into account each specimen the most unfavorable corrosion current density, the Series B specimens (with steel fiber) reveal lower reinforcement corrosion activity than in the series A specimens (without fiber added) by approx. 66%, in series C specimens (containing polypropylene fibers) by approx. 35%.

The reinforcement stationary potential measurements results (Tab. 3) were not as clear as the corrosion current density results. The specimens A series at the first stage the reinforcement stationary potential measurements in most points indicated a 5% corrosion probability ($E_{st} = -114 \div -199$ mV), but in the eight points there was a likelihood of 50% ($E_{st} = -211 \div -257$ mV), which could not reflect the reality (the rods were not corroded). In the second stage, A series specimens at all points measurements showed corrosion probability of 50% ($E_{st} = -212 \div -350$ mV). In the B series specimens in the first measurement stage of fixed the reinforcement stationary potential at all points indicated a 5% corrosion probability ($E_{st} = -26 \div -93$ mV). In the second measurements stage in thirteen examined points the probability increased to 50% ($E_{st} = -280 \div -348$ mV) and in eleven points even to 95% ($E_{st} = -352 \div -379$ mV), which, taking into account visual inspection rather do not correspond to the reality . The Series C specimens in all the examined points the stationary potential indicated the increased likelihood in the reinforcement corrosion from 5% ($E_{st} = -42 \div -104$ mV) in the first measurement stage to 50% ($E_{st} = -211 \div -349$ mV)) in the second measurements stage.

However, it should be noted that the reinforcement stationary potential and the corrosion current density measured in the first and second measurements stage were consistent with each other - at all measurement points the corrosion current density increase was accompanied by a drop in stationary potential.

The concrete cover resistivity measurements results in all specimens points, both in the first and second measurements stage are smaller than 10 kΩ·cm (Tab. 4) which, in accordance with the criterion· (Tab. 1), indicate a high corrosion probability. However, this results interpretation in this case is misleading, because the measurement process enforces itself the need for intensive concrete surface moistening with the water to obtain the relatively great concrete cover conductivity [21] and at the same time also the effect on the resistivity reduction.

SUMMARY AND CONCLUSIONS

Electrochemical studies conducted by measuring the galvanostatic pulse allow you to estimate the main reinforcement bars corrosion progress in the specimens in which in order to initiate corrosion processes the freezing and thawing cycles were subjected in a 3% NaCl solution. Necessary however, is to conduct the expanded research, i.e. three parameters simultaneous measurement of: corrosion current density, reinforcement stationary potential and concrete cover resistivity of which the corrosion current density measurement is most important and most reliable. Measurements of the other two parameters can only be considered as complementary measurements not decisive in the reinforcement corrosion evaluation.

1. On the basis of the corrosion current density measurement results it is said that reinforcement corrosion activity in the specimens subjected to the freezing cycles in a 3% NaCl solution increased:
    - in A series specimens from negligible to moderate,
    - in B series samples from negligible to low,
    - in C series specimens from negligible or low to low or moderate.
2. The current density measurements results analysis of three specimens series showed the differences in the reinforcement corrosion progress which depend whether to the concrete mixture the micro fibers were added and what kind:
    - specimens of the series B, in which to the concrete mix short steel fibers were added to 1%, the main reinforcing bars corrosion activity was lower about 66% in relation to Series A specimens (without fibers),
    - the C series specimens in which to the concrete mix polypropylene fibers were added 0.9 kg/m^3 of the main reinforcement bars corrosion activity was lower on average by 35% in relation to the Series A specimens (without fibers).
3. Limiting the corrosion progress in series B and C specimens may be due to the coating "seal" by adding the fibers.
4. Based on the reinforcement stationary potential measurements results we can say that they are consistent with the corrosion current density measurement results - the increase in the corrosion current density was accompanied by a drop in reinforcement stationary potential; however, the values obtained at certain points providing a 50% corrosion likelihood in the first measuring stage or 95% corrosion likelihood in the measurement second stage, they were unreliable.
5. The results of resistivity measurements concrete cover, because of the need for intensive hydration of concrete, during the tests, was not meaningful to quantify the progress of corrosion of the test samples.

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