Florence City Centre Historical Mortars: Digital Image Analysis of thin sections in view of conservation actions

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Abstract. Conservation actions in historical urban centres must consider compatibility criteria in the selection of repair materials to ensure effective long-term intervention. Along this, compatibility between old and new mortars employed in conservation action requires the characterization of the historical mortar to design a new mortar mix. Digital image analysis (DIA) of thin sections of historical mortars observed under a transmitted polarised light optical microscope appears as an effective methodology for the characterization of mortars. In this work, three samples of bedding mortar were collected from historical monumental buildings of the period between the 14th and 15th centuries, in the city centre of Florence, a UNESCO Heritage Site since 1982, and subjected to petrographic investigation through DIA. Quantitative data about the composition of the analysed historical bedding mortars were determined, such as binder/aggregate ratio, percentage of porosity, the type and the percentage of granulometric selection. The comparison of the results obtained has made it possible to highlight the weaknesses and strengths aspects of the construction technique.

1 Introduction

The high vulnerability of the architectural heritage of Italian historic city centres to the many environmental threats has stimulated an in-depth debate around the issues of the protection of the built, in terms of safety, prevention, consolidation and conservation actions [1, 2].

The heritage of historical buildings, both monumental and housing, mostly in the aggregate, is characterised by an intrinsic vulnerability linked to the heterogeneity and quality of the masonry material, consisting of the assembly of blocks and bedding mortars in wall

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These proceedings are published with the support of EuLA.

texture [2, 3, 4]. The strength and durability of the mortar influence the performance of masonry. Any erosion or deterioration of the mortar leads to a reduction of the in-plane and out-of-plane capacity of the masonry walls [4, 5].

The achievement of certain safety and performance standards, however, must follow the conservation, compatibility and consistency criteria set out in the ICOMOS [6] maps and the new conservation and consolidation principles [7]. Recently, issues related to the reversibility and sustainability of interventions have also become increasingly involved in the definition of new materials for conservation [8, 9]. Such instances are often considered in the search of additives with the ability to modify the microstructure of the mortar to improve its workability, durability, and mechanical strength [10, 11, 12].

According to ICOMOS conservation and consolidation principles, the process of knowledge and characterisation of historic mortar becomes fundamental for the definition of a mix design for the repair mortars. Indeed, the new materials must have the same chemical, physical and mechanical characteristics of the original mortar to achieve compatibility [13, 14, 15, 16, 17], avoiding interventions that cause further degradation of the architectural heritage [18, 19, 20, 21].

So that the composition of the new mortar is strictly controlled in terms of chemical-physical and mechanical characteristics, suitable for consolidation actions on the existing constructions, the first step is the study of the original material that will be affected by the consolidation action. Using the mechanical, physical and chemical data of the historic mortar, it is possible to define the repair mix design, i.e. binder/aggregate ratio, type of binder, type and grain size of the aggregate, quantity of water and any additives.

The results obtained from physical and mechanical tests applied to both the historic and new repair mortar samples validate the compatibility, through the direct comparison between the two mortars. Possible corrections of the mix design of the new mortar can be implementable to satisfy the fixed compatibility criteria. To define an operating procedure for mix design correction, it is fundamental the knowledge of the link between the chemical, physical and mechanical characteristics and the composition of the mortars.

Moreover, the choice of raw materials to produce binders, the selection of the type of aggregate, and the addition of any additives, as well as being the result of specific technological knowledge and *ancient local recipes* are further factors that give certain physical and mechanical properties to the mortar [18].

The water/binder ratio cannot be reduced because it affects the consistency and thus the development of the bond between the masonry elements and the mortars themselves [5]. The more water inside the mortar, causing the more porosity of the mortar [22]. In particular, the amount of water in the mortar depends on the binder/aggregate ratio [23]. The abundant presence of binder gives greater strength within certain limits (2:1 ratio). Binder/aggregate ratios greater than 2 show lower strength values and greater porosity, therefore a certain amount of aggregate must be ensured to confer an adequate skeletal structure to the binder [22, 24]. In addition, with the same binder/aggregate ratio, the well-selected grain size, the smaller amount of water required to achieve optimal workability [22], and the greater the resistance, the lower the porosity. Siliceous reactive aggregate, such as pozzolana, increases the hydraulic properties of the mortar as well as the strength [25], and a further contribution to strength is the presence of calcite aggregates, for the chemical similarity between aggregate and binder [22, 24].

For characterization and knowledge as complete as possible of the historical mortars, the contribution to various surveys and the combination of standard methodologies with innovative procedures would be necessary. The difficulty of extrapolating samples in quantities and shapes necessary for a complete and extensive characterization restricts the type of tests that can be performed [26]. A first mechanical characterization through indirect non-destructive penetrometric tests in situ, useful for the definition of compressive strength

[27, 28, 29], should be added to the results obtained from the physical [16, 30], chemical, mineralogical [16, 31, 32] and petrographic tests [16, 32], conducted in the laboratory on samples taken in situ.

In particular, physical characterisation laboratory tests allow the extrapolation of data on bulk volume and water-accessible porosity, characteristics directly linked to the mechanical properties and durability of the material. Imbibition coefficient, saturation index and coefficient of thermal variation also influence the durability of a mortar, as cracks caused by differentiated thermal expansions are a frequent cause of degradation. The simplest direct method for determining the bulk volume and the water absorption is based on the hydrostatic thrust that exploits Archimedes' principle through the hydrostatic balance and the mercury pycnometer [33, 34, 35]. This method is desirable for irregularly shaped samples such as mortar extracted from masonry.

The X-ray diffractometric analysis, performed on a sample of mortar reduced to dust, is a semi-qualitative analysis, which allows to obtain the mineralogical composition, as well as to highlight, through the presence of certain mineralogical phases, the phenomenology of decay occurring or already occurring, characteristic of a particular type of lime [16, 31].

The observation of thin sections under the transmitted polarised light optical microscope (PLM) allows us to obtain a large amount of information concerning the texture, microstructure and binder/aggregate ratio of mortars, the presence of any additives, hydration products, residues from the firing processes of the binders, firing relicts or fragments, lumps, as well as information on the production technology and the place of extraction of the materials, as well as provide information on the packaging of the same, the origin of the materials used, type of granulometric section carried out, shape and orientation of granules, type of aggregate used, etc. [16, 32, 36, 37, 38, 39].

Compared to traditional manual or chemical mechanical acid dissolution techniques [32], causing the production of waste and toxic pollutants, the observation of thin sections represents an improvement, which is becoming increasingly specialised thanks to the progress in digitisation and computerisation [40]. Innovative technologies of digital image processing applied to the study of thin sections have allowed more effective, expeditious and statistically reliable procedures for the characterisation of materials observed under the transmitted polarised light optical microscope. The development of artificial intelligence has also been supported in the process of identification of minerals [41, 42], using techniques such as neural networks, machine learning and deep learning [43, 44].

Digital image analysis (DIA) applied on thin sections allows us to obtain quantitative information starting from the morphological or textural characteristics of a mortar's image [45]. DIA methodology applied to the observation of thin sections under the transmitted polarised light optical microscope can be used to overcome gaps in microscopic thin section studies, such as the need to use comparative tables and graphs [16, 32, 37]. Through the acquisition of the image, it is possible to obtain and analyse a more extensive area of the thin section obtained from the observation under the transmitted polarised light optical microscope, facilitating studies of texture [46]. The method can allow for obtaining a statistically superior quality of data, despite uncertainties due to deficiencies in the same method and errors of interpretation due to the great variety and heterogeneity of historical mortars [36, 46, 47, 48, 49, 50, 51]. Several studies on mortars and concretes report in the literature the results of the use of DIA on thin sections in terms of macro-porosity [46, 47], particle size curves of aggregates [46, 48, 49], shape, orientation and other morphological characteristics of aggregates [51], and the binder/aggregate ratio [36, 48, 49, 50, 51].

In this work, the procedure of DIA of thin sections of mortars observed under the transmitted polarised light optical microscope is applied to the study of mortars from three emblematic historical monumental buildings of the period between the 14th and 15th centuries in the city of Florence, to investigate the construction techniques and materials used thus learn about the construction culture of such an important historical period as that of the Renaissance and extrapolate information about the composition of each mortar [16, 43].

The three monumental buildings investigated in this work are Brunelleschi's Dome of the Cathedral of Santa Maria del Fiore (1400 d. C.), the Tornabuoni Chapel in Santa Maria Novella (1350 d. C.), and Palazzo Davanzati (1350 d. C.).

The analysis was conducted using the ImageJ software, which allows, using specific algorithms, to calculate areas and other geometric parameters of the different components of the mortar. The comparison of the results obtained has made it possible to highlight similarities, weaknesses and strengths of the construction technique used [16, 52, 53, 54]

1.1 Digital Image Analysis (DIA) of thin sections of historical bedding mortars

The general procedure of the applied digital image analysis (DIA) has been summarised below and in Figure 1.

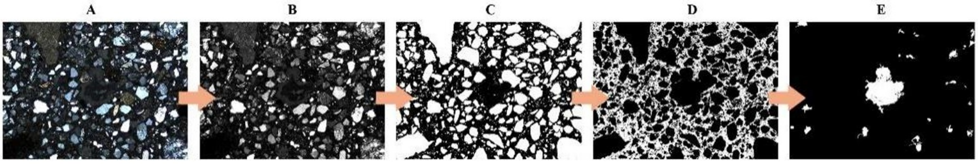

Fig. 1. Digital image analysis (DIA). Segmentation process of the 2D image of the thin section. A) image under PLM, xpl; B) image in 8-bit color; C) extrapolation of aggregate, in white; D) extrapolation of binder, in white; E) extrapolation of pores, in white.

Under a transmitted polarised light optical microscope, the mortar thin section is analysed and photographed. Frames are extracted, descriptive of the entire section, both cross and parallel Nicols. Next, for the photo merging, ICE-Microsoft, Photoshop software, are used and both images, with cross Nicols (xpl) and with parallel Nicols (ppl), are extracted in TIFF format.

The first fundamental step is the calibration of the images obtained, with the transition from pixels to lengths, establishing a dimensional scale. After the calibration process, responsible for most of the errors in the procedure, the calibrated image is binarized and transformed into black and white through 8-bit conversion, using software such as ImageJ (Java), Photoshop, Laica Application Suite X, etc. [47, 46, 48, 50, 51]. Working on the black and white image allows the user to distinguish the aggregate which in the thin section appears with a light colour compared to the darker binder.

The segmentation phase allows the user to select pixels that have common characteristics (colour, intensity, texture). Nevertheless, to avoid errors or inaccuracies in the reading of the image, it is necessary to intervene manually, inserting any missing elements and making the appropriate corrections.

Selected and isolated elements of interest could be possible to get different information, about the total area of the aggregate present in the section and the area of binder, for the determination of the binder/aggregate ratio, the affected area from the pores and the percentage of porosity.

It is important to obtain information on the type of grain size and the orientation because these characteristics affect other properties such as permeability, workability and porosity. For the definition of the particle size curve, the diameter (d) of each grain of aggregate, where d= minimum Feret diameter extracted from the analysis, is directly linked to the phi (φ) parameter, calculated using the equation $\varphi=-\log_2(d)$, introduced by Krumbein in 1932 [55]. Size ranges define limits of classes that are given names in the Krumbein phi (φ) scale. Minimum Feret diameters extracted from the analysis are compared with the reference table of the classes that identify the type of granules. The reference scale used was that of Udden-

Wentworth [56], modified by Krumbein in the 1932, in which limits between particle size fractions range from values > 2 mm for gravel, between 2 mm and 0,063 mm for sand, from 0,063 mm to 0,004 mm for silt, up to values <0,004 mm for clays. The fractions referred to gravel and sand are then sub-articulated according to the size or less of the grain.

2 The case study: three monumental buildings in the city centre of Florence

Throughout history, Florence has had a great influence on the development of the arts and architecture. The city's cultural, artistic and scientific renewal since the middle of the 14th-century, ahead of the rest of Europe, is based on the rediscovery of the great classics and makes possible the affirmation, during the 15th-century, of the Renaissance. Artists and architects, from Brunelleschi to Donatello, from Masaccio to Leonardo da Vinci, from Michelangelo to Sandro Botticelli, found support and inspiration in the city, thanks to the family of Medici, a rich family of great patrons of art, philosophy and science. The Renaissance monumental buildings of the city of Florence, today, bear witness to the artistic and architectural heritage of that age; a real open-air museum was declared a UNESCO World Heritage Site in 1982 [1, 57].

To best plan actions for the prevention and safeguarding of this huge artistic heritage, it is important to know the built culture, i.e. materials and construction techniques which allowed the product of such important buildings still handed down to the present day. Understanding the constructive culture of that flourishing historical period becomes the purpose of this work, focusing the study specifically on mortars. In particular, the study of mortars is indeed particularly significant to understanding the phenomena of degradation and formulating new mixes compatible with conservation actions [58, 59, 60].

In this work, three bedding mortar samples of three emblematic historical monumental buildings of 14th-15th-century of Florence have been analysed. The three monuments, located within the core zone of UNESCO World Heritage Site, are:

1. Brunelleschi’s Dome of the Florence Cathedral, built at the beginning of 1400 (Figure 2a); the mortar sample is identified as 1_DB;
2. Tornabuoni Chapel of Santa Maria Novella’s church, built in 1350, famous for the series of frescoes by Orcagna before and Ghirlandaio after (Figure 2b); the mortar sample is identified as 2_TC;
3. Davanzati Palace, built in 1350, fully represents the typical features of the 14th-century palace (Figure 2c); the mortar sample is identified as 3_DP.

Fig. 2. a) Brunelleschi’s Dome of the Florence Cathedral (1400); b) Tornabuoni Chapel of Santa Maria Novella’s church (1350); c) Davanzati Palace (1350).

2.1 Observation of Thin Sections supported by DIA

The digital image analysis procedure (DIA) is applied to thin sections of three mortars from the three monumental buildings of Florence analysed (1_BD, 2_TC and 3_DP samples).

To create a thin section, a small representative fragment of the sample (such as stone, mortar, or brick) is cut using a diamond blade saw to a size of approximately 30x20mm. If the sample is not coherent prior to cutting, it is embedded in a resin. Next, the sample is reduced to a thickness of 30 microns using abrasive wipes. This thinness allows for the passage of light radiation, enabling the sample to be examined under a petrographic microscope. In this case, one specimen of mortar from each building was considered. The mortar samples were sent to the institute TS lab and Geoservices (Pisa), responsible for the thin sections' realisation.

The thin sections were examined and photographed using an Axio Scope A1-Zeiss, transmitted polarised light optical microscope, with a magnification of 2.5X.

Cross and parallel Nicols frames (xpl and ppl) have been extrapolated, and the photo merge was carried out with the help of the software ICE-Image Composite Editor of Microsoft. For the segmentation and analysis process, Java ImageJ software was used [47, 46, 48, 50, 51].

All the steps of the process are summarised in Figure 3, through the orderly sequence of the extracted images, from the image to nicols crossed (xpl) to the segmentation of the binary image with the extrapolation of the different elements: aggregates, pores, binder.

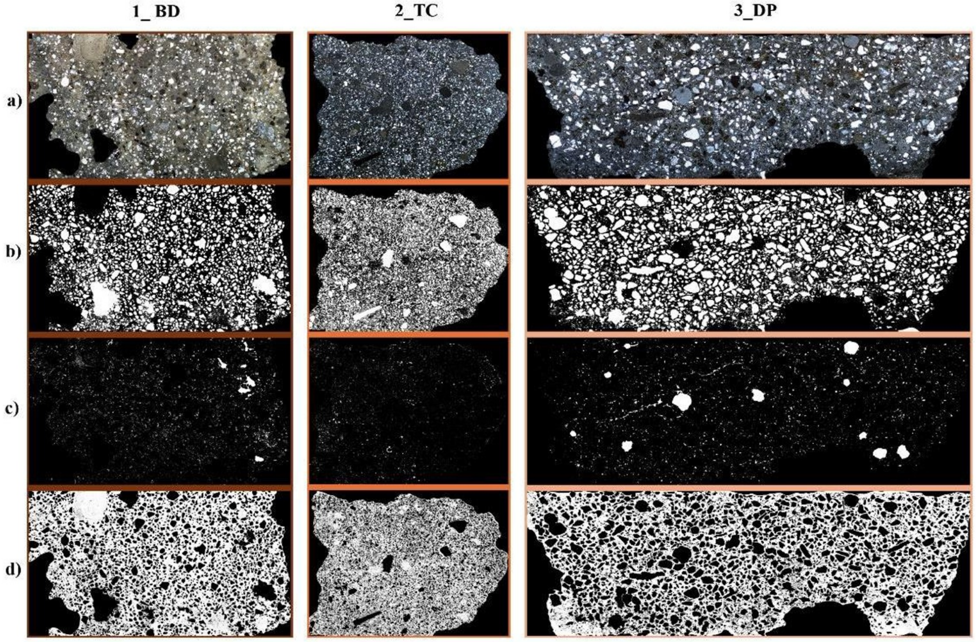

Fig. 3. Digital image analysis (DIA). Segmentation process of the 2D image of the thin section. a) image under PLM, xpl; b) extrapolation of aggregate, in white; c) extrapolation of pores, in white; d) extrapolation of binder, in white.

The difficulty of extrapolating samples in quantities and shapes necessary for a complete and extensive characterization represents a limitation of the analysis on historical mortars, restricting the type of tests that can be performed [26].

In this regard, analysing a single thin section for each selected building certainly does not allow an exhaustive description of the characteristics of the mortar investigated. The levels of statistical reliability required for new materials are not possible for historical ones.

However, the possibility of analysing even a single image, but extended, allows us to obtain acceptable information about the main characteristics of the mortar under study.

In the study cases analysed, because of limits imposed on survey and sampling actions only a limited quantity of mortar was extracted. The analysis has anyway allowed us to understand the main characteristics of walls considered representative. In addition to this, the selection of each mortar was carried out paying attention to take the historical mortars and not mortars related to subsequent operations.

The digital image analysis (DIA) of each thin section made it possible to extrapolate for each section the binder/aggregate ratio, the percentage of porosity and the particle size distribution. In particular, the values for each mortar, corresponding to a single sample, are summarised in Table 1.

Table 1. Main results from digital image analysis (DIA) of thin sections.

MORTARS	BINDER/ AGGREGATE	% OF POROSITY	% OF AGGREGATE	% OF BINDER
1_BD	1,79 (2:1)	3%	36%	61%
2_TC	1,52 (1.5:1)	2%	40%	58%
3_DP	0,91 (1:1)	4%	46%	50%

The binder/aggregate ratio, in the two cases of 1_BD and 2_TC, is an indicator of a fat mortar paste, characterised by an abundant binder. This is particularly evident in the case of 1_BD, where although the amount of binder is abundant, no shrinkage fractures are reported.

The percentage of surface porosity, as a percentage of the area occupied by the pores detected on the surface compared to the total area, ranges from 2% to 4%.

In case 3_DP the presence of filled shrinkage fractures due to leaching and re-precipitation phenomena in the next phase is noted. Regarding this sample, the percentage porosity value of 4%, higher than the values obtained for the previous two sections, depends on having considered those shrinkage fractures filled by leaching and re-precipitation phenomena as open porosity in the analysis. The reason is temporal, considering these fractures belonged to the recipe and original invoice and only later filled.

Figure 4 shows the particle size distribution for the aggregate in mortar 1_DB, 2_TC, and 3_DP.

The diameters of grains race from 0.063 mm to 8 mm. The values in percentage are summarised in Table 2. As shown in Figure 4, in all three cases, there is an unimodal trend. The “moda” represents the most frequent diameter present. In particular, the main percentage of grain diameters ranges from 0.063 mm to 0.25 mm, and grains have geologically compatible dimensions with those of the sands already observed in literature as sands of the Arno present in Florence [61, 62]. This trend was planned given the use of the sands of the Arno to pack the historic mortars of Florence [38, 61, 62, 63].

In particular, in the case of 1_DB, there is an unimodal trend even if the previous and subsequent classes are well expressed, from medium to very fine sand; in the case of 2_TC there is an unimodal and well-expressed trend, the classes that concern fine and very fine sand; finally, the same applies in case 3_DP. The particle size assortment does not include large-sized clasts, as a good rule of art would have it instead.

The most widely expressed classes range from 0.25 mm to 0.063 mm in all three mixtures: this trend was planned given the use of the sands of the Arno to pack the historic mortars of Florence [38, 61, 62, 63], and the pattern of the particle size curves in cases 2_TC and 3_DP are fairly similar. The 1_DB section is richer in binder, compared to cases 2_TC and 3_DP, although even in these two cases the dark colour of the aggregates, very similar to that of the binder, could be misleading compared to the actual amount of aggregate present.

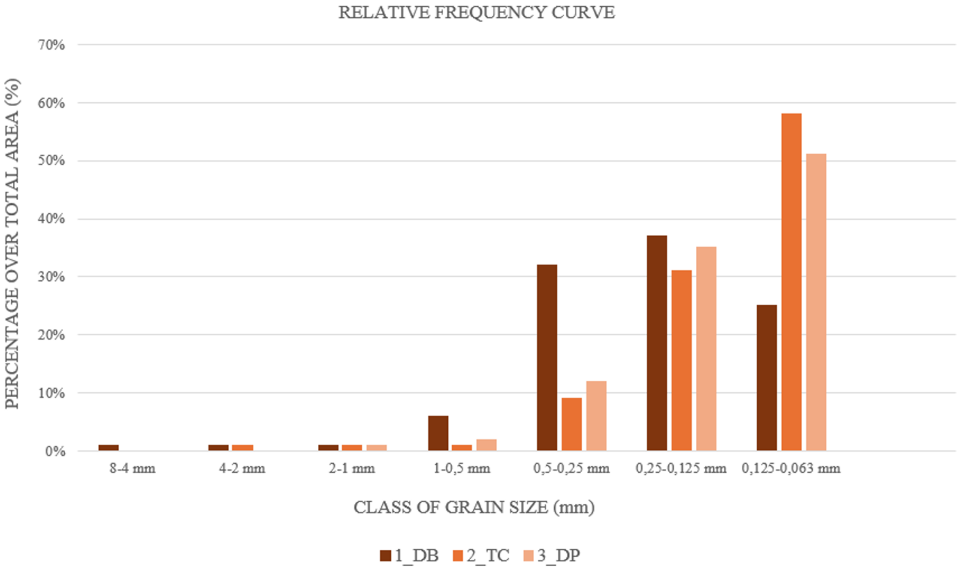

Fig. 4. Grain distribution of aggregate referring to mortar 1_DB, 2_TC, 3_DP. Comparison between the different grain distributions.

Table 2. Grain size range of the aggregates in the mortars and percentage.

	GRAIN SIZE RANGE (mm)						
MORTARS	**8-4 mm**	**4-2 mm**	**2-1 mm**	**1-0,5 mm**	**0,5-0,25 mm**	**0,25-0,125 mm**	**0,125-0,063 mm**
1_BD	1%	1%	1%	6%	31%	36%	24%
2_TC	0%	1%	1%	1%	9%	31%	57%
3_DP	0%	0%	1%	2%	12%	34%	51%

In addition to the quantitative information already reported, the petrographic study of three historic mortars allowed to obtain information about the type of stone used to produce the binder, the technology and the different stages of processing (presence of lumps, firing relicts, shrinkage cracks, any additives, etc.) and information about the hydraulicity of the mortar.

In particular, the hydraulicity of a mortar may be due to the use as raw materials for the production processes of limestone containing a percentage of clay minerals or silicate constituents, or it may be induced in an aerial lime by the presence of aggregates with pozzolanic characteristics that react with the lime to promote the formation of hydraulic compounds [64]. In the case of hydraulic mortars, the binder is opaque, not birefringent, and grey-blues in colour under polarised light. The unburned residuals and the identification of the use of Alberese's stone give preliminary information about the hydraulicity of the mortar. The use of a more clay type of Alberese (strong calcin) produces a naturally hydraulic lime. Morphologically there could also be a difference in porosity between hydraulic lime mortars and aerial lime mortars. Hydraulic mortars tend to be less porous of the air mortars [65].

Overall, therefore, the following information was obtained for each sample analysed:

1. 1_DB: the mortar is characterised by abundant binder with an impure appearance and micritic texture (Figure 5a) and is characterised by a binder/aggregate ratio of 1,79 ≃ 2:1. The aggregate is well selected and distributed homogeneously, with a size from 0,063 mm to 8 mm. The main aggregate consists of quartz (mono and polycrystalline), feldspars, fragments of carbonate and sandstone rocks, rare fragments of cocciopesto and very rare lumps of under-burnt fragments of micritic limestone, probably Alberese stone. This stone has a variable amount of clay minerals, from 7% up to 20% [63, 66, 67, 68], in this case, a variety poor in clay minerals must have been used to produce lime. Although it is a mortar with a fat paste, no shrinkage fractures are observed, and the percentage of porosity is 3%. This fact reflects particular care both in the selection of the mortar and in the process of seasoning the mortar in opera, kept wet throughout the process of hardening. Given the composition, 1_DB is therefore a weakly hydraulic mortar. As for the aggregate, comprising a well-selected sand, it is possible to state that it comes from the Arno River.
2. 2_TC: the mortar shows a binder with an impure appearance and micritic texture (Figure 5b) and is characterised by a binder/aggregate ratio of 1,52 ≃ 1.5:1. The aggregate is well selected and distributed homogeneously, with a size from 0,063 mm to 4 mm. The main aggregate consists of quartz, feldspars, fragments of carbonate and sandstone rocks, clay minerals and rare fragments of cocciopesto. There are lumps of lime putty and under-burnt fragments of micritic limestone (Alberese stone). The porosity amounts to a percentage of 2% and consists of pores of irregular shape and large shrinkage cracks. It is a hydraulic lime, probably obtained from the firing of the local stone Alberese, as in the case of the Brunelleschi's Dome mortar, but with a greater content in clay minerals. Although it is a lean mortar, cracks have formed, which may be due to either poor quality of lime or poor curing in opera.
3. 3_DP: the mortar shows a binder with an impure appearance and micritic texture (Figure 5c) and is characterised by a binder/aggregate ratio of 0,91≃ 1:1. The aggregate is not well selected and distributed in-homogeneously, with a size from 0,063 mm to 2 mm. The main aggregate consists of quartz, feldspars, fragments of carbonate and sandstone rocks, clay minerals and fragments of cocciopesto. The porosity is scarce and consists of pores of irregular shape; shrinkage fractures are also present, many of which were filled by leaching and re-precipitation phenomena, as mentioned before. The mortar is a hydraulic lime mortar, also in this case probably produced by the firing of Alberese stone rich in clay minerals [16, 59], a characteristic which gives it the adjective of strong lime. The presence of shrinkage fractures is related to the same causes indicated for the mortar of Tornabuoni Chapel.

Fig. 5. Frame of thin section: image under PLM, xpl. a) Bedding mortar of Brunelleschi's Dome of the Florence Cathedral; b) Bedding mortar of Tornabuoni Chapel of Santa Maria Novella's church; c) Bedding mortar of Davanzati Palace.

From the results obtained for each mortar analysed it is possible to observe that the stone used to make the lime is compatible with the Alberese stone, a local stone that came from the Monte Morello (north of Florence) or the Calvana (north-east of Prato), as well as from outcrops in the area are in Grassina, Galluzzo, Scandicci and Lastra a Signa, widely used in the Florentine territory for the production of lime in the years when the mortars themselves were made, information also confirmed in [63, 66, 67, 68].

As for aggregates, the information obtained from the analyses carried out confirms the origin from the bank of the Arno River, as confirmed in [38, 63].

3 Conclusion

In this work, an application of petrographic analysis, supported by digital image analysis (DIA) on historical mortars, was carried out focusing the study on monumental buildings of the Renaissance period in the historic centre of Florence.

The three historical monumental buildings analysed are Brunelleschi's Dome of the Cathedral of Santa Maria del Fiore (1400 d. C.), the Tornabuoni Chapel in Santa Maria Novella (1350 d. C.), Palazzo Davanzati (1350 d. C.).

The petrographic and compositional results carried out from the study of the historical mortars allowed us to obtain information about the constructive culture and the materials used in the period between the 14th and 15th centuries in Florence.

In particular, the results obtained from the petrographic analysis comprise the composition of mortars, the type of stone used to produce the binder, the binder/aggregate ratio, the percentage of porosity, the type and the percentage of granulometric selection, and information on the technology and the different stages of processing of mortars.

ImageJ software was used to extrapolate the information from the different components highlighted by image segmentation.

The following issues were thoroughly considered: choice of DIA methodology for the study of thin sections of historical mortars, the statistical validity of the results, the need for a preliminary and effective calibration of the image and the use of a quality image.

Despite the limitations related to statistical validity due to the number of samples that can be analysed, the DIA technique on thin sections offers useful results to understand the performance and compositional characteristics of a mortar.

In particular, the main information obtained from the observation of thin sections of the three mortars analysed in this work are:

- The three hydraulic mortars analysed were probably produced by firing the Alberese stone, a marly limestone, hard, very fine grain, ash-coloured, that provided the mortars with particular durability and hydraulic characteristics;
- The binder/aggregate ratio, especially for the mortar 1_BD (Brunelleschi's Dome of the Cathedral of Santa Maria del Fiore) and for mortar 2_TC (Tornabuoni Chapel of Santa Maria Novella's church), is an indicator of a fat mortar paste, characterised by an abundant binder;
- Regarding the aggregate, for all three mortars analysed, the use of a well-selected sand coming from the Arno River can be assumed;
- The particle size assortment does not include large-sized clasts, as a good rule of art would have it instead. In all three mortars analysed, there is an unimodal trend: the main percentage of grain diameters races from 0.063 mm to 0.25 mm (Table 2);
- In all three mortars analysed rare fragments of cocciopesto are noted;

- Regarding the percentage of porosity, the values between 2-4% (Table 1) from DIA are to be considered quite acceptable for historical mortar;
- Low porosity, few shrinkage fractures, not abundant presence of lumps and firing relicts or fragments, reflects a particular care both in the selection of the materials used and in the process of seasoning the mortar in opera, kept wet throughout the process of hardening;
- The mortars of the Brunelleschi's Dome and the Tornabuoni Chapel were made with greater care than that of Davanzati Palace, probably for the greater value of the first two religious buildings;
- In general, the good quality of these analysed mortars is linked not only to the appropriate construction technique developed in that period (stone selection and production process from grinding of stone to the firing and process of seasoning the mortar in opera) but also the coincidence of the availability in loco of an optimal stone, that of Alberese, capable of offering hydraulic qualities and durability to the mortar.

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