The Building Stones of Prato’s Cathedral and Bell Tower, Italy

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Featured Application: This paper establishes the assemblages, building stones and mechanical parameters of Prato’s Cathedral and Bell-Tower external quoins; these data can be used for conservation purposes of this historical building and the method can be replicated for other historical buildings.

Abstract: This study defines the assemblage, lithotypes and mechanical parameters of the building stones used for the external cladding of Prato’s Cathedral and Bell Tower (XIV century), now subject to extensive conservation work. By means of a drone flight, a full 3D model of the Cathedral and Bell-Tower complex was developed with photoplanes of the façades. On this basis, a GIS of the façades with all the stone elements embedded was developed. Historical data and organoleptic analysis enabled the identification of the types of the stones constituting the cladding. The results show that the building stones used for the cladding are all local historical stones, namely white Alberese and Palombini limestones, green Verde Prato peridotites, and grey Pietra Serena sandstone. The quarries of provenance of these stones were determined, along with their physical-mechanical properties and decay processes, in order to contribute to conservation works according to authenticity and integrity principles.

Keywords: building stones; Prato cathedral and Bell Tower; historical quarries; physical-mechanical properties

1. Introduction

Historic-monumental buildings are the expression of the cultural context in which they were built, and denote a profound relationship with the territory. The choice of construction materials is an integral part of the creative vision of the architect who oversees the design. Prato’s Cathedral and Bell Tower (Figure 1) are tangible examples of the union between art, science and the technologies of Renaissance humanistic culture [1]. The aim of this paper was to catalogue and characterize the stone materials utilized, and to define their physical, mechanical, mineral and petrographic characteristics, their state of conservation and stability, and to determine the quarries of provenance.

To preserve their integrity and authenticity over time [2], each lithotype on site was mapped and characterized by commercial name, origin, geology, petrography, product category, mining history, use in work, technical-analytical data, problems of degradation, and physical-mechanical properties.

The knowledge of the geodiversity of historical-monumental stone buildings starts from the stone materials and extends to the characterization of various historical quarry sites, according to geology, materials present and their properties, mining, and commodity history. Therefore, the quarries, which are the place of origin of the lithotypes used, become locus genii and sites of historical and social interest, too [3].

Today the tendency towards a general globalization tends to ignore the cultural, historical, and economic roots of a territory, which should be preserved, disseminated, and handed down by scientific and technical recovery of the knowledge of the roots of a territory.
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2. Materials and Methods

In Italy, the rules in force [4,5] define the roadmap for the assessment of historical cultural buildings.

The first step towards a conservation project is the anamnesis of the building in terms of construction history, followed by the identification of the stone materials in place, their geology and technical data.

To carry out preparatory studies for a restoration project that would be drawn up later, we followed the following road map:

1. A short analysis of the main structural points regarding the Cathedral and Bell Tower.
2. A full 3D photogrammetric survey by drone, with the development of georeferenced photoplanes of all the façades.
3. Production of a wireframe of all the stone elements of the façades with implementation in a GIS (Geographic Information System).
4. Identification and mapping of all the stone types on site.
5. Analysis of the territory and historical documents, as well as witnesses to locate the historical quarries of provenance of the building stones utilized.
6. Sampling in the quarries of the diverse lithotypes to perform physical, mechanical tests and mineral and petrographic characterization.

The use of GIS allows us to manage the state of knowledge regarding the façades of historic stone buildings due to the extreme versatility presented by the GIS platform in representing objects georeferenced in space at any scale. Secondly, it provides the possibility of updating and implementing the information database in real time. Thirdly, it provides a large storage capacity and simplicity in managing a large amount of diverse data [6–8].

3. Results

The investigation was carried out on the stones constituting the external façades of the Cathedral and Bell Tower through the observation of photoplanes derived from images taken by a drone and through direct observation performed using an elevation platform and scaffolding.

The historical analysis made it possible to trace important elements regarding the construction and transformations of the building, as well as the restoration interventions that involved the stone cladding.

A photogrammetric survey by means of the geometric reconstruction of the facades made it possible to investigate and map even the less accessible surfaces of the building.
A study of territorial geology and the identification of the quarries is a functional practice for the characterization of the materials and for understanding the types of in situ degradation that they develop.

The possibility of taking samples from the extraction sites allowed the start of an experimental test campaign (USC, volume weight, water absorption, porosity and sonic velocity) that provided initial results for a physical-mechanical characterization of the lithotypes.

Finally, the construction of a GIS database of the entire stone cladding representing the “container” of all information enabled systematic archiving and consultation at all stages of the project and construction site.

3.1. Historical Anamnesis

The first document about the existence in Prato of a church on the site of the present cathedral dates to the 10th century. In 1211, the construction of a church was entrusted to Guido or Guidetto de Sancti Martini da Lucca, who was simultaneously working on the façade of the Cathedral of Lucca. Purchases of stones for Prato’s Cathedral were already documented in 1165 [9].

Guido probably had to intervene on the construction site in full activity by grafting onto pre-existing walls. The construction of the original façade, partly visible under the current renaissance one, is attributed to him, as are the three naves divided by large archways resting on columns. Guido’s configuration of the church was largely transformed in subsequent periods. In the 14th century, the church was enlarged to create a chapel for the relic of the Sacra Cintola in correspondence with the first arch of the left side [10,11].

Outside and inside, Guido’s architecture is characterized by accentuated polychrome effects obtained using white and dark-green stones, effects that would be taken up, albeit with different meanings, in the subsequent transformations of the church.

The construction of the new façade started in 1385 and lasted until 1457. An example of the Florentine late Gothic style, it features polychromy on the lateral sides with the combination of a lower monochrome order and an upper order with white and dark-green rows. The façade was completed by the time of the construction, in 1428, of the new pulpit by Donatello and Michelozzo for the exposition of the Sacra Cingola, as well as by the construction, in 1457, of the clock face, [12] and, in 1489, the insertion in the portal of the glazed lunette by Andrea della Robbia.

In 1933 the triple lancet windows and the corbels crowning the bell tower were renewed, and in the 1980s substantial restoration and consolidation interventions were undertaken on the Cathedral [12]. These interventions involved many aspects, but in particular they concerned the Romanesque façade and the external side façade.

3.2. Photogrammetric Survey and Wireframe Drawing

The monumental complex of the Duomo of Prato and the bell tower was the subject of an extensive survey using aerial photogrammetry.

The air survey was carried out by Studio Micheloni S.R.L. (Florence, Italy) in the context of a cooperation with the DST. A Phantom 4 Pro drone (https://www.dji.com/it/phantom-4-pro, accessed on 5 October 2022) with an RTK antenna, GPS, and a 20 Mp resolution camera was used. The drone flight, at about at 5 m distance from the walls, obtained a GSD = 0.41 cm. This type of survey was integrated with a photographic survey carried out from the ground level with a SONY α6500 camera, with 24 megapixel resolution. In total, more than 3000 photos were taken.

The planning of the survey campaign involved the execution of two types of drone survey. One was a planned flight out over the entire area of the monumental complex, while the other was a series of frontal photos in manual mode at a distance of five meters from the facades and with an overlap of about 70% between one shot and the next.

The information obtained from the planned flight allowed the reconstruction of a 3D point cloud model and textured mesh, as well as an orthophoto of the area.
The integrated processing of the drone photos and the photos from the ground enabled the reconstruction of high-resolution photoplanes and their subsequent two-dimensional digitization. The façades were classified and named according to a unique code in plain view and accordingly in the relative photoplanes (Figure 2).

Figure 2. (a) Map of the cathedral and bell-tower complex with the side reference (A to L); (b) the relative photoplanes.

Starting from the photoplanes in raster format, vectorization was carried out in the CAD environment (Figure 3). The primary element is represented by the stone element digitized by means of a closed polygon. Closed geometries are essential to have correct import and identification in the GIS environment.

In the CAD environment, layers were created through which different types of stone elements (slabs, frames, statues, among others) and architectural elements (doors, windows, grates, gutters, among others) were classified, and an initial classification of the deterioration visible above on Verde Prato elements.

The operations carried out in this phase were essential to allow the correct setting of the geometries for the GIS database.

3.3. GIS Development

The archiving system created with a GIS approach allowed the extraction and rapid selection of information in an integrated form between alphanumeric and graphical data. The results were not a simple list because the system allows users to check all the information and data available in a single environment. By obtaining detailed information from each single element constituting the external cladding of the building, it also allowed the realization of quantitative, qualitative and spatial analyses.

The system and the data infrastructure created can be defined as a “decision support system (DSS)”. The stored information is always available, searchable, comparable, reinterpretable, and implementable [8].
The operations carried out in this phase were essential to allow the correct setting of the different elements on distinct layers, and the decomposition of complex objects into simple primitives.

To place each element in the drawing space, a “Reference system” must be defined. In the present work, for each photoplane, the coordinate reference system was the plane xz with the x set at an arbitrary zero left of the photoplane and the z corresponding to the datum above sea level.

Each ashlar of the cladding was defined as single stone element and, by a CAD wireframe, was imported into the GIS system in the correct coordinates in relation to all the other modelled objects. For the purpose of implementation in GIS, the vector data transmitted were all transformed into shapefiles optimized and, when possible, unified in order to make management and use easier. The available table information was reworked and linked to the relative spatial data in order to have as much information as possible available.

Once positioned in the space of the reference system and in relation to the other basic elements that make up the individual façades of the monument, each geometry, ashlar, and more was “attributed” by assigning it an ID and the type of stone material, thus making each element identifiable (Figure 4).

Subsequently, for each basic geometric unit we proceeded to the compilation of attributes, closure of polygons, the subdivision of the different elements on distinct layers, and the decomposition of complex objects into simple primitives.

3.4. Stone Types, Characterisation and Quarries

In the study of the materials used on a specific monument/building there are three different types of approach for determining the type of material in place:

- Organoleptic analysis carried out by experts based on their knowledge and concerning lithology, grain-size, texture and warp.
- Documentary analysis carried out using archives and historical texts that report orders, origin, and type of materials.
- Technical analyses of a petrographic, mineralogical, geochemical and isotopic nature which, based on international databases, allow the attribution of the analysed sample to that specific lithotype.
Therefore, the physical-mechanical characterisation was carried out on fresh samples collected in the historical quarries of provenance.

In this work, the various stone materials were defined by organoleptic observation and petrographic and microfossil analysis. These were compared with previous data from general documentation [13], the Prato Emperor’s Castle, [14] and the geological literature. The organoleptic study was complete and led to a mapping of all the quoins of the façades of Duomo and Bell Tower with their typological attribution, then embedded into GIS.

The quoins of the external façades of the Cathedral and Bell Tower of Prato represent a paradigm of the local Prato “historical stones”. They refer to Alberese, Verde Prato, Palombino, Pietra Serena. There are also some elements of Carrara Marble (Figure 5).

Field surveys and historical documentation allowed us to locate the historical quarries that supplied these building stones in the medieval age in Prato’s territory (Figure 6). As a whole, the Cathedral consists of 19,718 quoins and the Bell Tower of 9359 (Table 1).

In the following, a detailed report on these stone is presented, except for the Carrara Marble, imported from Carrara and well-known in the literature [15–17].

3.4.1. Alberese

Alberese is the typical building stone of Prato, widely used in the Emperor’s Castle, in the city walls, and in many historic buildings. It derives its name from the presence of thin manganese dendrites in the shape of saplings along the layers [18]. It is part of the Monte Morello Formation largely outcropping near the north of Prato. It is a greyish limestone, in regular decimetric and multidecimetric layers with a fine grain and a conchoidal fracture, and is of Eocene age evidenced by globigerina fauna [19], which was present in the few samples analysed.
Figure 5. Façade of Prato’s Cathedral with all the types of building stones used: green Verde Prato, grey Pietra Serena, white Alberese, brownish Palombino. The pulpit parament is Carrara marble.

The stone lends itself well to the cutting process, exploiting the thickness of the layer for its height and then dimensioning it laterally in quoins according to the natural spacing of joints. Usually, installation was flat with horizontal layering, but in the revetment of the Cathedral and Bell Tower it appears with the bedding plane placed vertically.

Alberese CaCO₃ content is around 90%, about 10% being of clay minerals (Illite 50%, Chlorite 25%, and Chlorite-Vermiculite 25%), and the iron oxide content is about 0.9% [20]. It was quarried in Figline, Retaia, Lastre and in the southern offshoots of Calvana [21]. There have been no actives quarries in decades and it is difficult to find memory, or traces, of many of them.

3.4.2. Palombino

Palombino was derived from the cultivation of limestone layers interlayered in the Palombini Shales of the Ophiolithic Unit outcropping at north of Prato [21], where several shale quarries for bricks and terracotta were active. It therefore represents a resultant material whose use and marketing were secondary to the extraction of clays. It is Late Cretaceous in age [22] with sponge spicules, as in the few samples collected for this job.

The blocks were obtained by dismantling the calcareous layers interlayered in the shales, and have a dimension of the height of the bed and other dimensions according to joint spacing, then regularized to quoins.
Figure 6. Historical quarries of the Prato territory that supplied the building stones for the Cathedral and Bell Tower: green Verde Prato, brown Pietra Serena, blue Alberese, purple Palombino (Gauss-Boaga Ovest reference system).
Table 1. Quoins number and stone types.

| Lithotype     | Cathedral | Bell Tower |
|---------------|-----------|------------|
| Alberese      | 10,451    | 6536       |
| Palombino     | 2940      | 187        |
| Carrara Marble| 357       | 17         |
| Verde Prato   | 5428      | 2565       |
| Pietra Serena | 542       | 54         |

This limestone consists of light grey fine calcilutites, whose average mineralogical composition is characterized by CaCO$_3$ 65–80%, of which 15% is fossils and calcareous grains, 35% quartz, 6% feldspar, and 5% phyllosilicates. The cement is made up of spathic calcite [23,24].

3.4.3. Pietra Serena

Pietra Serena is a light grey quartz-feldspar arenaceous turbidite in medium to thick layers (10–70 cm) and even amalgamated banks (up to 12 m), with a clayey matrix and scarce calcite cement (<15%), presence of Bouma Ta-d Tb-e sequences, and an A/P ratio >1 [25].

Petrographically it is a medium-large grain greywacke made up of quartz, feldspar, mica and fragments of metamorphic rocks. The matrix is abundant and consists of illite, kaolinite, and chlorite-vermiculite. The granulometry of the layers used in architecture varies from medium to medium-fine (about 0.25–0.3 mm) [26].

Pietra Serena has excellent resistance properties, as it is almost entirely constituted by a sequence with no sedimentary structures; therefore, it has excellent workability, which is why Pietra Serena has been widely used in construction to strengthen walls and as shelves corbels.

Pietra Serena was supplied from the best layers of Macigno outcropping in the area of Monte Javello and from the great quarries of the Gonfolina. Currently, Pietra Serena is no longer quarried. In the Cathedral and Bell Tower of Prato, the use of Pietra Serena is secondary and used to build projecting load bearing and balustrades.

3.4.4. Verde Prato

The first information on the use of Verde Prato dates back to the 12th century. Subsequently, the Verde Prato was widely used in the duotone white-green in the Florentine and Prato area until the 15th century and then again in the 19th and 20th centuries for coatings and restorations of various churches.

Verde Prato comes from the Ophiolithic body outcropping north of Prato in uncertain tectonic-stratigraphic relationships with the surrounding Monte Morello Unit. It is of Middle Jurassic age [27,28].

Verde Prato is a Lherzolitic Peridotite more or less serpentinized in oceanic metamorphism at low pressure and high temperature. The peridotite-serpentinite mass appears compact but is actually affected by widespread micro fracturing, which makes it difficult to obtain blocks of good strength and large.

Verde Prato is used as blocks clamped into the masonry, and the inlays are in strips a few cm thick. Several capitals and tympanums of the attic ornaments are also in Verde Prato blocks. Historic quarries were north of Prato, in the Monteferato hill area. The quarries have been closed for decades for environmental reasons.

3.5. Decay Processes

As is well known, decay processes can be physical or chemical. Physical decay is related to thermal and crio-clastism, to loading/unloading changes, alo-clastism and gelifivity, the dilating action of the root systems of plants, and abrasion breaking due to the mechanical action of wind and water. Chemical decay is due to liquids and gases in the atmosphere, namely CO$_2$, H$_2$O, and those due to pollution that act by hydrolysis.
Over the centuries, the stones in place have undergone different decay processes according to their mineral, petrographic and texture setting. The general climate conditions also play a role, which are those typical of the Italian region, described in the cited references.

3.5.1. Alberese

The Alberese in place has had long durability and low deterioration over the centuries, except for the formation of a whitish patina on the exposed surface of the blocks due to slight decarbonation, and the loss of a few small slabs due to water percolating and freezing in some microcracks (Figure 7a).

3.5.2. Palombino

The abundant presence of ferrous minerals means that, when exposed to alteration, Palombino tends to oxidize, gradually giving rise to a more brownish-reddish colour of the quoins in place [23] (Figure 7b).

3.5.3. Pietra Serena

Pietra Serena is particularly sensitive to the action of water that washes out the clay of the matrix and swells the network of clayey minerals, leading to the exfoliation and disintegration of the surface [27]. Its high permeability (5–6%) fosters the freeze-thaw cycles that tend to disintegrate the stone elements in place [27].

Water can cause the dissolution and reprecipitation of a small fraction of calcite (about 4–5%), giving rise to the formation of cohesive low porosity crusts which, being discontinuous with the support, tend to fall and reform, resulting in the progressive destruction of the architectural element (Figure 7c).

![Figure 7. Cont.](a) Alberese (b) Palombino)
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3.5.4. Verde Prato

Apparently resistant, Verde Prato decays by physical processes due to high heat absorption with low thermal conductivity. Moreover, it has a high-water saturation index in microfractures (effective permeability 1.62%), which causes exfoliation and disintegration starting from the edges of the elements in place [27] (Figure 7d).

3.6. Physical-Mechanical Properties

Physical and mechanical parameters of building stones play a role both in ensuring the stability of the building and in fostering or hindering decay processes due to weathering and pollution.

For hard building stones, such as those in place on the Prato Cathedral and Bell Tower walls, the main physical-mechanical properties to be defined are usually USC, volume weight, water absorption, porosity, and sonic velocity. Hence, we collected fresh samples in the historical quarries of provenance of the stones used. The standards followed [29–32] and laboratory analysis results are reported in Table 2.

**Table 2.** Physical and mechanical properties and standards [29–32] followed.

| Properties                  | Standard            | Alberese | Palombino | Pietra Serena | Verde Prato |
|-----------------------------|---------------------|----------|-----------|---------------|-------------|
| UCS (MPa)                   | UNI-EN 1926:2007    | 108      | 73        | 95            | 45          |
| Volume weight (kN/m$^3$)    | UNI-EN 1936:2007    | 27       | 27        | 26            | 26          |
| Water absorption (%)        | UNI EN 13755:2008   | 0.2      | 0.2       | 2.3           | 1.6         |
| Imbibition coefficient (%)  | UNI EN 1936:2007    | 0.2      | 0.5       | 2.0           | 1.0         |
| Porosity (%)                | UNI-EN 1936:2007    | 0.5      | 1.4       | 5.3           | 2.5         |
| Sonic velocity (m/s)        | UNI EN 14579:2005   | 4890     | 4700      | 3000          | 3800        |
4. Discussion

The studies developed on the building stone of the external facades of Pratos Cathedral and Bell Tower, combined with archival and library documents and field surveys, allowed identification of the types of stones and their quarries of provenance.

The principles of local territorial provenance [13,33] was confirmed in the context of best exploitation of the local stone resources for the realisation of outstanding monumental-architectural buildings.

All the stones used were supplied locally with a maximum distance of transport of about 20 km (from the Gonfolina area), which occurred by boats sailing upstream, first on the Arno and then the Bisenzio rivers, whose banks are about 200 m from the cathedral. The other stones were transported by chariots downslope from the quarries to Prato.

Stone decay processes and the main physical-mechanical properties (USC, volume weight, water absorption, porosity, and sonic velocity) were defined for each of the stone types used in the Prato Cathedral and Bell Tower.

5. Conclusions

This study represents the first omni-comprehensive study about the building stones used for Prato’s Cathedral and Bell Tower and the historical quarries in the Prato area.

GIS implementation provided a record of the research performed and is an instrument that provides a content that can be kept updated for further conservation interventions and studies.

The definition of degradation processes and physical and mechanical properties provide basic knowledge for the proper design of ongoing restoration work.

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