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Comportamiento mecánico de secciones de hormigón y mortero.
Mechanical behavior of concrete-mortar sections.

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***Resumen*— El objetivo del presente trabajo es comparar el comportamiento de los elementos estructurales sometidos a flexión o compresión después de haber sido reparados, mediante la sustitución del hormigón deteriorado por mortero de cemento Portland o mortero modificado con polímeros. En primer lugar, las probetas cúbicas se fabricaron con diferentes proporciones de reparación de mortero de cemento para ensayar a compresión, con los materiales colocados tanto en serie como en paralelo. Del análisis de resultados, se puede concluir que los sistemas mixtos - mortero de hormigón modificado con polímeros sometido a compresión pueden soportar cargas mayores que la reparación del mortero de cemento Portland, aunque en ningún caso pueden restaurar la capacidad de carga del hormigón. En los elementos sometidos a flexión, las vigas reparadas pueden alcanzar la resistencia inicial a la fractura de las vigas y soportar cargas aún mayores. Por lo tanto, la reparación de estructuras de cemento deterioradas con morteros de reparación es una buena alternativa, especialmente en elementos estructurales sometidos a flexión, y se realizan con morteros de cemento Portland. En las estructuras sometidas a compresión, es mejor utilizar morteros de reparación modificados con polímeros que aumentan la ductilidad cuando el mortero de reparación se ubica en serie con respecto a la carga.**

Palabras clave— Mortero de reparación, resistencia a la flexión, resistencia a la compresión, cantidades, ductilidad, hormigón.

***Abstract*- The aim of the present work is to compare the behavior of structural elements subjected to bending or compression after having been repaired, by substituting the deteriorated concrete by Portland cement mortar or mortar modified with polymers. Firstly, cubic specimens were manufactured with different repair concrete-mortar proportions to be tested to compression, with the materials placed both in series and in parallel. From the results analysis, it can be concluded that mixed systems - polymer-modified concrete mortar subjected to compression can withstand greater loads than the repair Portland cement mortar, although they are in no case able to restore the load capacity of concrete. In elements subjected to bending, the repaired beams are able to achieve the initial fracture strength of the beams, and support even higher loads. Therefore, repairing deteriorated concrete structures using repair mortars is a good alternative, especially in structural elements subjected to bending, and performed using Portland cement mortars. In structures subject to compression, it is better to use repair mortars modified with polymers which increase the ductility when the repair mortar is located in series regarding the load.**

Index Terms— Repair mortar, bending strength, compression strength, quantities, ductility, concrete.

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I. Introduction

Despite durability strategies included in the different regulations, deterioration of reinforced concrete structures prior to the lifetime for which they have been projected is a common problem in construction, civil engineering and construction (EHE, 2008; Eurocode 2 – EN 1992, 20014; ACI-318S-08, 2008). The origin of this deterioration is due to different factors, ranging from the aggressiveness of the environment to the conditions of use and maintenance, making it necessary to know the damage origin in order to determine the more appropriate repair methods, as well as to ensure the durability of those repairs (Fernández, 1994; Calavera, 2005).

To ensure the repair durability of concrete structures, it is necessary to select the repair materials taking into account the chemical, physical, electrochemical, structural, mechanical and dimensional compatibility between the repair material and that of concrete (Morgan, 1996; Emberson & Mays, 1990; Mays & Wilkinson, 1987).

The most used repair mortars are based on Portland cement mortars, but these are limited, as in the case of beams subjected to aggressive conditions in environments with chlorides, when over time, cement mortars show an excessive cracking and are able to restore only 50% of the carrying capacity. As a result, alternatives which offer better features are searched, such as micro concrete, that presents more resistance to the addition of chlorides and does hardly ever crack (Nounu & Chaudhary, 1999), mortars modified with polymers or mortars to which different materials are added such as reinforcement fibers, hybrid fibers, recycled glass, magnesium phosphate or geopolymers, confering certain features depending on the material added (Al-Zahrani et al, 2003; Mallat & Alliche, 2011; Eethar Thanon & Mahyuddin, 2011; Calmon et al, 2014; Quanbin et al, 2000; Quiao et al, 2010; Hemanth, 2006).

Focusing on mortar with polymers, their properties are influenced by the cement hydration, the association between the organic and inorganic phases and the distribution of the polymer in mortar (Xiang-Ming, 2013; Xiang-Ming et al, 2013). Studies have shown that mortars with polymers tend to be more ductile than cement mortars; their lower elasticity modulus produces a smaller risk of cracking by retraction, thus avoiding the formation of cracks at the repair concrete-mortar interphase and they increase durability (Ming-Gin et al, 2007; Phoo-ngernkham et al, 2015; Metcherine, 2013; Pascal et al, 2004; Shash, 2005; Hassan et al, 2001; Cabrera & Al-Hasan, 1997; Mangat & Limbachiya, 1997; Robery & Shaw, 1997; Medeiros et al, 2009). Another aspect to be considered, is curing and its influence on the repair concrete-mortar bonding, being necessary to control the humidity in the interphase since it can affect hydration and produce high porosity in the area (Zhou & Van Breguel, 2016; Rashid et al, 2015). On the other hand, the addition of polymers to repair cement mortars improves their workability, reaching its maximum bending strength in 15% polymer/cement proportions, in addition to increasing impermeability and frost resistance (Hongyan & Zongjin, 2013; Mirza et al, 2002; Wang et al, 2005). Nevertheless, disadvantages also appear, and studies have shown factors such as cost, toxicity and flammability of such repairs (Ohama, 1996; Fowler, 1999).

As for cracking of elements subjected to bending, studies in beams repaired with mortars modified with polymers show that most fracture to shear, which indicates that the application of this type of mortar is more effective to control flexural cracks. Repaired beams reinforced to bending and shear strengths, showed a greater rigidity than beams reinforced only to bending. Applying greater amounts of polymers, when beams are subjected to permanent loads, can imply more effective outcomes (Ahmad et al, 2012). Of great importance is to evaluate the cracks produced on the concrete-mortar interphase, their length and width, as well as the bonding between the two. Studies show the direct influence between the quality of the repair mortar and its behavior in the interphase (Valcuende, 1994).

Despite numerous researches published, no previous experiences have been found assessing the mechanical compression behavior of sections from mixed repair concrete-mortar, having variable proportions of repair concrete-mortar and different placement regarding the load direction. On the other hand, there are no studies on the bending behavior of structural elements damaged up to fracture and subsequently repaired with polymer-modified mortar, neither from the point of view of its residual strength, nor of its cracking and deformation control. The objective of this study is therefore, to compare the behavior of sections of mixed repair concrete-mortar made with Portland cement mortars and organic base mortar modified with polymers, subjected to compression or bending loads, in order to assess the best options of repair for each case.

II. Experimental Work

A. *Materials*

The experimental process corresponding to this research work, has been developed using H-25 concrete and two types of repair mortar, one of Portland cement and the other one modified with polymers, in order to study the behavior of mixed structural elements both to compression, and to bending. Necessary materials for both cases are shown below and proportions and specific characteristics of the cubic specimens and beams are detailed in table 1:

- Portland cement types CEM II a-l 42.5 and CEM II B-L 32.5, according to UNE-EN 197-1:2011 and RC-08 (AENOR, 2011; RC-08, 2009).
- Organic base non-shrinking cement, with addition of

TABLE I
PROPORTIONS AND MATERIALS OF SPECIMENS AND BEAMS

	Cubic specimens			Beams			
	Concrete (H-25)	Portland cement mortar	Mortar modified with polymers	Concrete (H-25)	Steel		
Cement type	CEM II A-L 42,5	CEM II A-L 42,5	R4 class (type CC)	CEM II B-L 32,5	Longitudinal reinforcement		Transversal reinforcement at 45°
Materials	Proportions				Steel types		B 500 SD
Cement	1.00	1.00	1.00	1.00	B 500 SD	2 ϕ8	c ϕ8 every 10
Sand	2.00	3.00	0.32	2.66	B 500 SD	2 ϕ16	c ϕ8 every 7
Gravel	3.50	--------	--------	2.58	AISI 2304	2 ϕ8	c ϕ8 every 10
Water	0.50	0.50	0.12	0.55	AISI 2304	2 ϕ16	c ϕ8 every 7

mineral products and modified with polymers and corrosion inhibitors, type CC, class R4 according to UNE-EN 1504-3:2006 (AENOR, 2006).

- Natural aggregates. Siliceous river sand in agreement with standard UNE-EN 13139/AC: 2004 (AENOR, 2004), and stone gravel, 10mm maximum size, according to the standard UNE-EN 12620:2003 + A1:2009 (AENOR, 2009).
- Fresh running water from the Canal de Isabel II of Madrid Autonomous region, which complies with the technical requirements established for structural concrete.
- Carbon steel B 500 SD, diameters 8 and 16 mm, according to UNE 36065:2011 (AENOR, 2011).
- Duplex stainless steel AISI 2304, diameters 8 and 16 mm, according to UNE-EN 10088-1:2015 (AENOR, 2015).

B. Experimental work phases

To evaluate the behavior of structural concrete elements, where the resistant capacity had been fixed using repair mortars, two phases were developed. In the first phase, a total of 45 cubic specimens were manufactured in order to study the compression behavior of specimens with a single material, and that of mixed repair concrete-mortar specimens in different proportions. For each type of mixed specimens, three were tested in series and three in parallel.

All specimens were manufactured in cubic molds of $100x100x100cm^3$ and comply with the parameters established in the standard UNE-EN 12390-1:2013 (AENOR, 2013). Specimens were made with concrete H-25 and two types of repair mortars (Portland cement and polymer-modified mortar) in different proportions, as shown in figure 1(a).

In order to implement the second phase, four beams of reinforced concrete $100x150x1200mm^3$ were used. These

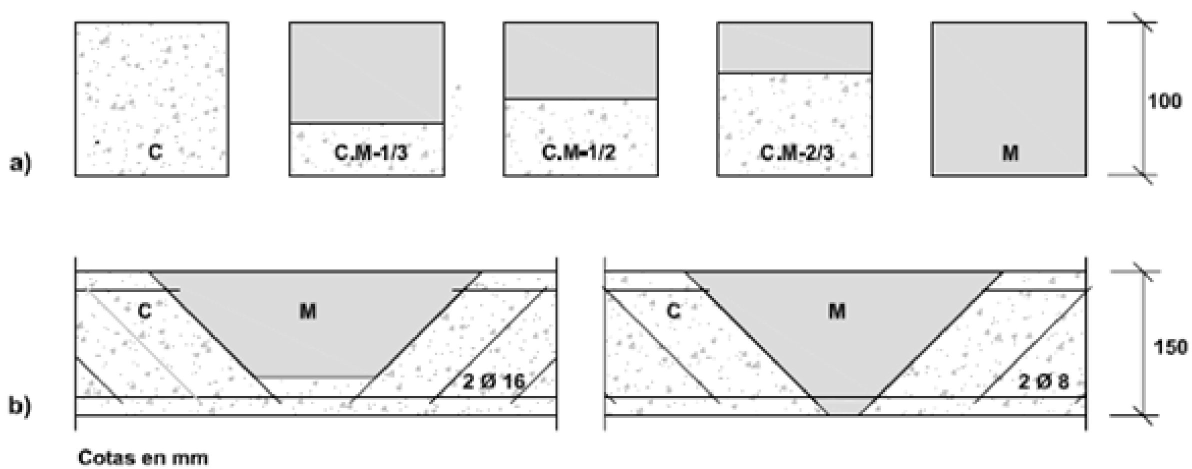

Fig. 1. Scheme of the concrete-mortar cubic specimens (a) and of the repaired beams (b).

beams have different amounts and types of steel as shown in table 1, and the placement scheme is shown in Figure 1(b). They were repaired with the same repair mortars used in the first phase, and they had earlier been tested to bending up to fracture.

Nomenclature and types of tests performed, both with mixed specimens and with beams, can be seen in table 2.

TABLE II
NOMENCLATURE, CHARACTERISTICS AND TEST TYPES FOR SPECIMENS AND BEAMS

Cubic specimens (Compression strength test)			
	Specimens of a single material		
Concrete	C-1	C-2	C-3
Portland cement mortar	MC-1	MC-2	MC-3
Mortar modified with polymers	MP-1	MP-2	MP-3
	Mixed specimens		
Concrete-Portland cement mortar	C.MC-1/3-s1	C.MC-1/2-s1	C.MC-2/3-s1
	C.MC-1/3-s2	C.MC-1/2-s2	C.MC-2/3-s2
	C.MC-1/3-s3	C.MC-1/2-s3	C.MC-2/3-s3
	C.MC-1/3-p1	C.MC-1/2-p1	C.MC-2/3-p1
	C.MC-1/3-p2	C.MC-1/2-p2	C.MC-2/3-p2
	C.MC-1/3-p3	C.MC-1/2-p3	C.MC-2/3-p3
Concrete-mortar modified with polymers	C.MP-1/3-s1	C.MP-1/2-s1	C.MP-2/3-s1
	C.MP-1/3-s2	C.MP-1/2-s2	C.MP-2/3-s2
	C.MP-1/3-s3	C.MP-1/2-s3	C.MP-2/3-s3
	C.MP-1/3-p1	C.MP-1/2-p1	C.MP-2/3-p1
	C.MP-1/3-p2	C.MP-1/2-p2	C.MP-2/3-p2
	C.MP-1/3-p3	C.MP-1/2-p3	C.MP-2/3-p3
Beams (Bending test)			
	Before reparation	Repaired ones	
Concrete-Portland cement mortar	B-SD-8	B-SD-8-MC	
	B-SD-16	B-SD-16-MC	
Concrete-mortar modified with polymers	B-AISI-8	B-AISI-8-MP	
	B-AISI-16	B-AISI-16-MP	

C. Development of the Experimental Process

In order to manufacture the specimens of mixed repair concrete-mortar, first the concrete to be included in the cubic molds was mixed. Once the amounts of material corresponding to established proportions (table 1) were measured, cement, gravel and sand were kneaded in dry for 15 seconds to homogenize the specimen using a kneading machine of vertical axis IBERTEST CIB-701 model upgraded to IB32-040V0. After that, water was added and mixed for 2 minutes. The batch was left standing for a minute, and finally, kneaded during another minute. Then, molds were filled up with concrete up to the fixed proportions. During 24 hours specimens were kept at room temperature (22°C ± 3ºC) with a relative humidity of 60%, after which unmolding took place. Curing was carried out in a moist chamber (21°C and 95% relative humidity) for 9 days and after it, the manufacture of the corresponding repair mortars to finish filling up the molds began.

Proportions specified in table 1 were used in the manufacture of mortars, filling the molds according to the standard UNE-EN 12390-2:2009 (AENOR, 2009); they were brought to volume and kept at room temperature, 22°C ± 3ºC with a relative humidity of 60%, for 24 hours. After this time, specimens were unmolded and were cured in the humid chamber (21°C and 95% relative humidity) for 28 days. The manufacturing process of the specimens is shown in figure 2.

To study the bending behavior of reinforced concrete structural elements repaired with mortars, the damaged concrete was repaired and replaced in four reinforced concrete beams previously tested to bending in the laboratory of construction materials Felix Orús of the EUATM (School of Building Engineering of Madrid). Considerations when choosing these beams were:

- Beams had been made with concrete typically used in construction.
- Diameters 8 and 16 mm for carbon steel and stainless steel rebars, the most widely used in concrete structures in construction were used.
- The selected beams correspond to high and low amount of steel structural elements.
- Beams had been tested to bending before, and we had access the experimental results of the test (Medina, 2010).

Once the beams to work with had been chosen, the repair process with the two mortars planned started, developing the following phases. First, beams were cleaned up and prepared, removing the concrete damaged surface, located in the central section, using a pointer and a mallet, so that the beams had a section with angles greater than 90° for a better grip of the mortar.

After this, concrete at the central span of the joists was damped to avoid subsequent retractions, according to the standard UNE-EN 83702:1994 (AENOR, 1994). A wooden formwork was placed at the sides of each beam so that, subsequently, repair mortar pouring and pitting with the bar could take place.

Twenty-four hours after repair, beams were unmolded and cured for 28 days, reproducing the critical curing conditions common in practical situations, so that the moisture was kept through the fiber fabric, with more than 60% relative humidity. The process of repair of the beams can be seen in figure 2.

D. Tests

In to develop the present research, two types of tests were performed: compression test with mixed specimens, and bending test with beams. Features of the tests are detailed below (table 2).

Fig. 2. Mixed cubic specimens with different proportions (a) and beams repair process (b).

Fracture compression tests were carried out on 45 cubic specimens, and performed according to the UNE-EN 12390-3:2009 standard (AENOR, 2009), having previously polished the upper face to ensure flatness of the faces perpendicular to the load.

Compression test in mixed specimens was performed with materials arranged in series and in parallel, as shown in figure 3. Each type of mixed specimen was tested two times in parallel and one, placing the materials in series. Tests were conducted in the universal press IBERTEST MIB-60/AM, with a speed of the load application of 0.2 KN/s.

The bending test was performed on four beams with the central section repaired with the two repair mortars of the study, according to the standard UNE-EN 12390-5:2009 (AENOR, 2009). The test was carried out in the same universal IBERTEST MIB-60/AM press as the compression tests, interposing an auxiliary metal structure over two points placed at 333 mm of the supports and next to the interphase between the two materials, so that the load application produced a constant bending stress at the central section. The mean application speed of the load was of 0.2 KN/s, and the placement and amount of frames placed ensured the fracture of the beams by the effect of bending and not of that of shear. The layout of the test is shown in figure 3.

III. Results and Analysis

Figures 4 and 5 show the most representative results when evaluating the compression behavior of mixed concrete-mortar specimens, in different proportions, with materials placed in series and in parallel. As can be seen in figure 4, the proportion of concrete and mortar does not affect, in a significant way, the strength behavior of the mixed specimens when the materials are tested in series. However, the maximum strength slightly decreases as the amount of concrete diminishes and the amount of mortar increases. On the other hand, a better behavior is observed in specimens in which repair mortar modified with

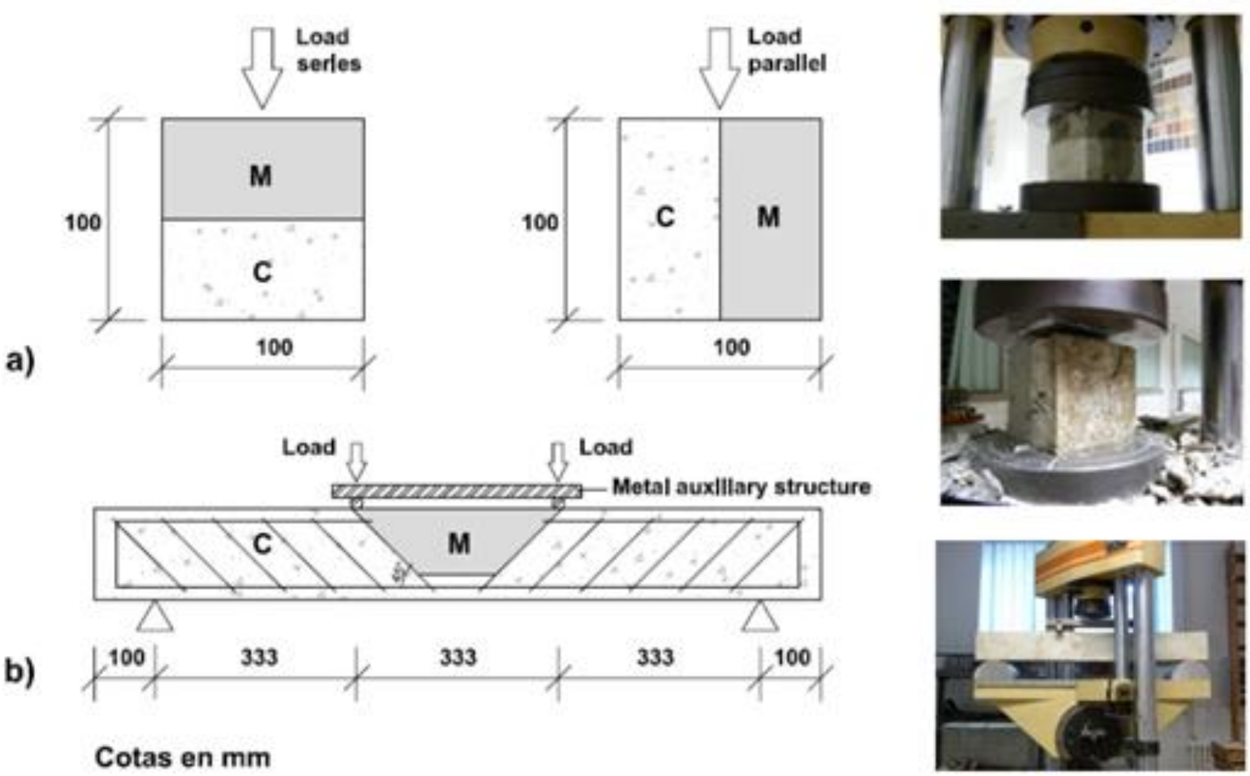

Fig. 3. Placement of specimens for the compression test (a) and for the bending test (b).

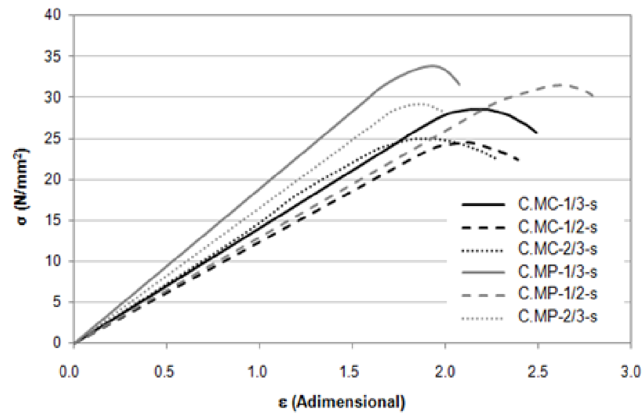

Fig.4. Evolution of normal unit stress in relation to the unitary longitudinal deformation in the compression test of mixed specimens, with the materials located in series.

polymers has been used, rather than in those where Portland cement mortars were used.

When materials are tested in parallel (Figure 5), specimens with polymer-modified mortar also show a better behavior, presenting a significant increase of the maximum unit longitudinal deformation (ε_{max}), of the ultimate unit longitudinal deformation (ε_u), and of the ductility, when compared to Portland cement-based mortars. These results coincide with those obtained by other researchers, showing the relationship between rigidity and the amount of polymers in elements subject to compression (Pascal et al, 2004).

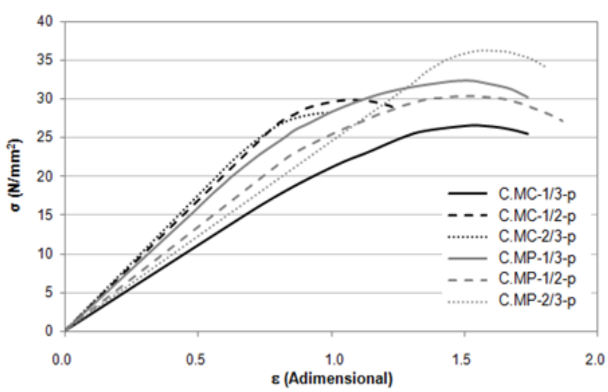

Fig.5. Evolution of the normal unitary stress in relation to the unitary longitudinal deformation in the compression test of mixed specimens, with the materials located in parallel.

Figure 6 shows the more representative results of the compression tests in specimens made with a single material. As can be seen, maximum strength and deformation are higher in specimens made with polymer-modified mortar than in the concrete ones, which shows the benefits of that material. Lower strengths are reached by the mortars made with Portland cement.

Figure 7 shows the results of the bending test in beams repaired with cement mortar and mortar modified with polymer. As can be seen, main differences in the strength capacity lay in the different amount of reinforcement beams have, but there are no significant differences between Portland cement mortars and mortars modified with polymers.

IV. DISCUCCION

Table 3 shows the most significant results of the compression tests performed --both in specimens with a single material as in mixed specimens—and obtained from figures 4 and 5. Data obtained includes maximum strength (σ_{max}), the ratio between the elasticity module of the specimens in relation to that of concrete (E/E_c), the ratio between the maximum strength of the different specimens with that of concrete ($\sigma_{max}/\sigma_{maxc}$) and the relationship between the energy density of maximum and ultimate deformation and those of concrete ($U_{max}/ U_{max}c$ and $U_{ult}/ U_{ult}c$).

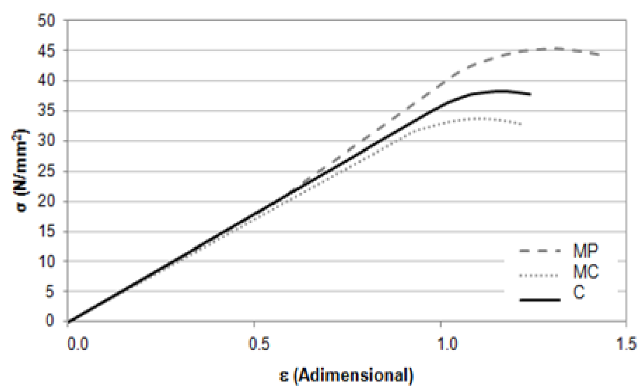

Fig.6. Diagram of normal unit stress concerning the unitary longitudinal deformation on test pieces made with a single material

As can be noticed, higher resistances are obtained with specimens of a single material; polymer-modified mortars reaching 28% more strength than Portland cement mortars. The latter, mortars modified with polymers, reach strengths and deformation energy densities even higher than the those of concrete.

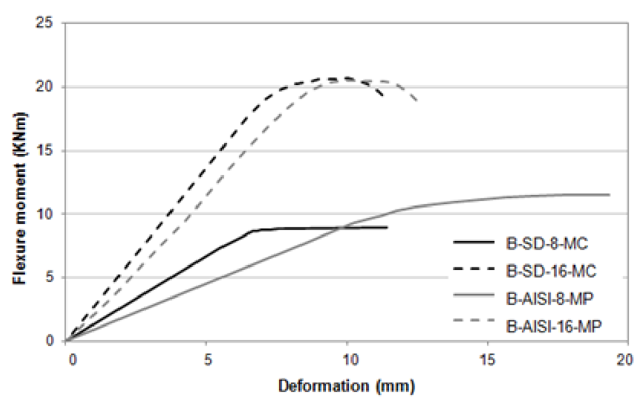

Fig.7. Diagram of the bending-deformation moment of the bending test in beams repaired with Portland cement or polymer-modified mortars.

TABLE III
MOST REPRESENTATIVE MEAN VALUES OF COMPRESSIVE STRENGTH TESTS, IN SPECIMENS WITH A SINGLE MATERIAL AND IN MIXED SPECIMENS WITH DIFFERENT PROPORTIONS

Cubic specimens (Compressive strength test)						
Specimens	σ_{max} (N/mm^2)	$\sigma_{max}/\sigma_{max}c$	$\varepsilon_{max}/\varepsilon_{max}c$	E/Ec	$U_{max}/U_{max}c$	$U_{ult}/U_{ult}c$
C	38.73	1.00	1.00	1.00	1.00	1.00
C.MC-1/3-s	28.72	0.74	1.84	0.40	1.34	1.29
C.MC-1/2-s	24.63	0.64	2.26	0.28	1.30	1.28
C.MC-2/3-s	25.04	0.65	2.18	0.30	1.11	1.12
C.MP-1/3-s	34.02	0.88	2.24	0.39	1.41	1.24
C.MP-1/2-s	31.75	0.82	2.79	0.29	1.84	1.63
C.MP-2/3-s	29.31	0.76	2.58	0.29	1.01	0.96
C.MC-1/3-p	26.67	0.69	1.79	0.39	0.99	0.99
C.MC-1/2-p	29.92	0.77	1.87	0.47	1.61	1.57
C.MC-2/3-p	28.23	0.73	1.52	0.51	0.71	1.13
C.MP-1/3-p	32.44	0.84	1.50	0.56	1.38	1.24
C.MP-1/2-p	30.54	0.79	1.81	0.44	1.21	1.14
C.MP-2/3-p	36.55	0.94	1.83	0.52	1.32	1.22
MC	34.41	0.89	1.30	0.71	0.87	0.88
MP	45.39	1.17	1.33	0.88	1.34	1.35

Regarding mixed specimens, with no mortar and no arrangement, they recover the load capacity of concrete, but it is not possible to reach strengths that specimens with single mortar do, because of the different elasticity modules of the materials.

However, deformations under maximum load are higher in mixed specimens than in specimens with a single material, reaching higher values in the tested specimens in series than in the ones tested in parallel, and greater in polymer-modified mortars than in Portland cement mortars. These results are confirmed by the analysis of longitudinal elasticity modules, reaching lower values in the specimens tested in series.

Ultimate and maximum densities of energy deformation improve the concrete ones in virtually all cases, having neither correlation between these data regarding the test type (in series or in parallel), nor of the repair concrete-mortar proportions, or the type of mortar used either.

Paradoxically, fractures in series and parallel are not within the range comprising the repair concrete and mortar curves, neither maximum strengths nor deformations. This is due to the different elasticity module of both materials, generating tangential stresses in the interphase, and showing dispersion of results.

The mechanical and structural behavior of beams tested to bending before and after being repaired, will now be analyzed.

Unrepaired concrete beams tested by Medina (Medina, 2010) and performed with longitudinal rebars, 8mm in diameter, fractured by bending due to an excessive elongation of the longitudinal reinforcement exceeding its elastic limit, produced major cracks on the underside of the beam. However, beams with longitudinal rebars, 16mm in diameter, failed by concrete exhaustion under compression in the central section and rebars could not strain excessively, therefore the width of cracks were not significant.

Figure 8 shows the behavior of beams with diameters 8 and 16 mm, before and after being repaired, with the two studied mortars. As can be observed, the repaired beams bending test present greater behavior differences between the two reinforced beams reinforced with Ø8, than between the two beams reinforced with Ø16 beams, as happens in the case of beams without repair. It is also proven that there is a uniform strength increase when comparing beams without repair and the repaired ones, in the two types of mortar.

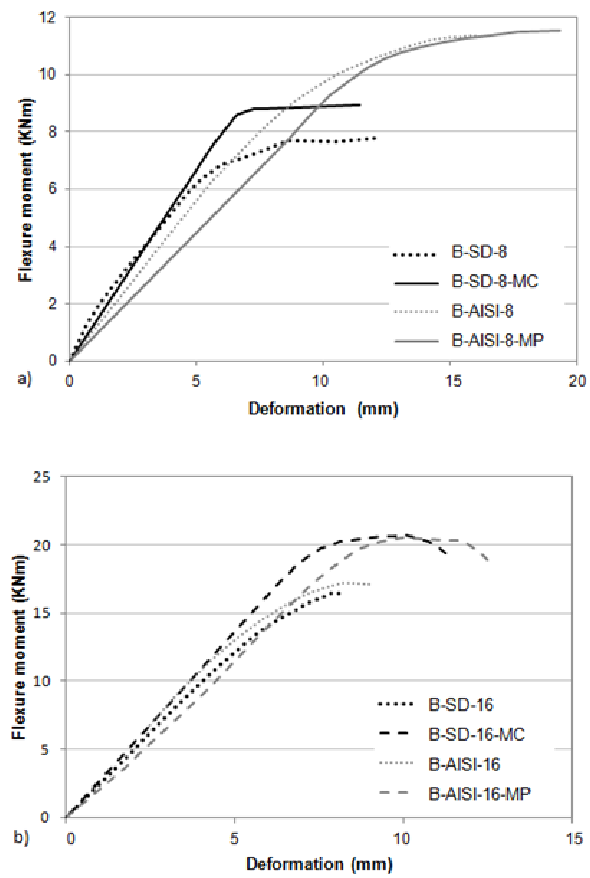

Fig. 8. Bending-deformation moment diagrams in beams before and after repair and with diameters Ø8 (a) and Ø 16 mm (b).

Table 4 allows us to compare the results obtained in the bending tests with the original beams and the repaired ones. As can be seen, the repaired beams have more load capacity (Qmax) and higher fracture moments (M), regardless of the type of repair mortar. On the other hand, beams repaired with polymer-modified mortar resist higher loads than those repaired with Portland cement mortars, showing smaller behavior differences when the diameter of the rebars increases. However, the cracks width (w) is almost 5 times higher in the repaired specimens than in the original specimens, regardless of the type of mortar used and the diameter of the rebars, influencing its durability.

Finally, it can be observed that beams repaired with Portland cement mortars or mortars modified with polymers, increase the ductility when compared to the beams in their original state. The only exception is the B-SD-8-MP beam, where the opposite situation happens. At the same time, a higher ductility and strength in beams reinforced with stainless steel, with respect to the ones reinforced with carbon steel, can also be observed.

Figure 9 shows the cracks formed on the beams, after the bending test, before and after repair, with both repair mortars, with two diameters and two types of steel. The formation of

TABLE IV
MOST REPRESENTATIVE VALUES OF BENDING TESTS PERFORMED WITH BEAMS BEFORE AND AFTER BEING REPAIRED

Beams (Bending test)				
Type	Beams	$Q_{máx}$ (KN)	w (mm)	M (kNm)
Before repair	B-SD-8	47.46	0.30	7.9095
	B-SD-16	98.88	0.10	16.4782
	B-AISI-8	68.21	0.30	11.367
	B-AISI-16	103.71	0.10	17.2839
After being repaired	B-SD-8-MC	54.27	1.40	8.9443
	B-SD-16-MC	123.82	0.50	20.6357
	B-AISI-8-MP	70.10	1.50	11.5860
	B-AISI-16-MP	124.39	0.40	20.6183

cracks in concrete subjected to tensile stresses substantially modifies the behavior of the structural element, in such a way that, between the fissure rims, steel absorbs all the tensile stress, but between cracks, anchoring of rebars in concrete is produced, and tensile stress is partly transferred to concrete. If the load exceeds the concrete tensile strength, a new fissure is produced. As can be seen, in all cases, the greatest number of cracks is concentrated in the span center, cracking not only the concrete but also the repair mortar, in the case of the repaired beams. In these repaired beams, important crack widths in the central area occur when beams have a minor reinforcement/concrete ratio (B-AISI-8-MP and B-SD-8-MC). On the other hand, in the B-SD-16-MC and B-AISI-16-MP beams reinforced with two Ø16, a significant increase of ductility is produced in repaired beams regarding the same beams at the initial state.

Figure 10 demonstrates the load capacity variation between the concrete elements (specimens and beams) and the corresponding mixed specimens and repaired beams, and hence the relationship of the behavior of mixed elements tested to compression and to bending.

As can be observed, when materials are in series and subject to compression, the load bearing capacity decreases as the amount of repair mortar increases. When materials are parallel to the applied load, this effect is not so noticeable, but greater losses of carrying capacity are produced when Portland cement mortars are used to repair the beams, than when polymer-modified mortars were used. As for bending tests, all the

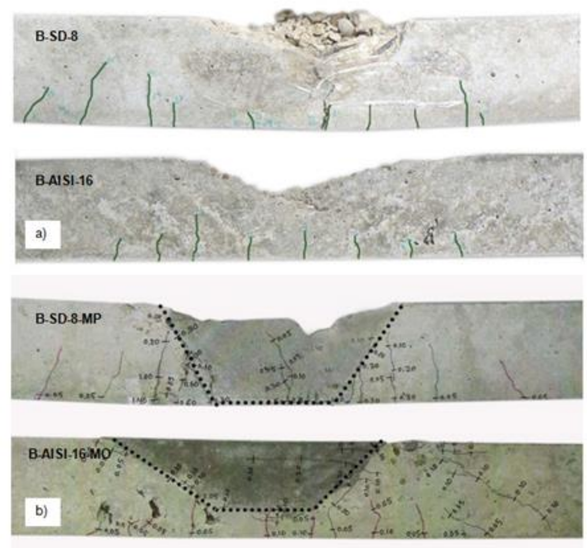

Fig. 9. Cracking pattern in central span: (a) unrepaired beams; (b) repaired beams.

repaired beams increase their load capacity, being a more pronounced effect on beams with greater concrete/reinforcement ratio, which increase values of approximately 25%, rather than for carbon steels. From these results, it can be concluded that the load capacity of repaired beams can be increased with respect to the original, being this load increase higher when using Portland cement mortar instead of a polymer-modified mortar.

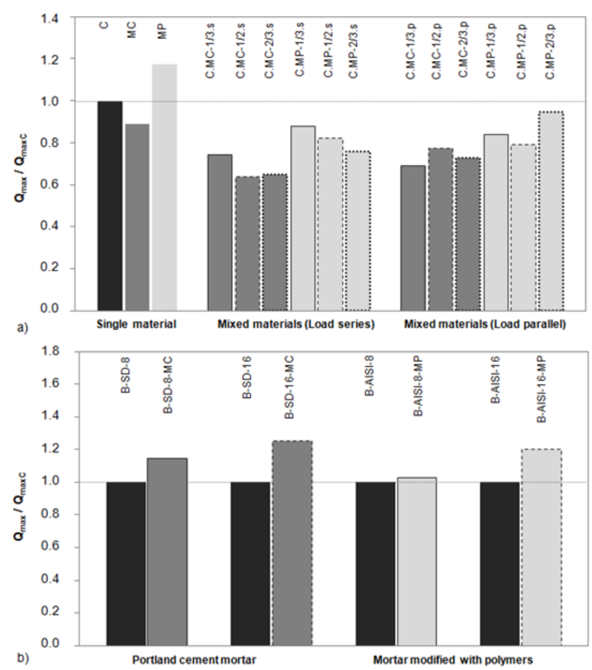

Fig.10. Ratio between the load capacity of mixed specimens subjected to compression (a) and repaired beams (b), compared to their concrete counterparts.

V. Conclusions

The analysis of the results obtained in the bending and compression tests of mixed structural elements (repair concrete-mortar, Portland cement based or polymer-modified), the following conclusions can be drawn:

- The mechanical behavior to compression of specimens from a single material presents important differences when compared to mixed repair concrete-mortar specimens, not only because of the composition, but also because of the fracture type (in series and in parallel) and the different elasticity module of both materials.
- Polymer-modified mortars are able to achieve strengths and deformation energy densities greater than concrete, which is not the case in Portland cement mortars.
- Mixed specimens are not able to recover the load bearing capacity of concrete, regardless of the type of mortar and the placement of the repair material in relation to the load, showing a more ductile behavior in mortars modified with polymers, when repair is arranged in series to the load.
- On the other hand, results of the mechanical bending tests have proven that the repaired beams are capable of reaching the fracture load strength of the initial beams, or even higher. In addition, the ductility of beams repaired with polymer-modified mortar is also higher than the beams repaired with cement mortar and the beams in the initial state.
- Results of the bending tests of the four repaired concrete beams in comparison with beams before repair have shown the effectiveness of the reparation with both types of repair mortar: Portland cement and polymer-modified mortar. Nevertheless, beams reinforced with carbon steel bars B500 SD of smaller concrete/reinforcement ratio, develop a fragile behavior after being repaired with Portland cement mortar.
- Regarding the study of cracks produced on the four beams tested to bending, it is observed that both the mean width between cracks and the number of them has increased in comparison to the beams before reparation.

From all the above, it can be concluded that when repairing reinforced concrete structures with repair mortars, the best behavior is produced when the structural element is subjected to bending and the reparation is performed with mortars of Portland cement. In structures subjected to compression, it is better to use repair mortars modified with polymers, which increased the ductility when the repair material is located in series regarding the load.

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