

Corrosion Susceptibility of Steel rebars at Construction Sites

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Abstract

Steel rebars represent a main component of reinforced concrete and their quality largely influences the structural and long-term behavior of structures. A quality control plan is established to monitor the supply on the site and the performance of the rebars. Generally, the tensile strength complies with the general requirements, due to the Tempcore production process, that forms a hard tempered martensitic layer in the outer shell of the rebars. On the other hand, the high number of MnS inclusions and the increased corrosion susceptibility of the steel rebar's outer layer as compared to the ferritic-perlitic microstructure of the steel rebar cores, requires a careful monitoring of the steel rebar's durability, to attain 100 years of service life of reinforced concrete infrastructures.

Keywords: Rebars, quality, construction site, tempered martensite, durability.

Introduction

Reinforced concrete structures contain a high amount of steel rebars. These latter are produced in industry plants from the raw minerals or in a recycled loop by melting steel scrap and using electric arc furnaces. Quality controls at production plants are regularly done, according to several standards Standard Sia 262, Concrete Structures (2013), Standard Sia 269/2 - the Swiss Code for Existing Concrete Structures (2010), Standard EN 10080, Steel for the reinforcement of concrete — Weldable reinforcing steel — General (2006), Standard EN ISO 15630-1, Steel for the reinforcement and prestressing of concrete -Test methods, Part 1: Reinforcing bars, rods and wire (2019) and Standard EN ISO 15630-2, Steel for the reinforcement and prestressing of concrete -Test methods -Part 2: Welded fabric and lattice girders (2019). Scattering of the main steel parameters may range within an interval of about 5-10% of the total produced rebar's amount. Usually, mechanical properties, such as the yield and ultimate tensile strength comply with the main requirements related to the type of the steel rebar. On the other hand, at the construction site, the origin of the steel rebars and the suppliers may be partially different from those required by the call for tenders. Furthermore, some main properties, such as the linear mass, the tensile strength, the strain, the ductility, the chemical composition as well as the weldability of the steel rebars may differ from the metallic material, that is supposed to be provided on site. In addition, the microstructure of the steel rebars and the content of intermetallics as well as the inclusions may influence the durability and the general corrosion behaviour of the steel rebars. Often an increase in the strength may result in a lowering of other properties. Thermal treatments and cooling procedures may provide a satisfactory

balance of the steel characteristics. However, the precipitate's distribution within the grains or along Grain Boundaries (GB) as well as the chemical composition, grain size and chemical depletion along GB's, influence the corrosion.

Steel rebars can be subjected to a Tempcore® process, where the rolling bar is rapidly cooled with water to form a martensitic surface layer and ferrite-perlite in the core. Heat flowing from the core to the surface causes a self-tempering of the martensite (Economopoulos et al., 1975). The rolling parameters control the thickness of the tempered martensite outer layer, the tempering temperature and the heat transfer (Sankar et al., 2010). The yield strength of Tempcore treated steel rebars B 500B C-Mn steel with diameters 10-16 mm is a function of the martensite presence and the water flow, pressure, temperature, quenching time and chemical composition of the bars (Purcell, 2000). The mechanical performance at room temperature of the steel rebars depends on the volume fraction of the phases (Rodríguez & Gutiérrez, 2004) and the quenching parameters may change the yield strength with a range 400-700 MPa that can be predicted by a finite difference model (Khalifa et al., 2016).

The Tempcore® treatment on steel rebars improves the strength and allows to achieve the ductility requirements, especially in seismic areas (Standard EN 1998-1:2005, Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings, 2005). Nonetheless, the martensitic outer layer of the rebars may adversely affect the durability (Kelestemur & Yıldız, 2009), with a higher

sensitivity to deterioration (Zhang et al., 2013) and pitting (Angst & Elsener, 2015). In this concern, dual phase steel with martensite contained in a ferritic matrix may exhibit a better corrosion resistance (Maffei et al., 2007, Caprili et al., 2019), although their adoption in the construction field may be limited, due to the different production procedure, the costs and the undefined yielding in the stress-strain curves.

Generally, the rebar's quality inspections on site may be largely underestimated. This fact leads to the placing of steel rebars within concrete, which may attain the required tensile strength, but may barely comply with the ductility and the corrosion resistance. These issues exhibit a relevant consequence in the

case of extraordinary events and may significantly shorten the durability. Therefore, a quality control plan of the steel rebars to be applied on site may help the owners of a structure and the engineers, to build more reliable and durable reinforced concrete structures.

Materials and Methods

Steel rebars must comply with the Swiss standard SIA 262 and the European standard SN EN 10080: 2005. Several steel rebars B 500 B-C with a diameter of 12 mm and a variable chemical composition between rebars and the rebars of the same delivery were investigated (Table 1).

Table 1: Chemical composition of the steel rebars.

Structure	ID.	Sn	Mo	Pb	Zn	Cu	Ni	Fe	Mn	Cr
24-0106.01	1a	0.048	0.062	< LOD	0.420	2.778	0.312	95.125	0.819	0.123
	1b	< LOD	0.055	< LOD	0.471	4.334	0.300	93.611	0.830	0.118
24-0106.02	1a	0.050	0.035	< LOD	1.347	5.446	0.125	91.812	0.678	0.147
	1b	< LOD	0.030	< LOD	1.966	4.788	0.166	91.881	0.668	0.181
24-0106.03	1a	0.042	0.032	< LOD	< LOD	7.967	0.206	90.424	0.857	0.090
	1b	0.049	0.036	< LOD	0.294	3.910	0.220	94.347	0.867	0.093
24-0106.04	1a	< LOD	0.059	< LOD	< LOD	7.353	0.153	91.087	0.727	0.141
	1b	0.043	0.055	< LOD	< LOD	5.298	0.187	93.203	0.710	0.128
24-0106.07	2a	< LOD	0.070	< LOD	0.117	6.791	0.268	91.292	0.755	0.226
	2b	< LOD	0.059	< LOD	0.069	1.479	0.454	96.805	0.724	0.223
24-0106.08	2a	0.057	0.074	< LOD	< LOD	4.315	0.287	94.090	0.843	0.152
	2b	0.043	0.067	< LOD	0.096	3.780	0.336	94.271	0.848	0.147
24-0106.09	1a	0.056	0.034	< LOD	0.808	6.862	0.200	90.827	0.724	0.242
	1b	0.041	0.036	< LOD	0.785	3.918	0.232	93.638	0.777	0.244
24-0106.10	3a	< LOD	0.042	< LOD	< LOD	4.557	0.334	93.574	0.793	0.396
	3b	< LOD	0.045	0.027	< LOD	3.310	0.407	94.729	0.746	0.388

Generally, the main properties, such as the yield strength (f_{sk} or $f_{sk0.2}$), the tensile strength (f_{tk}), the ductility (ϵ_{uk} and (f_{tk} / f_{sk})) ($-40^{\circ}\text{C} / +100^{\circ}\text{C}$), the bending properties, the rib surface (f_R), the diameter variation to the nominal value, the linear mass, the fatigue resistance ($\Delta\sigma_s$, fat), the brand name and the weldability are tested (Standard SIA 262, Concrete Structures, 2013). The steel quality controls are done at the production site with preliminary tests from an accredited institution, by the steel producers by means of internal controls and by sample testing at the production site from an accredited institution. The inspection from the construction management on site may require the steel rebars to belong to a registered list of steel

producers with an update every 6 months, periodical controls from accredited institution, and specimen's withdrawal of three samples of the same diameter from different rebars (Fig. 1 left). Steel rebars may exhibit a different corrosion susceptibility, depending on the rebar worked area and region (Fig. 1 right). A steel rebar quality control plan may comprise a technical document for planners / engineers with the steel type and part of the structure, a document for the construction company with the producer's documentation, the company and the delivery on site and a technical document for the construction site management and the engineers, indicating the tests to be done.

Figure 1: Steel rebar's supply on site.



Tensile tests at room temperature are done to characterize the main mechanical properties (Standard EN ISO 15630-1, Steel for the reinforcement and prestressing of concrete -Test methods, Part 1: Reinforcing bars, rods and wire, 2019, Caprili et al., 2019). The microstructure is investigated with optical microscopy and SEM. The surface of the specimens is ground by using 1200 grit SiC papers, polished and etched with a 2% Nital solution for 2 minutes (98% ethanol with 2% concentrated nitric acid). The corrosion susceptibility is investigated by immersing the specimens in tap water and in a 3.5 NaCl% solution.

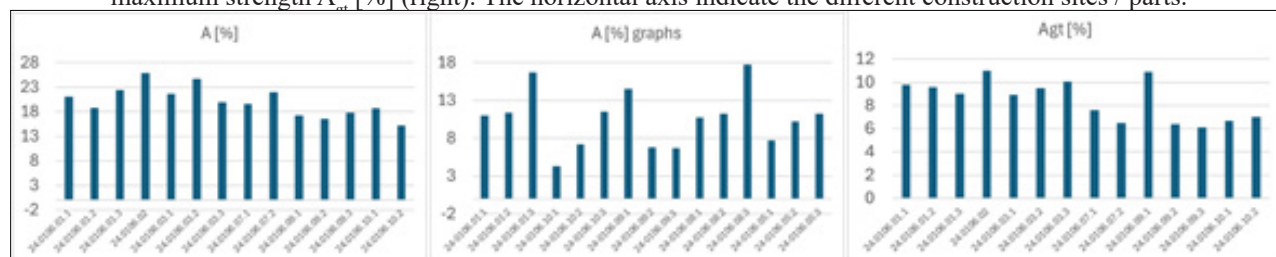
Results and Discussion

Mechanical Properties

On the construction site some issues related to the quality control approach must be faced. The adequate rebar's quantity is often missing for the testing. A minimum of three rebar pieces of approximately one meter length from 3 different rebars are required. A lack of clearly labeled material is sometimes observed. The brand name cannot always be recognized. On the other hand, only a few or no yield strength is below the lower limit of 500 MPa. The yield strength, which depends

on phases present in the rebar (Rodríguez & Gutiérrez, 2004) must be above 1.3 Fsk, e.g. above 650 MPa, with a minimum limit of 500 MPa, to avoid a ductility loss. This parameter is not always satisfied. Despite the ductility requirements are generally reached (Standard EN 1998-1:2005, Eurocode 8: Design of Structures for Earthquake Resistance - Part 1: General Rules, Seismic Actions and Rules for Buildings, 2005), a ductility variation is seen for the elongation to rupture A (Fig. 2 left-centre), also in the case of the same supply, while a limited ductility variation is measured for the elongation at maximum strength Agt (Fig. 2 right).

Figure 2: Elongation to rupture A [%] (measured with marks on the specimens-left; read from the graphs) and elongation at maximum strength A_{gt} [%] (right). The horizontal axis indicate the different construction sites / parts.



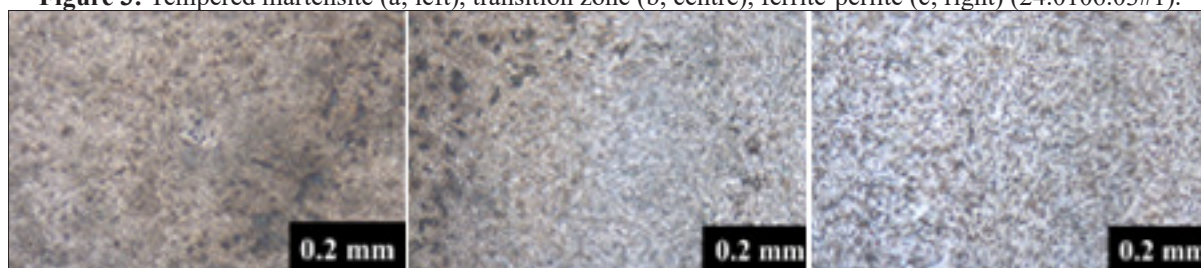
At the construction site, the total elongation at maximum load (A_{gt}) and the ratio tensile strength / yield strength (F_t/F_s)_k may be below the required standard limits for some B 500 rebars. The steel rebar diameter is measured with a caliber by including or excluding the ribs. However, the diameter must be measured with a rebar piece length, the mass and density, to determine the linear mass and to finally get the rebar diameter. The yield strength requirements are indicated in the Eurocode with a nominal and a minimal value, sometimes also a maximal value for a specific category (for instance B 500 A etc.). In some standards Sia 262 [Standard Sia 262, Concrete Structures, 2013], a nominal value is reported, without a minimal value. In this respect, a general acceptance trend, shows a 5% fractile for non-compliant values, which are below the nominal value, similarly as for the steel rebar's production stage. However, the supply on site is a different stage and the rebars outside the 5% fractile of the yield strength nominal value might be higher.

Microstructure

The microstructure relevantly influences the mechanical properties, such as the ductility. The same batch of rebars may exhibit an elongation at maximum force Agt varying from 4.56% to 6.75%, and 7.03%. The coarser grains along the border of some steel rebars (24.0106.10 nr. 3: elongation A 11.5%) as compared to specimens of the same batch (24.0106.10 nr. 1: elongation A 4.7%), cause an increase in the ductility. The grains of the border of some specimens (24.0106.09 nr. 2: elongation A 6.9 %) are more elongated as the core, indicating a lower ductility. The specimen with ferrite and perlite along the border and the core (24.0106.09 nr. 1: elongation A 14.5%) exhibits a higher elongation. Thus, the difference in rebar elongation to rupture (A) may reach 8% in the same steel bar's batch and is influenced by the treatment and the border-core microstructure of the rebars.

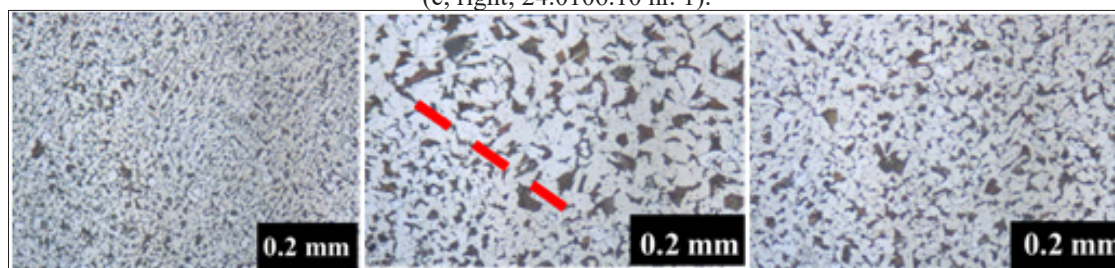
The microstructure of some rebars exhibits a variation from a dark border with tempered martensite (Economopoulos et al., 1975) and troostite to a ferritic-perlitic core (Fig. 3 a; left-b; centre-c; right).

Figure 3: Tempered martensite (a; left), transition zone (b; centre), ferrite-perlite (c; right) (24.0106.03#1).



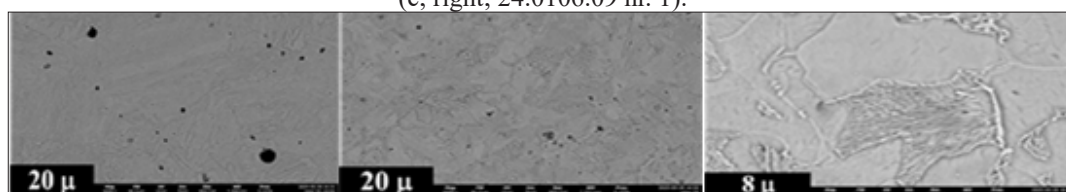
The border of some rebars may exhibit more elongated grains as compared to the core (Fig. 4 a; left). Ferritic-perlitic coarser grains can also be seen along the darker border (Fig. 4 b; centre), while in other rebars no clear distinction is present between the border and the core, being both composed of ferrite and fine perlite grains (Fig. 4 c; right).

Figure 4: Elongated grains of the border (a; left; 24.0106.09. nr. 2), coarser border grains (b; centre; 24.0106.10 nr. 1) and core (c; right; 24.0106.10 nr. 1).



The border with local tempered martensitic (Fig. 5 a; left) and the core with ferrite and perlite (Fig. 5 b; centre), can turn to fine perlite (Fig. 5 c; right).

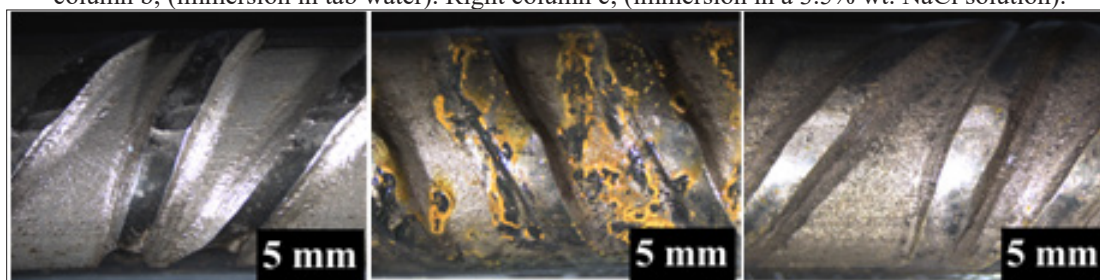
Figure 5: SEM images. Tempered martensitic border (a; left), ferritic-perlitic core (b; centre); (24.0106.04 nr. 1), and fine perlite (c; right; 24.0106.09 nr. 1).



Corrosion Susceptibility

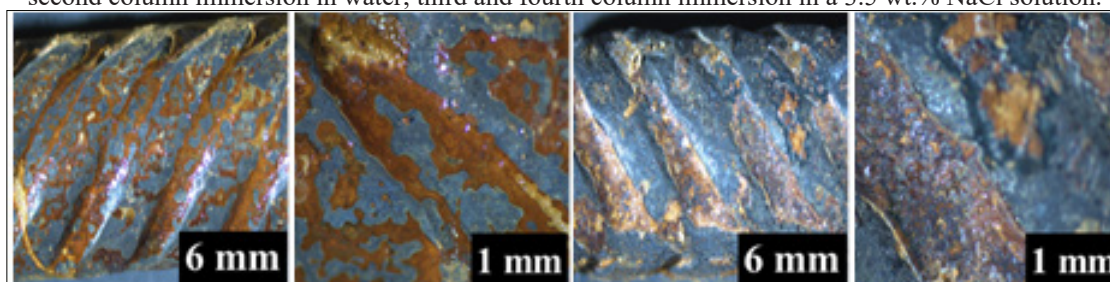
At an early stage within 24 hours, the steel rebars immersed in water show a higher corrosion degradation as compared to the specimens in a 3.5% NaCl solution and a difference in the corrosion susceptibility between the rebars is seen (Fig. 6). A similar trend is observed after 15 days of immersion.

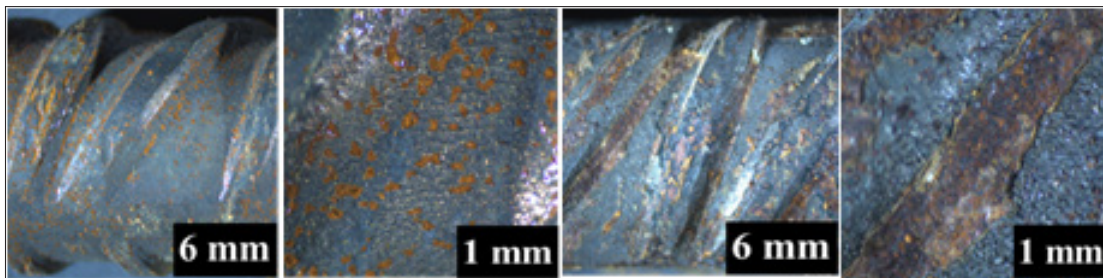
Figure 6: Corrosion immersion tests after 24 hours. Left column a; (references 24-0106.03 nr. 1; 24-0106.10 nr. 3). Middle column b; (immersion in tab water). Right column c; (immersion in a 3.5% wt. NaCl solution).



The difference in the corrosion susceptibility between the steel rebars becomes less different after 33 days of exposure. Not rarely, the corrosion starts in the upper parts of the ribs or along the rib's edge. At a later stage, the intensity of the localized corrosion is clearly higher for the NaCl specimens with exfoliation corrosion taking place (Fig. 7).

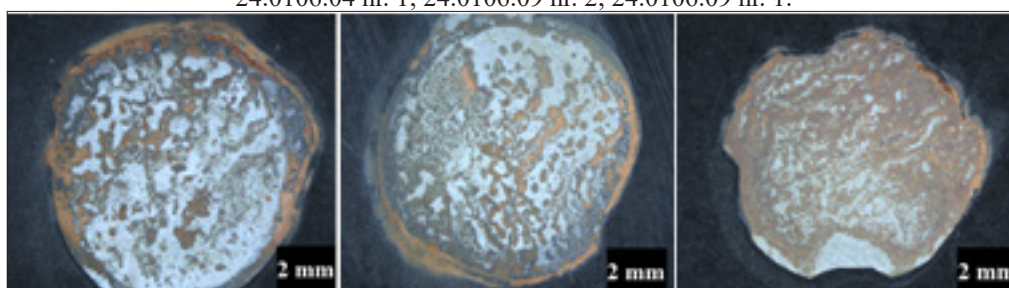
Figure 7: Corrosion immersion tests after 33 days. First row a: 24-0106.07 nr. 2; second row b: 24-0106.03 nr. 1. First and second column immersion in water; third and fourth column immersion in a 3.5 wt.% NaCl solution.





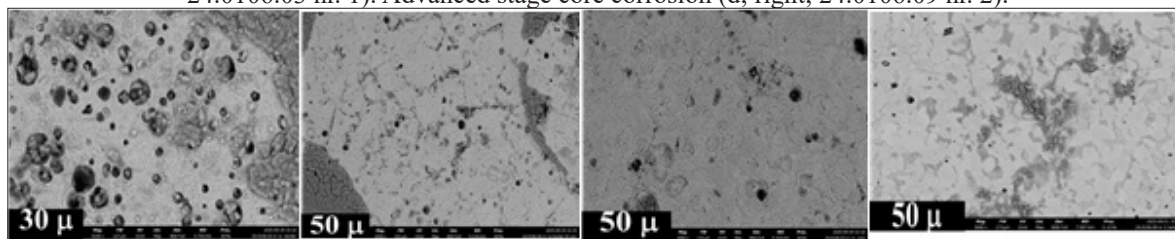
Polished and etched cross sections immersed for 24 hours in a 3.5 wt.% NaCl solution exhibit a different corrosion susceptibility of the outer shells (border) in some rebars (Fig. 8). Generally, a clear trend towards a higher corrosion susceptibility at the initial stage along the tempered martensitic borders as compared to the ferritic-perlitic core, can be seen Kelestemur & Yıldız, (2009). This also depends on the chemistry and the completeness of the treatment process.

Figure 8: Corrosion immersion tests and different corrosion susceptibility between the outer tempered martensitic shell and the ferritic-perlitic core. In some rebars, the corrosion is more uniform, due to the similar ferrite-perlite microstructure in the border and the core. First row from left to right: 24.0106.03 nr. 1; 24.0106.03 nr. 3; 24.0106.10 nr. 3. Second row from left to right: 24.0106.04 nr. 1; 24.0106.09 nr. 2; 24.0106.09 nr. 1.



The general high presence of inclusions within the steel rebars, especially MnS along the borders, causes pitting (Angst & Elsener, 2015) to occur in an extend form (Fig. 9 a; left). On the other hand, the corrosion susceptibility of the tempered martensite is increased to such an extent to cause intergranular corrosion (Fig. 9 b; centre-left). In the core, the pitting corrosion is relatively low (Fig. 9 c; centre-right), although with time, the rebar cores also corrode, starting from the fine perlitic grains (Fig. 9 d; right).

Figure 9: Pitting along the borders enriched in MnS inclusions (a; left; 24.0106.03 nr. 1) and intergranular corrosion of the tempered martensite outer shells (b; centre-left; 24.0106.04 nr. 1). Lowered pitting corrosion in the core (c; centre-right; 24.0106.03 nr. 1). Advanced stage core corrosion (d; right; 24.0106.09 nr. 2).



Conclusion

Generally, a variable microstructure (tempered martensite, coarse/elongated ferritic-perlitic structure) between borders and core is seen. This depends on the production and treatment process (Tempcore®). The thermal processing allows the formation of a tempered martensitic structure along the rebar's border, which allows to reach the required strength. On the other hand, the ductility is variable. The corrosion resistance of the outer shells is lowered, due to the formation of the tempered martensite. A higher localized corrosion susceptibility with pitting, especially at the MnS inclusions, and intergranular corrosion is seen along some borders. Therefore, the long-term service life targets up to 100 years required for some reinforced concrete infrastructures (Swiss standard Sia 262/1), such as,

tunnels and bridges may be questioned in the future. The use of future sustainable concrete and rebars with a trend towards an increase in the corrosion susceptibility of the rebar's borders, might require a careful monitoring of the structures.

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