Effect of corrosion and sandblasting on the high cycle fatigue behavior of reinforcing B500C steel bars

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ABSTRACT. In a series of applications, steel reinforced concrete structures are subjected to fatigue loads during their service life, what in most cases happens in corrosive environments. Surface treatments have been proved to represent proper processes in order to improve both fatigue and corrosion resistances. In this work, the effect of corrosion and sandblasting on the high cycle fatigue behavior reinforcing steel bars is investigated. The investigated material is the reinforcing steel bar of technical class B500C, of nominal diameter of 12 mm. Steel bars specimens were first exposed to corrosion in alternate salt spray environment for 30 and 60 days and subjected to both tensile and fatigue tests. Then, a series of specimens were subjected to common sandblasting, corroded and mechanically tested. Metallographic investigation and corrosion damage evaluation regarding mass loss and martensitic area reduction were performed. Tensile tests were conducted after each corrosion exposure period prior to the fatigue tests. Fatigue tests were performed at a stress ratio, R, of 0.1 and loading frequency of 20 Hz. All fatigue tests series as well as tensile test were also performed for as received steel bars to obtain the reference behavior. The results have shown that sandblasting hardly affects the tensile behavior of the uncorroded material. The effect of sandblasting on the tensile behavior of pre-corroded specimens seems to be also limited. On the other hand, fatigue results indicate an improved fatigue behavior for the sandblasted material after 60 days of corrosion exposure. Martensitic area reductions, mass loss and depth of the pits were significantly smaller for the case of sandblasted materials, which confirms an increased corrosion resistance.

KEYWORDS. Steel B500C; Corrosion; High Cycle Fatigue; Sandblasting.

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INTRODUCTION

Reinforced concrete structures are widely used in civil engineering constructions. Rebars represent the basic strengthening element of reinforced structures, being responsible for carrying loads and controlling displacements. In many cases, these structures are subjected to cyclic loading due to their operational lifespans, thus making it necessary to investigate their high cycle fatigue behavior [1].

In a wide range of applications the operational environment of the steel bars is corrosive. Corrosion of reinforced concrete is one of the major durability problems concerning civil construction [2–4], mainly when the rebar in the concrete is exposed to chlorides, either provided by concrete components or penetrated from the surrounding chloride-bearing environment. Corrosion mechanism in reinforcement steel bars can be presented in the form of an electrochemical cell, as illustrated in Fig. 1 [4], with anodic and cathodic reactions varying depending on the pH of the surroundings.

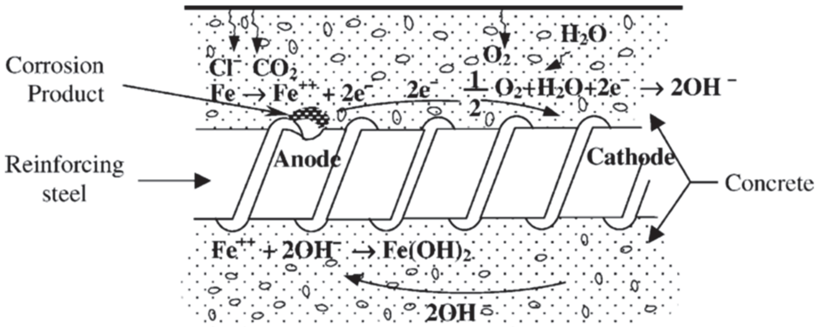


Figure 1: Schematic representation of the corrosion of reinforcement steel in concrete – as an electrochemical process.

It is worth mentioning that in coastal locations, the climatic conditions constitute one of the most aggressive environments for concrete structures due to the severe ambient salinity, high temperature and humidity, and also the ingress of chlorine through wind-borne salt spray [5].

It is obvious that corrosion damage degrades the mechanical behavior of steel bars. A wide range of experimental investigations have shown a decrease of tensile strength and ductility of the corroded steel bars, as well as a reduction of the bonding strength between the concrete and the steel bar [5–10]. In a number of studies [5, 6, 9–12] the local decrease of cross section and the consequential mass loss of the rebar were measured. Apostolopoulos and colleagues [7, 9, 10, 13, 14] have studied extensively the influence of corrosion on the mechanical properties of reinforcement steel bars, observing that it implies significant reductions in bar's strength and ductility, with progressive loss of mass with exposure time. Furthermore, the ability of the corroded steel bars to carry seismic loads has been reduced [5, 6].

On the other hand, there is still not enough information regarding life expectancy of pre corroded reinforcing materials employed after the changes performed in European regulations [7]. The design demands for strength and ductility, based on new requirements and principles, obliged the European Union to introduce to service dual-phase high performance steel such as S500s and B500c. The dual-phase steels of RC show an outer high strength core (martensitic phase) and a softer core (ferrite-perlite phase) with a bainitic transition zone. The mechanical performance of B500c steel results from the combination of the mechanical properties in each of the individual phases. The increased strength properties are credited to the presence of the outer martensitic zone and the increased ductility to the presence of the ferrite-pearlite core [7].

However, corrosion damage seems to be more severe on the new steel bars, questioning its improvements [15]. Several works [5, 6, 13] have been made aiming to better understand the effect of corrosion on the mechanical behavior of this specific steel, with both static and fatigue loads. It was observed that the corrosion resistance of BSt420 grade steel is higher than that of B500C in low cycle fatigue analysis [7], while a similar steel grade, BSt500s, presented considerable reduction in its post-corrosion fatigue limit due to a reduction of the exterior hard layer of Martensite [5].

The studies referring to the fatigue behavior of corroded rebar are by far less [5, 6, 16–18] as compared to the the studies referring to the quasistatic behavior of the material. It evidentiates the fact that the problem of fatigue of reinforced concrete structures has been for years underestimated. Zhang et al. [19] have shown that the mechanical behavior of pre-corroded rebars is less affected in tensile tests than in fatigue tests, while the work of Ma et al. [16], coupling together the corrosion growth kinetics and fatigue crack growth kinetics, shows that the stress intensity factor under corrosive environment presents an initial increase and later decrease with the increase of corrosion-induced mass loss.

To overcome the shortcomings mentioned above, alternative concrete reinforcement concepts have been considered. To these belong the employment of materials such as CFRPs and GFRPs [2, 20, 21]. Yet, their high costs make their widespread use prohibitive and limited to specific applications. Therefore, several efforts are in progress to improve both the corrosion and fatigue behavior of rebars by involving appropriate surface treatments.

Sandblasting is a process of using compressed air to propel abrasive grits at a very high speed at an object in order to remove oxide layers or any other debris from its surface [22]. The impact of the grits against the object's surface inserts compressive stresses in the material, contributing to the increase of fatigue live and diminishing corrosion damage in reinforcement steel bars [3, 6, 23]. Al-Dulaijan et al. [24] have studied the effect of two rebar cleaning procedures and repair materials on reinforcement corrosion and flexural strength of repaired concrete beams, observing that specimens subjected to sandblasting cleaning had higher corrosion resistance than uncleaned bars and the ones cleaned by wire brush. Akinlabi et al. [25] observed that sandblasting has an improving effect on mechanical properties of formed mild steel samples when compared to non-sandblasted ones, due to increase in the degree of grain elongation, as well as an improvement in the hardness of the material by strain hardening. This behavior was studied by several authors separately, but the amount of material available in the literature that combines studies regarding the effect of sandblasting, fatigue behavior and corrosion in rebars is quite scarce.

In the present work, the effect of corrosion and sandblasting on the high cycle fatigue behavior of reinforcing steel bars is investigated. Specimens of reinforcing steel bar of technical class B500C, of nominal diameter of 12 mm were first exposed to corrosion in alternate salt spray environment for 30 and 60 days and subjected to both tensile and fatigue tests. Then, a series of specimens were subjected to common sandblasting, corroded and mechanically tested. Tensile tests were conducted after each corrosion exposure period prior to the fatigue tests. Fatigue tests were performed at a stress ratio, R, of 0.1 and loading frequency of 20 Hz.

EXPERIMENTAL PROCEDURE

Material and specimens

The selected material was hot-rolled concrete reinforcing steel B500C, which is widely used since 2006 in civil constructions (buildings, bridges etc.), according to the Hellenic standard ELOT 1421-3 [26].The material has been produced by Sidenor Group (SD) according to DIN488 [27]. SD B500C has two longitudinal ribs and additional transverse ribs on two sides. Moreover, SD Steel bears the clear "SD" mark, for identification. A schematic drawing of the ribs pattern is given in Fig. 2.

Figure 2: Ribs pattern.

Both as-received and pre-corroded bars were subjected to tensile and fatigue testing. The material was delivered in the form of ribbed bars of 1 m length and nominal diameter of 12 mm, with nominal cross-section of 113 mm² and weight of 0.888±0.04 kg/m. The chemical composition of the final product according to the manufacturer is given in Tab. 1.

Grade	HEAT CHEMICAL ANALYSIS (%) max				
	C	S	P	N	C_{eq}
B500C	0.24	0.055	0.055	0.014	0.52

Table 1: Chemical Composition.

For the tensile tests, specimens of 460mm total length were cut according to standard ISO/FDIS15630-1 [28]. For the fatigue tests, specimens of a total length of 270 mm were cut. A free length (r) of 170mm was selected in accordance with standard ISO/FDIS 15630-1 [28]. The free length in axial tests should be of at least 140mm or 14 times the specimen diameter, whichever value is greater. Fig. 3 shows a schematic drawing of a fatigue specimen, with gripping sections (a) of 50mm and free length (r) of 170mm.

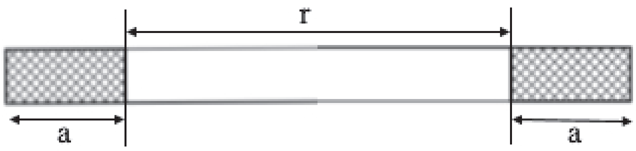


Figure 3: Fatigue specimen

The sandblasting method

For the surface treatment an ordinary sandblasting facility was employed to retain the costs as low as possible and avoid the use of expensive equipment. Yet, it is acknowledged that the applied sandblasting method is associated to increased scatter of mechanical properties. The sandblasting method was performed by propelling a stream of abrasive material against the steel bar surface under high pressure in a blast cabinet, as shown in Fig. 4a. A blast cabinet is a closed loop system that allows the operator to blast the part and recycle the abrasive. It usually consists of four components; the cabinet (Fig. 4a), the abrasive blasting system (Fig. 4b), the abrasive recycling system (Fig. 4c) and the dust collection. In this work, the process of sandblasting was performed manually; the operator blasts the parts for about one minute from the outside of the cabinet by placing his arms in gloves attached to glove holes on the cabinet, viewing the part through a view window. The material used as a sintershot was a common aluminum oxide of compound with spherical shape of 1.2 mm mean diameter, hardness value of 2035 HV and density of 2100 Kg/m^3. For flat surfaces the selected sintershot is suitable for achieving a uniform and clean surface as well as uniform compressive layers in the surface of the blasted material. Yet, the ribs of the investigated bars do not allow achieving a uniform blasting and compressive layer.

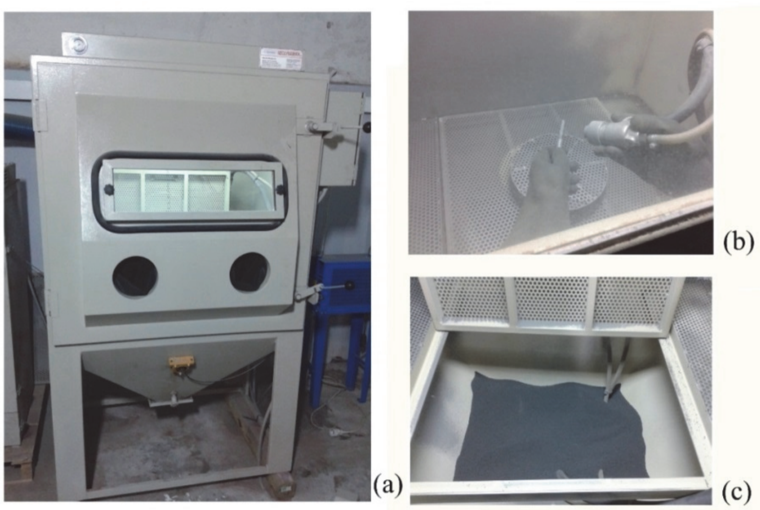


Figure 4: Sandblasting cabinet (a), process (b) and material (c).

Corrosion exposure and evaluation

Following to the surface treatment, specimens have been exposed in a salt spray environment. The salt spray water solution consisted of 5% NaCl and the exposure periods were set to 30 and 60 days. A cyclic exposure was employed, consisting of a 3 hours cycle with 1.5 hours exposure in salt fog and 1.5 hours in dry mode. After corrosion exposure, mass loss of both sandblasted (SB) and as-received (NB) specimens have been evaluated and compared. Mass loss evaluation was made in accordance with ASTM G1-03 [29] in order to determine the degree or level of corrosion. The weight of each specimen was measured before exposure initiation (M_i) and the final weight (M_f) was considered to be stable when the difference between weight measurements after consecutive cleaning procedures became smaller than 0.04g. The percentage mass loss was calculated as shown in Eq. 1:

$$M_1 = \frac{M_i - M_f}{M_i} \times 100 \quad (1)$$

For the metallographic analysis, namely, martensitic area reduction and mean corrosion depth measurements, five cross sections of specimens subjected to each exposure period were employed. The cross sections were embedded in metallographic resin, grinded and polished. Chemical etching was made utilizing Nital 5% to evidentiate the martensitic region.

Tensile tests

All specimens were subjected to tensile tests performed according to the DIN 488 specification [27]. For the tests a servo-hydraulic MTS 250 KN machine was used. The employed deformation rate was of 2 mm/min and upper yield stress (R_p), ultimate stress (R_m) and elongation to fracture (A_{100}) were evaluated. Five specimens of as-received material and five specimens of sandblasted material were employed for each period of corrosion exposure.

Fatigue tests

The effect of corrosion and sandblasting on the high cycle fatigue behavior of reinforcing steel bars of technical class B500C was investigated first according to ELOT 10080. The specification defines the as minimum requirements that specimens shall withstand a number of cycles equal to $2x10^6$. The stress should vary sinusoidally, over the specified range of stress $2\sigma_a$ from the specified σ_{max}. The parameters used for the fatigue testing were: maximum stress σ_{max}=300 MPa and frequency f= 20 Hz. Furthermore, a number of fatigue tests was conducted to obtain the S-N curves for both materials at a stress ratio R=0.1 and frequency of 20 Hz. Tension-tension fatigue tests were performed using an MTS servo-hydraulic test machine with load capacity of 250 KN. The specimens were subjected to fatigue up to final failure. To consider an experiment as valid, the fracture of the specimen should occur at at least 25mm from the clamped part of the bar. The number of cycles to failure was set to $5x10^6$ cycles. The S-N curves were obtained by using the Weibull distribution of 4 parameters. In order to estimate the effect of sandblasting on fatigue resistance of the material, the largest period of corrosion was considered for comparison. In Tab. 2 the total number of valid fatigue tests for all corrosion exposure periods for both materials, as-received and sandblasted is displayed.

	NB	SB
0 days	17	-
30 days	11	-
60 days	9	7

Table 2: Number of valid specimens of fatigue tests.

RESULTS

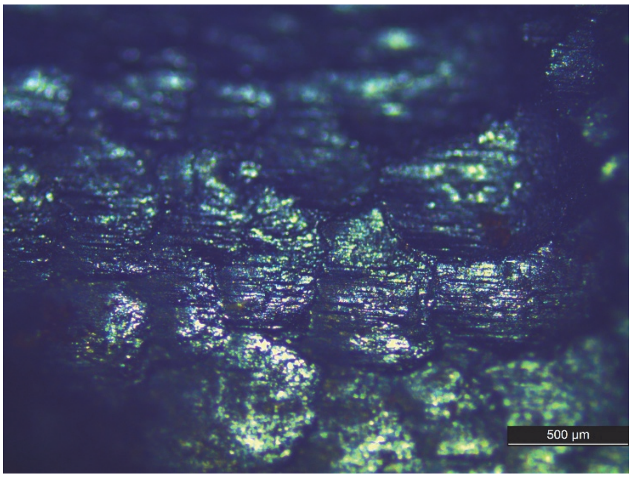
Metallography

The surface of the steel bars has been observed by involving an optical microscope, as it is illustrated in Fig. 5. Fig. 5a shows the surface of an untreated specimen, while Fig. 5b shows the surface of a sandblasted specimen. As it can be seen, a more uniform surface has been achieved by implementing the sandblasting treatment. Furthermore, no initial microcracks after the surface treatment could be observed.

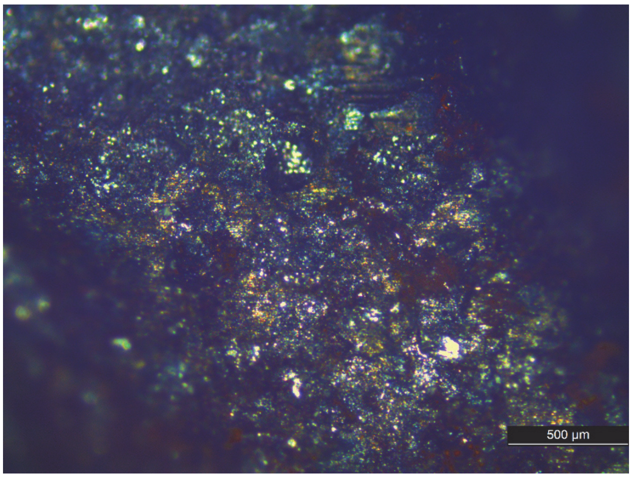
Corrosion evaluation

Tab. 3 displays the results obtained by the mass loss evaluation for both corrosion exposure periods, 30 and 60 days.
These values are in accordance with other values found in the literature. Koulouris et al. [3] observed that mass loss of as-received materials after 30 days of corrosion in a salt spray chamber with 5% NaCl was of 3.77%, while after 60 days the material lost 7.23% of its mass, while in [4] a mass reduction of 2.92% after 30 days and 5.43% after 60 days of exposure has been observed. It is noticeable that the mass reduction of specimens subjected to sandblasting is significantly smaller than the one presented by the as-received material. The same behavior was noticed in the work in [20] where the

sandblasted steel surface had the lowest corrosion rate and, accordingly, the best performance against corrosion, which was attributed to the formation of a stable passive film on the steel bars cleaned by sandblasting treatment.



(a)



(b)

Figure 5: Images of (a) non-blasted and (b) sandblasted surfaces of the steel bars

	Mass loss reduction (%)			
	30 days		60 days	
	NB	SB	NB	SB
Average	**4.84**	**2.68**	**6.49**	**4.62**
Deviation	0.83	0.63	1.04	1.68

Table 3: Mass loss reduction.

Representative cross-sections of all material states are illustrated in Fig. 6. Final areas were measured and compared using image processing software, ImageJ. The martensitic area reduction results are shown in Tab. 4. As expected, the values are consistent with the values of mass loss reduction. An improved resistance to corrosion damage is observed for the sandblasted material, indicated by the remaining martensitic area after the sandblasting process.

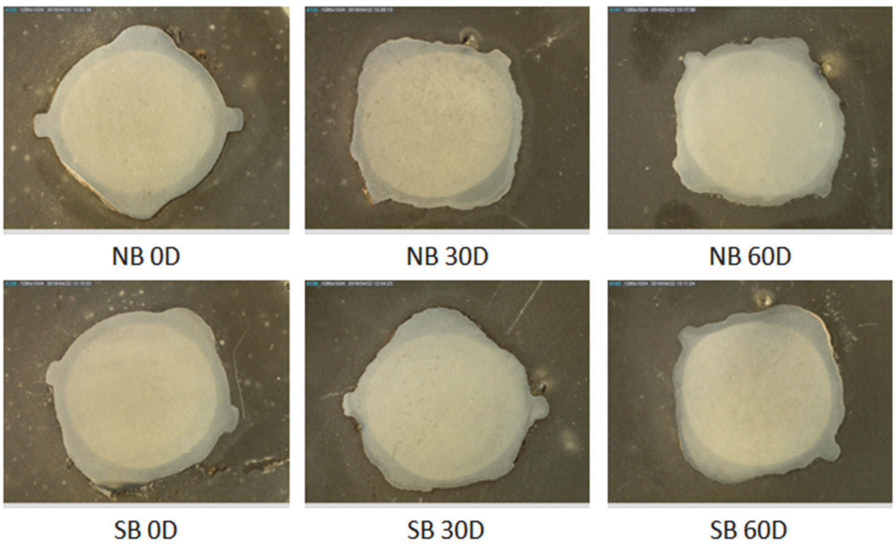


Figure 6: Martensitic area reduction with time of exposure.

	Martensitic area reduction (%)			
	30 days		60 days	
	NB	SB	NB	SB
Average	**3.09**	**1.96**	**7.49**	**4.45**
Deviation	2.31	1.64	1.74	1.45

Table 4: Martensitic area reduction

Representative images obtained from the optical microscope, concerning the corrosion damage developed on the above cases, are illustrated in Fig. 7. In this Figure, corrosion damage in the form of pits for non-blasted specimen (Fig. 7a), sandblasted specimen (Fig. 7b) after 30 days of corrosion exposure as well as for non-blasted specimen (Fig. 7c), sandblasted specimen (Fig. 7d) after 60 days of corrosion exposure is illustrated. Furthermore, the diameter of the pits is illustrated in Fig. 8. It is observed that a more extensive damage has occurred in the case of the non-blasted material. On the other hand, reduced pits do not allow expansion of the damage in the case of the sandblasted steel bars. This might be interpreted as the result of the compressive layer formed on the surface of the steel bars, which may prevent corrosion damage evolution. The calculated average depth of corrosion of four samples is given in Tab. 5. A 31.7% decrease of the depth corrosion for the case of sandblasted material after 30 days of exposure is observed. A higher decrease by more than 40% is observed for the case of sandblasted material after 60 days of exposure.

		30 days			60 days	
	NB	SB	**Difference (%)**	NB	SB	**Difference (%)**
Average	140.38	95.92	**31.67**	178.41	98.57	**44.75**
Deviation	82.42	53.34		69.54	51.01	

Table 5: Corrosion depth (μm).

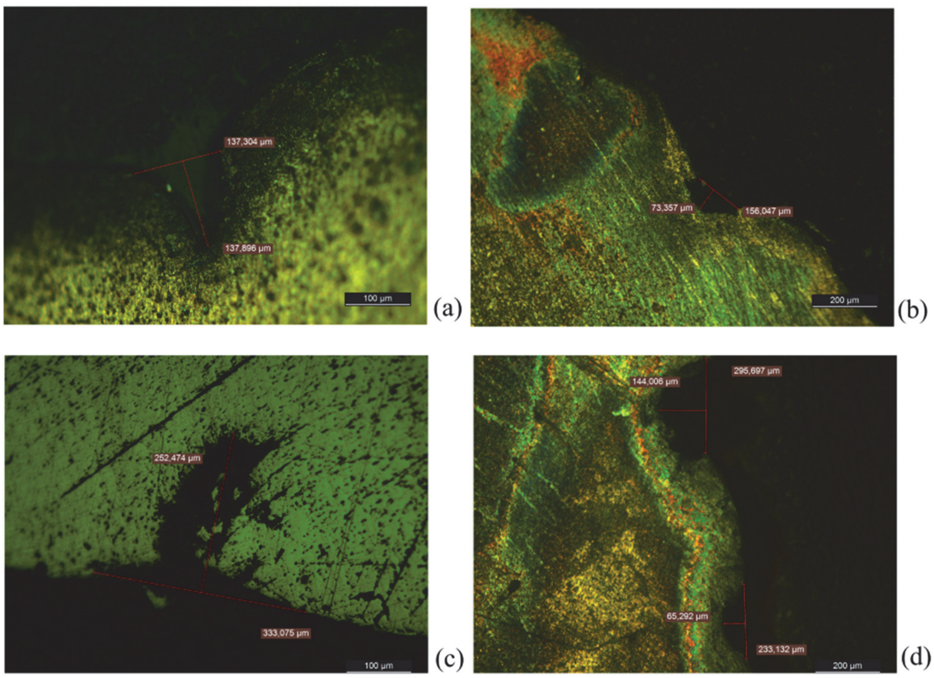


Figure 7: Corrosion damage: Depth of a pit after 30 days of corrosion of (a) non-blasted specimen and (b) of sandblasted specimen as well as pits after 60 days of corrosion of (c) non-blasted specimen and (d) sandblasted specimen.

Tensile test results of uncorroded specimens

Representative stress-strain curves of as-received and sandblasted specimens are illustrated in Fig. 9. The curves were constructed using load-displacement data recorded by the MTS 250kN. The stress was calculated assuming the cross sectional area as shown in Eq. 2, where d is the nominal diameter of the steel bars in mm. Hence, the cross sectional area is 113.04 mm².

$$A = \frac{\pi d^2}{4} \tag{2}$$

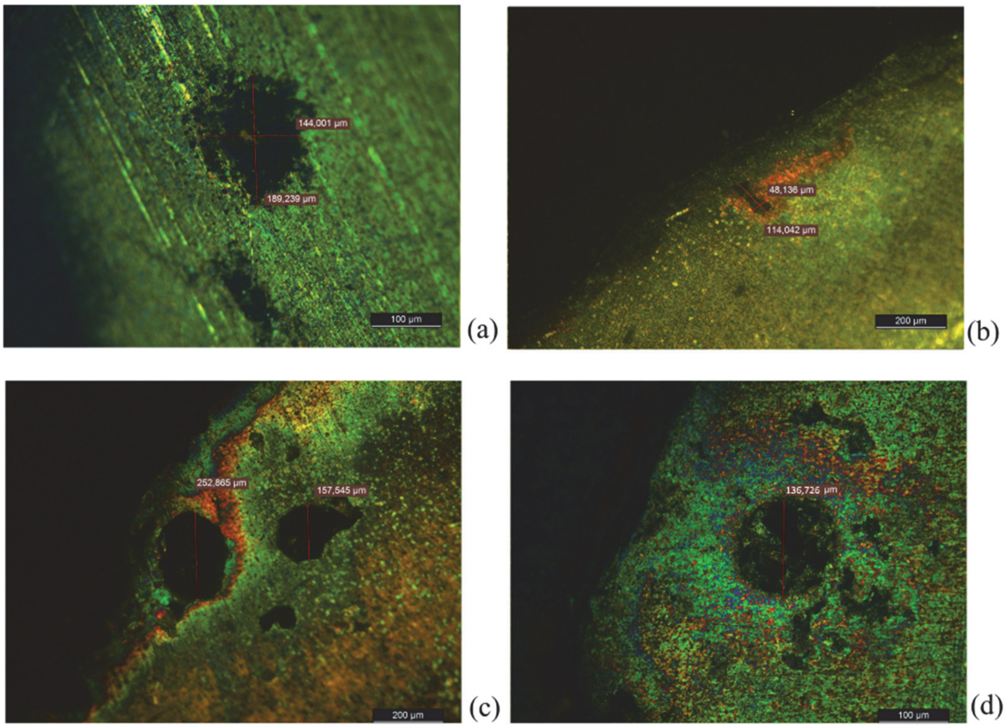


Figure 8: Corrosion damage: Diameter of a pit at a transverse cross-section of non-blasted specimen (a), of sandblasted specimen (b) after 30 days of corrosion as well as of non-blasted specimen (c), of sandblasted specimen (d) after 60 days of corrosion.

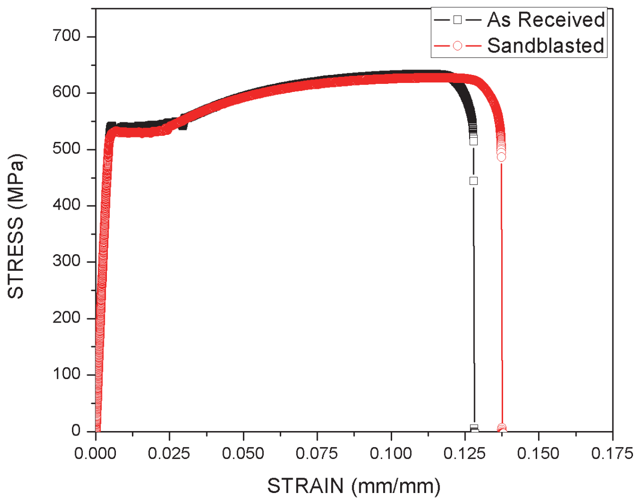


Figure 9: Representative tensile load-displacement curves of as-received as well as sandblasted specimen.

The detailed values of the tensile results concerning the yield and ultimate strength as well as the uniform elongation and the strain at break are presented in Tab. 6. Moreover, a comparison has been made to reveal the differences of the sandblasted material as compared to the as-received one. The values highlighted by red color indicate a reduction of the corresponding property. However, the results are in the range of the standard deviation. Only insignificant differences within the scatter limit are observed for the tensile properties.

		0 days		
		NB	SB	**Difference (%)**
Yield strength (MPa)	Average	536.29	521.02	**-2.85**
	Deviation	16.49	13.21	
Ultimate strength (MPa)	Average	634.96	629.25	**-0.90**
	Deviation	12.38	14.29	
Uniform elongation (%)	Average	10.54	10.23	**-2.94**
	Deviation	0.84	1.29	
Strain at break (%)	Average	19.57	19.12	**-2.30**
	Deviation	3.89	2.17	

Table 6: Tensile results values and comparison.

Fatigue results of uncorroded specimens

The results showed that the requirements of ELOT 10080 specification are fulfilled by both, as received and sandblasted materials, after all corrosion exposure periods. The fatigue behavior of the uncorroded material is illustrated in Fig. 10.

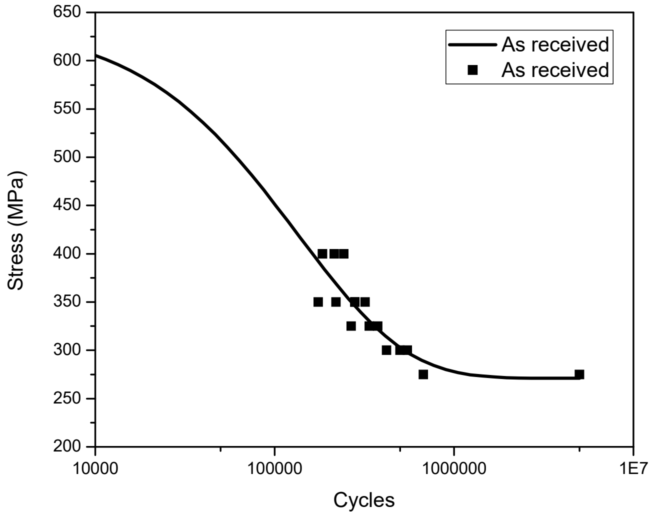


Figure 10: Fatigue results of the as-received material.

The value of the fatigue limit obtained by the Weibull function for the as-received material was of 270.95 MPa. The fatigue limit of the sandblasted material is not available, since it was not possible to construct an S-N curve for the sandblasted material due to missing experimental data. Problems related to gripping of the specimens are not uncommon in axial fatigue tests of reinforcement steel bars, since they present high stresses in the gripping section, where a significant amount of notches are present. Therefore, the results of such tests cannot be regarded as reliable and should be rejected [18, 24]. Many attempts of solving this issue have been made in the past [13, 20, 21, 23–25], without great success. In this work, the amount of valid experiments reached up to 40% of the total, thus showing that common sandblasting can be an efficient alternative to complicated systems that aim to increase the amount of valid experiments.

Mechanical behavior of pre-corroded reinforcing B500C steel bars: Tensile results

Representative stress-strain curves of as-received and sandblasted specimens after each corrosion exposure period are illustrated in Fig. 11. A significant effect of corrosion on the tensile behavior of both materials is observed. Fig. 12 shows stress-strain curves of the as-received as well as the sandblasted steel bars after each corrosion exposure period, where Fig. 12a refers to 30 days of corrosion and Fig. 12b refers to 60 days of corrosion.

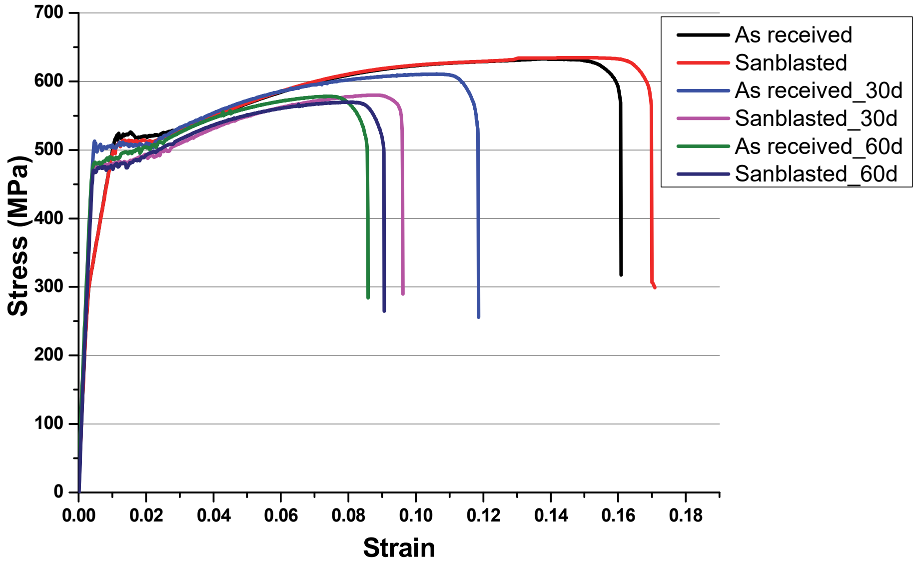


Figure 11: Tensile load-displacement curves of as-received as well as sandblasted specimen at each corrosion exposure period.

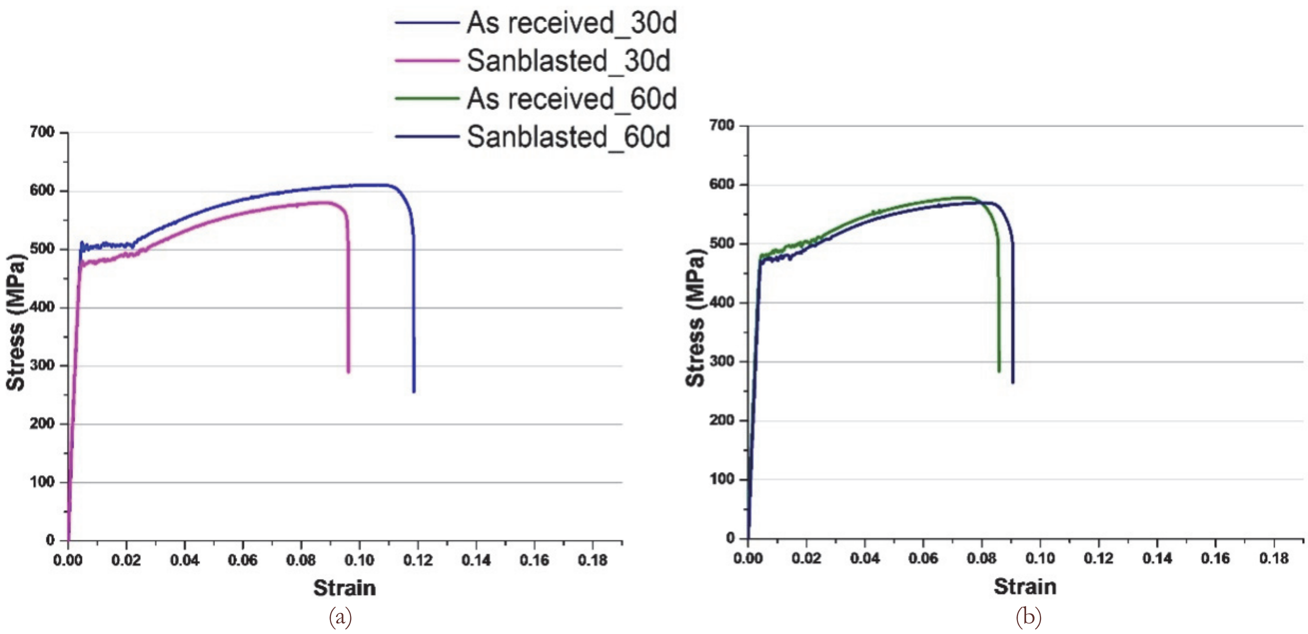


Figure 12: Tensile load-displacement curves of as-received as well as sandblasted specimen at 30 days of corrosion (a) as well as at 60 days of corrosion (b).

The degradation of yield and ultimate strengths of both materials is illustrated in Fig. 13. Almost the same degradation in the strength due to corrosion for both materials is observed. Uniform elongation and strain at break of both materials are illustrated in Fig. 14. A significant reduction of the strain at break after 30 days of corrosion exposure is observed for both materials, non-blasted and sandblasted. A further decrease of the strain at break after 60 days of corrosion exposure is shown in Fig. 14b. Slight differences are observed for the sandblasted material as compared to the as-received material; still, the results lie within the deviation range.

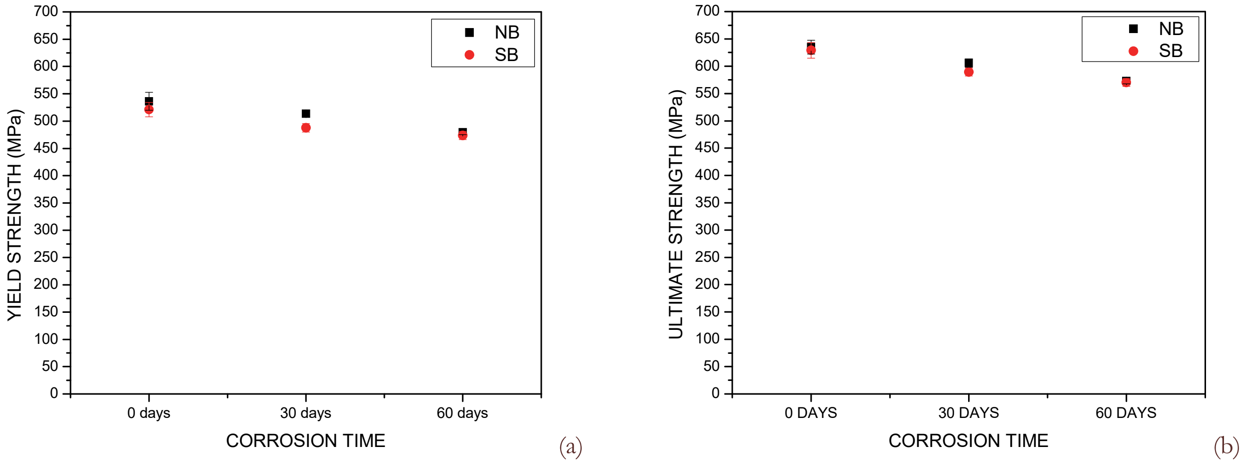


Figure 13: Yield strength (a) and ultimate strength (b) of as-received as well as sandblasted specimen at each corrosion exposure period.

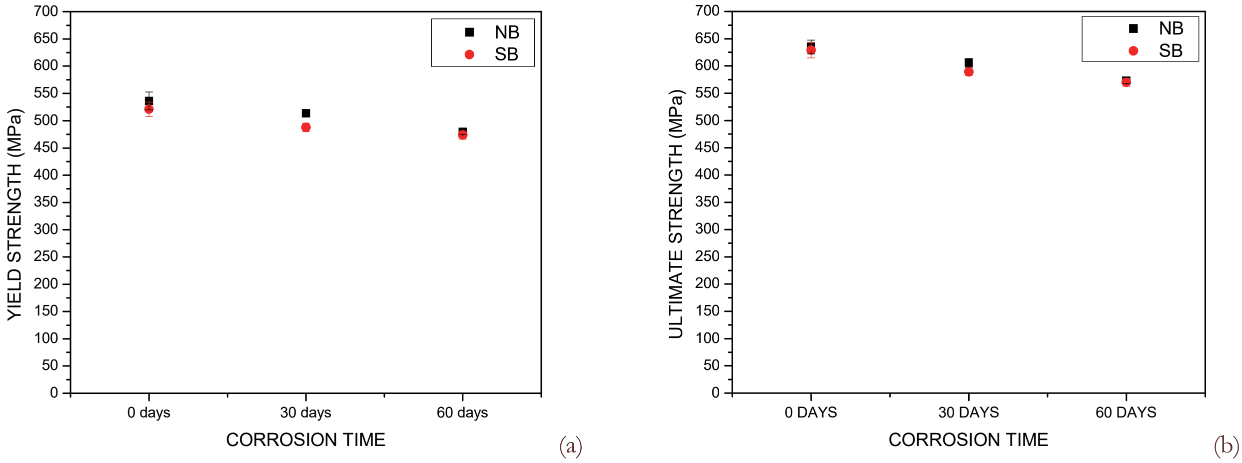


Figure 14: Uniform elongation (a) and strain at break (b) of as-received as well as sandblasted specimen at each corrosion exposure period.

The obtained values of the tensile properties are presented in Tab. 7. Moreover, a comparison has been made to reveal the differences of the sandblasted material as compared to the as-received one. The values highlighted by red color indicate a reduction, while green color indicates an increase of the corresponding property.

		30 days			60 days		
		NB	SB	**Difference (%)**	NB	SB	**Difference (%)**
Yield strength (MPa)	Average	513.27	487.81	**-4.96**	479.80	473.75	**-1.26**
	Deviation	5.71	7.78		4.53	7.47	
Ultimate strength (MPa)	Average	605.97	589.39	**-2.74**	573.14	570.18	**-0.52**
	Deviation	7.74	7.29		5.44	7.15	
Uniform elongation (%)	Average	10.47	10.72	**2.33**	8.66	8.69	**0.35**
	Deviation	1.20	2.14		2.12	1.09	
Strain at break (%)	Average	15.99	16.80	**5.06**	15.36	15.95	**3.85**
	Deviation	0.79	1.89		1.03	2.26	

Table 7: Tensile results values and comparison.

Mechanical behavior of pre-corroded reinforcing B500C steel bars: Fatigue results

The fatigue behavior of the as-received material at all corrosion exposure periods is illustrated in Fig. 15. Degradation on the fatigue behavior due to the effect of corrosion especially at the high and medium stress levels is observed.

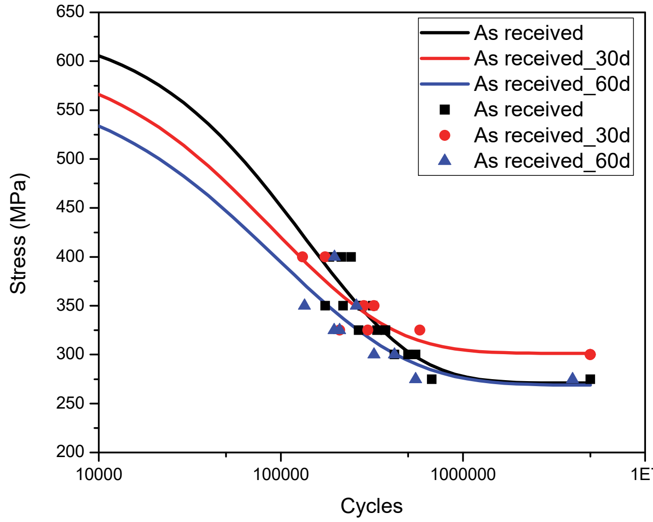


Figure 15: Fatigue results of the as-received material at all corrosion exposure periods.

The effect of sandblasting on the fatigue behavior for the longest corrosion exposure period is presented in Fig. 16. An improved fatigue life at the low regime stress levels is observed. The values of the fatigue limit obtained by the Weibull function are given in Tab. 8. An increase of 11.6% is observed for the fatigue limit of the sandblasted material as compared to the as-received one at this corrosion exposure period.

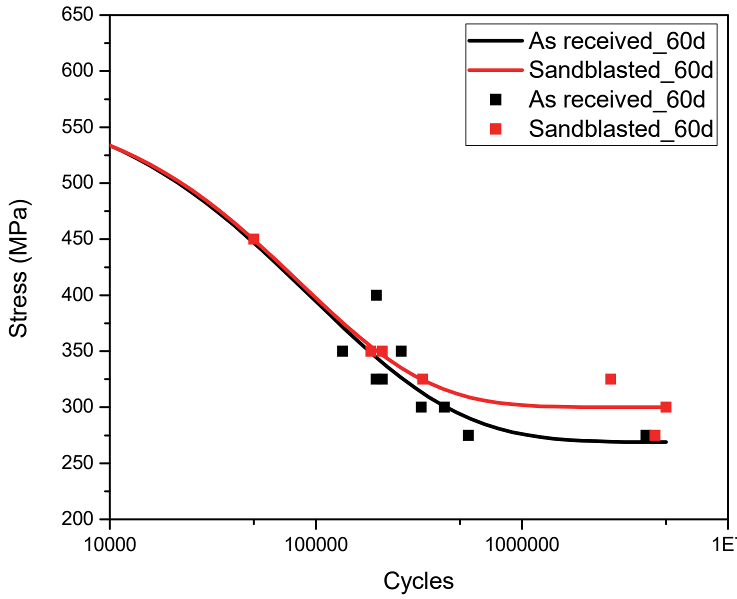


Figure 16: Fatigue results of the as-received as well as the sandblasted material at all corrosion exposure periods.

	NB	SB
0 days	270.95	NA
30 days	301.35	NA
60 days	268.86	300.07

Table 8: Fatigue limit (MPa).

The results of the fatigue life support the beneficial effect of sandblasting on the fatigue behavior of pre-corroded reinforcing steel bars. Combining the results of mass loss and martensitic area reduction, increased material properties in terms of corrosion resistance and fatigue life are achieved through the sandblasting method.

CONCLUSIONS

The effect of corrosion and sandblasting on the high cycle fatigue behavior of reinforcing steel bars of technical class B500C was investigated.

- The mass loss reduction after 30 days of corrosion was of 4.84% and 2.68%, while after 60 days of corrosion was of 6.49% and 4.62% for the as-received and the sandblasted material, respectively.
- The martensitic area reduction after 30 days of corrosion was of 3.09% and 1.96%, while after 60 days of corrosion was of 7.49% and 4.45% for the as-received and the sandblasted material, respectively.
- A 31.7% decrease of corrosion depth for the case of sandblasted material after 30 days of exposure is observed. A larger decrease by more than 40% is observed for the case of sandblasted material after 60 days of exposure.
- The tensile results showed slight differences of the as-received and the sandblasted material. It seems that the sandblasting method has neither negative nor positive impact on the tensile behavior of the steel bars.
- The fatigue results indicate an improved corrosion resistence, with observed increase of 11.6% of the fatigue limit of the sandblasted material after 60 days of corrosion when compared to the as-received one.

The sandblasting method is a cheap and easily accessible procedure with positive effects on both corrosion and fatigue resistance. Nevertheless, more experimental investigation is required in order to be massively applied.

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