Lisbon's centenary Power Plant – Central Tejo – Characterization of materials and anomalies

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Absract

Central Tejo was the first thermoelectric plant operating in Portugal with a period of activity between 1909 and 1972. In order to meet high levels of power demand throughout its period of operation several extensions and modifications occurred.

The study developed focused on the two of the main buildings of the current *Museu da Eletricidade* complex, the Low Pressure and High Pressure Buildings, and had the support of the *Fundação EDP*.

An experimental characterization was done in a set of either material samples that had been previously collected from the site and bricks used in to replaced existing ones, on last intervention (2011).

Such characterization campaign contributed to enhance the knowledge about the constituting wall as well as of the materials used during the most recent interventions. The bricks of the walls proved to be more porous with higher absorption capacity and faster drying capacity than any of the bricks used to replace the pre-existing.

Keywords

Central Tejo, Low Pressure building, High Pressure building, sample bricks, replacement bricks

1. Introduction

Central Tejo (CT) was a thermal power plant fueled by coal, owned by former CRGE, "*Companhias Reunidas de Gás e Electricidade*", which supplied electricity not only to the city but also to the entire region of Lisbon. This Central was built in Belém, a part of the Portuguese capital next to the River Tagus estuary (**Figure 1**) and operated between 1909 and 1972. It was classified as an asset Public Interest in 1986 and since 1990 has been the house of the *Museu da Eletricidade* (Museum of electricity).

Figure 1 – *Central Tejo location.*

With the increasing needs in power demand over the first half to the XX century, CT has undergone several modifications and extensions to meet such demand. This meant that, over the years, various stages of construction and production were held.

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[1] *Instituto Superior Técnico – UTL; Lisbon; Portugal - 2013.*

The various buildings within the complex are generally constituted by clay brick masonry with embed metallic profiles, which support the rooftop and intermediate floors.

Although appearing to be the perfect location for a power station, due to port accessibility and water availability for the cooling circuits, the salty environment of the River Tagus estuary and prolonged exposure to winds, essentially from SW, caused the constituent materials of masonries degrade. The occurrence of different kind of anomalies in these elements has contributed to the appearance of several areas of water infiltration in the various buildings that make the complex.

The main types of anomalies identified in the masonries was: the cracks in the masonry elements, the superficial disaggregation and delaminating of bricks, the lack of cohesion of mortar in joints and even, in some cases, the absence of material in joints. On the façades were still possible to find efflorescence's caused by the presence and migration of soluble salts, the fixation of parasitic vegetation and biologic colonization, the black spots of pollution and/or dirt and still areas where was possible to find changes of tonality.

During 2011 an intervention was carried out to tackle this issue. Two of the major buildings covered by this operation and targeted in this study, were the buildings where the low and high pressure boilers where previous located. From now on, as shown on **Figure 2**, these buildings will be designated by Low Pressure Building (**BP**) and High Pressure Building (**AP**) respectively.

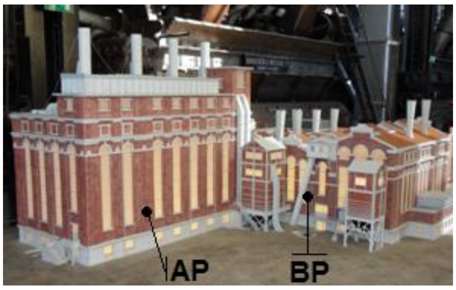

Figure 2 – *High Pressure (AP) and Low Pressure (BP) Buildings.*

During the rehabilitation process not only various repairs were performed but also the strengthening of masonry elements was carried out. New bricks were also applied in different areas to replace those, that had become greatly degraded.

Throughout this article an experimental campaign performed on either original bricks and replacement bricks will presented and discussed. The main objective of this study is to understand the behavior of various materials due to the presence of water, which was considered main cause of degradation and triggered the last intervention (2011). A colorimetric characterization was also done to allow the complex understanding that such an important factor has is the process of selecting materials for replacement of elements in classified heritage.

2. Experimental characterization

2.1 Materials

Samples of new bricks applied as replacement bricks, as well as original bricks that had already been removed from the façades during the last intervention (2011) were analyzed. More in detail, original samples from the South and West façades of the BP Building were characterized, **BP.S** and **BP.P** respectively, and from the West facade of the AP Building (**AP.P**), **Figure 3**.

Figure 3 – *Original bricks.*

Regarding the replacement bricks three different types were evaluated, namely Portuguese (**P**), English (**I**) and Spanish (**E**), being the first solid and the last two perforated, **Figure 4**.

Figure 4 – *Replacement bricks.*

All of samples and new bricks were kindly provided by *Fundação EDP*.
Table 1 summarizes the types of replacement bricks used on the different façades and the correspondent preexisting original bricks on those same façades.

Table 1 – *Bricks compared.*

Building	***Frontage***	***Original bricks***	***Replacement bricks***		
			Portuguese (P)	***English(I)***	***Spanish (E)***
Low Pressure	***West***	*BP.P*	√	√	-
Low Pressure	***South***	*BP.S*	√	-	-
High Pressure	***West***	*AP.P*	√	-	√

(√) - Compare; (-) do not compare.

2.2. Test Methods

Physical characterization was carried out by performing tests on prismatic specimens and colorimetric characterization was made either on the smaller samples or entire bricks.
Given the configuration and dimensions of the bricks and the various types of samples collected from the façades, and to ensure that their physical characterization was based on similar sized samples, the procedure include cutting specimens with the following dimensions: *4x4x0,8* [cm] and *3x3x6,5* [cm]. The configuration of Spanish bricks did not allow to obtain specimens of *3x3x6,5* [cm], so for all replacement bricks a specimens of size *1,5x1,5x6,5* [cm] was also used.
The physical characterization tests performed were the following:

- Porosity and real density: according to RILEM Test No. I.1 [1];
- Water content by 48hours immersion;
- Water absorption by capillarity: based on EN 1015-18 [2];
- Kinetics drying[2]: according to RILEM Test No. II.5 [3];
- Water vapor conductivity[3]: according to RILEM Test No. II.2 [4].

[2] *Evaluated on 3x3x3 [cm] samples.*
[3] *Evaluated on 4x4x0,8 [cm] samples.*

3. Results and discussion

3.1. Low Pressure Building

Figure 5 presents the average values of the density and porosity obtained from the original bricks and replacement brick samples.

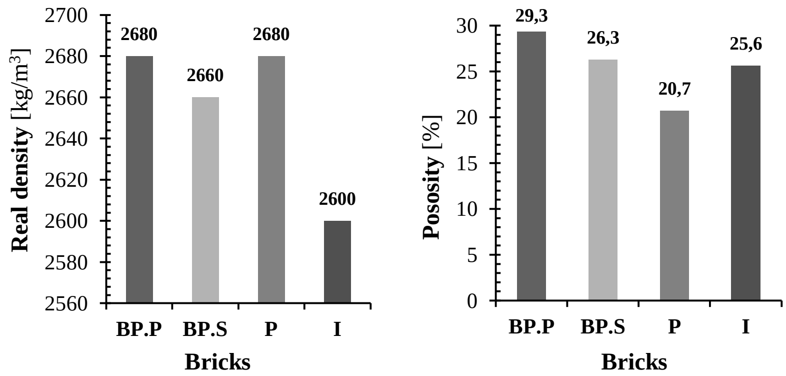

Figure 5 – *Medium values of real density (left) and porosity (right).*

From the analysis of these results we conclude that the Portuguese type of replacement brick and the original bricks have very similar values of real density (2660 to 2680 kg/m^3). These values are higher than those obtained for the English brick.

On two of the façades that were analyzed the original bricks generally exhibit higher porosity values than those obtained for the replacement bricks. In the West façade, the Portuguese brick has the lowest porosity of the whole sample (21%), while the English brick and ***BP.P*** present higher porosities, 26% and 29% respectively.

Through the analysis of **Table 2** it is observable that the original brick samples has a greater absorption capacity than the newer replacement samples, with higher water contents and saturation coefficients (CS). The brick with the lower absorption capacity is the Portuguese replacement one.

Table 2 – *Water content and saturation coefficient.*

Brick	***Water content***		***Saturation coefficient***
	maximum	***after 48hours of immersion***	
	W_{max} [%]	W_{48h} [%]	***CS***[4] [%]
BP.P	15,5	13,0	84
BP.S	13,4	12,0	90
I	13,0	9,0	73
P	9,6	7,3	76

While comparing the mean capillary absorption curves, as a function of the root of time, presented in **Figure 6**, we can conclude that the sample of the original obtained from the West facade present an initial rate of water absorption by capillarity (CC) much larger than the replacement bricks, thus having a greater capacity for water absorption by the end of the test.

In the same figure the capillary coefficients resulting from these curves are also shown. Despite having a lower capillary coefficient than the Portuguese brick, the English specimen has a greater water absorption capacity.

[4] *CS is the W_{48h} and W_{max} percentual relation.*

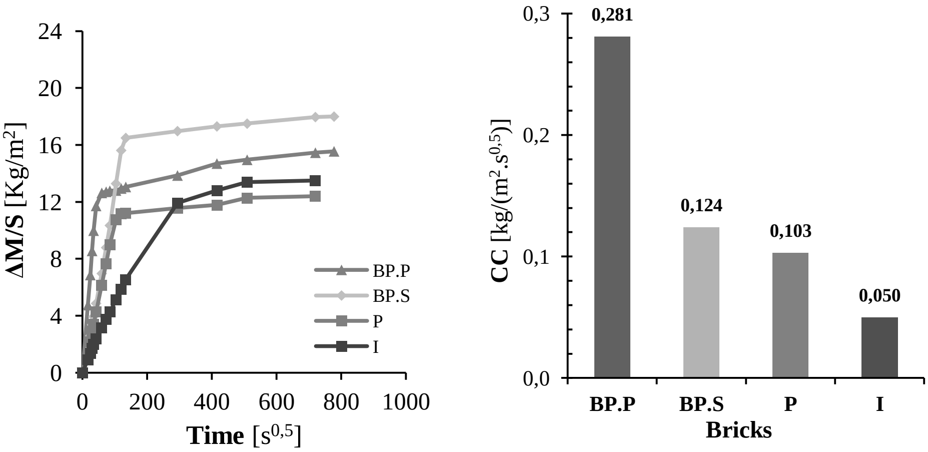

Figure 6 – *Water absorption by capillarity curves (left) and her coefficient (CC) (right).*

In the South facade (***BP.S***) the older bricks generally exhibits a slightly higher capillary coefficient than the newer Portuguese bricks.

Figure 7 shows the drying curves and the average values of the drying index (IS) for the materials which are present in the two façades (***BP.P*** and ***BP.S***).

To obtain the drying index the test includes sealing the four sides of the test specimen with the application of an epoxy resin, followed by immersion the specimen in water for 48 hours. After that, the lower side of the test specimen is sealed using a plastic film, forcing the steam flow to occur only vertically and upwardly. Then, the test specimens are left to dry under laboratory conditions and their mass is daily monitored until constant mass is reached. This allowed the characterization of bricks drying kinetics, obtained from the determination of the drying curves that plot the water content versus time and also the calculation of a drying index as follows:

$$IS = \frac{\int_{t_0}^{t_f} f(W_i) \times dt}{W_0 \times t_f}$$

where:

$f(W_i)$ – drying curve;
W_0 – Initial water content [%];
t_f – Total testing time [days].

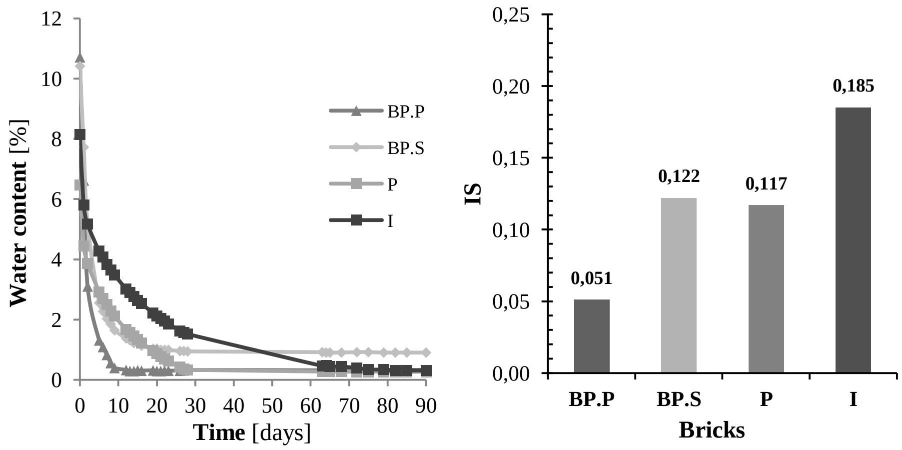

Figure 7 – *Drying curves (left) and drying indexes (IS) (right).*

At the West facade is possible to observe that the original brick dry more easily (IS=0,051) than the replacement ones. This ease of drying is in great extend caused by a higher porosity that this

sample displays. On the other hand the English brick, which had also shown a considerable higher porosity, has a higher IS than the remaining samples.
In the South facade despite the Portuguese brick presenting a lower porosity than the older brick, the index is slightly lower. This phenomenon is due to the fact that the final stabilization phase (1% of water content) is probably provided by the mass of the original brick.
The values of the coefficients of water vapor permeability (CP) are presented on **Figure 8**. From the analysis of this figure it is clear that, the original bricks, in regard of its higher porosity than replacement bricks, have a higher value of this coefficient.

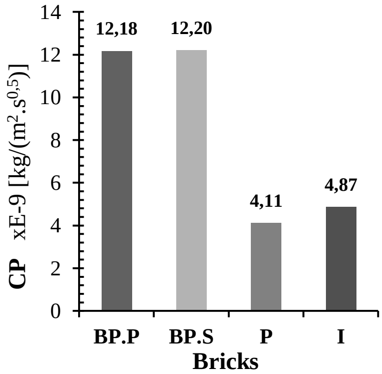

Figure 8 – *Coefficient of water vapor conductivity.*

Color measurements were performed on the outer surface of bricks. The color of tested bricks was evaluated in a quantitative way by using the CIELAB coordinates, L^*, a^* and b^*, **Figure 9**. The value of chroma, i.e., the color saturation, C^*, is obtained by: $C^*=\sqrt{(a^*+b^*)}$

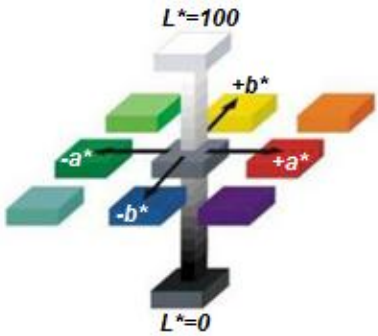

Figure 9 – *CIELAB coordinates, L^*, a^* and b^*.*

Figure 10 represents the colorimetric components of the bricks, plotted as L^* versus chroma, and the coordinate a^* versus b^*.
In the West facade the original brick manifest a smaller values of luminosity (L^*) than replacement ones, presenting also a higher variability in the sample. In the South facade the replacement brick shows slightly lower values of luminosity. In both cases the older bricks have lower values of chroma (C^*).

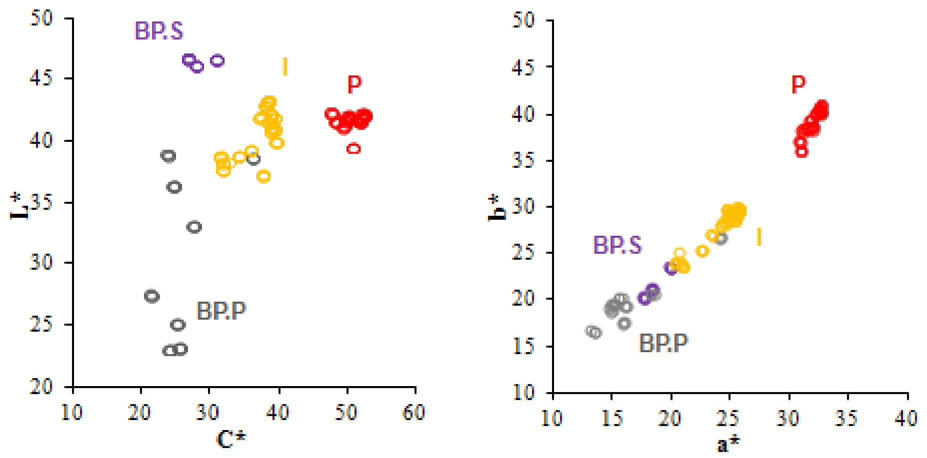

Figure 10 – *Color of the tested samples. Luminosity (L^*) versus chroma (C^*) (left) and a^* versus b^* (right).*

Regarding the a^* and b^* coordinates, in the West facade the English brick is closer to the sample of original brick, while the Portuguese brick is clearly further away, as it is also perceivable on the location.

3.2. High Pressure Building

Figure 11 presents the average values of the real density and porosity obtained for the original bricks and replacement bricks used in the High Pressure building (AP).

The Portuguese replacement brick and the original bricks feature values of real density (2670 to 2680 kg/m^3), which in turn are slightly higher than those reported for the Spanish Brick (2640 kg/m^3).

On this facade the original bricks generally exhibit a higher porosity than those obtained for replacement ones considered, while Spanish type have the lowest porosity of all (17%).

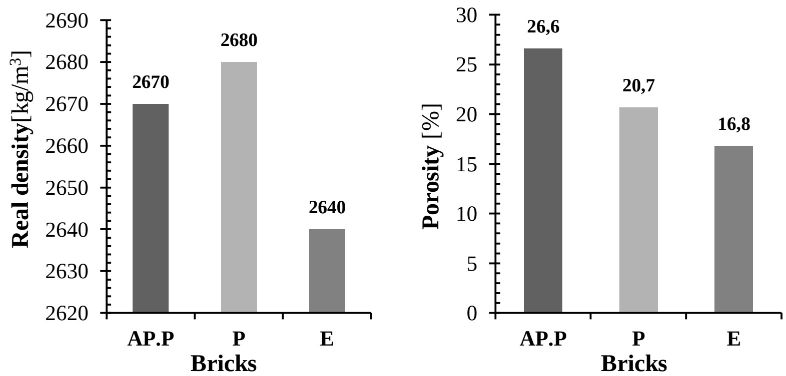

Figure 11 – *Medium values of real density (left) and porosity (right).*

The samples of original bricks manifested greater absorption capacity than the two replacement bricks, as summarized on **Table 3**, with higher water contents and ease of saturation (CS). The Spanish is the brick that has a lower absorption capacity.

Table 3 – *Water content and saturation coefficient.*

Brick	*Water content*		*Saturation Coefficient*
	maximum	*after 48 hours of immersion*	
	W_{max} [%]	*W_{48h} [%]*	*CS [%]*
AP.P	13,6	12,1	89
P	9,6	7,3	76
E[(1)]	7,7	5,9	77

[(1)] Only on 1,5x1,5x6,5 [cm] samples.

Comparing the capillary absorption curves, as a function of the root of time, presented in **Figure 12**, we conclude that not only the original brick sample presents a larger initial rate of water absorption by capillarity than the substitution bricks, but also a larger capacity for water absorption by the end of the test.

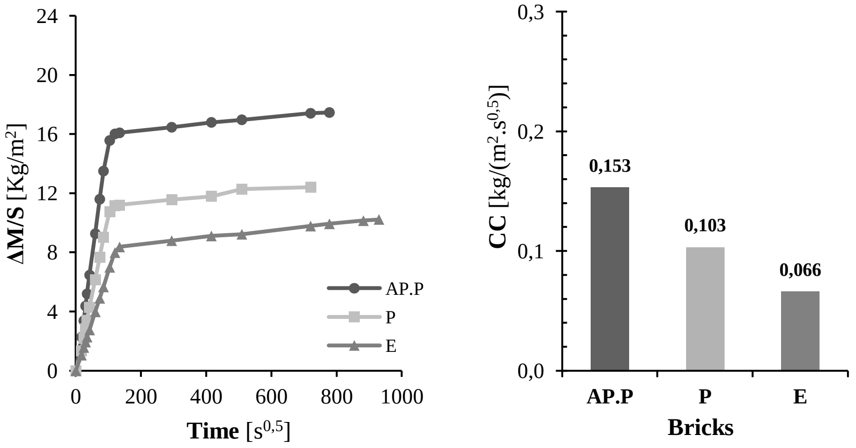

Figure 12 – *Water absorption by capillarity curves (left) and her coefficient (CC) (right).*

In the same figure the capillary coefficients resulting from these same curves are also shown. As expected on the other end the Spanish brick has the lowest capillary coefficient and smallest water absorption capacity of sample.

Figure 13 shows the medium drying and the average value of the drying indexes (IS) for the materials present in this facade. Due to the impossibility of cutting specimens with cubic dimensions (3x3x3 [cm]), the Spanish brick was not evaluated in this test.

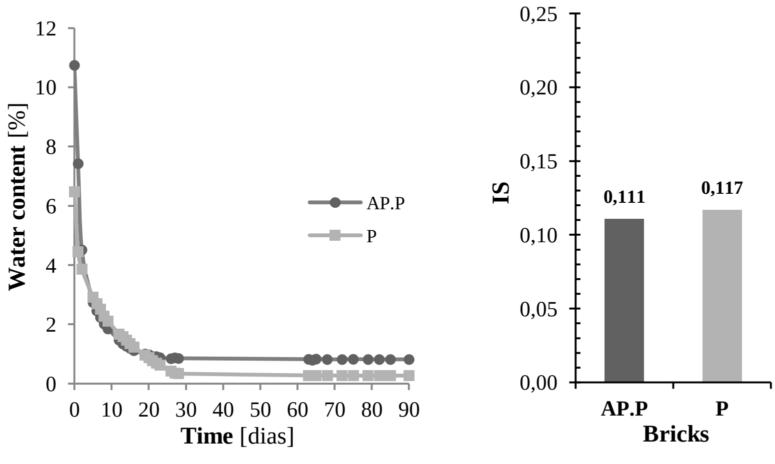

Figure 13 – *Drying curves (left) and drying indexes (IS) (right).*

From the analysis of **Figure 13** one can conclude that, although having different porosities, the two bricks have a similar drying index.

The values of the coefficient of water vapor permeability are presented on **Figure 14**. From the analysis of this figure it is clear that, the original bricks, in line of their higher porosity than replacement bricks, have also a higher value for vapor coefficient. Once again, the Spanish brick is the one with smaller water vapor permeability.

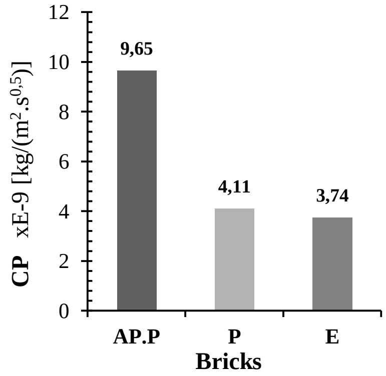

Figure 14 – *Coefficient of water vapor permeability.*

Figure 15 presents the color characterization carried on original and replacement bricks from the West façade of High Pressure building. The original bricks present a higher variability on Luminosity (L^*) and chroma (C^*) while the Portuguese and Spanish specimens manifest very close values in Luminosity (L^*).

Relatively to colorimetric coordinates, a^* and b^*, the replacement bricks analysis shows that the Spanish is the most similar while the presents higher values for these indexes and further away from the original sample.

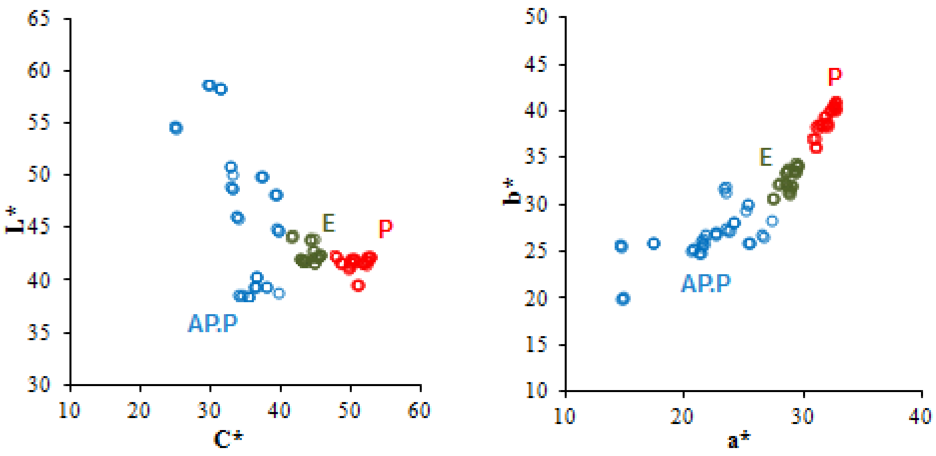

Figure 15 – *Color of the tested samples. Luminosity (L^*) versus chroma (C^*) (left) and a^* versus b^* (right).*

4. Conclusions

The materials characterization contributed to further increase the knowledge concerning the existing masonries elements, as well as, of the ones used for replenishing existing damaged elements.

The replacement bricks used in the West façade of Low Pressure building were the Portuguese and English bricks. On this façade, the characteristics of the Portuguese brick were be closer to the material of the facade than the features of English brick, in that refers to the real density, water absorption by capillarity and drying characteristics. The colorimetric characterization showed that the English bricks have values closer to those obtained in the original samples.

On the south facade of the Low Pressure building, the bricks replacement was carried out by Portuguese brick. The water absorption by capillarity and kinetics drying of the Portuguese bricks was similar of the obtained in the original bricks.

Finally, on the West façade of High Pressure building, the replacements were performed by applying of Portuguese and Spanish bricks. With the exception of color, the Portuguese brick have great similarity of characteristics with the original bricks, particularly in the water absorption by capillarity and kinetics drying.

References

[1] RILEM Test No. I.1 – *Porosity accessible to water.* RILEM 25-PEM 1980 – Recommandations provisoires. Essais recommandés pour mesurer l'altération des pierres et évaluer l'éfficacité des methods de traitement. Matériaux et Construction, Vol.13, Nº75.

[2] EN 1015-18 – *Methods of test mortar for masonry - Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar.* European Committee for Standardization (CEN), Brussels, 2002.

[3] RILEM Test No. II.5 - *Evaporation Curve.* RILEM 25-PEM 1980 – Recommandations provisoires. Essais recommandés pour mesurer l'altération des pierres et évaluer l'éfficacité des methods de traitement. Matériaux et Construction, Vol.13, Nº75.

[4] RILEM Test No. II.2 – *Coefficient of water vapor conductivity.* RILEM 25-PEM 1980 – Recommandations provisoires. Essais recommandés pour mesurer l'altération des pierres et évaluer l'éfficacité des methods de traitement. Matériaux et Construction, Vol.13, Nº75.