ALCONPAT Journal

Journal of the Latin-American Association of Quality Control, Pathology and Recovery of Construction

Durability of sustainable repair mortars exposed to industrial environments

J. M. Mendoza-Rangel[1], J. M. Flores-Jarquín[1], E. U. De Los Santos[1], P. Garcés Terradillos[2]

[1] Universidad Autónoma de Nuevo León, UANL, FIC, Av. Universidad S/N, Ciudad Universitaria, San Nicolás de los Garza, Nuevo León, C.P. 66451, Mexico.
[2] Civil Engineering Department, Universidad de Alicante, Carretera de San Vicente del Raspeig S/N, San Vicente del Raspeig, Spain

ABSTRACT

The repair and maintenance of concrete structures has increased in the activities of the construction industry. In this work, the durability of two mortars elaborated with fly ash substitutes (FA) is evaluated by weight with respect to the total cement; furthermore, its performance is compared to three commercial repair mortars, exposed to the CO_2 attack in an industrial environment. To evaluate its performance as repair material, tests were carried out to evaluate its resistance to compression, bending, and adherence. Durability tests are also presented as potential measurements, corrosion rate, permeability, and carbonation depth.
Keywords: Mortar; repair materials; corrosion; carbonation; durability.

RESUMEN

La reparación y mantenimiento de estructuras de concreto se ha incrementado en las actividades de la industria de la construcción. En el presente trabajo, se evalúa la durabilidad de dos morteros elaborados con sustituciones de ceniza volante (CV) en peso con respecto al cementante total, adicionalmente se compara su desempeño con tres morteros de reparación comerciales, expuestos al ataque de CO_2 en ambiente industrial. Para evaluar el desempeño como materiales de reparación se realizaron ensayos de resistencia a la compresión, flexión y adherencia. Se presentan también pruebas de durabilidad como mediciones de potencial, velocidad de corrosión, permeabilidad y profundidad de carbonatación
Palabras clave: Mortero; materiales de reparación; corrosión; carbonatación; durabilidad.

RESUMO

O reparo e manutenção de estruturas de concreto tem crescido dentre as atividades da indústria da construção. Foi avaliada a durabilidade de duas argamassas obtidas a partir de substituição de cinzas volantes (CV), em massa em relação à quantidade total de produto aglomerante. Foi comparado o desempenho dessa argamassa com o desempenho de três argamassas de reparo comerciais, frente a um ataque de CO_2 num ambiente industrial. Para avaliar o desempenho como materiais de reparo foram realizados ensaios de resistência à compressão, flexão e aderência. São apresentadas também provas de durabilidade com medidas de potencial de corrosão, velocidades de corrosão, permeabilidade e profundidade de carbonatação.
Palavras-chave: Argamassa; materiais de reparo; corrosão: carbonatação; durabilidade.

_____
Contact author: José Manuel Mendoza Rangel (jmmr.rangel@gmail.com)

1. INTRODUCTION

The main problem for which a concrete structure needs repair is the corrosion of steel, which negatively impacts the durability of the constructions, putting at risk their functionality and safety (Andrade C., Feliu S., 1989). In industrial and urban environments, the big concentrations of CO_2 represent a problem for the reinforced concrete due to the carbonation of the same, which causes a reduction in alkalinity and generates the depassivation and corrosion of steel. For the development of carbonation, the humidity and temperature are factors that modify its advance rate.

After having detected the corrosion in a structure, it is necessary to take actions to do repairs and prolong its useful life. The repair work can be divided into the following steps: elimination of the concrete, cleaning the exposed steel, and the application of a repair material (Fernández Cánovas, 1989).

The selection of the repair material is the most important criterion to consider in the repair work; normally, the resistance to compression is taken into consideration to select a repair mortar, this is completely insufficient if other parameters that are equally important, such as the compatibility of the mortar with the concrete substrate, are not taken into consideration. The topic of compatibility implies the study of the difference between the properties of the concrete substrate and the repair mortar, as said difference could cause negative effects on the repair, causing cracking and thus decreasing its durability (Decter, 1997).

Several studies have been conducted to evaluate the different types of repair materials that are available on the market. Unfortunately, the properties that should be considered for the evaluation and selection of the repair materials are not specified (Cabrera, 1997). Some authors (Emmons, 1994) present the considerations that affect the compatibility for a new selection of the repair materials. From these considerations, the most important is probably the capacity to support changes in volume, without loss of adherence or cracks; this is known as "Dimensional compatibility". In addition to the volume changes, a repair should also have a protector effect and to ensure this, the chemical, electro-chemical, and permeability of the repair material should be considered.

The problems related to the properties to be evaluated and the selection of the repair materials are attributed to the lack of regulation in relation to the repair activities, maintenance, and renovation (Kay, 1987; Treadaway, 1987), in addition to the lack of information that the manufacturers of the repair materials provide. For this reason, it is necessary to carry out researches on the repair materials that are adequate to the environment and the service conditions of each structure. In turn, the use of alternative cement materials such as fly ash, will allow the use of repair materials of low environmental impact, due to the decrease in the use of ordinary Portland cement (OPC), and that comply with the necessary characteristics for a lasting repair.

The objective of this work is to evaluate the durability and potential performance of three mortars prepared in the laboratory, two with substitution of FA (20 and 50%) for OPC and three mortars of commercial repair; in particular their mechanical behavior, dimensional stability, adherence, and their capacity to protect steel from corrosion by carbonation in an industrial environment.

2. EXPERIMENTAL PROCEDURE

Table 1 shows the proportion of the mortars elaborated in the laboratory. The MR mortar is used as reference, mortars M1 and M2 were elaborated with the same water/cement and cement-sand ratio as the reference one, but with FA additions of 20 and 50% in substitution with regard to the weight of MR cement. The cement used is an OPC 40 and the FA is type F—it was obtained from the *Carboeléctrica* of the city of Nava Coahuila, Mexico. The chemical composition of the OPC and FA can be observed in Table 2, obtained by X-ray fluorescence (XRF).

Table 1. Proportions of the repair mortars manufactured in the laboratory.

Mortar	Component	Proportion
MR	OPC	1
	Sand	3
	Water	0,5
M1	OPC	0,8
	FA	0,2
	Sand	3
	Water	0,5
M2	OPC	0,5
	FA	0,5
	Sand	3
	Water	0,5

The commercial repair mortars are identified as C1, C2, and C3, these are pre-packaged mortars, cement based and of only one component; C1 is a reinforced mortar with fiber,; C2 is fast-setting; C1 and C3 are modified with polymers and with additions of micro-silica in proportions that are known by the manufacturer. The mixture and the amounts of water used were the ones specified in the data sheet of each mortar.

Table 2. Chemical composition in oxides of the Portland Cement and Fly Ash

Oxides	OPC (%)	FA (%)
SiO_2	17,43	56,51
Al_2O_3	4,67	33,11
Fe_2O_3	2,25	1,49
CaO	63,27	0,70
MgO	1,23	1,67
SO_3	4,98	0,34
Na_2O	0,56	3,32
K_2O	0,75	0,52

Different types of specimens were manufactured in accordance with the test to be carried out; after their manufacture, the specimens were kept in a curing chamber at 100% Relative Humidity (RH) and at 21±2 ºC, for 14 days. After curing, the specimens were removed from the chamber until they reached 28 days of age.

For the corrosion potentials test, specimens with two steel bars of 6 mm in diameter were manufactured to leave a coating of 7 mm; additionally, a graphite column of the same diameter was placed to be used as a counter electrode.

To evaluate the capacity to resist the entry of aggressive agents, the specimens were exposed to carbonation in an industrial environment.

In the industry where the specimens were placed, industrial processes of sodium carbonate and bicarbonate are carried out, which creates an aggressive and damaging environment for concrete.

2.1 Resistance to compression and flexural strength

To determine the resistance to compression, mortar cubes with a side length of 50 mm were manufactured. The filling procedure of the cubes and the testing were done in accordance with the provisions in the standard (ASTM C 109). The flexural strength was done according to the procedure described in the standard, in 40x40x160 mm prismatic test tubes (ASTM C 348).

2.2 Adherence

The test used is known as inclined cutoff testing, which uses a 100x100x300 mm prism made from two identic halves joined at 30º and tested under axial compression (Momayez, 2005).

2.3 Permeability

The procedure to determine the air permeability of the repair mortars was done through the Torrent Permeability Tester (TPT) on 150 mm cubic test tubes (Torrent, 1992; Kucharczykova, 2010).

2.4 Carbonation Depth

For this test, 20x55x280 mm prismatic test tubes were used. The samples were placed in the industrial environment mentioned above, which does not present consistent values as it depends on the production in the plant; the data mentioned before -were reported in a previous article ((Durán-Herrera, 2015). The monitoring was done using phenolphthalein as depth indicator for carbonation on the samples that were freshly cut at different ages.

2.5 Corrosion potentials and rates

The corrosion potentials (E_{corr}) and rates (i_{corr}) are determined through the resistance to polarization test (ASTM G 59) with a sweep feed of 0.06 mV/s; only in the cathodic zone does it go from 0 to -10 mV. This methodology is applicable for the study of the protection that the repair mortars provide to reinforced steel.

The steel used was prepared and cleaned following the procedure established in the ASTM G1 (ASTM G 1) standard, which completely removes the corrosion products that it could have before starting the test. After the cleaning of the steel, it was weighted and carefully wrapped to define the area of study (50 mm).
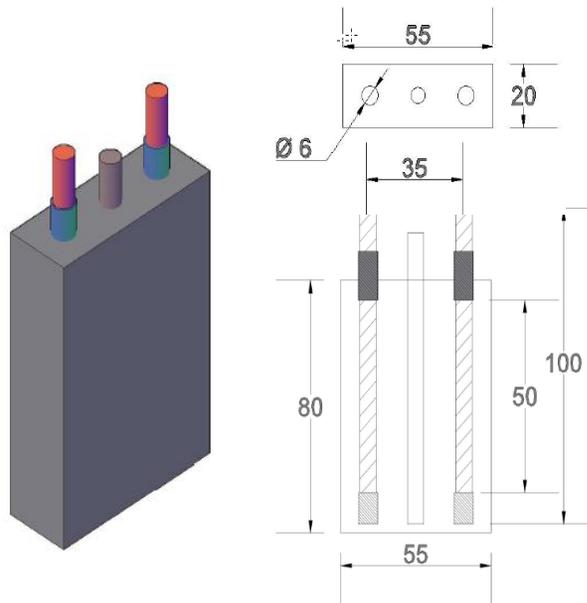
Figure 1. Specimen to evaluate the durability of the repair mortars (units in mm)

3. RESULTS AND DISCUSSION

Table 3 shows the mechanical behavior of each repair mortar and the results of the tests at 28 days. It can be observed that the C1 commercial repair mortar shows resistance at the highest compression, which is due to the content of fibers that decrease deformation in the face of a load and their role as reinforcement for the mortar.

The M1 mortar follows in the order of resistance, its value being higher than the MR mortar and the commercial C1 and C3 mortars. As per flexural strength, the C1 mortar shows the highest resistance due to the addition of fibers. The commercial C2 mortar is the lowest in regard to its mechanical behavior—its low resistance can be associated to the high porosity which, as is mentioned in figure 2, is not visible due to it being more permeable and it does not appear because it is outside the scale ranges. According to various investigations (Bjegovic 1990; Jiang, 2009), the lower resistance of the C2 and C3 mortars is probably the result of their additives.

Table 3. Mechanical behavior of the repair mortars.

Mortar	Resistance to Compression 28 days (MPa)	Flexural Strength 28 days (MPa)
MR	57,4	12,7
M1	65,8	11,7
M2	32,6	10,6
C1	75,4	16,4
C2	30,0	7,4
C3	49,2	14,3

C2 mortar, being a fast-setting mortar, could contain magnesium sulfate or higher amounts of calcium sulfate, thus increasing its setting speed but decreasing its final resistance; for its part, C3

mortar contains polymers and microsilica in addition to having a higher content of air in order to improve its resistance to freezing and melting, this is not evident on the permeability graph, due to the fact that the polymers allow creating a greater amount of pores, but in an isolated and well-distributed manner.

The adherence was evaluated by the type of failure that the prisms present; Table 4 shows the resistance to adherence of each mortar at 28 days as well as their type of failure. If there is good adherence, the sample malfunctions monolithically as one piece, presenting cracks that spread from the repaired concrete to the repair mortar, instead of faltering throughout the union in one plane at 45°.

The other type of failure presented is on the interface, where the adherence failure between the concrete and the mortar happens before either of the two materials fails. The results of the resistance to adherence show that the mortars with the best behavior are C1 and C3 due to the failure presenting itself along with the concrete (monolithic); even though the monolithic failure is desirable, it can be observed that the M1 mortar presented a failure in the interface and yet showed the highest resistance for adherence (Cabrera, 1997). This advantage is possibly due to the cement used for the manufacture of repair mortars being the same as the one used for the manufacture of the concrete samples on which the repair was done.

Table 4. Adherence of the repair mortars

Mortar	Resistance to Adherence 28 days (MPa)	Type of Failure
MR	22,2	Interface
M1	26,1	Interface
M2	13,4	Interface
C1	19,4	Monolithic
C2	0,0	Interface
C3	22,5	Monolithic

The C2 mortar, for its part, is the mortar with the least mechanical properties; in the adherence test, the failure immediately showed at the beginning of the test, not allowing the team to record anything. It is worth noting that the compatibility of the deformations is important to do a good repair, in materials with lower elasticity modulus (usually related to lower resistance) more deformations for the same level of load will manifest, originating the failure in the material with more deformations.

Figure 2 shows the relation of air permeability in time for the different mortars. It can be observed how permeability increases in almost all the mortars, with C3 mortar being the one that presents the lowest permeability values and without any increases in relation to time. The C2 mortar is not shown in the ranges on the scale because it is too permeable. While the commercial C1 mortar was not tested due to it having a rough surface and the presence of larger sized aggregates compared to the rest of the mortars, but as can be observed in carbonation, it is not possible to measure its advance as it does not present any reaction to phenolphthalein (Figure 3).

Therefore, it can be said that the M1 mortar shows a good resistance to the influx of CO_2, as this test has been shown to have a good correlation with other durability tests as good as the C3 commercial mortar. MR and M1 presented values classified as low permeability (0.01-0.1) while M2 presented moderate permeability coefficients (0.1-1.0), the rest of the classifications are shown in table 5. The results obtained through the quick permeability method have shown

a good correlation with the permeability tests to water, chlorides, and carbonation (Ebensperger, 2010).

Table 5. Permeability classification in terms of kT (Ebensperger, 2010).

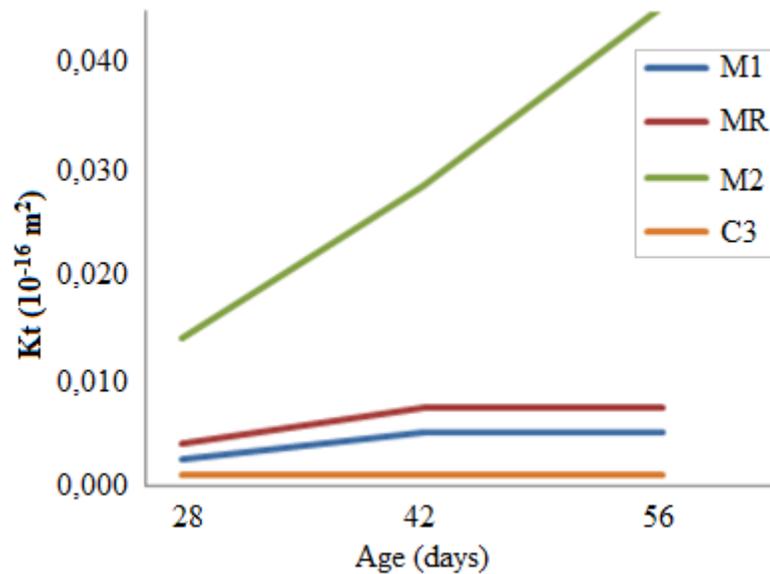| Class	kT ($10^{-16}m^2$)	Permeability
1	<0,01	Very low
2	0,01-0,1	Low
3	0,1.1,0	Moderate
4	1,0-10	High
5	>10	Very high

Figure 2. Evolution of the permeability of the mortar (Kt) over time.

The carbonation depth gives an indication of how the advance of CO_2 reaches the steel and causes a significant decrease in the pH of the mortar; with the decrease of pH, depassivation of the layer begins, which starts the corrosion of the steel. The coating for the steel is of 7 mm, the behavior of the repair mortars versus the advancement of carbonation can be seen in Figure 3. The mortars that showed more advancement in carbonation are M2 and C2, whereas M1, C1, and C3 mortars are the ones that show a lesser depth of carbonation; these results are related to the permeability of each mortar, their CaO content, and with the presence of some polymers which are frequently present in commercial products. The CaO content can be observed in Table 2, said content is lower for FA and its content in the mixtures in the mortars decreases with the increase of the substitution. It is important to mention that for the C1 mortar it was not possible to obtain the measurements as there was no reaction with the phenolphthalein indicator. The carbonation of M2 was higher due to the ingress being higher in relation to the short face of the specimens, thus influencing the final average.
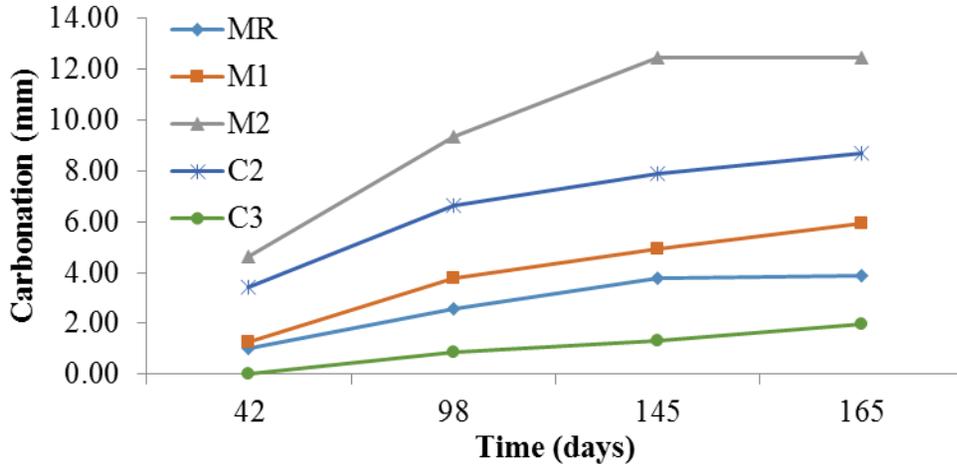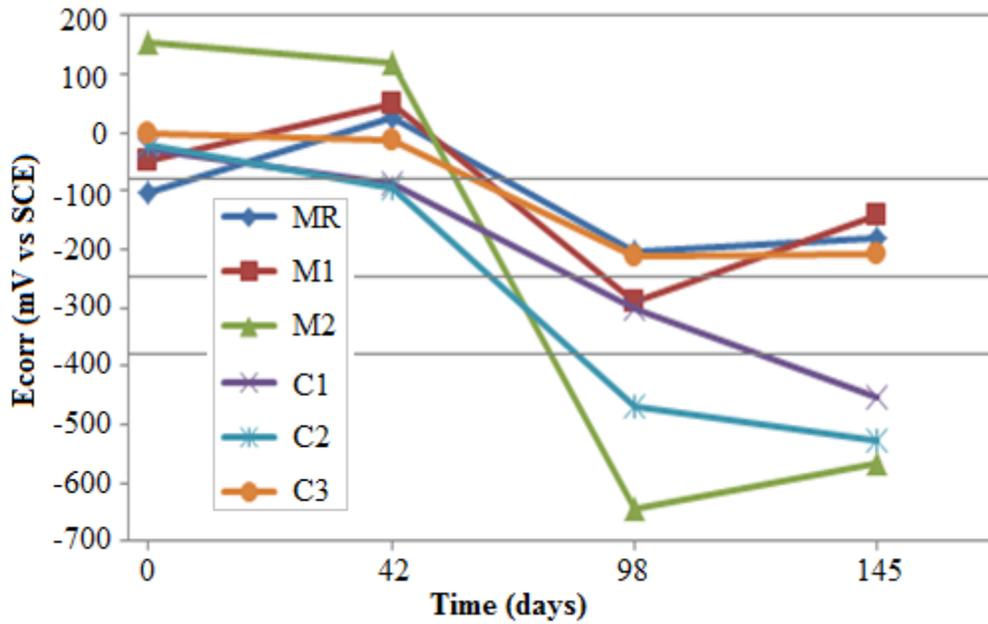
Figure 3. Carbonation Depth.

Figure 4. Ecorr evolution during the time of exposure.

Figure 4 shows the corrosion potentials (Ecorr) in regard to the Saturated Salomel Electrode (SCE). Mortars M2, C1, and C2 show a high probability that there could be corrosion on the steel starting from 98 days, as per what is presented in Table 6, and in accordance with the ASTM C 876 standard. The mortars that present a lower probability of corrosion are MR, M1, and C3 for which the behavior was very similar.

Table 6. Criteria used to evaluate the corrosion potentials in steel

Ecorr vs CuSO4 (mV)	Ecorr vs Calomel (mV)	Corrosion probability
> - 200	> - 80	10% chance that it occurs
- 200 to - 350	- 80 to - 230	Uncertain zone
< - 350	< - 230	90% chance that it occurs
< - 500	< - 380	Severe corrosion

The evolution of i_{corr} during the carbonation process is shown in Figure 5. From this, it is possible to say that, at the start, the values of i_{corr} at first age show passivity in the reinforced steel (lower than 0.1 $\mu A/cm^2$) in all mortars. However, as Ecorr indicates, for the steel within mortars M2, C1, and C2 depassivation occurs after 42 days.
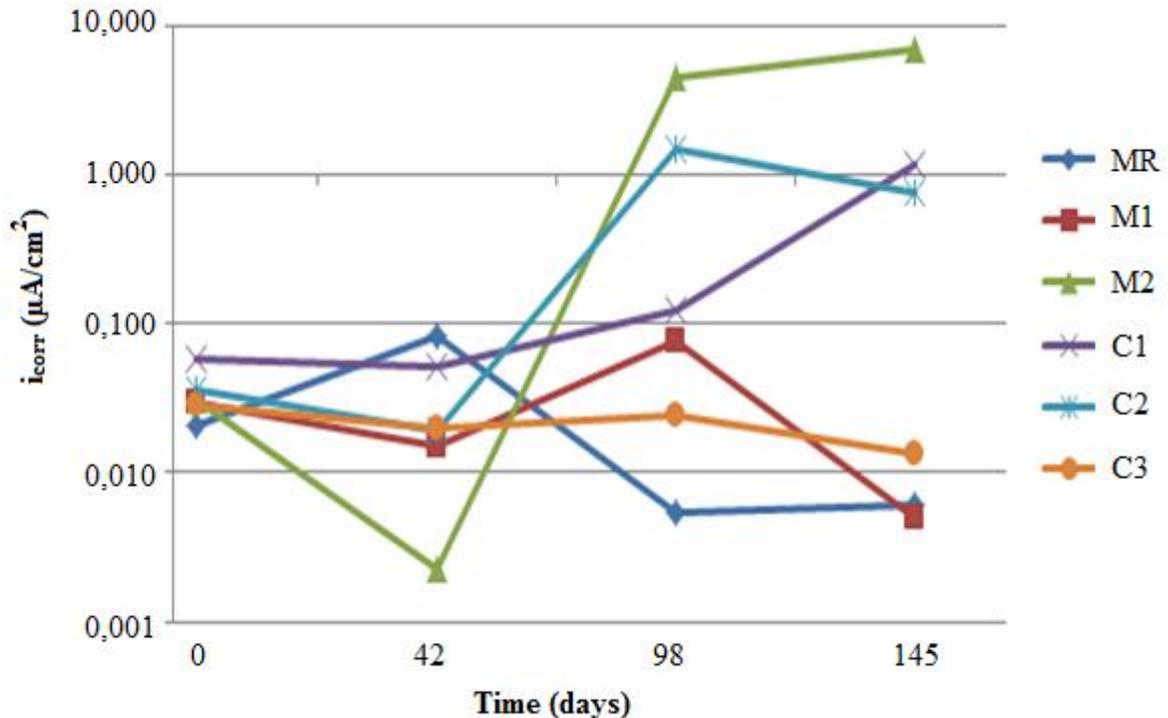

Figure 5. Corrosion rate (i_{corr}) in reinforcement Steel for each repair mortar.

The behavior of M2 and C2 mortars can be confirmed due to its low mechanical behavior with greater porosity and a greater carbonation depth. While for mortar C1, despite having excellent mechanical properties due to the use of fibers, it is very permeable and allows access of CO_2 to the steel, which creates high corrosion values.

As previously mentioned, mortar C1 did not present a reaction with the phenolphthalein indicator that allowed for a correct read of the carbonation.

4. CONCLUSIONS

In terms of performance and durability, the mortars that showed the best behavior are M1 and C3. The M1 mortar with a substitution of FA of 20%p/p surpasses the behavior of the reference mortar (MR) with regard to the attacks of CO_2, even showing a better behavior than the commercial mortars C1 and C2.

Regarding corrosion, only commercial mortar C3 shows good durability properties. If the use of traditional mortars with good durability properties is implemented, then it is not necessary to use a commercial mortar with a higher cost due to the additions and modifications that could be unnecessary for some repairs.

The durability tests carried out determine, with greater certainty, the protection given to a repair in terms of the corrosion on the reinforcement steel. These tests, in addition to the tests for resistance

to compression, flexure and adherence, leads us to think that a traditional mortar (cement-sand with mineral substitutions) could behave as an effective and durable repair.

5. ACKNOWLEDGEMENTS

6. REFERENCES

Andrade, C., Feliu, S. (1989). "*Manual de inspección de obras dañadas por corrosión de armaduras*", Publicado ICCT, Madrid, España.

ASTM C 109 (1999), *"Standard Test Method for Compressive Strength of Hydraulic Cement Mortars" (Using 50 mm Cube Specimens),* ASTM International.

ASTM C 348 (1997), *"Standard Test Method for Flexural Strength of Hydraulic Cement Mortars".*

ASTM C 876 (2009), *"Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete".*

ASTM G 1 (2003), *"Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens".* ASTM International.

ASTM G 59 (2014), *"Standard Test Method for Conducting Potientodynamic Polarization Resistance Measurements".* ASTM International.

Bjegovic, D., Ukraincik, V., Beus, Z. (1990). *"Evaluation and Repair of Concrete Structure in Urban Environment: Case Study"*, Special Publication 122: pp. 427-450.

Cabrera, J. G., Al-Hasan, A. S. (1997). "*Performance properties of concrete repair materials"*, Construction and Building Materials 11, 5: pp 283-290.

Decter, M. H. (1997). "*Durable concrete repair—Importance of compatibility and low shrinkage"*, Construction and building materials 11, 5: pp. 267-273.

Duran-Herrera, A., Mendoza-Rangel, J. M., De-Los-Santos, E. U., Vázquez, F., Valdez, P., & Bentz, D. P. (2015). *"Accelerated and natural carbonation of concretes with internal curing and shrinkage/viscosity modifiers"*, Materials and Structures 48, 4: pp 1207-1214.

Ebensperger, L., & Torrent, R. (2010). *"Medición" in situ" de la permeabilidad al aire del hormigón: status quo"*, Revista ingeniería de construcción 25,3: pp. 371-382.

Fernández Cánovas M. (1989). *" Hormigón",* Servicio de publicaciones del Colegio de Ingenieros de Caminos, Canales y Puertos, Madrid, 3ª edición.

Emmons, P. H., Vaysburd, A. M., & McDonald, J. E. (1993). *"A rational approach to durable concrete repairs"*, Concrete international Detroit 15: pp. 40-40.

Jiang, C., Chen, D., Wu, Y., & Zhang, W. (2009). *"Study on the Mechanisms and Properties of Repair Mortar for Hydraulic Concrete Surface"*, Advances in Water Resources and Hydraulic Engineering: pp. 1619-1624.

Kay, E. A., & Regan, J. (1987). *"Acceptance and compliance testing of patch repair systems--proceedings of the second international conference on deterioration and repair of reinforced concrete in the arabian gulf",* Bahrain, Publication of: Bahrain Society of Engineers. 1,2 :pp. 11-13,.

Kucharczyková, B., Misák, P., & Vymazal, T. (2010). *"The Air-permeability measurement by torrent permeability tester"*, In Proceedings of the 10th international conference on modern building materials, structures and techniques*, Vilnius*: pp. 162-166.

Momayez, A., Ehsani, M. R., Ramezanianpour, A. A., & Rajaie, H. (2005*), "Comparison of methods for evaluating bond strength between concrete substrate and repair materials"*. Cement and Concrete Research 35, 4: pp. 748-757.

Torrent, R. J. (1992)*. "A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site"*, Materials and Structures 25.6: pp. 358-365.

Treadaway K. W. J. (1987) *"Testing the properties of materials for concrete repair- A review".* Proceedings of the Second International Conference on Deterioration and Repair of Reinforced Concrete in the Arabian Gulf.