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Consequences of steel corrosion on the ductility properties of reinforcement bar

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Abstract

In all concrete constructions besides the common strength problems, in presence or not of seismic activity, serious problems from environmental attack may be presented which significantly decrease their durability and service lifetime. The most common case of construction deterioration is the corrosion of steel reinforcement. The initiation mechanisms leading to steel depassivation, such as concrete carbonation and chloride penetration, have been thoroughly studied and modeled in the past. However, for the corrosion propagation period still there are no acceptable models to simulate the corrosion rate and further to estimate precisely the time when the corrosion progress signals the end of the structure service life. In the present work, the main corrosion initiation mechanisms are shortly presented. Further, the propagation period and the main consequences on mechanical properties of steel and concrete are analyzed. The experimental results show that with increasing duration of exposure to a corrosive environment, the steel mass loss increases appreciably. This leads to a significant increase of the applied stress. In addition, a significant reduction of the tensile ductility of the material was observed. For laboratory salt spray exposure periods, some of the tensile properties of steel bars drop to values lying below the limits, which are set in the existing standards for using steels in reinforced concrete members. The experimental results from the accelerated corrosion tests on bare steel bars are in a good qualitative agreement with results from steel bars embedded in aged concrete.
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1. Introduction

The good performance of concrete in service, including durability, is the second important characteristic after the usual required mechanical properties, such as strength. However, in the last decades the problems of unsatisfactory durability of structures, especially reinforced concrete ones, are in a dramatic increase. This causes not only economic impacts, because the repairing expenses of deteriorated structures are almost equal to the cost of construction of new ones, but also industrial, environmental and social problems due to decrease of reliability and safety. The type and rate of degradation processes for concrete and reinforcement define the resistance and the rigidity of the materials, the sections and the elements making up the structure. This reflects in the safety, the serviceability and the appearance of a structure, i.e. determines the performance of the structure. Concrete working life or service lifetime is the period of time during which the performance of the concrete structure will be kept at a level compatible with the fulfillment of the performance requirements of the structure, provided it is properly maintained. This service life may be achieved either due to initial good quality, or due to repeated repair of a not so good structure.

The ability of a structure to resist against environmental attacks without its performance to drop below a minimum acceptable limit is called durability. Three following main factors define the concrete durability: the initial mix design

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(quality and relevant quantity of the concrete constituents), structure design, construction and maintenance, and the specific environmental conditions. Deterioration of concrete and steel in service is every loss of performance, and it may be the result of a variety of mechanical, physical, chemical or biological processes (see Fig. 1). The final result of these mechanisms is mainly cracking. Cracking will occur whenever the tensile strain to which concrete is subjected exceeds the tensile strain capacity of the concrete. Corrosion of steel reinforcement is the most serious durability problem of reinforced concrete structures [1–5]. It impairs not only the appearance of the structure, but also its strength and safety, due to the reduction in the cross-sectional area of the reinforcement and to the deterioration of bond with the surrounding concrete. The various forms of damage detected on structures that suffer by steel corrosion show that it is necessary to interpose for the static rehabilitation of these structures. This interposition (either pre or post- earthquake) is imperative in the case of buildings, which are currently in use or are places of large gatherings such as schools, hotels, churches etc.

One of the most complex matters faced by the international scientific groups involved in the static rehabilitation of such structures is the precise knowledge of the actual mechanical characteristics of the main construction materials, such as the reinforcing steel and concrete, as well as the wear mechanisms which cause the degradation of the mechanical properties [6–8]. In recent years, although the problem of the actual residual strength degradation of aging reinforced concrete structures has attracted considerable attention, it is far from being fully understood and even less resolved. It is worth noting that up to now, little work has been done [4] to account for the effects of corrosion on the mechanical properties of the reinforcing steel bars and hence on the degradation of the load bearing ability of a reinforced concrete element. Such effects are the reduction of the effective cross-section of the reinforcing steel, micro and macro cracking of concrete and finally the spalling of the concrete cover.

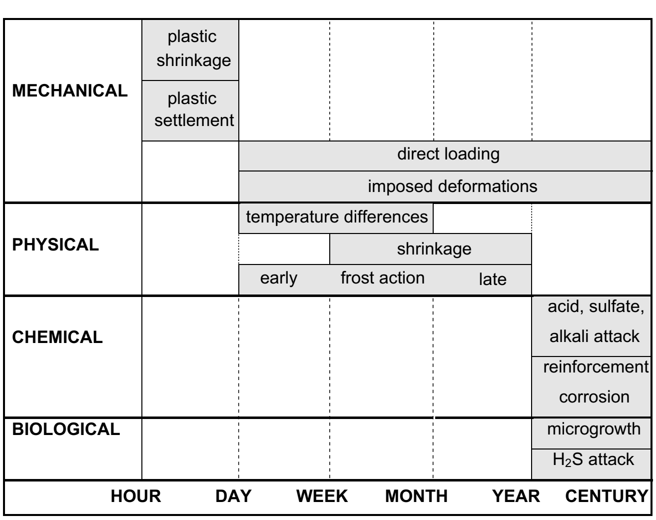

Fig. 1. Concrete deterioration mechanisms and possible time of appearance of cracking or damage.

The above considerations do not account for the effect of corrosion on the mechanical behavior of the reinforcing steels. Most of the available studies on the corrosion of reinforcing steels refer to the metallurgical aspects of corrosion such as the mass loss, the depth and the density of pitting. [6–8]. It is worth noting that the corroded steel bars are located in a zone of high tensile or shear stresses. Maslehuddin et al. [9] evaluated the effect of atmospheric corrosion on the mechanical properties of steel bars. They concluded that for a period of 16 months of exposure to atmospheric corrosion, rusting had an insignificant effect on the yield and ultimate tensile strength of the steel bars. On the other hand, Almusallam [10] evaluated the effect of the degree of corrosion of the steel bars in concrete, expressed as percent mass loss, on their mechanical properties. The results indicated a close relationship between the failure characteristics of steel bars and slabs with corroded reinforcement. A sudden failure of slabs in flexure was observed when the degree of reinforcement corrosion, expressed as percent mass loss, exceeded 13%. Thus, an aged reinforced concrete structure during its life span has accumulated damage in the load bearing elements from corrosion damage that suffered. This accumulated damage causes a degradation of the mechanical properties of the reinforcing steel bars. However, this degradation is neglected by the regulations in force, for static rehabilitation of such structures.

In the present work, the most serious mechanisms leading to steel corrosion are shortly presented. Some of the consequences of the steel corrosion on the mechanical properties of the reinforcing bars are further experimentally measured using both accelerated tests on bare bars and long-term exposure results from embedded bars in concrete. The tensile properties of the corroded material were compared against the requirements set in the standards for involving steels in reinforced concrete structures. The present approach will contribute towards the modeling of the total deterioration cycle, including initiation and propagation periods, and thus to the quantitative approach of the total concrete service life.

2. Corrosion initiation and propagation

As observed in Fig. 1, all physical and mechanical mechanisms for concrete deterioration, except direct loading and imposed deformations, may exhibit their effect on concrete performance during the first year of the service life. The chemical and biological mechanisms actually start from the beginning; however, their detrimental results are observed after the first year. In reinforced concrete, the most serious deterioration mechanisms are those leading to corrosion of the reinforcement, which occurs after depassivation due to carbon dioxide or chloride ion penetration. It is therefore necessary, if a long service life prediction is required, the modeling attempts to turn towards the corrosion initiation and propagation mechanisms.

In concrete, reinforcing bars are protected from corrosion by a thin oxide layer which is formed and maintained on their surface due to the highly alkaline environment of the surrounding concrete (pH values around 12.6). The alkalinity of the concrete mass is due to the $Ca(OH)_2$ produced during the reaction of the cement with water (cement hydration). Depassivation of the reinforcing bars (Fig. 2) occurs either when chloride ions diffuse in the pore water and reach the bars or when the pH value of the concrete surrounding the bars drops below 9, due to diffusion of atmospheric CO_2 and its reaction with the $Ca(OH)_2$ of the concrete mass, or by a combination of these two mechanisms, in which the second mechanism accelerates the first. The former mechanism (chloride penetration) predominates in marine environments, in coastal areas, and when deicing salts come in contact with the concrete surface (pavements and bridge decks, floors of parking garages, etc.). In urban and industrial areas, where environmental pollution results in a significant concentration of carbon dioxide, carbonation-initiated reinforcement corrosion prevails.

2.1. Corrosion of reinforcement induced by carbonation

The carbonation of concrete is a complex physicochemical process [11,12]. The process of carbonation involves gaseous, aqueous and solid reactants. The solids which react with CO_2 include not only $Ca(OH)_2$, but also the main strength component of cement paste CSH, and the unhydrated constituents of C_3S and C_2S. Water is always present in larger or lesser amounts in the pores of the hardened cement paste and plays a key role in the process of carbonation. The role of water is twofold: first it blocks the pores and thus hinders diffusion of CO_2 through the pores; second, it provides a medium for reaction between CO_2 and $Ca(OH)_2$. The above qualitative considerations can explain why the rate of carbonation has been reported to go through a maximum with increasing ambient relative humidity. At very low ambient relative humidity levels, CO_2 can diffuse fast, but most pores are dry and the rate of carbonation is very slow. At high ambient relative humidity levels, practically all the pores are filled with water, therefore diffusion of CO_2 becomes very slow.

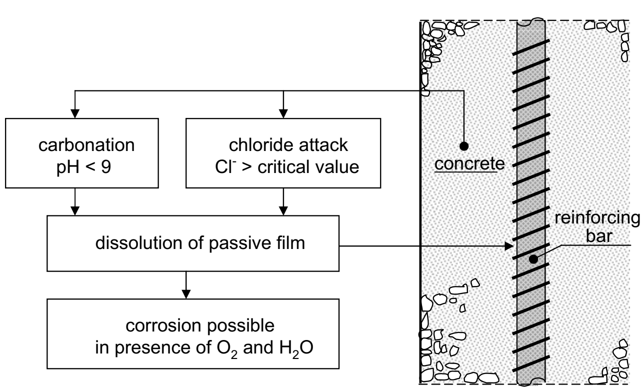

Fig. 2. Initiation mechanisms of steel corrosion in concrete.

Papadakis et al. [11–14] were the first to develop a reaction engineering model of the processes leading to concrete carbonation. These processes include the diffusion of CO_2 in the gas-phase of pores, its dissolution in the aqueous film of these pores, the dissolution of solid $Ca(OH)_2$ in pore water, its ultimate reaction with the dissolved CO_2, and the reaction of CO_2 with CSH. The mathematical model yields a nonlinear system of differential equations in space and time and must be solved numerically for the unknown concentrations of the materials involved. For the usual range of parameters (especially, for ambient relative humidity RH $\geqslant$ 55%), certain simplifying assumptions can be made, which lead to the formation of a carbonation front, separating completely carbonated regions from the ones in which carbonation has not yet started. The above models are recently included in a software package [15].

Until now, in reinforced concrete structures it can be reasonably assumed that major repair will be necessary once corrosion of the reinforcement causes generalized cracking of the concrete cover, signaling the end of the service life of the structure. The period of time required to crack the concrete cover is equal to the period required for the carbonation front to reach the bar (period to initiation of corrosion) plus the period of time necessary for the layer of rust to build up around the bar until to split the cover (corrosion propagation period). According to various researchers [16,17], the corrosion rate in carbonated concrete at high RH values is so high that the arrival of the carbonation front at the bar is shortly followed by splitting of the concrete cover. Therefore, the time required for the carbonation front to penetrate the concrete cover, c, can be considered with good approximation as a narrow lower bound (minimum) to the service life of reinforced concrete.

If an approximation of the propagation period is however required, then a full model of the physicochemical processes of corrosion and its consequences has to be applied. For example, an analytical model is proposed [18] to evaluate the reduction in bond strength as a function of reinforcement corrosion, and an attempt has also been made to evaluate the flexural strength of RC beams with corroding reinforcement failing in bond. However, until now there is no a generally accepted fundamental model for corrosion propagation of the concrete reinforcement [3,4,19] covering all corrosion consequences. This is due to complex phenomena of corrosion as well to the definition of detectable effects that define the limit of an acceptable damage, such as the cracking degree. Further research is required to develop a reliable corrosion model with strong predictive capability.

2.2. Corrosion of reinforcement induced by chlorides

Numerous surveys have indicated that chloride ions (Cl^-), originating from de-icing salts or seawater, are the primary cause of reinforcing steel corrosion in highways and marine or coastal structures [1–5,19]. Chlorides, transported through the concrete pore network and microcracks, depassivate the oxide film covering the reinforcing steel and accelerate the reaction of corrosion and concrete deterioration. Chloride penetration is a process which takes place in totally or partly water-filled pores. This is the main reason that as a process is much slower than carbonation, where CO_2 molecule may penetrate faster via air-filled pores.

In many studies, chloride transport in concrete is modeled using Fick's second law of diffusion, neglecting the chloride interaction with the solid phase. However, the latter process is very important including binding of chlorides by cement hydration products, ionic interaction, lagging motion of cations and formation of an electrical double layer on the solid surface, etc. Pereira and Hegedus [20] modeled chloride diffusion and reaction in fully saturated concrete as a Langmuirian equilibrium process coupled with Fickian diffusion. Papadakis et al. [14,21,22] extended this approach to more general conditions, offering a simpler solution, proven experimentally. The physicochemical processes of diffusion of Cl^- in the aqueous phase, their adsorption and binding in the solid phase of concrete, and their desorption therefrom are described by a nonlinear partial differential equation for the concentration of Cl^- in the aqueous phase, from which that of Cl^- bound in the solid phase can be computed algebraically. This system can be solved only numerically, e.g. using a finite difference or element method [15]. The solution of the above system allows estimation of the time (critical time for chloride-induced corrosion) required for the total chloride concentration surrounding the reinforcement (located at a distance *c* from surface) to increase over the threshold for depassivation. A way of threshold expression is by measurement of the total chloride ion content in concrete required for the onset of reinforcement corrosion, and a mean value of 0.4–1% by weight of binder is adopted [4,23].

Afterwards, the propagation of corrosion process takes place at a rate that depends strongly on the availability of both oxygen and water. The possible mechanism of chloride ion interaction with the reinforcement and passive layer has not been fully resolved. Moreover, the estimation of the propagation period and the definition of the end of the service life due to chloride-induced corrosion contain a lot of uncertainties [4,17]. Therefore, as in the case of carbonation, the time required for Cl^- to exceed the critical value at the concrete cover, *c*, can be considered in good approximation as a narrow lower bound to the service life of reinforced concrete. The results presented in the next chapter could contribute in the definition of the above limits regarding the end of the service life of a structure exposed to chloride attack.

3. Consequences from reinforcement corrosion

In the present study, the additional effects of corrosion on the tensile behavior of reinforcing steel bars Class BSt

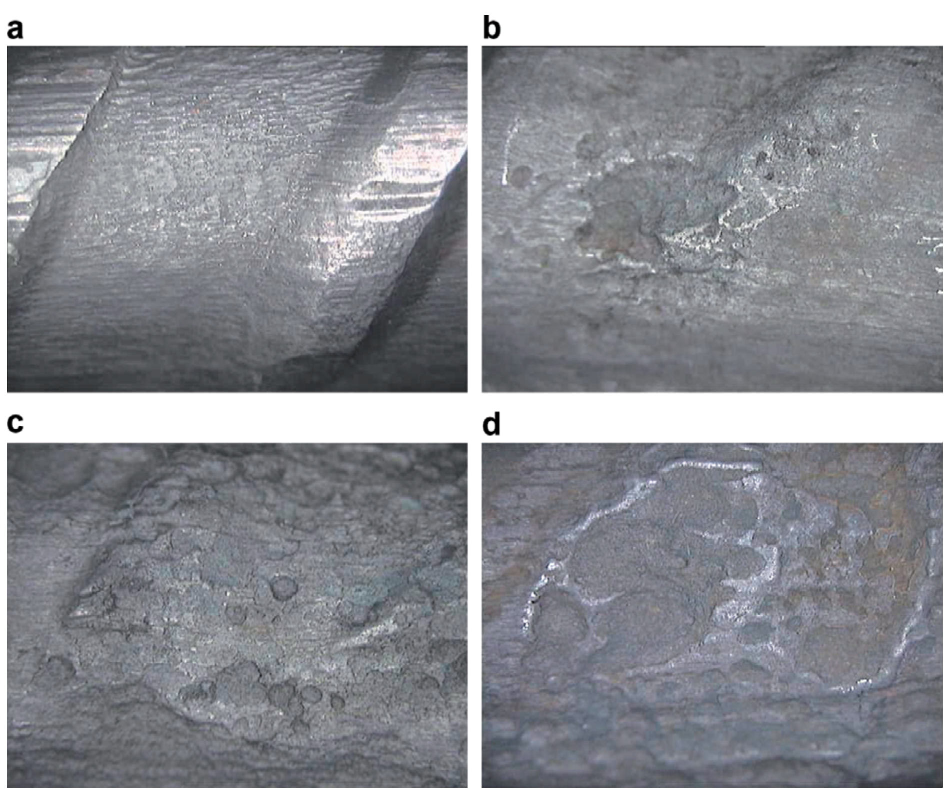

Fig. 3. Stereoscopic images (35×) of the reinforcing steel bar (a) non-corroded material and material exposed to (b) 10 days, (c) 20 days and (d) 30 days of accelerated salt spray corrosion.

420 are investigated. This type of steel is not produced anymore, however as it was used in the structures for the period 1960–1990 in Greece, its investigation regarding corrosion is very important. After the literature research, no studies were found dealing with the degradation of corroded reinforcing bars BSt 420 of DIN 488. The specimens were pre-corroded using laboratory salt spray tests for several exposure times. The dependencies of the degradation of the tensile properties on the corrosion exposure period have been derived. The tensile properties of the corroded material were compared against the requirements set in the standards for involving steels in reinforced concrete structures. The experimental results from the accelerated corrosion tests on bare steel bars are compared with results from steel bars embedded in aged concrete.

3.1. Experimental

The experiments were conducted for the steel BSt 420 of DIN 488-1. The maximum contents of C, P, S and N of the final product are 0.24%, 0.055%, 0.055% and 0.013%, respectively. The material was produced by a Greek industry and was delivered in the form of ribbed bars. The nominal diameter of the bars was 10 mm (Ø10). From the bars, tensile specimens of 250 mm length, 150 mm gauge length, were cut according to the specification DIN 488-3. Prior to the tensile tests, the specimens were pre-corroded using accelerated laboratory corrosion tests in salt spray environment.

Salt spray (fog) tests were conducted according to the ASTM B117-94 specification. For the tests, a special apparatus, model SF 450 made by Cand W. Specialist Equipment Ltd was used. The salt solution was prepared by dissolving 5 parts by mass of sodium chloride (NaCl) into 95 parts of distilled water (p? range 6.5–7.2). The temperature in the zone of the reinforcement material exposed inside the salt spray chamber was maintained at 35 °C (+1.1–1.7) °C. When exposure was completed, the specimens were washed with clean running water to remove any salt deposits from their surfaces, and then were air-dried. The accelerated salt spray corrosion was carried out for 10, 20, 30, 40 and 60 days.

Five pre-corroded specimens from each corrosion period were subjected to the tensile tests and the mean values are reported. The tensile tests were performed according to the DIN 488 specification. For the tests, a servo-hydraulic MTS 250KN machine was used. The deformation rate was 2 mm/min. The tensile properties, yield stress R_p, ultimate stress R_u, elongation to failure f_u and energy density W, were evaluated. Energy density is calculated from the area under the true stress–true strain curve. In the present work, as an engineering approximation, the energy density has been evaluated from the engineering stress–engineering strain curves as follows:

$$W = \int_0^{f_u} \sigma \, d\varepsilon \tag{1}$$

3.2. Results and discussion

As expected, corrosion damage increases with increasing exposure time to salt spray. Removal of the rust oxide layer by using a bristle brush according to the ASTM G1-90 specification has shown an extensive pitting of the specimens already after 10 days of exposure to salt spray. The stereoscopic image of a specimen after exposure to salt spray for 10 (b), 20 (c) and 30 (d) days is shown in Fig. 3, and compared to the image of the non-corroded material (a). It is observed that the corrosion attack initiated at the rib roots and advanced towards the area between the ribs. The indentations of the corrosion attack left on the specimen surface after removal of the oxide layer increase in dimensions and depth with increasing duration of the exposure.

The production of the oxide layer is associated to appreciable loss of the specimen mass. The dependency of the obtained mass loss on the salt spray duration is displayed in Fig. 4a. As seen from the figure, mass reduction can be considered linear with time. As seen also, for salt spray duration of 60 days, the mass loss of the corroded specimen is about 11% of the mass of the non-corroded specimen. By assuming a uniform production of the oxide layer around

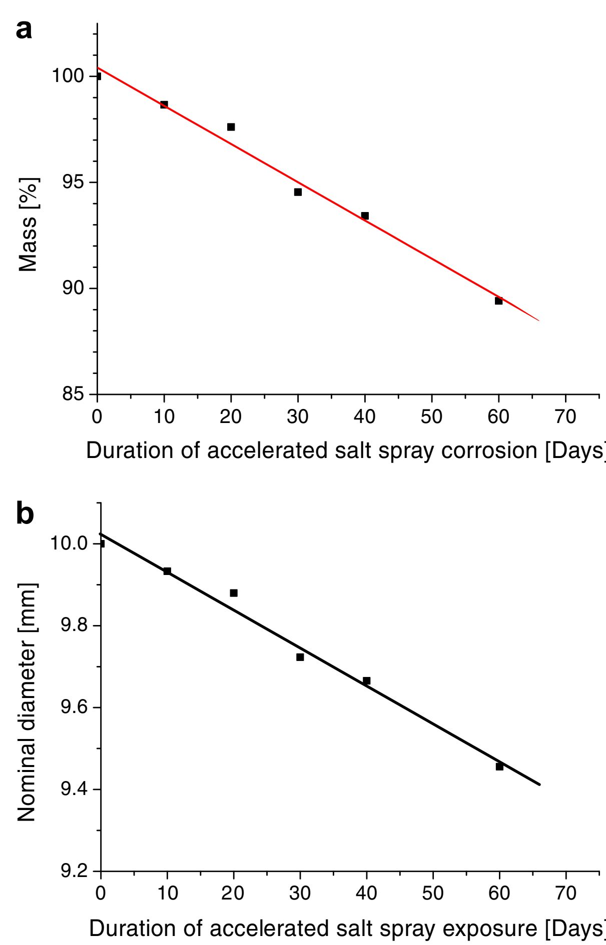

Fig. 4. Effect of corrosion on: (a) mass and (b) diameter of the steel bar.

the specimen, the results of Fig. 4a can be exploited to calculate the reduction of the nominal specimen diameter with the duration of the salt spray test, Fig. 4b. The reduced diameter d_r is calculated as:

$$d_r = \sqrt{a}.d \tag{2}$$

where a is the reduced mass factor and d is the original diameter (10 mm).

In Fig. 5a and b, the apparent and the effective values of yield stress R_p and ultimate stress R_u are given, respectively, over the duration of salt spray exposure, by neglecting the reduction of the cross- section of the corroded specimens. Note the two different determinations, effective stress and apparent stress. The apparent stress is calculated as the quotient of the load capacity, divided by the initial, uncorroded cross-section of the steel bars. This demonstrates the stress, according to the standards, which consider the mass, and therefore the cross-sectional area of the specimens remains constant over time. The effective stress is the quotient of the load capacity divided by the true cross-section of the corroded specimens, which is calculated as a function of the mass and length of each specimen. As shown in the Fig. 5, the apparent value of R_p drops below the limit of 420 MPa, which is set by DIN 488-1, after 30 days of exposure to salt spray. The effective value of R_p remains well above the lower limits set by DIN 488-1 even after 60 days of exposure to accelerated salt spray corrosion.

It is worth mentioning that even though the actual effect of corrosion on the tensile engineering strength properties of the reinforcing steel is moderate, the corrosion damage problem for the integrity of an older reinforced concrete structure remains significant [24]. As the loads of a reinforced concrete structure remain the same during the service life of the structure, the reduction of the load carrying cross-section of the bars due to corrosion damage results to an increase of the stress applied to the bars. This increase in stress reduces the safety factors taken for the properties of the reinforcing steel. The reduction of the cross-section of a reinforcing bar reduces also the moment of inertia and, hence, the maximum buckling load of the steel bar.

The effect of the increasing corrosion damage on the tensile ductility of the investigated steel bars is shown in Fig. 6. The curves in Figs. 5 and Fig. 6 have been well fitted by using the Weibull function [24]. Both, elongation to failure, Fig. 6a, and energy density, Fig. 6b, decrease appreciably

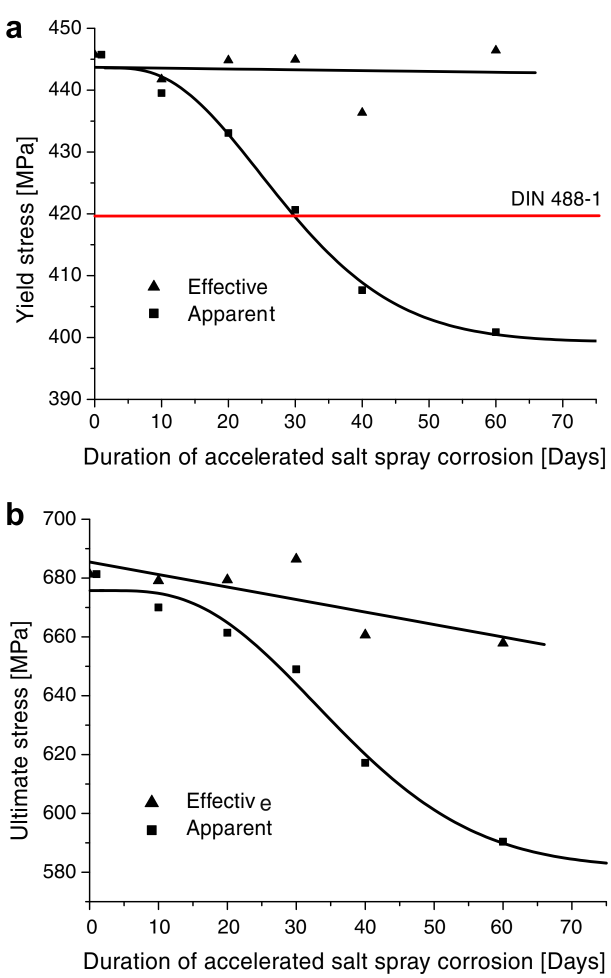

Fig. 5. Effect of corrosion on: (a) yield and (b) ultimate stress.

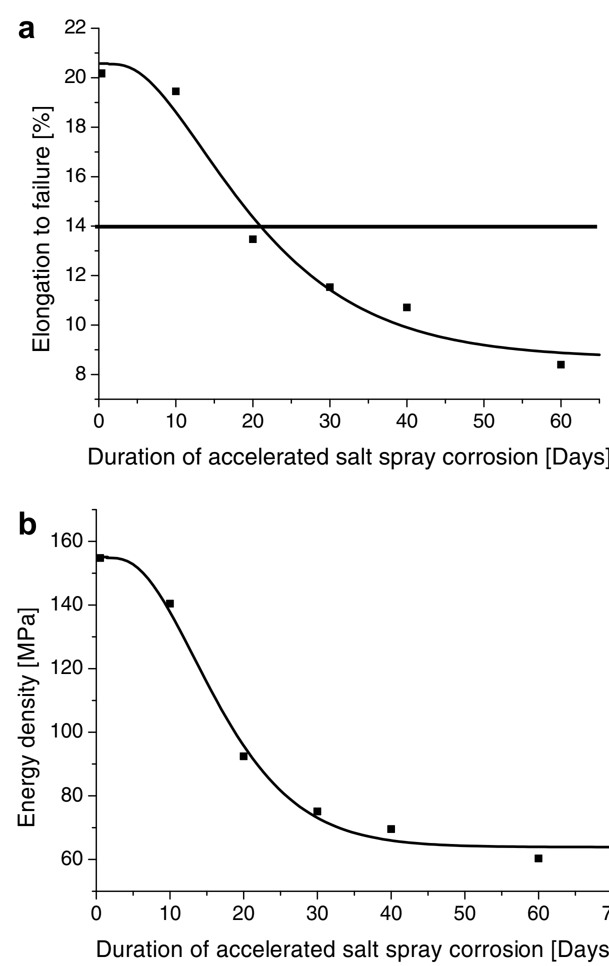

Fig. 6. Effect of corrosion on: (a) elongation to failure and (b) energy density.

with increasing duration of the salt spray exposure. The value of elongation to failure meets the requirement $f_u \geqslant 14\%$, according to the Greek standards, for exposures to salt spray of up to 20 days, where the bar diameter is reduced only to 9.88 mm. It is also observed elsewhere [25] that bars subjected to local or pitting corrosion may suffer a relatively modest loss of strength but a significant loss of ductility, and this is related principally to the variability of attack along the length of the bar [26].

The standards do not require for the evaluation of the energy density W, Eq. (1), of the reinforcing steel. Energy density is a material property which characterizes the damage tolerance potential of a material and may be used to evaluate the material fracture under both, static and fatigue loading conditions. Note that energy density may be directly related to the plain strain fracture toughness value, which evaluates the fracture of a cracked member under plain strain loading conditions. The observed appreciable reduction on tensile ductility may represent a serious problem for the safety of old and monumental constructions in seismically active areas. As during the seismic erection, the reinforcement is often subjected to low cycle fatigue, the need for a sufficient storage capacity of the material is imperative.

3.3. Comparison with long-term data from embedded bars

It is worth noting that the involved salt spray test is an accelerated corrosion test which is performed at the laboratory. Although the salt spray test environment, to some extent, simulates qualitatively the natural corrosion in coastal environment, it is much more aggressive and causes a very severe corrosion attack in a short time. The Cl^- concentration in the Atlantic Ocean, for instance, is about 20 kg/m^3, and when attacks an embedded steel bar in a concrete structure this concentration decreases, according to the concrete porosity. The present Cl^- concentration is about 31 kg/m^3 and it acts directly on the steel surface. Currently, there is no direct correlation between the accelerated laboratory salt spray test and the natural corrosion of reinforcing steel, this could be part of a future work.

However, in order to study whether the above conclusions are valid for real structures, where steel bars are embedded in concrete, the following additional experiments were performed. Specimens from reinforcement bars embedded for years in real structures and exposed in natural corrosion were taken, as these structures were demolished. Specimens from two different buildings were taken, an offshore house from the coastal area of Athens, Greece, about 40 years old, exposed in chloride environment, and an industrial building from the Aegion area, Greece, about 30 years old, exposed mostly in carbonating and high humidity environment. The reinforcement used in these buildings was BSt 420 of DIN 488-1 and the nominal diameter of the tested specimens was 10 mm (Ø10). From the bars, specimens of 250 mm length, 150 mm gauge length,

Table 1
Ductility properties versus mass loss values for corroded steel bars of deteriorated structures

No.	Mass loss, Δm (%)	Yield stress, R_p (MPa)	ΔR_p (%)	Ultimate stress, R_u (MPa)	ΔR_u (%)	Elongation to failure, f_u (%)	Δf_u (%)
Offshore house							
Athens, Greece, age: 40 years old, 2007							
A1	14.50	413.80	15.74	540.00	22.69	16.00	46.67
A2	8.67	491.10	0.00	625.16	10.50	30.00	0.00
A3	16.00	479.26	2.41	571.74	18.15	20.00	33.33
A4	11.90	466.36	5.04	589.65	15.58	6.00	80.00
A5	15.46	433.02	11.83	579.22	17.08	20.00	33.33
A6	13.70	437.30	10.95	698.51	0.00	4.00	86.67
A7	8.96	424.36	13.59	677.65	2.99	30.00	0.00
Industrial building							
Aegion, Greece, age: 30 years old, 2007							
B1	3.71	476.00	21.63	744.20	9.80	17.80	3.26
B2	5.69	461.80	23.97	743.10	9.94	17.30	5.98
B3	7.63	499.90	17.70	750.70	9.02	15.00	18.48
B4	4.42	537.20	11.56	745.50	9.65	11.80	35.87
B5	6.63	473.90	21.98	768.10	6.91	13.70	25.54
B6	8.88	429.00	29.37	688.40	16.57	14.30	22.28
B7	6.80	429.00	29.37	688.60	16.54	15.40	16.30
B9	4.81	565.90	6.83	825.10	0.00	8.30	54.89
B10	9.79	531.60	12.48	819.60	0.67	11.20	39.13
B13	2.77	505.30	16.81	742.90	9.96	11.80	35.87
B15	4.58	451.50	25.67	715.80	13.25	18.40	0.00
B16	9.74	512.20	15.67	792.00	4.01	8.10	55.98
B17	0.25	537.70	11.48	773.30	6.28	6.60	64.13
B18	3.30	584.80	3.72	808.70	1.99	8.00	56.52
B19	3.48	572.70	5.71	806.80	2.22	7.60	58.70
B20	5.80	607.40	0.00	805.00	2.44	7.80	57.61

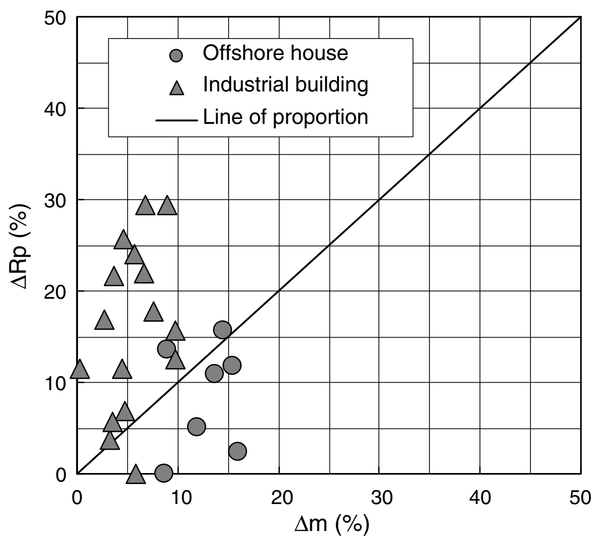

Fig. 7. Effect of mass reduction of the reinforcement bar due to steel corrosion on the reduction of the yield stress.

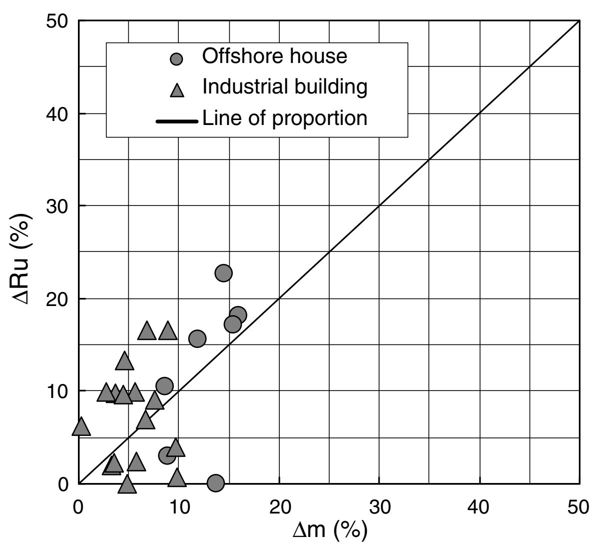

Fig. 8. Effect of mass reduction of the reinforcement bar due to steel corrosion on the reduction of the ultimate stress.

were cut according to the specification DIN 488-3. The tensile tests were performed according to the DIN 488 specification by using the same machine as in the accelerated tests.

In the above specimens, the mass loss was calculated by subtracting the present weigh of each bar (after removal of the rust by using a bristle brush according to the ASTM G1-90 specification) from the approached initial mass (given by multiplying the assumed initial volume by the steel density). The tensile properties, yield stress (apparent) R_p, ultimate stress (apparent) R_u, and elongation to failure f_u, were measured and reported in Table 1, as a function of corresponding mass loss.

The percentage reduction of the ductility properties, defined as:

$$\Delta(\text{property}), \% = [(\text{maximum value-current value})/\text{maximum value}]100 \tag{3}$$

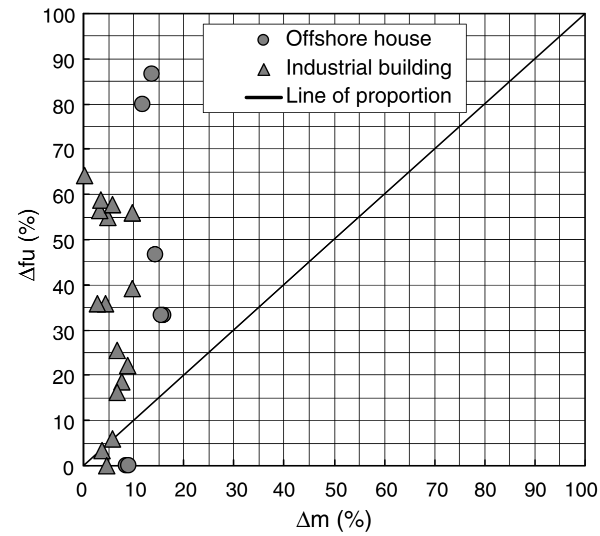

Fig. 9. Effect of mass reduction of the reinforcement bar due to steel corrosion on the reduction of the elongation to failure.

for yield stress, ΔR_p, ultimate stress, ΔR_u, and elongation to failure, Δf_u, were calculated and presented in Figs. 7–9, respectively, as a function of mass loss (Δm,%).

It is obvious that both yield and ultimate stress reduction (%) is proportional to the corresponding mass loss (see Figs. 7 and 8, where ΔR_p, and ΔR_u are almost equal to mass loss, Δm) as similarly observed in the accelerated tests (see Fig. 5 in conjunction with Fig. 4a, where the % reduction in R_p, and R_u is almost equal to % mass loss). On the other hand, the % reduction of the elongation to failure has an exponential dependence with the mass loss (see Fig. 9) as also similarly observed in the accelerated tests (see Fig. 6a in conjunction with Fig. 4a). Thus, a first conclusion is derived that there is a qualitative, at least, relationship for corrosion among accelerated tests in bare steel bars and long-term tests in embedded bars in concrete. In addition, the main result from the accelerated corrosion tests in bare steel bars, that the important ductility property of the elongation to failure is very sensitive to mass loss due to corrosion, it is valid and in real structures. A small amount of corrosion despite the fact that has a proportional effect on yield and ultimate stress, it has an exponential effect on elongation to failure, and consequently on energy density and anti-seismic behavior of the structure.

4. Conclusions

In the case of the significant corrosion-induced mechanisms, such as concrete carbonation and chloride penetration there are reliable predictive models. However, in the case of the propagation of reinforcement corrosion and its various consequences on steel bars and concrete structure that signal the end of the service lifetime, there are still no widely accepted models. In the present work, some experimental observations that could contribute to the above requirements are presented.

The exposure of the steel bars (in this work: BSt 420) to salt spray environment results to an appreciable mass loss, which increases with increasing duration of exposure. The effect of salt spray exposure on the strength properties of the steel BSt 420 is moderate. Yet, with regard to the observed appreciable mass loss, the increase on the effective engineering stress is essential, such as to spend the reserves on strength which are required in the standards through safety factors. The effect of salt spray exposure on the tensile ductility of the material is also appreciable. For salt spray exposures longer than 20 days, elongation to failure drops to values lying below the $f_u = 14\%$ limit, which is required in the standards. The existing standards for calculating strength of reinforced concrete members do not account for the appreciable property degradation of the reinforcing steel bars due to the gradually accumulating corrosion damage. The experimental results from the accelerated corrosion tests on bare steel bars are in a good qualitative agreement with results from steel bars embedded in aged concrete. It was observed in both cases, that bars subjected to corrosion may suffer a relatively modest loss of strength but a significant loss of ductility.

As already known, corrosion of concrete reinforcing steel is a chemical procedure, which leads to the degradation of the mechanical properties of the steel. Taking into account the fact, that steel grade BSt 420 has been used in structures constructed at times when knowledge on matters concerning the corrosion mechanisms was still at primitive stages, the results of this work clearly imply that the deterioration of many aged structures may be much worse than expected. This leads to the conclusion that such aged structures, may be less safe than expected, and more generally, that the end of the service lifetime could be earlier than when a crack in the concrete cover is observed.

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