

PROTECTION OF THE REINFORCEMENT OF MASONRY IN CORROSIVE ENVIRONMENTS

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SUMMARY

The protection against corrosion offered by seven masonry mortar compositions to the reinforcement placed in the bed joints of the masonry is being investigated. Durability protection was evaluated on the basis of three parameters: carbonation area of the specimens, mass loss of steel and electrochemical potential. Tests were performed against two corrosive environments, with and without chloride ions and were carried out for two periods: three months and six months. Two types of steel were used, plain steel and galvanized steel. Moreover, the steel protection action of a corrosion inhibitor, sodium nitrite, was examined.

INTRODUCTION

Usually reinforcing bars are incorporated in masonry structures to improve their behaviour under service conditions and mainly against seismic action. Reinforcement in masonry is placed in the horizontal mortar joints (horizontal reinforcement) and in special holes made out

in vertically perforated clay or concrete units (vertical reinforcement); these holes are filled with grout. In the case of the horizontal reinforcement the thickness of the overlaying mortar is particularly small, even when the thickness of the joint is 15 mm (the maximum allowed according to EC8) the overlaying mortar thickness of an 8 mm steel bar is only 3.5 mm. On the contrary the vertical reinforcement is covered with adequate mortar. Therefore, the mortar of the bed joints should be able to provide corrosion protection to the reinforcement as it will be exposed to the aggressive agents of the environment.

In the initial stages, mortar and grout offer to the reinforcement a passive protection thanks to the alkalic environment due to the presence of calcium hydroxide (PH value about 12.5). A thin protective oxide layer is then formed, strongly attached at the surface of the bars. As CO_2 of the environment penetrates in the joints and under the simultaneous presence of appropriate moisture content mortar carbonates and the PH value sinks. The protective layer is destroyed and the electrochemical corrosive procedure (for the realisation of which the simultaneous presence of O_2 and H_2O is required) initiates. Depassivation of the bars can also be obtained if chloride ions under the simultaneous presence of O_2 and H_2O penetrate into the structure. If the chloride to OH^- ions ratio becomes greater than a threshold value, corrosion may initiate. Chloride ions may be present in the environment at marine areas or in mortar and grout additives or even in the mix water.

The rate of realisation of the corrosive procedure depends on the rate of penetration of the aggressive environmental agents through a capillary action and through the minor cracks of the mortar or grout. This rate is mainly affected by the permeability of the mix which is conditioned by several factors, i.e. the chemical composition of its constituent materials, the water to binder ratio used, its porosity, its compaction and curing conditions and finally the presence of initial minor cracks. In fact, under suitable environmental conditions (appropriate moisture level, presence of corrosive agents, appropriate temperature level) the aggressive agents of the environment, penetrated into the structure through a capillary action or through minor initial cracks in the mortar mass, can possibly reach and attack the reinforcement. The increase of the volume of the produced rust on the attacked bars leads to the creation of the internal stresses in the mortar. New cracks open and the rate and intensity of the bars damage increases. Finally, a loss of the bars section with simultaneous reduction of the strength and of the ductility of the bars occurs causing severe cracking and even spalling of the mortar occur. Eventually, the integrity of structures is lost and their performance characteristics (safety, serviceability, aesthetic, etc) are drastically modified.

Only in the past three decades was realised that reinforced masonry structures should be designed to be safe not only against mechanical actions, but also as to exhibit adequate durability against physical and chemical environmental actions without losing their strength and service properties under a permissible level.

It has been reported, however, that the carbonation ratio (carbonation depth) of typical mortars in masonry structures is tenfold greater than the carbonation area of concrete. The difference becomes stronger at higher water to binder ratios. However, this is perhaps due to improper selection of the constituent materials and to unsuccessful compositions of the mortars examined. The authors' opinion, based on previous experience on durability behaviour of concrete and light concrete, is that the preparation of steel reinforced mortars concerning workability, mechanical and durability characteristics is possible.

EXPERIMENTAL PROCEDURES

Seven compositions, 3 cement mortars and 4 lime-cement mortars (see Table 1), complying with the requirements of prEN 998-2 and the European codes EC6 and EC8 were selected to be checked against durability parameters. Lime-cement mortars (A1M, A2M, A3 and A4) were investigated as it was expected that the presence of hydrated lime would enhance durability properties due to the excessive quantity of Ca(OH)_2 in the mix. Moreover, it is well known that lime-cement mortars exhibit good workability properties. Additionally, two prototype cement mortars M and T0 were used as the reference compositions, since their durability behaviour proved to be similar to that of concrete.

All mortar compositions exhibited a certain level of workability, complying with the requirements of EN 1015-2, i.e. 175 ± 10 mm slump. It should be noted that in order to obtain water to binder ratios as low as possible, a super plasticizer (Daracem 140, i.e. a mixture based on sulfom polymers dissolvable in water) was added in all cement mixes in a dosage of 1.5% per cement weight.

For the preparation of the mixes Portland cement (with up to 55% of pozzolanic constituents) was employed, referred as Portland cement IV 32.5 N, according to EN 197-1. Hydrated lime in dry form and in paste form (with 60% free water) and marble crushed sand (with maximum grain diameter of 4 mm) were used.

Table 1. Mortars and material ratios by mass of cement

mortar	Material ratios of mortar tests by mass of cement						type of lime
	cement	lime	aggregate	water	plasticizer	corrosion inhibitor	
M	1	-	3,0	0,51	1.5%	-	-
T0	1	-	3,3	0,59	1.5%	-	-
T1	1	-	7,5	1,10	1.5%	-	-
T1 α	1	-	7,5	1,10	1.5%	3,5%	-
A1M	1	0,26	6,0	1,00	-	-	dry
A1M α	1	0,26	6,0	1,00	-	3,5%	dry
A2M	1	0,10	5,2	0,87	-	-	dry
A2M α	1	0,10	5,2	0,87	-	3,5%	dry
A3	1	0,28	6,0	1,11	-	-	paste
A3 α	1	0,28	6,0	1,11	-	3,5%	paste
A4	1	0,10	5,2	0,87	-	-	paste
A4 α	1	0,10	5,2	0,89	-	3,5%	paste

For the estimation of the mechanical characteristics of mortars, three prismatic specimens were tested at the age of 28 days against flexure and consequently against compression according to prEn1015-11. Test results are given in Table 2. Furthermore, for each mortar composition a prismatic specimen was prepared to be used for the measurement of the total porosity, the mean pore radius and the dry bulk density of the mortars at the age of 6 months. The measurements were carried out on small portions of these specimens by means of a mercurus porosimeter Milestone 2000 of Carlo Erba. Tests results are depicted in Table 3.

Durability protection behaviour of the mortars was evaluated on the basis of three parameters: 1) carbonation area of the specimens, 2) mass loss of steel and 3) electrochemical potential.

Table 2. Mean flexural and compressive strength of mortars at 28 days.

mortar	Mean flexural strength (MPa)	Mean compressive strength (MPa)
M	6,41	45,23
T0	6,14	42,75
T1	3,96	15,43
T1 α	3,92	18,87
A1M	3,41	20,01
A1M α	3,65	19,95
A2M	4,33	21,92
A2M α	4,35	23,55
A3	2,45	13,33
A3 α	2,53	12,99
A4	3,81	18,67
A4 α	3,81	18,05

 Table 3. Mean pore radius, total porosity (%) and dry bulk density (Kg / m³) of each mortar

mortar	M	T0	T1	T1 α	A1M	A1M α	A2M	A2M α	A3	A3 α	A4	A4 α
pore radius average (Å)	0,211	0,223	0,783	0,783	0,407	0,432	0,432	0,538	0,432	0,538	0,538	0,562
total porosity (%)	15,01	15,11	18,02	18,69	18,45	20,86	21,47	19,96	23,66	23,16	20,26	21,67
dry bulk density (Kg/m ³)	2,2	2,2	2,17	2,15	2,13	2,09	2,06	2,11	2,03	2,01	2,11	2,09

Table 4. Number of corrosion specimens according to the considered parameters

mortar	Corrosion environment MX2, plain steel			Corrosion environment MX4, plain steel			Corrosion environment MX4, galvanised steel		
	3 months	6 months	12 months	3 months	6 months	12 months	3 months	6 months	12 months
M	3	3	3	3	3	3	3	3	3
T0	3	3	3	3	3	3	3	3	3
T1	3	3	3	3	3	3	3	3	3
T1 α				3	3	3			
A1M	3	3	3	3	3	3	3	3	3
A1M α				3	3	3			
A2M	3	3	3	3	3	3	3	3	3
A2M α				3	3	3			
A3	3	3	3	3	3	3	3	3	3
A3 α				3	3	3			
A4	3	3	3	3	3	3	3	3	3
A4 α				3	3	3			

Carbonation area of the specimens and mass loss of steel were measured at 3 and 6 months; whereas the measurements of the electrochemical potential were carried out throughout a nine month period. For each mortar composition, each type of steel and each corrosion

environment nine specimens were constructed; three specimens for the 3 months, three specimens for the 6 months and three specimens for one year (see Table 4, measurements of one year have not yet been completed). The total number of the specimens is 234. For the medium corrosion environment MX2 plain steel bars were used, whereas for the intensively corrosion environment MX4 both plain and galvanized steel bars were checked. The steel protection action of a corrosion inhibitor, sodium nitrite, was examined in the case of MX4 environment with plain steel bars.

To this purpose, small cylindrical specimens of a diameter of 40 mm and of a height of 100 mm with embedded reinforcement of a diameter of 4 mm were prepared. The reinforcement protruded 20 mm of the specimen's upper surface. Specimens were partially immersed in de-ionized water and in 3.5% NaCl (which correspond to exposure classes MX2 and MX4 of European code EC6), to accelerate corrosive procedure. The results are thus likely to represent a "best case" in relation to site conditions of a wall section just above the ground, in an agricultural and in a marine area respectively. The upper surface of the specimen as well as the protruding bar of each specimen were covered with a thin layer of epoxy resin in order to avoid the corrosion of the unprotected surface of the steel bar. The characteristics of the specimens are shown in Figure 1.

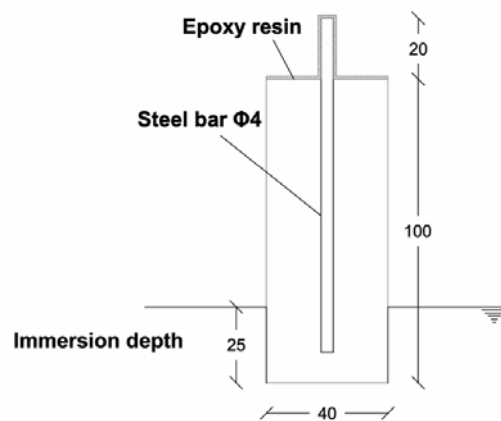


Figure 1. Specimen characteristics

TEST RESULTS

Carbonation Area of the Specimens

After the end of each period of time, specimens are removed from each corrosive environment and then they are split into two pieces parallel to steel bar axis. The carbonation area of each specimen is determined on the surface of each specimen by means of a phenolphthalein indicator; the carbonized surface of the specimen remains uncolored whereas the carbonized area is dyed purple. The carbonation depth is increased from bottom to top; it is approximately zero at the immersed area of the specimen and takes its higher value at the top (see Figure 2). Table 5 depicts the mean values of the carbonation depth at the bottom, in the middle and at the top of the specimen for each type of mortar and corrosion environment at two periods of time (3 and 6 months respectively).

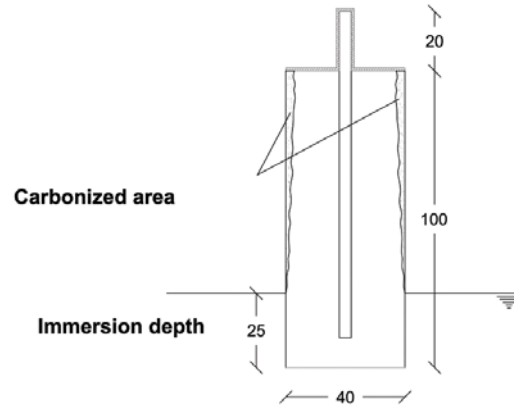


Figure 2. Carbonized area of the specimens

Table 5. Carbonized depth on the bottom, in the middle and on top of the specimens

mortar	corrosive environment	carbonized depth - 3 months			carbonized depth - 6 months		
		bottom (mm)	middle (mm)	top (mm)	bottom (mm)	middle (mm)	top (mm)
M	MX2	0,08	0,71	1,13	0,97	2,55	3,83
	MX4	0,45	1,05	1,65	1,28	2,29	2,98
T0	MX2	0,13	1,17	1,94	0,67	3,04	4,22
	MX4	0,43	0,98	1,21	1,26	2,23	2,96
T1	MX2	1,99	2,01	2,07	0,68	2,10	6,10
	MX4	1,98	2,65	3,35	1,33	3,18	5,32
T1α	MX4	2,38	2,70	3,51	1,30	2,73	4,92
A1M	MX2	0,49	1,13	1,83	1,07	1,48	4,15
	MX4	0,32	1,85	2,69	1,28	2,74	4,33
A1Mα	MX4	1,21	1,48	2,16	1,12	2,30	4,63
A2M	MX2	0,49	0,83	1,51	1,08	1,65	5,32
	MX4	1,61	2,01	2,94	1,28	2,73	5,35
A2Mα	MX4	1,56	1,74	2,46	1,27	2,50	5,32
A3	MX2	0,17	1,08	1,77	1,08	1,30	4,70
	MX4	1,48	1,91	2,44	1,18	2,51	4,68
A3α	MX4	1,31	1,53	1,92	0,88	2,18	2,95
A4	MX2	0,15	1,15	1,78	1,23	1,18	5,63
	MX4	0,98	1,89	2,67	1,23	2,72	5,02
A4α	MX4	1,12	1,63	2,16	1,00	2,42	3,90

The results indicate that carbonation depth is smaller in the case of the reference mortars both in MX2 and MX4 environment as expected.

The values in the corrosion environment MX4 are 40-60% higher than the values in the environment MX2 in the period of 3 months, whereas they turn out to be the same or even lower (0-20%) in the period of 6 months.

T1 cement mortar exhibits the higher values both in MX2 and in MX4 environment for both periods of time.

The increase of the hydrated lime percentage, from 10 to 25% of cement, leads to lower carbonation depths regardless the type of hydrated lime (dry or paste). However, mortars containing hydrated lime in the form of paste tend to have lower values than the corresponding ones containing lime in dry form. This holds true both for the 3 and the 6 months period.

The addition of the corrosion inhibitor results in lower values of the carbonated depth; particularly in the 6 months period the carbonation depth of the specimens with sodium nitrite

(in a MX4 environment) appears to be even lower than the corresponding depth of the same type of mortars in a MX2 environment.

Generally, the carbonation depth has been increased about two times between the 3 and the 6 months period of time.

Mass Loss Of Steel Bars

Before the preparation of the specimens, the steel bars have been numbered and weighed with an accuracy of 0.0001 gr. After the ending of each period of time in the corrosive environment specimens are removed and split into two pieces parallel to the steel bar axis. Bars are taken away and cleaned up of any corrosive product by immersion in a solution of HCl with inhibitors in the case of plain steel bars, and in a solution of NH_4OH (10.5 % NH_4OH in distilled water) in the case of galvanized steel bars. Further, they are washed with water and dried. The final weight of the bars is again measured with an accuracy of 0.0001 gr. Table 6 depicts the mean values of the mass loss (%) of the steel bars for each type of mortar, corrosion environment and steel type for the period of 3 and 6 months respectively.

Table 6. Mass loss of steel bars

mortar	corrosive environment	type of steel	mass loss (%) 3 months	mass loss (%) 6 months
M	MX2	plain steel	0,06	0,11
	MX4	plain steel	0,08	0,16
	MX4	galvanized steel	0,20	0,27
T0	MX2	plain steel	0,08	0,12
	MX4	plain steel	0,10	0,12
	MX4	galvanized steel	0,08	0,09
T1	MX2	plain steel	0,10	0,09
	MX4	plain steel	0,16	0,32
	MX4	galvanized steel	0,22	0,29
T1α	MX4	plain steel	0,11	0,23
A1M	MX2	plain steel	0,09	0,10
	MX4	plain steel	0,26	0,48
	MX4	galvanized steel	0,24	0,21
A1Mα	MX4	plain steel	0,10	0,23
A2M	MX2	plain steel	0,10	0,09
	MX4	plain steel	0,15	0,26
	MX4	galvanized steel	0,18	0,15
A2Mα	MX4	plain steel	0,09	0,10
A3	MX2	plain steel	0,09	0,14
	MX4	plain steel	0,22	0,16
	MX4	galvanized steel	0,08	0,09
A3α	MX4	plain steel	0,12	0,15
A4	MX2	plain steel	0,09	0,08
	MX4	plain steel	0,14	0,14
	MX4	galvanized steel	0,06	0,05
A4α	MX4	plain steel	0,05	0,11

Results indicate that the mass loss of steel bars, regardless the type of steel, is higher in the case of MX4 environment than in MX2 environment in all mortars both in 3 and 6 months period.

Steel bars of the reference mortars exhibit the lowest mass loss especially in MX4 environment both for the 3 and 6 months period.

Mass loss of steel bars of the mortars containing hydrated lime is less pronounced than that of cement mortar T1 both in 3 and 6 months period.

The increase of the hydrated lime percentage, from 10 to 25% of cement, leads to higher mass loss of bars, regardless the type of the lime. However, lime in the form of paste results in lower mass loss.

The addition of the corrosive inhibitor results in lower mass loss of steel bars (30 – 60 %) in all mortar compositions (MX4 environment). These values are approximately the same with the corresponding values of the same mortars in the less corrosive environment MX2, and slightly higher than the ones of the representative mortars.

The mass loss of galvanized steel is lower than the equivalent of the plain steel in the environment MX4. For all the mortar compositions the mass loss of galvanized steel is approximately the same (about 0.3 %) with the exception of the mortars containing hydrated lime in the form of paste in which case the mass loss is less than 0.1 %. There is no significant change between the 3 and the 6 months period of time; mass loss of galvanized steel remains practically the same.

In general the mass loss of steel in the case of 6 months is 25-125 % higher than the equivalent of the 3 months for all mortar compositions.

Electrochemical potential

The electrochemical potential of the steel bars is measured during exposure of the specimens, at intervals of one week for the first three months of exposure, and once a month afterwards, by means of saturated calomel electrode (SCE). For this purpose, Cu wires were positioned at the protruding bars of all specimens. Figures 3, 4 and 5 show the in-time development of the electrochemical potential of the steel bar of the test mortars in the case of MX2 environment and plain steel, in the case of MX4 environment and plain steel and in the case of MX4 environment and galvanized steel respectively.

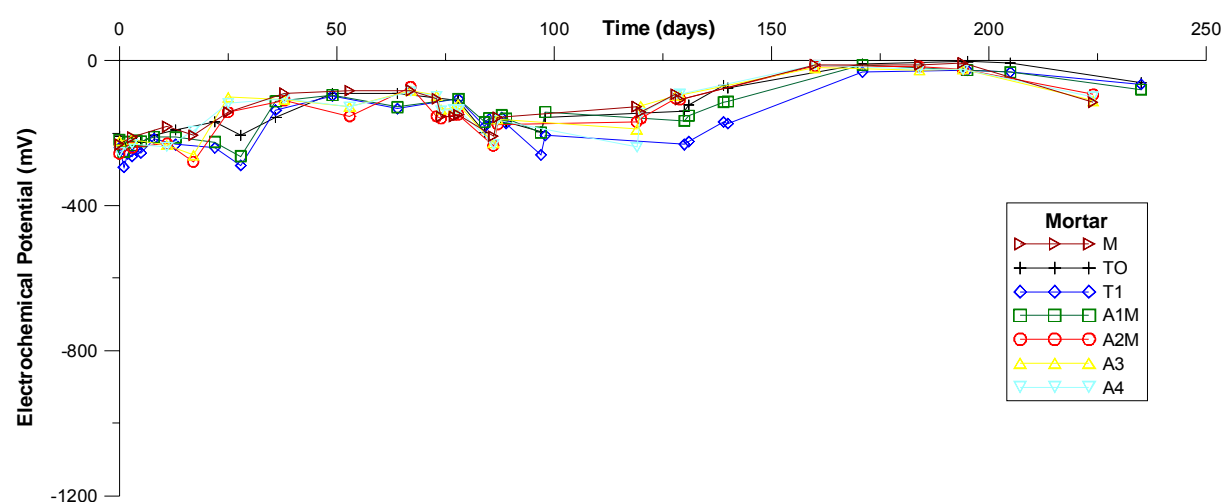


Figure 3. In-time development of the electrochemical potential of steel bar of test mortars in the case of MX2 environment and plain steel

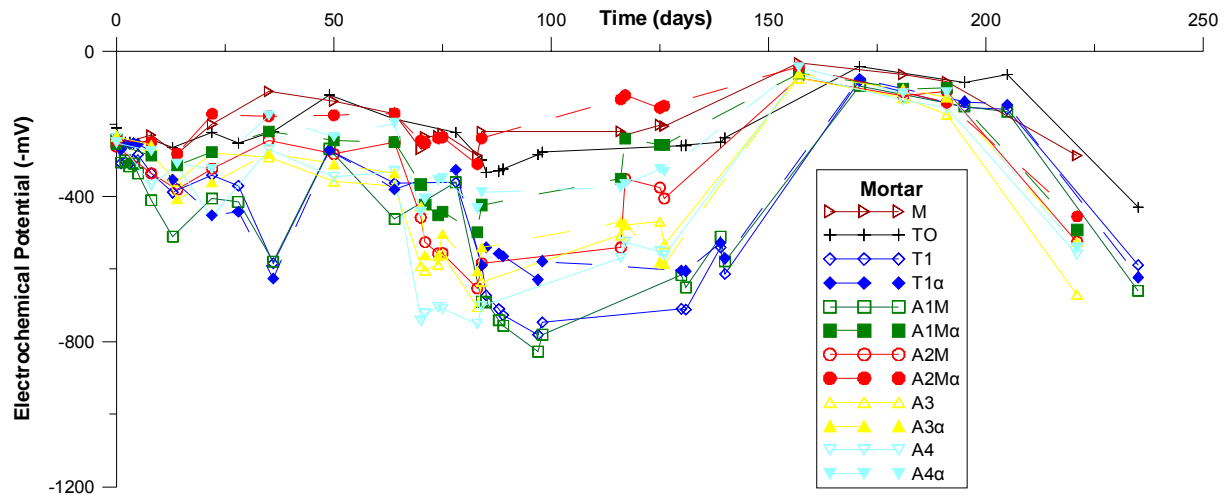


Figure 4. In-time development of the electrochemical potential of steel bar of test mortars in the case of MX4 environment and plain steel

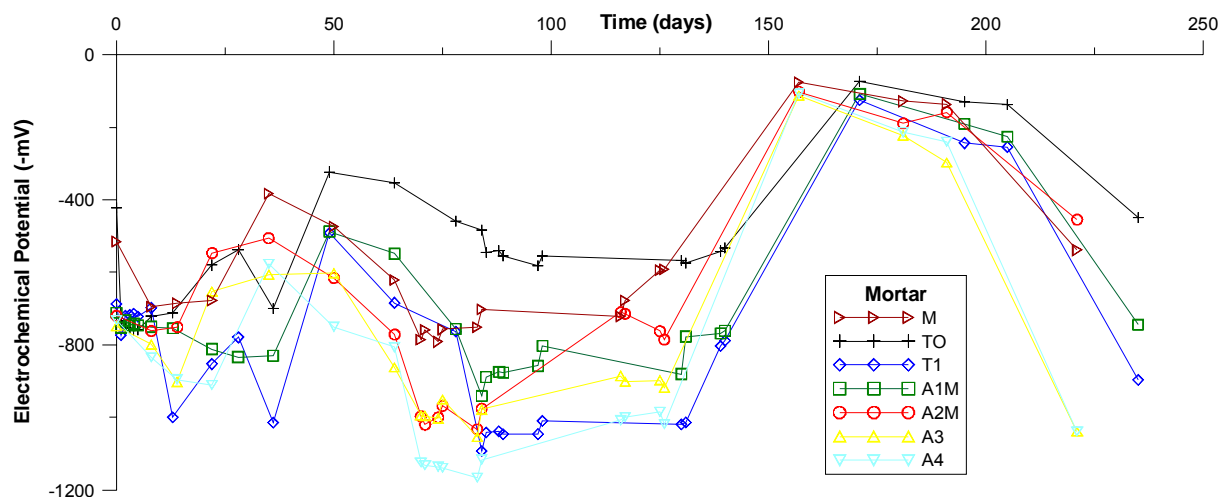


Figure 5. In-time development of the electrochemical potential of steel bar of test mortars in the case of MX4 environment and galvanized steel

The above diagrams indicate that the electrochemical potential mean values of the steel bars of the reference mortars are higher in all three cases.

The electrochemical potential mean values of steel bars in all compositions and type of steel are lower in the environment MX4 than in the environment MX2.

The differences in the mean values of the electrochemical potential are more intense in the environment MX4 regardless of the steel type.

The addition of sodium nitrite shifts the electrochemical potential mean values in higher prices.

The cement mortar T1 exhibits the lower electrochemical potential mean values.

The electrochemical potential mean values of galvanized steel bars are lower than those of plain steel and display a higher decrease through time due to the conversion of zinc to zinc oxide.

CONCLUSIONS

From the results reported in this paper it may be concluded that the preparation of mortars for reinforced masonry structures, which bring durability characteristics, is possible. Lime-cement mortars in low lime content are possible to exhibit similar properties against corrosion as compared to prototype reference mortars. Hence, durability properties of these mortars are judged as adequate for reinforced masonry structures. Moreover, the durability of mortars with the addition of anodic corrosion inhibitor (sodium nitrite) can be significantly improved.

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