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ASSESSMENT OF THE BÔCO HISTORICAL RC BRIDGE

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ABSTRACT

The Bôco Bridge is located along the portuguese road EM595-1, breaching the valley of the Cávado river and dividing the regions of Amares and Vieira do Minho, in the district of Braga. This bridge was designed by the architect Sebastião Lopes and built in between the years of 1909 and 1910 by the company Moreira de Sá & Malevez, dealers of the patented Hennebique system in Portugal. It is considered the fourth oldest reinforced concrete (RC) bridge in Portugal. The original bridge was 33 m long and 4.55 m wide. The two parallel arches with a rectangular cross-section of 0.30 m by 0.70 m are supported at each end by abutments directly casted on the rock. A comprehensive study of Bôco Bridge was carried out including historical, geometrical and damage surveys, as well as the physical and chemical characterization of existing structural materials (steel and concrete). This paper presents and analyses the most important results of this study.

Keywords: *Concrete bridge, Hennebique system, Survey*

1. INTRODUCTION

The Bocô bridge over the Cávado River splits the regions of Amares and Vieira do Minho, in the north of Portugal. It is located along the Portuguese road EM595-1 (GPS coordinates: 41º39'12.52"N, 8º14'55.91"W). The bridge was built in between the years of 1909 and 1910 by Moreira de Sá & Malevez Company, dealers of the patented Hennebique system in Portugal. It was designed by the architect Sebastião Lopes. The reinforced concrete design project was by the bureau *d'etudes Hennebique* in Paris and the technical bureau of Moreira de Sá & Malevez in Lisbon. No information was found about the motivation for the construction of this bridge. It is considered to be the second oldest concrete bridge in use in Portugal.

According to the *Le Béton Armé* journal [1] the original bridge was 33 m long (see Fig. 1) and was submitted similar load tests to the ones of Luiz Bandeira Bridge did, mainly [2]: an uniform load composed of sandbags; filling bridge with horse-drawn carriages; measuring the deflection during the passage of a single horse-drawn carriage; and, for conclusion, a gym session with 50 men to check the vibrations.

In June 20th 1950 the bridge was inspected by several engineers involving different institutions. According to the survey report, the bridge was in bad condition. Concrete spalling and corrosion of the reinforcements were the main damages found in the arch and deck. In addition, the traffic on the Bridge was limited to the maximum load of 5 ton per vehicle, not crossing at the same time, until the corresponding strengthening. The project for the rehabilitation was designed by the Engineer J. Duarte Carrilho, the General Directorate of Urban Services of the Ministry of Public Works. Only on September 12th 1961, the company Alberto Sousa Beetle & Gautier started the work. The rehabilitation (including the strengthening) had a total cost of €1099 and it was finished in March 16th 1962.

After 50 years rehabilitation has happened, without any additional intervention, the Bridge presents some degradation level. In spite of that, a nice landscape can be seen, as shown in Fig. 2. A comprehensive study of Bôco Bridge was carried out. These studies include the geometrical and

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damage survey, the physical and chemical characterization of existing structural materials. The main results obtained from these studies are summarized in the following sections.

Fig. 1 Photo of the bridge after its construction [1]

Fig. 2 View of the Bôco Bridge revealing its current state

2. GEOMETRICAL DESCRIPTION DAMAGE SURVEY

The previously referred project for the rehabilitation of the bridge included the geometrical survey of the original configuration (see Fig. 3). Fig. 4 includes hypothetic cross-sections of the different structural elements composing the bridge, based on the existing information. The original bridge was 33 m long and 4.55 m wide. The two parallel arches, with a rectangular cross-section of 0.30 m × 0.70 m at the abutments, and with 12 longitudinal steel bars of 22 mm of diameter (12Ø22) and stirrups with the characteristic U-shape, are supported at each end by abutments directly casted on the rock. These arches are connected together by a set of cross beams with a rectangular cross-section of 0.20 m × 0.30 m. The deck of the bridge, with 0.12 m thick, is supported by two lateral longitudinal girders with a cross-section of 0.20 m × 0.50 m with 2Ø15 at the top (negative bending moments) and 2Ø12 + 2Ø15 at the bottom (positive bending moments) and one intermediate girder with a cross-section of 0.20 m × 0.30 m with similar longitudinal reinforcement. These girders are supported at the ends by two abutments of concrete (masonry-surfaced) and by the arch at the mid-span, and several transverse girders of 0.20 m × 0.35 m with 4Ø15 longitudinal rebars. Between the abutments and the middle of the arch span, a set of columns with square cross-section (0.25 m wide) additionally support the longitudinal girders. The longitudinal reinforcement of these columns was composed by 4Ø15.

Fig. 4 and Fig. 5 include the current geometry of the bridge. The geometrical survey of the current state was performed by laser distance meter, tape measure, camera and ruler. The reinforcement detailing specified in Fig. 4 was based on the rehabilitation project.

During the course of the damage mapping and condition assessment of the bridge, several prevalent degradation mechanisms were observed. The main damage inducing aspects identified are:

- Corrosion of reinforcement and loss of concrete cover due to spalling (Fig. 6a);
- Concrete spalling probably due to corrosion of reinforcement (Fig. 6b);
- Cracks in the masonry abutment (Fig. 6c);
- Biological growth (Fig. 6d).

The bridge is subject to extensive biological growth due to the ideal conditions to the development of these organisms. In general, the bridge presents good condition. However, arches at the abutments vicinity show some degradation due to corroded reinforcement. Spalling is an indirect effect caused by the reinforcement expansion due to corrosion.

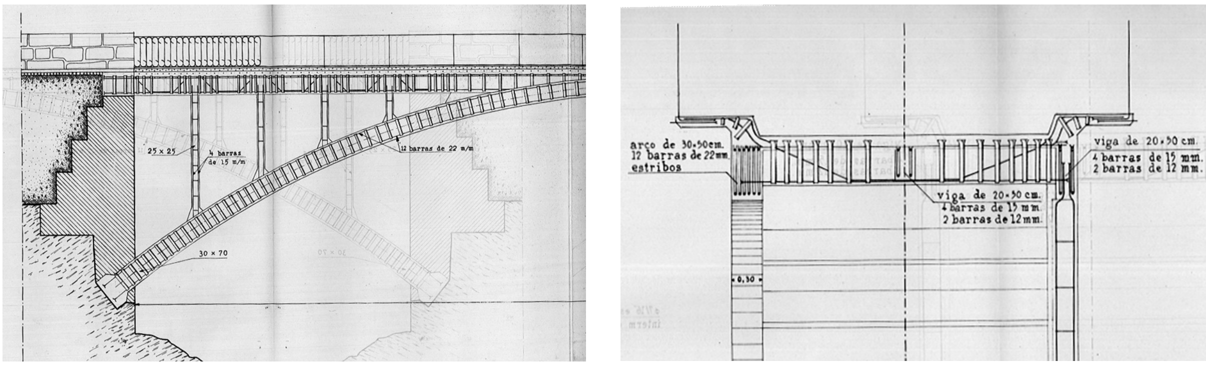
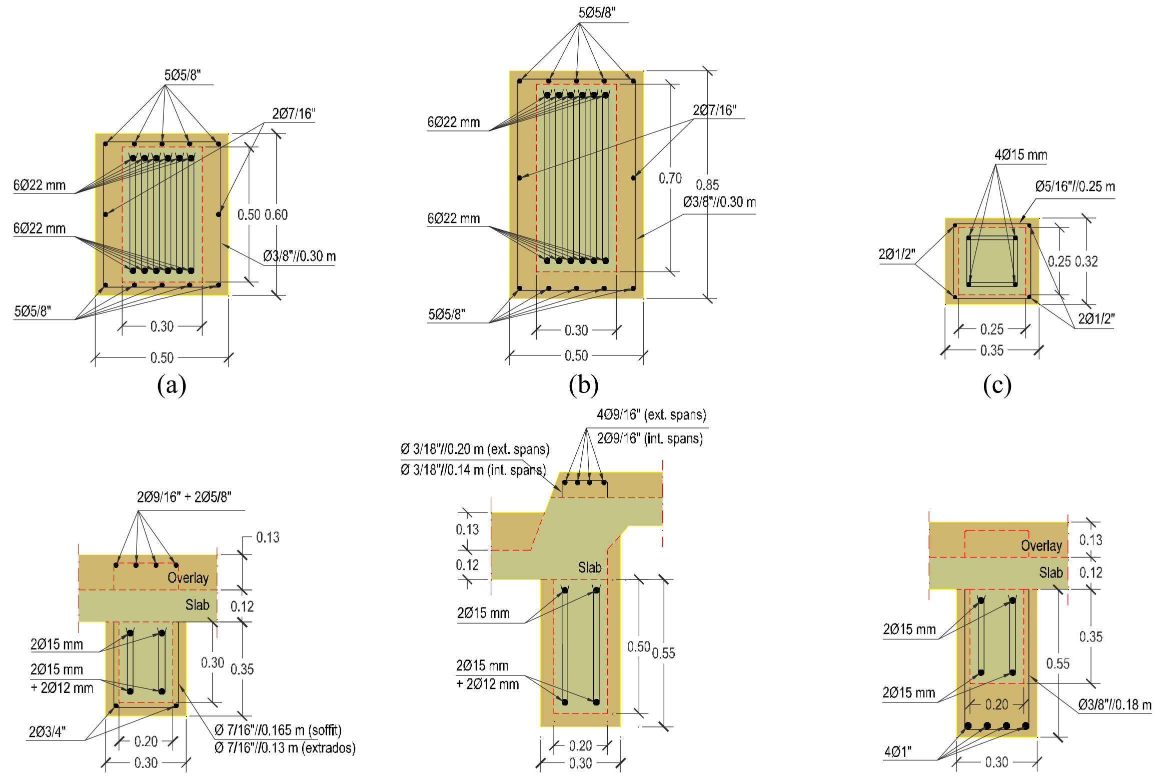
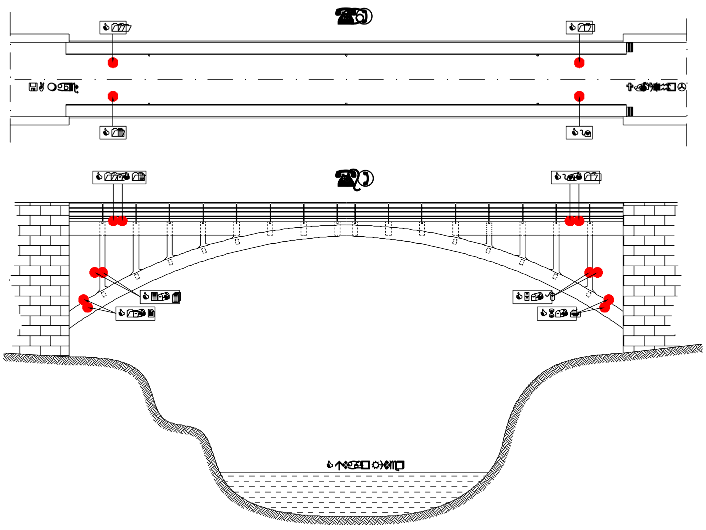

(a) (b)

Fig. 3 Original geometry and steel reinforcements: (a) downstream elevation; (b) cross-section of the deck



(a) (b) (c)
(d) (e) (f)

Fig. 4 Current cross-section geometry versus original one of different structural elements: (a) arches at the mid span; (b) arches at the abutments; (c) columns; (d) intermediate longitudinal girder; (e) lateral longitudinal girders; (f) transverse girders.



(a)

(b)

Fig. 5 Current geometry obtained from the geometrical survey: (a) top view; (b) downstream elevation

Fig. 6 (a) Corrosion of the steel reinforcement and loss of concrete cover due to spalling (b) Concrete spalling; (c) Cracks in the masonry abutment; (d) Biological growth on the bridge

3. MATERIAL CHARACTERIZATION

3.1. Concrete

The concrete characterization included mix design, composition and physical properties, as well as mechanical performance. This characterization was based on 12 cylindrical core samples (see red circles in Fig. 5) taken from different types of structural elements of the bridge. The restrictions on access to site and level of degradation the bridge were the two main reasons for the limited number of samples taken. After cores have been drilled and before be sealed with a plastic film, remained during a few minutes in-situ environment in order to surface moisture be evaporated.

3.1.1. Mix design and composition

From the visual inspection to the cores, it was clear the existence of 3 layers: mortar and new concrete place during the rehabilitation in the 1962 and the old concrete. In the ambit of the present work, the mix design and composition was only analysed for the old concrete.

Three distinct core samples were used to analyse the composition of the original concrete. The ratio binder/aggregate, the chemical composition of the binder and aggregate and, the granulometric distribution of the aggregate were the main parameters analysed (see Table 1). The determination of the ratio binder/aggregate was obtained by selective dissolution of the binder in aqueous hydrochloric acid, followed by a gravimetric procedure. X-ray fluorescence spectrometer and scanning electron microscope (SEM) with energy dispersive spectroscopy were used to determine the chemical composition of the constituents of the concrete. Results revealed a binder/aggregate ration of 1:6.3, in weight. An important portion of calcium oxide was found in the binder, as well as silica (quartz) for binder and aggregate. The binder is Portland cement.

Table 1 Ratio binder/aggregate, chemical composition of binder and aggregate and granulometric grading of the sand

Property	Sample 1	Sample 2	Sample 3
Binder/aggregate (in weight)	1:5.3	1:7.7	1:5.9
Chemical composition of binder	CaO – 59.0% Al_2O_3 – 3.2% Fe_2O_3 – 1.0% MgO – 0.41% SiO_2 – 35.5% SO_3 – 0.81%	CaO – 55.8% Al_2O_3 – 4.9% Fe_2O_3 – 0.7% MgO – 2.4% Na_2O – 0.8% K_2O – 0.24% SiO_2 – 35.2%	CaO – 60.8% Al_2O_3 – 2.2% SiO_2 – 37.0%
Chemical composition of aggregate	SiO_2 – 87.3% Al_2O_3 – 6.0% K_2O – 3.9% Fe_2O_3 – 0.26% CaO – 0.57% TiO_2 – 0.34%	SiO_2 – 81.8% Al_2O_3 – 9.6% K_2O – 5.9% Fe_2O_3 – 0.36% CaO – 0.91% TiO_2 – 0.17%	SiO_2 – 82.7% Al_2O_3 – 8.6% K_2O – 4.6% Fe_2O_3 – 0.50% CaO – 1.6% TiO_2 – 0.29%
Granulometric grading of the sand	Insoluble fraction (79%) >1.4 mm – 75.2% 1.0–1.4 mm – 7.1% 0.50 to 1.0 mm – 9.7% 0.355–0.50 mm – 2.2% 0.18–0.355 mm - 2.8% 0.075–0.18 mm - 1.4% < 0.075 mm – 1.7%	Insoluble fraction (87%) > 1.4 mm – 87.7% 1.0–1.4 mm – 3.2% 0.50–1.0 mm – 4.4% 0.355–0.50 mm – 1.1% 0.18–0.355 mm – 1.6% 0.075–0.18 mm – 0.7% < 0.075 mm – 1.3%	Insoluble fraction (83%) > 1.4 mm – 76.4% 1.0–1.4 mm – 5.8% 0.50–1.0 mm – 7.4% 0.355–0.50 mm – 1.8% 0.18–0.355 mm – 3.1% 0.075–0.18 mm – 3.2% < 0.075 mm – 2.3%

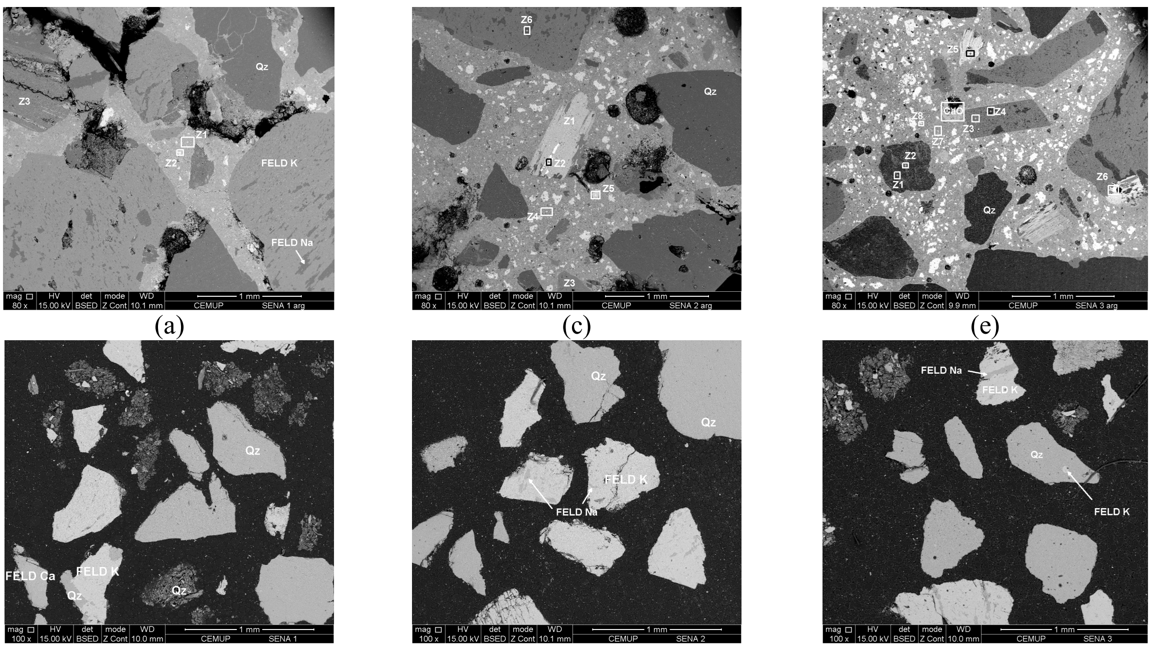


Fig. 7 (a) SEM images of sample 1 (a-b), sample 2 (c-d) and sample 3 (e-f)

3.1.2. *Physical and mechanical laboratory tests*

The physical properties evaluated were the depth of carbonation, porosity and density according to the standards LNEC E391:1993 [3], and LNEC E395:1993 [4], respectively. In addition, the thickness of the mortar and new concrete place during the rehabilitation in the 1962 was also measured. Fig. 8 shows three cores used in these tests.

The porosity of the concrete varies significantly according to the type of concrete. The highest value was obtained for the new concrete, 9.8% (average value), with a coefficient of variation (CoV) of 8.6%. On the other hand, for the old concrete very low values of porosity were found, mainly 3.2% (CoV = 27.7%). A higher specific mass of 2418 kg/m^3 (average value) with CoV = 3.9% was found for the old concrete, when compared with the new one, those average value was equal to 2144 kg/m^3 (CoV = 1.7%). As expected both properties (porosity and density) are well correlated and clearly expected, after the visual inspection of the cores (see Fig. 8b and Fig. 8c). These results should be reflected in both the mechanical properties of the concrete as well as in the carbonation depths.

Table 2 includes the obtained results in terms of thickness (t) and corresponding carbonation depth (C) of each layer composing the sample, mainly the mortar (MO), new concrete (NC) and old concrete (OC). Fig. 8a shows core C3 after being tested for the evaluation of the carbonation depth. From these values it is clear that the mortar layer is completely carbonated. For the cases analysed old concrete does not have carbonation. This may be explained by the procedures adopted in rehabilitation performed in sixty decade of the past century. In fact prior doing the concrete enlargement of the cross-sections, a layer of the existing concrete was removing.

Table 2 Main results obtained from the geometrical characterization of the distinct layers composing each core and carbonation depth

Specimen	Structural element	Mortar		New concrete		Old concrete
		t_{MO} (mm)	C_{MO} (mm)	t_{NC} (mm)	C_{NC} (mm)	C_{OC} (mm)
C1	Arch	5.0	0.0	99.0	0.0	0.0
C2	Arch	0.0	0.0	41.5	0.0	0.0
C3	Column	6.1	6.1	24.9	9.3	0.0
C4	Column	5.4	5.4	31.5	8.8	0.0
C5	Column	6.3	6.3	27.7	0.0	0.0
C6	Arch	2.4	2.4	82.4	8.5	0.0
C7	Arch	11.2	8.9	55.8	0.0	0.0
C8	Column	4.7	4.7	26.4	8.9	0.0
C9	Deck	14.0	14.0	0.0	0.0	0.0
C10	Deck	19.1	19.1	130.0	0.0	0.0
C11	Deck	8.4	8.4	0.0	0.0	0.0
C12	Deck	5.0	5.0	0.0	0.0	0.0

Note: t_{MO} – thickness of mortar; C_{MO} – carbonation depth in the mortar; t_{NC} – thickness of new concrete; C_{NC} – carbonation depth in the new concrete; C_{NC} – carbonation depth in the old concrete.

The modulus of elasticity and the compressive strength of concrete were assessed according to LNEC E397:1993 [4] and NP EN 12390-3:2003 [5], respectively. Prior the evaluation of the modulus of elasticity at least one specimen of each structural element type were test under compression, to evaluate the corresponding the compressive strength.

Table 3 presents the main results obtained, not only for the old concrete, but also for new concrete place during the rehabilitation in 1962. In this table D and H are the core diameter and height, respectively; E_c is modulus of elasticity; F_{max} is the maximum compressive force; $K_{is,cyl}$ is a parameter converting the actual core result into an equivalent in-situ 2:1 cylinder strength, according to National Annex of the BS EN 13791:2007 standard [6]; $f_{is,cyl}$ is the in-situ compressive strength of a normalize cylinder with 150 mm of diameter and 300 mm of height. According to these results, an average value of 41.3 GPa with a coefficient of variation, CoV, of 24.7% was obtained for the modulus of elasticity of old concrete, which is quite high. However, the value could be explained by the type and size of the aggregates composing the concrete. In fact, in this concrete granite gravel with large diameters (about 30 mm) was used. In terms of overall structure an average value of 52.1 MPa (CoV = 22.7%) was found for the compressive strength of old concrete. To find out the compressive strength class of old concrete according to EN 206-1:2007 [7], the procedures suggested by the BS EN 13791:2007 [6] standard were followed, being C35/45 the class obtained. Comparing this value with the one obtained by the Luiz Bandeira Bridge [2], which is 2 years older, the former has one class higher. Remark that both Bridges were built by the same company, Moreira de Sá & Malevez.

(a) (b) (c)

Fig. 8 Cylindrical cores: (a) Carbonation depth evaluation; (b) New concrete; (c) Old concrete

Table 3 Main results obtained from the mechanical characterization

Specimen	**Structural element**	**Type of concrete**	***D*** (mm)	***H*** (mm)	E_c (MPa)	F_{max} (kN)	$K_{is,cyl}$ (-)	$f_{is,cyl}$ (MPa)
C1	Arch	New	103.51	92.21	–	163.9	0.763	14.9
C10	Deck		104.33	84.36	–	318.7	0.731	27.2
C3	Pillars	Old	103.83	98.03	54.08	637.1	0.782	58.8
C4			103.82	99.64	45.73	516.6	0.787	48.0
C5			103.83	98.08	–	641.2	0.782	59.2
C6.2	Arch		103.78	100.85	43.15	620.1	0.791	58.0
C9	Deck		104.08	98.78	36.61	324.7	0.783	29.9
C11			104.76	98.11	–	717.0	0.779	64.8
C12.2			104.60	100.74	26.86	503.2	0.788	46.1

3.2. Steel

A sample of steel was taken from the bridge and was subject to chemical analysis by X-ray fluorescence spectrometer and a basic carbon element test. The results are presented in Table 4. The analysis revealed a mild steel with low level of carbon. Then the specimen was observed in SEM (see Fig. 9). The micrograph shows the existence of manganese sulphide inclusions, often aligned along the ferrite grain boundaries.

Table 4 Chemical composition of steel

Element	**Portion (%)**
C	0.024
Mn	0.29
S	0.043
P	0.067
Si	0.046
Pb	0.095
Fe	Remaining part to 100%

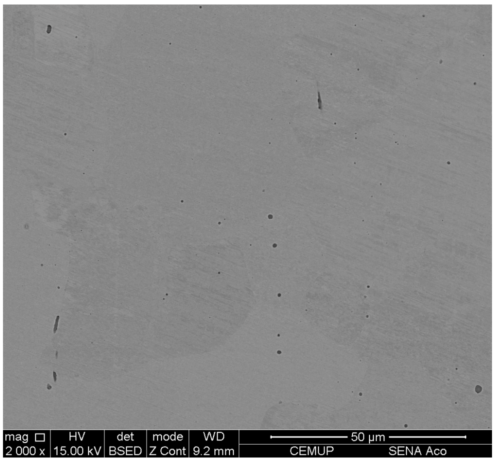


Fig. 9 Micrograph of the steel

4. CONCLUSIONS

The present work resumes the studies performed on the Bôco Bridge, considered to be the second oldest concrete bridge in use in Portugal. The analysis' included historical, geometrical and damage surveys, the physical and chemical characterization of existing structural materials.

From the structural material analysis, both the mechanical properties and the durability performance (carbonation) reflect the physical properties of the concrete, namely the high porosity. The porosity of the new concrete deck was high (9.8%) while the old concrete had an average value of approximately 3.2%. Strength class obtained was C35/45 and the average modulus of elasticity was 41.3 GPa with a coefficient of variation of 24.7%.

The binder used was a Portland cement, and the binder/aggregate ratio was 1:6.3, in weight. The fine aggregate was a quartzcitic/feldspathic sand. The steel used for reinforcement was a mild steel with a very low carbon content.

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