Research Article

Wioletta Raczkiwicz*

Use of polypropylene fibres to increase the resistance of reinforcement to chloride corrosion in concretes

<https://doi.org/10.1515/secm-2021-0053>

received June 18, 2021; accepted September 24, 2021

Abstract: Concrete with the addition of polypropylene fibres is more cohesive and has better adhesion, deformability and tightness because the fibres “bind” the concrete matrix together and prevent large pores from forming in the concrete mix and limit the formation and spread of shrinkage cracks. Therefore, it can be assumed that polypropylene fibres affect the effectiveness of the concrete cover as a layer protecting steel bars against corrosion. This article presents the results of tests allowing us to estimate the effect of addition of polypropylene fibres on the reduction of reinforcing bars corrosion in concrete caused by the action of chlorides. Evaluation of the degree of corrosion of the reinforcement was analysed using the electrochemical polarisation galvanostatic pulse technique. The use of such a method allowed for the quantitative estimation of the effect of the addition of polypropylene fibre on the reduction of corrosion activity of the reinforcement in concrete.

Keywords: concrete, polypropylene fibres, rebar, chloride corrosion

1 Introduction

Research on concretes with randomly dispersed micro-reinforcement fibres has been conducted for decades, including concretes with the addition of polypropylene fibres (polymer fiber reinforced concrete (PFRC)) [1–3]. Many properties of this composite have been recognized, investigated and described [4–8]. The properties and application scope of polymer fibres are covered by PN-EN 14889-

2:2007 [9]. However, this issue is still relevant, as evidenced by the latest publications from recent months. They mainly concern the mechanical properties of the PFRC [10–13], as well as rheological ones, especially analysed in the context of using fibre-reinforced concrete for repair [14]. In recent years, particular attention has also been paid to the analysis of the effectiveness of fibres in the context of resistance to high temperatures [15–17]. Although concrete is a material with high thermal resistance, the addition of polypropylene fibres additionally protects the structure during a fire – it extends the time to save people and delays the spread of the fire. Moreover, randomly dispersed reinforcement fibres prevent concrete spattering during fire exposure [18,19]. Concrete with dispersed reinforcement is a “quasi-plastic” and “quasi-uniform” material, so it has better adhesion, deformability and tightness, as well as higher early strength, which is important for structures exposed to aggressive environmental impact, i.e. bridges, tunnels, viaducts, car parks, thin-walled elements (tanks and basins), weirs, retaining walls, elements subjected to dynamic loads, concrete surfaces, industrial floors, as well as for repairs of such structures. The randomly dispersed fibres in the concrete mix reduce stress concentrations and thus limit cracking [20,21]. Concrete with the addition of fibres is more cohesive as the fibres “bind” the concrete matrix together and prevent large pores from forming in the concrete mix and limit the formation and spread of shrinkage cracks that develop during the setting and final setting of the concrete. When added to a fresh concrete mix, they act as micro-reinforcement to reduce plastic shrinkage and limit the formation of shrinkage cracks in hardened concrete. Adding fibres to the concrete mix further aerates the concrete, which improves its frost resistance. The fibres are completely chemically inert, do not affect the hydration rate or the setting final time of the concrete, and do not require a change in the proportions of its components. They act purely mechanically. Zych [22] found that the addition of polypropylene fibres slightly increased the absorbability. However, the author does not state this definitively and suggests that more thorough research needs to be done. On the other

* Corresponding author: Wioletta Raczkiwicz, Department of Concrete Construction and Geotechnics, Kielce University of Technology, Al. 1000 lecia PP 7, 25-314 Kielce, Poland, e-mail: wiolar@tu.kielce.pl

hand, Kařna [23] shows that polypropylene fibres reduce absorbability. The effect of the addition of polypropylene fibres on the physical and mechanical properties of concrete mixes was studied by Sun and Xu [24]. They made observations of the microstructure and transition zone of concrete mixes under a scanning electron microscope. The described studies show that the proportion of microcracks in concrete mixes and the size and content of microcracks in the transition zone decrease with the addition of fibres. There are also ongoing studies on the workability of a concrete mix with the addition of polypropylene fibres. Although it has been established that the optimum addition of polypropylene fibres to concrete mixes should be $0.6\text{--}0.9\text{ kg/m}^3$, the authors in ref. [25] indicate the influence of the share of fibres on workability. The addition of fibres to the concrete reduces the workability of the mix, which is obviously a disadvantage and necessitates the adoption of certain modifications to the mix recipe [26,27]. It is necessary to use plasticizers and fluidizing admixtures, the water/cement ratio should not be less than 0.55, and the aggregate grain diameter should not exceed 16 mm (or even 8 mm in thin elements) [28]. It should also be remembered that the addition of fibres to the concrete increases the cost of the mixture by about 4–6%.

Despite so many publications on concretes with randomly dispersed polypropylene fibres, a few of them were aimed at assessing the effect of the addition of fibres on improving the properties of concretes as a layer protecting reinforcement against corrosion [20,29,30]. The above-mentioned objects, in which polypropylene fibres are added to the construction of reinforced concrete structural elements, are usually exposed to negative environmental influences, which often lead to the initiation and development of the corrosion process, including chloride corrosion. The publications on this subject mainly describe the indirect effect of fibres on the reduction of corrosion in concrete, i.e. the reduction of shrinkage or crack formation [31]. However, there are no quantitative data on how micro-reinforcement in the form of polypropylene fibres limits the corrosive activity of the reinforcement in concrete. Therefore it is worth assessing whether the addition of polypropylene fibres to concrete, despite their possible slight effect on increasing water absorption, but at the same time clearly limiting shrinkage (both plastic and drying shrinkage), will improve the performance of the concrete cover as a layer protecting the rebar against corrosion. This is a very important issue because reinforcement corrosion degree assessment and the corrosion progress prediction are, from the point of view of determining the structural durability, crucial [32–34]. This is of particular importance in the case of industrial and engineering

facilities, which are usually operated under conditions of increased corrosive aggressiveness of the environment.

One of the main causes of reinforcement corrosion, besides the carbonation of concrete, is chloride corrosion [35,36]. Chloride ions dissolved in water (Cl^-) penetrate deep into the pores in the concrete structure, which is often related to the use of de-icing agents in winter containing NaCl and the cyclic freezing and de-icing of liquids in the concrete pores [37,38]. Corrosion centres are formed on the surface of the reinforcement due to electrochemical reactions and the corrosion process develops very quickly [35,36,39–42]. In winter, bridge and road structures are mainly exposed to this type of corrosion. However, chloride corrosion also develops on coastal structures sited in the coastal zone, which, irrespective of the season, are affected by the so-called salt spray [43–46]. It is worth mentioning that the development of chloride corrosion occurs even at high, seemingly safe concrete pH, i.e. $\text{pH} > 11.8$ [47–49]. Chloride corrosion [50–53] is pitting corrosion, which acts punctually and can lead to the bursting of the concrete cover from the inside without any visible changes on the surface of an element. An additional factor increasing the risk of chloride corrosion initiation and development may be any microdefects in the concrete cover, e.g. shrinkage cracks that develop as a result of using the structure in adverse environmental conditions or as a result of recurring freezing and de-freezing of the liquid in winter, which generates stresses causing the concrete to crack. As a result of the microcracks, chloride ions penetrate by diffusion into the concrete cover and damage the passive layer protecting the reinforcement [54,55]. Chloride ions penetrate the concrete cover mainly by diffusion through liquid-filled capillaries. The wetter the environment and the more porous the concrete, with continuous (interconnected) pores, the deeper the ions penetrate with the liquid [36,39,52]. If there are cracks in the concrete, the progression of ion diffusion is even greater [40]. A key factor in protecting the reinforcement against chloride corrosion is therefore the concrete cover made of suitable materials, characterised, among other things, by high tightness, which prevents the penetration of chloride ions [56–59]. A very good way to limit chloride diffusion is to use so-called blast-furnace cements for concrete production. Unfortunately, concretes with blast-furnace cement are much less resistant to carbonation compared to concretes with Portland cement [49]. Therefore, the use of blast-furnace cement in concrete instead of Portland cement (except where increased resistance to chemical aggression is required) is not always beneficial.

An alternative solution, which may improve the protective properties of the concrete cover against the reinforcement in a chloride corrosion risk situation, may be the addition of synthetic polypropylene micro-reinforcement fibres to the concrete mix. This article presents research aimed at assessing the effect of the addition of polypropylene fibres to concrete on the improvement of concrete cover parameters in the context of its protective role in relation to reinforcement in an aggressive environment of chloride ions.

As already mentioned, despite many publications on polypropylene fibre-reinforced concrete, a few of them aimed at assessing the effect of fibre addition on improving the properties of concrete as a layer protecting reinforcement against corrosion. Laboratory tests usually involve either testing the parameters of the fibres or fibre-reinforced concrete, but not steel in the fibre-reinforced concrete. Therefore, it is worth undertaking laboratory tests that will allow us to assess the impact of polypropylene fibres in concrete on reducing the corrosion process of the reinforcement. This article presents the results of such tests.

Measurements were made using the electrochemical polarisation galvanostatic pulse technique. It is one of the few non-destructive methods that allow for a quantitative estimation of the corrosion degree of reinforcement based on the measurements of the corrosion current density [59,60], the only method that allows the simultaneous measurement of three parameters for the assessment of the corrosion risk of reinforcement in concrete [60]. This method allows a relatively simple and quick way to estimate the size of the corrosion probability in the tested specimens and to assess the corrosion activity of the tested reinforcement.

In addition, shrinkage deformation measurements were made and the compressive strength of concrete mixes was determined, with and without fibres.

2 Materials and methods

2.1 Galvanostatic pulse technique

Due to the electrochemical nature of the corrosion process of reinforcement in concrete, it is possible to use electrochemical measurement methods to estimate the degree of corrosion of the rebar and to predict the corrosion rate over time under given environmental conditions [59,61–63]. Tests of this type involve measuring certain electrical quantities that indicate an ongoing corrosion process [64–67]. The tests performed cover measurements of the concrete cover resistivity and measurements of the stationary potential of the reinforcement on the concrete surface of the element, as well as measurements of the corrosion current density of the rebar. The obtained values, after referring them to the limit criteria values (Table 1), allow one to locate the areas of corrosion with a certain probability (based on the results of the concrete cover resistivity and the stationary reinforcement potential) and to estimate the corrosion activity of the reinforcement (based on the results of the reinforcement corrosion current density). It is also possible to estimate the corrosion rate if Faraday's law relating to the electrochemical equivalent is applied, which states that a corrosion current density of $i_{\text{cor}} = 1 \mu\text{A}/\text{cm}^2$

Table 1: Criteria for assessing the degree of reinforcement corrosion risk

Criteria for assessing the degree of reinforcement corrosion risk			
Reinforcement stationary potential, E_{st} (mV)	>–200		5% of corrosion probability
	–350 to –200		50% of corrosion probability
	<–350		95% of corrosion probability
Concrete cover resistivity, θ (k Ω /cm)	≥ 20		Small corrosion probability
	10–20		Medium corrosion probability
	≤ 10		High corrosion probability
		Reinforcement corrosion activity, i_{cor} ($\mu\text{A}/\text{cm}^2$)	Corrosion rate, ($\mu\text{m}/\text{year}$)
Corrosion current density	<0.5	Not forecasted corrosion activity	<6
	0.5–2.0	Irrelevant corrosion activity	6–23
	2.0–5.0	Low corrosion activity	23–58
	5.0–15.0	Moderate corrosion activity	58–174
	>15.0	High corrosion activity	>174

Figure 1: Diagram of GP-5000 GalvaPulse™ connection to reinforcement.

corresponds approximately to a depth of cross-sectional loss of the rebar equal to $11.6 \mu\text{m}/\text{year}$ [60].

Measurements of this type can be made using the polarisation galvanostatic pulse technique. In order to perform such measurements, it is necessary to polarize the tested reinforcement, i.e. to disturb the dynamic equilibrium of the corrosive system, which prevails on the electrode (rebar) immersed in the electrolyte (concrete with pores filled with liquid). In the galvanostatic pulse technique, in order to polarize the rebar and thus excite the flow of electric charges in the corrosive system (which becomes a steel bar immersed in concrete with liquid pores), a current of a certain value should be applied, i.e. generate an electric pulse. Immediately after inducing a charge flow, the corrosion current density should be measured, as well as the stationary potential of the reinforcement and the concrete cover resistivity. Diagrams of

the connection of the tested reinforcing bar with a measuring device that allows for this type of measurement are shown in Figure 1. More detailed information on the method used can be found in publications [59,60,68,69]. This article presents the results of measurements performed using the galvanostatic pulse technique with the GP-5000 GalvaPulse™ kit, which allows measurements of the stationary potential of the reinforcement, the concrete cover resistivity and the corrosion current density simultaneously [60].

This article presents the results of the tests performed using the above-mentioned technique that allowed one to determine the differences in the degree of corrosion of the main reinforcement in standard concrete and fibre-reinforced concrete with randomly dispersed polypropylene fibres. In order to reflect the impact of the aggressive corrosive environment and to initiate corrosion processes on the reinforcement, the specimens were soaked in a 3% sodium chloride solution. In addition, shrinkage deformations were measured and compressive strength values were determined for concrete and fibre-reinforced concrete specimens.

2.2 Testing to assess the degree of reinforcement corrosion

For the main tests to assess the degree of corrosion of the reinforcement in concrete, four specimens were prepared (Figure 2a), including two concrete (C) specimens and two fibre-reinforced concrete (PFC) specimens with the addition of polypropylene fibres in the amount of $0.6 \text{ kg per } 1 \text{ m}^3$ of concrete mix. The specimens had dimensions

Figure 2: Test specimens. (a) Tested specimens, (b) location of the measurement points on the specimen surface.

Figure 3: Photo of polypropylene fibres added to the concrete mix.

of 210 mm × 228 mm × 100 mm, which allowed four measuring points to be located on the surface of each specimen. The measuring points were placed along the bar position line at equal 70 mm intervals (Figure 2b). Thus, for each type of specimen (concrete and fibre-reinforced concrete), results were obtained from 8 measurement points (16 points in total). The specimens were made according to the standard [70] from a concrete mix with the following composition per 1 m³: cement CEM I – 384 kg, sand – 680 kg, gravel 2–8 mm – 600 kg, gravel 8–16 mm – 650 kg, water – 166 L, and plasticizer Adva Flow 440 (0.6% of the cement volume).

BauCon fibres with the following parameters were used in fibre-reinforced polypropylene concrete specimens: fibre length $l_w = 12$ mm, fibre diameter $\varnothing 38 \mu\text{m}$ and shape – straight fibres (Figure 3).

Two parallel $\varnothing 8$ mm diameter ribbed bars of BST 500 steel were placed in each specimen, spaced 70 mm apart from the side edges of the specimen. The assumed cover was 25 mm. The specimens were made under identical laboratory conditions at $20 \pm 2^\circ\text{C}$ and $50 \pm 5\%$ relative humidity. The specimens were removed from the moulds the day after concreting.

In order to initiate chloride corrosion, the specimens were kept for a period of 50 days in a 3% sodium chloride solution. The specimens were stored in a plastic bath in which the specimens were half submerged and the bath was covered with foil so that half of each specimen with one rebar placed there was directly affected by the sodium chloride solution, while the other half of the specimen with the other rebar was affected by the salt spray. The bath was placed in the laboratory hall at a temperature of $20 \pm 2^\circ\text{C}$. The main measurements – estimations of the corrosion probability and corrosion activity of the reinforcement included reference measurements (stage: E I) made before soaking the specimens and measurements after taking the specimens out of solution after 50 days of soaking (stage: E II). The tests used the galvanostatic pulse measurement technique and the GP-5000 GalvaPulseTM measurement kit. Measurements of the relevant parameters, i.e. the potential of the stationary reinforcement (E_{st}) and the concrete cover resistivity (θ) to estimate the probability of corrosion on the tested surface, as well as a measurement of the corrosion current density (i_{cor}) to determine the corrosion activity of the bar, were performed for each bar in each specimen at two measurement points. The results obtained (shown

Table 2: Summary of the measurement results in successive test stages for each bar tested at the selected measuring point

Point No.	Reinforcement stationary potential, E_{st} (mV)		Concrete cover resistivity, θ (k Ω /cm)		Corrosion current density, i_{cor} ($\mu\text{A}/\text{cm}^2$)		Corrosion rate, ($\mu\text{m}/\text{year}$)	
	E I	E II	E I	E II	E I	E II	E I	E II
C_air 1	–146	–411	16.0	3.3	0.58	7.68	7	89
C_air 2	–157	–399	16.8	3.2	0.64	7.25	7	84
C_air 3	–182	–428	13.2	4.1	1.11	8.93	13	104
C_air 4	–187	–434	12.3	5.5	0.68	13.65	8	158
C_sol 1	–103	–251	15.4	1.2	0.58	3.67	7	43
C_sol 2	–133	–237	16.3	1.2	0.79	3.92	9	45
C_sol 3	–167	–235	11.7	3.8	0.73	4.2	9	49
C_sol 4	–194	–213	11.4	2.9	0.64	6.64	7	77
PFC_air 1	–159	–442	13.0	2.6	0.72	8.41	8	98
PFC_air 2	–122	–427	11.4	3.2	0.43	10.07	5	117
PFC_air 3	–102	–397	13.2	1.0	0.5	6.10	6	71
PFC_air 4	–159	–406	12.7	1.1	0.5	9.50	6	110
PFC_sol 1	–155	–248	11.9	10.7	0.78	4.32	9	50
PFC_sol 2	–123	–215	13.8	8.9	0.63	4.44	7	52
PFC_sol 3	–114	–207	9.7	9.7	1.07	3.15	12	37
PFC_sol 4	–124	–201	10.2	12.3	1.14	4.49	13	52

in Table 2) were compared to a database of benchmark results, as summarised in Table 1.

2.3 Measurements of shrinkage strain

As accompanying measurements, shrinkage strain measurements were performed on the specimens intended for testing reinforcement corrosion. For this purpose, in two bases located on the side surfaces of the specimens, along the position line of the rebars, benchmarks were glued (Figure 4) to allow the measurement of shrinkage strains. The shrinkage strain was measured three times: the first time before immersing the specimens in the solution (reference measurement), the second time the day after removing the specimens from the solution (in which the specimens had been for 50 days) and the third time after a further 2 days. A Demec strain gauge manufactured by W.H. Mayes & Son on with a base of 200 mm and an accuracy of 0.002 mm was used for the measurements; the strain gauge constant was 1.6×10^{-5} . The results from the shrinkage strain measurements are summarised in Table 3.

2.4 Testing the compressive strength of concretes

In addition, 18 cubic specimens measuring $150 \text{ mm} \times 150 \text{ mm} \times 150 \text{ mm}$ were made to determine compressive strength, including nine concrete specimens and nine fibre-reinforced concrete specimens.

Testing specimens for compressive strength was performed 28 days after concreting in accordance with the

Figure 4: Photo of specimen used in the test with visible strain measurement benchmarks.

Table 3: Linear strain increments determined in C and PFC specimens

Base number	Measurement I	Measurement II
C _{air} A	−0.064	−0.064
C _{air} B	−0.128	−0.128
Mean value	−0.096	−0.096
C _{sol} A	−0.736	−0.544
C _{sol} B	−0.752	−0.672
Mean value	−0.744	−0.608
PFC _{air} A	−0.016	0.000
PFC _{air} B	−0.032	−0.016
Mean value	−0.024	−0.008
PFC _{sol} A	−0.416	−0.384
PFC _{sol} B	−0.368	−0.352
Mean value	−0.392	−0.368

standard [71]. The specimens were destroyed in a Zwick/Roell SP-Z6000 testing machine with a maximum compressive force of 6,000 kN. The specimens were loaded continuously until destruction at a loading rate of $\sim 0.5 \text{ MPa/s}$. The results (Table 4) were generated in testXpert software compatible with the testing machine.

3 Results

3.1 The degree of reinforcement corrosion

Specimens for estimating the probability of corrosion on the test surface and for assessing the corrosion activity of the reinforcement provided results from 16 measurement points (including 8 points for each type of specimen). The stationary potential of the reinforcement, the concrete cover resistivity and the corrosion current density (E_{st} , θ , i_{cor}) were measured at each point. Based on the corrosion current density values, the corrosion rate determining the depth of loss of the rebar cross-section was calculated and given in ($\mu\text{m/year}$). Measurements were

Table 4: Concrete compressive strength results for specimens C and PFC

	C specimens	PFC specimens
Mean breaking force, $F_{c,cub}$ (kN)	1406.4	1547.6
Mean compressive strength, f_{cm} (MPa)	62.5	68.8
Standard deviation, s (MPa)	2.3	2.5
Coefficient of variation, v	3.7	3.6

Figure 5: Results of the stationary reinforcement potential measurements.

taken twice: first, reference measurements were taken before immersing the specimens in a 3% sodium chloride solution, and then after 50 days, after removing the specimens from the solution. All results are summarised in Table 2 and presented in graphs (Figures 5–7). The specimen symbols in the table mean: C_{air} , PFC_{air} – the halves of the specimens above the solution, while C_{sol} , PFC_{sol} – the halves of the specimens immersed in the

solution, respectively, concrete and fibre-reinforced concrete specimens.

The results obtained are related to the criterion limits shown in Table 1.

The analysis of the results obtained focused on three aspects:

- A comparison of the results of reference measurements and measurements after 50 days of immersion

Figure 6: Results of concrete cover resistivity measurements.

Figure 7: The corrosion current density measurement results.

- of the specimens in a 3% NaCl solution was performed on all tested specimens.
- (b) A comparison of the results obtained depending on whether the areas of the specimens with the measurement points analysed were directly in a solution or whether they were above the solution and therefore subjected to salt spray and possibly to capillary action.
 - (c) A comparison of the results depending on whether there were concrete or fibre-reinforced concrete specimens.

The results of measurements performed using the galvanostatic pulse technique after 50 days of exposure of the specimens to chloride ions by half immersion in a 3% NaCl solution, i.e. partly as a result of the direct action of the solution and partly as a result of salt spray and up to a certain level of capillary action, showed very clearly the impact of this factor on the increased probability of corrosion and the high corrosion activity of the rebars.

The values of the stationary potential of the reinforcement, regardless of whether the specimens were concrete or fibre-reinforced concrete, were $E_{st} = -102$ to -194 mV at the reference measurement stage, indicating a negligible 5% of corrosion probability (according to Table 1). These values increased significantly after the treatment of the specimens with chlorides. In the concrete specimens, values of $E_{st} = -213$ to -251 mV were recorded in areas that were immersed in the solution,

and in areas above the solution, $E_{st} = -399$ to -434 mV. Referring to the criteria values given in Table 1, it can be seen that the probability of corrosion increased to 50% in the halves of the specimens immersed in the solution and to 95% in the halves of the specimens above the solution. A similar trend was observed in the fibre-reinforced concrete specimens: the values of the stationary potential of the reinforcement in the halves of the specimens immersed in the solution were $E_{st} = -201$ to 248 mV, and in the halves above the solution: $E_{st} = -397$ to -442 mV, which indicated, respectively, 50% and 95% probability of corrosion as in the concrete specimens. In both types of specimens, a clear difference was observed in the values of the measured parameters depending on whether the part of the specimen tested was directly immersed in the solution or above the solution. In contrast, no significant effect was observed with the addition of micro-reinforcement fibres (Figure 5). Judging by the clear changes in the value of the stationary reinforcement potential, it can be assumed that chloride ions penetrated deep into the concrete cover along its entire thickness, reaching a high concentration at the reinforcement surface [14].

Concrete cover resistivity measurements made after 50 days of storing the specimens in 3% NaCl solution also indicated significant changes with respect to the reference measurements (Table 2, Figure 6). In concrete specimens, the reference measurement values were in the range $\theta = 11.4$ – 16.8 kΩ/cm, indicating a medium corrosion probability.

In this case, the medium (rather than low) level of probability of corrosion recorded at the reference measurement stage was probably due to the fact that concrete is an unstabilised material in which physical and chemical processes continue to occur long after the mix has set (even for years) and affect the formation of the internal structure of the concrete [47,59]. However, the measurement values taken after 50 days of storing the specimens in solution turned out to be much lower, indicating high corrosion probability: in concrete specimens in halves immersed in solution they were $\theta = 1.2\text{--}3.8\text{ k}\Omega/\text{cm}$, and in halves of specimens above solution, $\theta = 3.2\text{--}5.5\text{ k}\Omega/\text{cm}$. In contrast, in the fibre-reinforced concrete specimens, the resistivity values of the concrete cover varied markedly depending on whether the tested part of the specimen was immersed in the solution ($\theta = 7.7\text{--}8.9\text{ k}\Omega/\text{cm}$), whether this was part of the specimen above the solution ($\theta = 1.0\text{--}3.2\text{ k}\Omega/\text{cm}$). The parts of the specimens that were fully immersed in the solution had significantly higher resistivity.

Measurements of the stationary potential of the reinforcement as well as of the concrete cover resistivity can sometimes lead to very misleading conclusions, as shown, among others, in studies [42,56,57]. Therefore, the most reliable results are provided by measurements of the corrosion current density. In the conducted tests, the values of reference measurements of this parameter, irrespective of whether they concerned concrete or fibre-reinforced concrete specimens, were within the range $i_{\text{cor}} = 0.5\text{--}1.14\text{ }\mu\text{A}/\text{cm}^2$, which indicated insignificant corrosion activity of the reinforcement (Table 1). On the other hand, the measurements taken after 50 days of storing the specimens in solution showed clearly higher values. Similar to the measurements of the previously described parameters: the stationary potential of the reinforcement and the concrete cover resistivity, the values varied depending on whether the tested halves of the specimens were immersed in the solution or were above the solution (Figure 7). In concrete specimens the halves of which were immersed, at most of the measured points the corrosion current density was in the range $i_{\text{cor}} = 3.67\text{--}4.2\text{ }\mu\text{A}/\text{cm}^2$ and only at one point it reached the value $i_{\text{cor}} = 6.64\text{ }\mu\text{A}/\text{cm}^2$, which indicated rather a low corrosion activity of the reinforcement, while in the halves of the specimens above the solution it reached values in the range $i_{\text{cor}} = 7.25\text{--}13.65\text{ }\mu\text{A}/\text{cm}^2$ indicating an average corrosion activity of the reinforcement. A similar trend was observed in the fibre-reinforced concrete specimens: the corrosion current density of the reinforcement in the halves of the specimens immersed in the solution was $i_{\text{cor}} = 3.15\text{--}4.49\text{ }\mu\text{A}/\text{cm}^2$ (low corrosion activity of the reinforcement), while in the halves above the solution: $i_{\text{cor}} = 6.10\text{--}10.07\text{ }\mu\text{A}/\text{cm}^2$ (average corrosion activity

of the reinforcement). In addition, it can be noted that the results for the fibre-reinforced concrete specimens indicated a lower corrosion activity of the reinforcement than in the concrete specimens – when comparing the maximum values from both specimen types, the differences reached 30%. These differences indicate that the use of polypropylene fibres in concrete increases the tightness of the concrete cover probably by blocking the formation of an interconnected pore system in the concrete, as well as a more uniform distribution of the concrete mix components.

The corrosion current density measurements made it possible not only to determine the corrosion activity of the reinforcement, but also, after conversion, to estimate the corrosion rate. In the concrete specimens, in those halves that were immersed in the solution, this value indicated a depth of bar section loss of approx. $43\text{--}77\text{ }\mu\text{m}/\text{year}$, and in the halves above the solution: $84\text{--}158\text{ }\mu\text{m}/\text{year}$. In contrast, these values were slightly lower in the fibre-reinforced concrete specimens and were, respectively, $37\text{--}52\text{ }\mu\text{m}/\text{year}$ for halves of specimens immersed in the solution and $71\text{--}117\text{ }\mu\text{m}/\text{year}$ for halves of specimens from the above solution.

Note that the above values predict the corrosion activity of the reinforcement in specimens subjected to constant, aggressive external environmental factors, such as those encountered during the test. If these factors change, the corrosion activity of the reinforcement also changes.

The differences in the values of the parameters that were measured on the same specimens but in their different halves (immersed in the solution and above the solution) indicating that corrosion of the reinforcement is clearly more likely to occur and faster in the parts of the specimens above the solution, are due to the corrosion process itself. Admittedly, the concentration of chloride ions in the solution is probably greater than in the “salt spray” (although this was not measured in the described tests) but for corrosion to develop on the reinforcement, the presence of oxygen, which is contained in the air, is required to penetrate more easily into the concrete cover above the solution [34,35,47].

3.2 Shrinkage strain

Linear strains were also measured during the tests. These measurements were made in each specimen (on the two side walls) three times, i.e. before immersing the specimens in the solution (reference measurement), the day after removing the specimens from the solution (in which

Figure 8: Compression strength test charts: (a) C specimens and (b) PFC specimens.

they had been 50 days) and after another 2 days. On the basis of the performed measurements, the strain increments were calculated in relation to the reference measurements, which are presented in Table 3.

The second contains the values of strain increments obtained from measurements taken on the day after the removal of the specimens from solution referred to the measurements before immersion, and the third column contains the values of the strain increments 2 days later. A minus sign indicates that swelling associated with 50 days storage of specimens in solution has occurred in all specimens. However, the magnitude of the changes varied. Obviously, the magnitude of strains was very much affected by whether the wall of the specimen on which the measuring benchmarks were located was immersed in the solution or was above the solution. Furthermore, the effect of the addition of polypropylene fibres on the values obtained is also evident. In the fibre-reinforced concrete specimens on the walls that were immersed in the solution,

the strain increments were on average 47% lower than in the similarly recorded concrete specimens. This confirms the conclusions of the electrochemical tests, which show that the use of polypropylene fibres in concrete has the effect of blocking the formation of a system of interconnected pores and thus limits the extent of penetration of the solution deep into the concrete.

3.3 Concrete compressive strength

Concrete compressive strength tests were performed as accompanying tests. The tests were performed on cubic specimens prepared for two types of concrete mixes: concrete without fibres (9 specimens) and concrete with polypropylene fibres (nine specimens). From the results obtained, the mean compressive strength, standard deviation and coefficient of variation were calculated. Specimen compression charts (generated in the testXpert program

compatible with the testing machine) are shown in Figure 8 and the values obtained are summarised in Table 4.

The result shows that the addition of polypropylene fibres at a rate of 0.6 kg/m^3 of the concrete mix did not significantly affect its strength parameters. The compressive strength of the fibre-reinforced concrete (PFC) specimens increased by 10% compared to the concrete specimens, and the standard deviation and coefficient of variation were comparable.

4 Conclusion

The tests presented in this paper were aimed at determining whether randomly dispersed polypropylene fibres in the concrete mix have an effect on improving the properties of the concrete cover as a layer protecting rebar against chloride-induced corrosion.

- (1) Based on the results obtained from electrochemical polarisation measurements using the galvanostatic pulse technique, and a comparative analysis performed for concrete and fibre-reinforced concrete specimens, it was found that the addition of 0.6 kg/m^3 polypropylene fibres to the concrete mix reduced corrosion of the reinforcement in the specimens tested.
- (2) The analysis of the results of the corrosion current density (the most reliable of the three parameters measured by the galvanostatic pulse method) indicated nearly 30% lower corrosion activity of the reinforcement in specimens with the addition of polypropylene fibres than in concrete specimens. At the same time, it means a slower corrosion rate of the reinforcement in specimens with the addition of polypropylene fibres.
- (3) The results of the concrete cover resistivity measurements showed a positive effect of the fibre addition on increasing the protective role of the concrete cover in relation to the reinforcement.
- (4) The reinforcement stationary potential measurements gave comparable results in both types of specimens. However, it can be concluded that the addition of fibres did not adversely affect the properties of the concrete cover.
- (5) On the basis of the performed tests, it was found that the exposure of reinforced concrete specimens to a 3% sodium chloride solution for 50 days has a significant impact on the corrosive activity of the tested bars and significantly increases the likelihood of corrosion development.
- (6) The tests showed that the rods that were placed in the parts of the specimens located above the solution, and not directly in the solution, are more exposed to the development of chloride corrosion.
- (7) It was found that the addition of polypropylene fibres reduces linear strains in concrete.
- (8) It was also found that the addition of polypropylene fibres only slightly improves the compressive strength of the specimens.

Funding information: This research was funded by grant number 02.0.06.00/2.01.01.01.00.0000; SUBB.BKWB.20.002 “Concrete structure tests” [Kielce University of Technology, Kielce, Poland].

Conflict of interest: Author states no conflict of interest.

References

- [1] Ramakrishnan V. Materials and properties of fibre reinforced concrete. *Proc ISFRC*. 1987;1(1):3–24.
- [2] Brandt AM. Fibre reinforced cement-based (FRC) composites after over 40 years of development in building and civil engineering. *Compos Struct*. 2008;86:3–9.
- [3] Brandt AM. Cement based composites: materials, mechanical properties and performance. Boca Raton, Florida, United States: Taylor & Francis, CRC Press; 2009.
- [4] Adhikary SK, Rudžionis Ž, Balakrishnan A, Jayakumar V. Investigation on the mechanical properties and post-cracking behavior of polyolefin fibre reinforced concrete. *Fibres*. 2019;7(1):8. doi: 10.3390/fib7010008.
- [5] Glinicki MA. Testing of macro-fibres reinforced concrete for industrial floors. *Cem Lime Concr*. 2008;13:184–95.
- [6] Kurlapov D, Klyuev S, Biryukov Y, Vatin N, Biryukov D, Fediuk R, et al. Reinforcement of flexural members with basalt fibre mortar. *Fibres*. 2021;9(4):26. doi: 10.3390/fib9040026.
- [7] Karwowska J, Łapko A. The usability of using modern fibre reinforced composites in building constructions (in polish). *Civ Environ Eng*. 2011;2:41–6.
- [8] Jasiczak J, Mikołajczak P. Technology of concrete modified with admixtures and additives: overview of domestic and foreign trends (in polish). Poznań: Monograph, Poznan University of Technology Publisher; 1997.
- [9] PN-EN 14889-2:2007 Fibres for concrete – Part 2: Polymer fibres – Definitions, requirements and compliance.
- [10] Jhatila AA, Mastoi AK, Siyal ZA, Rind TA, Memon IA. Influence of long polypropylene fibre on the properties of concrete. *Quest Res J*. 2020;18(2):38–43. doi: 10.52584/QRJ.1802.06.
- [11] Vivas JC, Zerbino R, Torrijos MC, Giaccio G. Effect of the fibre type on concrete impact resistance. *Constr Build Mater*. 2020;264:120200. doi: 10.1016/j.conbuildmat.2020.120200.
- [12] Korneeva I. Extensibility of fibre reinforced concrete. *IOP Conf Ser Mater Sci Eng*. 2019;667:012044. doi: 10.1088/1757-899X/667/1/012044.

- [13] Logoń D, Schabowicz K, Roskosz M, Fryczowski K. The increase in the elastic range and strengthening control of quasi brittle cement composites by low-module dispersed reinforcement: an assessment of reinforcement effects. *Materials*. 2021;14(2):341. doi: 10.3390/ma14020341.
- [14] Mandava N, Murali K, Reddy MS, Reddy N. Investigation of reinforced concrete beams by incorporating polypropylene fibre reinforced polymer composites. *Int J Civ Eng Technol*. 2018;9(1):423–30.
- [15] Schabowicz K, Sulik P, Zawiślak Ł. Reduction of load capacity of fibre cement board facade cladding under the influence of fire. *Materials*. 2021;14(7):1769. doi: 10.3390/ma14071769.
- [16] Morgan AB, Gilman JW. An overview of flame retardancy of polymeric materials: application, technology, and future directions. *Fire Mater*. 2013;37(4):259–79. doi: 10.1002/fam.2128.
- [17] Wang DY. Novel fire retardant polymers and composite materials. Duxford, UK: Woodhead Publishing; 2017.
- [18] Ede A, Aina AO. Effects of coconut husk fibre and polypropylene fibre on fire resistance of concrete. *Int J Eng Sci Manag*. 2015;5(1):171–9.
- [19] Chang CP, Huang SW, Li XF, Tian B, Hou ZY. A study of the capability for fire resistance of polypropylene fibre concrete. *Adv Mater Res*. 2013;857:116–23. doi: 10.4028/www.scientific.net/AMR.857.116.
- [20] Berrocal CG, Lundgren K, Löfgren I. The effect of fibres on corrosion of reinforced concrete. In: *fib Bulletin 95. Fibre reinforced concrete: from design to structural applications*. Switzerland: Ecole Polytechnique Fédérale de Lausanne; 2020. doi: 10.35789/fib.BULL.0095.Ch37.
- [21] Zhao X, Liu R, Qi W, Yang Y. Corrosion resistance of concrete reinforced by zinc phosphate pretreated steel fibre in the presence of chloride ions. *Materials*. 2020;13(16):3636. doi: 10.3390/ma13163636.
- [22] Zych T. Study on water permeability, frost damage and de-icing salt scaling of hybrid fibre reinforced concretes. 11th International Symposium on Brittle Matrix Composites (BMC). Vol. 11. Warsaw: Brittle Matrix Composites; Sep 28–30, 2015. p. 239–50.
- [23] Kaźna Z. The use of fibres for cement slurries in boreholes. *Kerosene – Gas* 3, 2009.
- [24] Sun Z, Xu Q. Microscopic, physical and mechanical analysis of polypropylene fibre reinforced concrete. *Mater Sci Eng A*. 2009;527:198–204. doi: 10.1016/j.msea.2009.07.056.
- [25] Nelyubova V, Babaev V, Alfimova N, Usikov S, Masanin O. Improving the efficiency of fibre concrete production. *Constr Mater Products*. 2020;2(2):1–7. doi: 10.34031/2618-7183-2019-2-2-4-9.
- [26] Muley P, Varpe S, Ralwani R. Chopped carbon fibres innovative material for enhancement of concrete performances. *Int J Sci Eng Appl Sci (IJSEAS)*. 2015;1(4):164–9.
- [27] Jena B, Sahoo K, Mohanty BB. Comparative study on self-compacting concrete reinforced with different chopped fibres. *Proc Inst Civ Engineers: Constr Mater*. 2018;171(2):72–84.
- [28] Glinicki MA. Concrete with structural reinforcement. XXV Nationwide Workshops Struct Designers; 2010. p. 279–308.
- [29] Racziewicz W, Kossakowski PG. Electrochemical diagnostics of sprayed fibre-reinforced concrete corrosion. *Appl Sci*. 2019;9:3763. doi: 10.3390/app9183763.
- [30] Srikumar R, Das BB, Goudar SK. Durability studies of polypropylene fibre reinforced concrete: select proceedings of ICSCBM 2018. *Sustain Constr Build Mater*. Singapore: Springer; 2019. doi: 10.1007/978-981-13-3317-0_65.
- [31] Mardani-Aghabaglou A, İlhan M, Özen S. The effect of shrinkage reducing admixture and polypropylene fibres on drying shrinkage behaviour of concrete. *Cem Lime Concr*. 2019;22/84(3):227–31. doi: 10.32047/CWB.2019.24.3.227.
- [32] Hoła J, Bień J, Sadowski Ł, Schabowicz K. Non-destructive and semi-destructive diagnostics of concrete structures in assessment of their durability. *Bull Pol Acad Sci Technical Sci*. 2015;63(1):87–96. doi: 10.1515/bpasts-2015-0010.
- [33] Kothari A, Habermehl-Cwirzen K, Hedlund H, Cwirzen A. A review of the mechanical properties and durability of ecological concretes in a cold climate in comparison to standard ordinary portland cement-based concrete. *Materials*. 2020;13(16):3467. doi: 10.3390/ma13163467.
- [34] Landa Ruiz L, Croche Belin R, Santiago Hurtado G, Baltazar Zamora M, Moreno Landeros VM, Cuevas-Rodríguez J, et al. Evaluation of the influence of the level of corrosion of the reinforcing steel in the moment-curvature diagrams of rectangular concrete columns. *Eur J Eng Res Sci*. 2021;6(3):74–80. doi: 10.24018/ejers.2021.6.3.2423.
- [35] Bertolini L, Elsener B, Pedersen P, Polder R. Corrosion of steel in concrete. 2nd edn. Weinheim: Wiley VCH; 2004.
- [36] Kurdowski W. Cement and concrete chemistry. Industrial chemistry and chemical engineering. Warsaw, Poland: Springer, Ringier Axel Springer Polska; 2014.
- [37] Verma SK, Bhaduria SS, Akhtar S. Monitoring corrosion of steel bars in reinforced concrete structures. *Sci World J*. 2014;2014:957904. doi: 10.1155/2014/957904.
- [38] Luo D, Li Y, Li J, Lim KS, Nazal NAM, Ahmad H. A recent progress of steel bar corrosion diagnostic techniques in RC structures. *Sensors*. 2018;19:34.
- [39] Jaśniok M. Assessing effects of chloride-induced corrosion of galvanized reinforcing steel in cement mortar, using impedance spectroscopy and scanning microscopy. *Prot Corros*. 2018;61(7):176–81. doi: 10.15199/41.2018.7.1.
- [40] Krykowski T, Jaśniok T, Recha F, Karolak M. A cracking model for reinforced concrete cover, taking account of the accumulation of corrosion products in the ITZ layer, and including computational and experimental verification. *Materials*. 2020;13(23):5375. doi: 10.3390/ma13235375.
- [41] Racziewicz W, Wójcicki A, Grzmil W, Zapła-Sławeta J. Impact of environment conditions on the degradation process of selected reinforced concrete elements. *Mater Sci Eng*. 2019;471:032048. doi: 10.1088/1757-899X/471/3/032048.
- [42] Racziewicz W. Influence of the air-entraining agent in the concrete coating on the reinforcement corrosion process in case of simultaneous action of chlorides and frost. *Adv Mater Sci*. 2018;18(1):13. doi: 10.1515/adms-2017-0023.
- [43] Jaśniok M, Jaśniok T. Measurements on corrosion rate of reinforcing steel under various environmental conditions, using an insulator to delimit the polarized area. In: 9th International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures, *Procedia Engineering*. Vol. 193; 2017. p. 4310438. doi: 10.1016/j.proeng.2017.06.234.

- [44] Melchers R. Long-term durability of marine reinforced concrete structures. *Mar Sci Eng.* 2020;8(4):290. doi: 10.3390/jmse8040290.
- [45] Liu J, Jiang Z, Zhao Y, Zhou H, Wang X, Zhou H, et al. Chloride distribution and steel corrosion in a concrete bridge after a long-term exposure to natural marine environment. *Materials.* 2020;13(17):3900. doi: 10.3390/ma13173900.
- [46] Wang Y, Liu C, Li Q, Wu L. Chloride ion concentration distribution characteristics within concrete covering-layer considering the reinforcement bar presence. *Ocean Eng.* 2019;173:608–16.
- [47] Ściślewski Z. Durability of reinforced concrete structures. Warsaw: Arkady; 1999. (in Polish).
- [48] Chess P, Green W. Durability of reinforced concrete structures. 1st edn. Boca Raton, FL, USA: CRC Press; 2019.
- [49] Raczkiwicz W, Grzmil W. Assessment of the impact of cement type on the process of concrete carbonation and reinforcement corrosion in reinforced concrete specimens. *Cem Lime Concr.* 2017;4:311–9.
- [50] Kuziak J, Woyciechowski P, Kobyłka R, Wcisło A. The content of chlorides in blast-furnace slag cement as a factor affecting the diffusion of chloride ions in concrete. *MATEC Web Conf.* 2018;163:05007. doi: 10.1051/mateconf/201816305007.
- [51] Ariza-Figueroa HA, Bosch J, Baltazar-Zamora MA, Croche R, Santiago-Hurtado G, Landa-Ruiz L, et al. Corrosion behavior of AISI 304 stainless steel reinforcements in SCBA-SF ternary ecological concrete exposed to MgSO_4 . *Materials.* 2020;13(10):2412. doi: 10.3390/ma13102412.
- [52] Brodnan M, Koteš P. Assessment of the current state of the concrete structure of the tribune. *Structure.* 2020;12(2):72–6. doi: 10.30540/sae-2020-008.
- [53] Hajkova K, Smilauer V, Jendele L, Červenka J. Prediction of reinforcement corrosion due to chloride ingress and its effects on serviceability. *Eng Struct.* 2018;174:768–77.
- [54] Trąpczyński W, Goszczyńska B, Bacharz M. Acoustic emission for determining early age concrete damage as an important indicator of concrete quality/condition before loading. *Materials.* 2020;13(16):3523. doi: 10.3390/ma13163523.
- [55] Świt G. Acoustic emission method for locating and identifying active destructive processes in operating facilities. *Appl Sci.* 2018;8(8):1295. doi: 10.3390/app8081295.
- [56] Bacharz K, Raczkiwicz W, Bacharz M, Grzmil W. Manufacturing errors of concrete cover as a reason of reinforcement corrosion in a precast element—case study. *Coatings.* 2019;9(11):702. doi: 10.3390/coatings9110702.
- [57] Tworzewski P. Impact of concrete cover thickness deviations on the expected durability of reinforced concrete structures. *Constr Rev.* 2017;11:52–5 (in Polish).
- [58] Otieno M, Ikotun J, Ballim Y. Experimental investigations on the influence of cover depth and concrete quality on time to cover cracking due to carbonation-induced corrosion of steel in RC structures in an urban, inland environment. *Constr Build Mater.* 2019;198:172–81. doi: 10.1016/j.conbuildmat.2018.11.215.
- [59] Raczkiwicz W, Wójcicki A. Evaluation of effectiveness of concrete coat as a steel bars protection in the structure – galvanostatic pulse method. In: *Proceedings of the 26th International Conference on Metallurgy and Materials.* Brno, Czech; 2017.
- [60] GalvaPulse. Available online: <http://www.germann.org/TestSystems/GalvaPulse/GalvaPulse.pdf> (Accessed on 28 September 2019).
- [61] Brodnan M, Koteš P, Bahleda F, Šebök M, Kučera M, Kubissa W. Using non-destructive methods for measurement of reinforcement corrosion in practice. *Prot Corros.* 2017;3:55–8. doi: 10.15199/40.2017.3.1.
- [62] Helal J, Sofi M, Mendis P. Non-destructive testing of concrete: a review of methods. *Electron J Struct Eng.* 2015;14(1):97–105.
- [63] Nikoo M, Sadowski Ł, Nikoo M. Prediction of the corrosion current density in reinforced concrete using a self-organizing feature map. *Coatings.* 2017;7(10):1–14. doi: 10.3390/coatings7100160.
- [64] Zhu XE, Dai MX. A discuss on basing half-cell potential method for estimating steel corrosion rate in concrete. *Appl Mech Mater.* 2012;166–169:1926–30. doi: 10.4028/www.scientific.net/AMM.166-169.1926.
- [65] Jaśniok M, Jaśniok T. Evaluation of maximum and minimum corrosion rate of steel rebars in concrete structures, based on laboratory measurements on drilled cores. *Procedia Eng.* 2017;193:486–93. doi: 10.15199/40.2019.8.1.
- [66] Rengaraju S, Neelakantan L, Pillai R. Investigation on the polarization resistance of steel embedded in highly resistive cementitious systems – an attempt and challenges. *Electrochim Acta.* 2019;308:131–41. doi: 10.1016/j.electacta.2019.03.200.
- [67] Vedalakshmi R, Balamurugan L, Saraswathy V, Kim S-H, Ann KY. Reliability of galvanostatic pulse technique in assessing the corrosion rate of rebar in concrete structures: laboratory vs field studies. *KSCE J Civ Eng.* 2010;14:867–77. doi: 10.1007/s12205-010-1023-6.
- [68] Tworzewski P, Raczkiwicz W, Grzmil W, Czapik P. Condition assessment of selected reinforced concrete structural elements of the bus station in Kielce. *MATEC Web Conf.* 2019;284:06007. doi: 10.1051/mateconf/201928406007.
- [69] Raczkiwicz W, Wójcicki A. Some aspects of the reinforcing steel corrosion level prediction in concrete using electrochemical method. *Weld Technol Rev.* 2017;89(11):28–33. doi: 10.26628/wtr.v89i11.830.
- [70] PN-EN 206 + A1:2016-12 Concrete – specification, qualities, production and conformity. Warsaw, Poland: Polish Committee for Standardization; 2017.
- [71] PN-EN 12390-3: 2002 Testing of concrete – Part 3: compressive strength of concrete specimens. Warsaw, Poland: Polish Committee for Standardization; 2008.