POLITECNICO DI TORINO

LAUREA MAGISTRALE IN INGEGNERIA
PER L'AMBIENTE E IL TERRITORIO

The technological properties of natural stone from Itria Valley for the protection of cultural heritage

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Marzo 2021

ABSTRACT

A major challenge in the approach to the sustainable management of landscapes and cities is the identification, conservation and protection of Cultural Heritage. In a geographic area like Itria Valley, which is recognised by UNESCO as a site of great relevance in territorial identity because of the dense presence of trulli, masserie and dry-built walls, natural stone protection is even more demanding, because of a lack of characterisation of this material employed for building and ornamental purposes, both in terms of geological and technological properties.

Standardised methods of investigation, both destructive and non-destructive, on stone samples coming from different sources and sites can help in the process of classification. The variability and unpredictability of natural stone is an important drawback in the study of these materials on-site. Many factors – both external and intrinsic – can affect the reliability of non-destructive testing. Furthermore, these investigations can only assess the properties of the medium indirectly. On the other hand, laboratory tests – although conducted in a controlled environment – necessitate a robust and representative population of samples to overcome the variability of natural stone. This can represent an obstacle in the case of material coming from cultural heritage sites, since the availability of samples can be very limited, making the advantages of laboratory testing irrelevant.

The main goal of this work is to further characterise Itria Valley natural stone, by means of analyses and correlations between physical-mechanical properties, including water absorption, open porosity, petrographic analysis, accelerated ageing and flexural strength. All these tests are compared with ultrasonic pulse velocity (UPV) measures, which represent a quick and reliable way of on-site investigation, to simplify direct on-site characterisation in the case of natural stone coming from Itria Valley cultural buildings, such as churches and trulli, and have an immediate understanding of strategies for choice, use and restoration of the material.

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Un sincero ringraziamento alla Professoressa Rossana Bellopede, a Claudio DeRegibus,
alla Professoressa Paola Marini e all’Architetto Piernicola Intini,
per l’aiuto indispensabile nella realizzazione di questa tesi.

INTRODUCTION

This work of thesis has been required in the perspective of a series of books, named "Natural Stones and World Heritage", edited by Taylor and Francis group and linked to the promotion of Itria Valley and its Cultural Heritage. The book series was strongly encouraged by the IUGS Subcommission for Natural Stone, and the first two books were published in 2019 ("Natural Stone and World Heritage, Salamanca – Spain") and in 2020 ("Natural Stone and World Heritage, Delhi and Agra – India").

The scope of the thesis is to characterise, through a number of laboratory tests, natural stone material coming from Itria Valley, a geographic area of Puglia, Italy, which was recognised by UNESCO as a World Heritage Site, because of the use of natural stone in the construction of territorial Cultural Heritage. The material analysed comes from both historic monuments, such as the belltower of "Chiesa Madre" of Noci and Trullo Palmullo in Martina Franca, and local quarries, both active and historic.

The thesis is organised in three main parts: part one includes chapter 1, which presents a general framework to establish the setting this work falls into, both in terms of geographical and cultural aspects. Chapters 2 and 3 refer to works of literature to define the geological context and the mechanical properties studied by other authors. The second part of the work includes chapter 4, which presents the results of on-site investigations conducted before the beginning of this study. The third part begins with chapter 5, which explains the laboratory tests that were conducted: how they were carried out and with which references. Chapters 6 and 7 present the results of the tests, the analyses performed and the conclusions that could be drawn out.

1. GEOGRAPHICAL AND CULTURAL FRAMEWORK

1.1 THE EXTENSION OF ITRIA VALLEY

The territory investigated in this work belongs to a geographical area of Puglia Region known as Itria Valley, included in the provincial limits of Bari, Taranto and Brindisi. More specifically, as indicated in the PPTR, the Plan for Technical Regional Planning, Part 7, of Regione Puglia, Itria Valley is an historical geographical region, which includes a landscape context, named Murgia dei Trulli, easier to be delimited, as it is composed by the following municipalities (table 1.1):

Table 1.1: The list of cities included in Murgia dei Trulli (M.d.T.), and their relative territorial relevance to the context.

City	Surface included in M.d.T. (km^2)	Surface included / tot municipality surf.
Alberobello	40.31	100%
Carovigno	26.94	100%
Castellana Grotte	67.77	99%
Ceglie Messapica	130.44	100%
Cisternino	54.07	100%
Crispiano	11.24	26%
Fasano	128.94	100%
Gioia del Colle	32.77	16%
Grottaglie	1.06	100%
Locorotondo	47.52	100%
Martina Franca	295.31	100%
Massafra	32.15	26%
Monopoli	156.66	100%
Mottola	136.68	64%
Noci	148.83	100%
Ostuni	223.82	100%
Polignano a Mare	62.16	99%
Putignano	99.13	100%
Taranto	1.54	1%

Starting from this classification, the boundaries of Itria Valley are identified as the municipal limits of those cities which have a high value of representativeness in the Murgia dei Trulli context, discarding those with lower percentages, namely: Taranto, Mottola, Massafra, Gioia del Colle and Crispiano.

The main area of interest of this work revolves around a few cities, the locations of on-site measurements and the sources of material analysed in laboratory: Martina Franca, Locorotondo, Noci, Fasano and Alberobello. The following figure 1.1 shows the location of these places of interests, thanks to a thematic map drawn in QGIS 3.14:

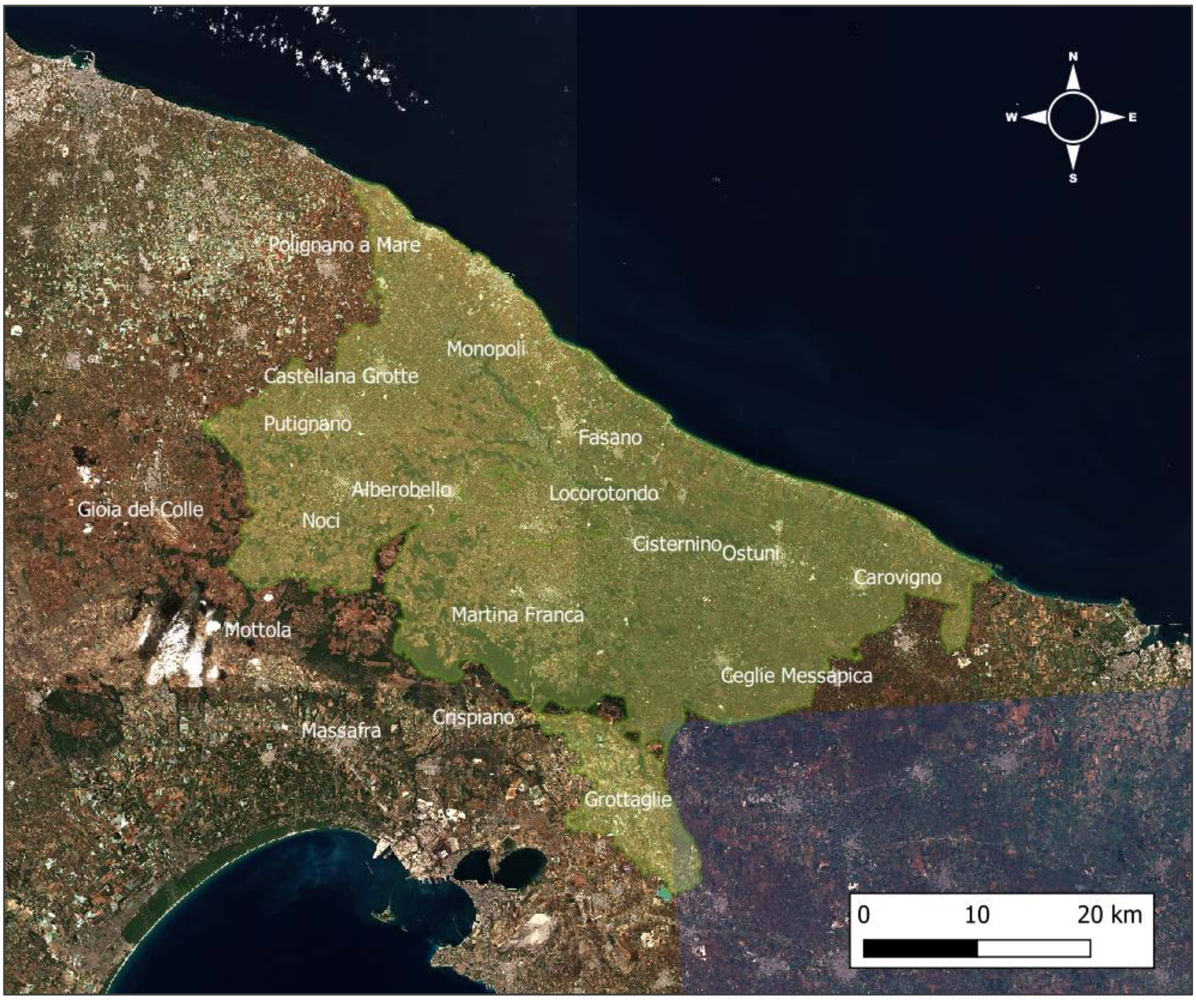

Figure 1.1: In this map, drawn in QGIS 3.14, the cities composing Murgia dei Trulli are represented, and the areal extension of Itria Valley, based on the considerations mentioned above.

The cartography is obtained by satellite images from Sentinel2 mission, and have been selected to present as little cloud interference as possible, with a ground resolution of 10 m; the scale of representation is 1:500000, to give a wide view and include all of the territory under investigation. Shapefiles come directly from sit.puglia.it, the official geographic portal of Regione Puglia.

1.2 THE CULTURAL-ANTHROPOLOGICAL RELEVANCE OF RURAL BUILDINGS IN ITRIA VALLEY

The cartography in figure 1.1 allows us to appreciate the vastness of the territory under investigation, and its variety: some parts of it, like Fasano and Carovigno, are very close to the seaside, while Noci, Locorotondo, Alberobello and Martina Franca fall in the inland of Apulian countryside. Such a spread-out distribution of points of interest over Itria Valley is not casual, as it has been studied that the average density of rural buildings in Murgia dei Trulli is the absolute highest in all of Apulian territory [Ruggiero G. et al., 2019]. This study refers to Murgia dei Trulli, but given the considerations from chapter 1.1, its results have been extended to Itria Valley, and they provide a key for interpretation of anthropological and historical networks of the territory; this is remarked in D.L. 22/10/2004: “Code of cultural heritage and landscape”, which includes rural architectures of historical and ethnical-cultural interest as evidence of traditional commerce in cultural heritage. Also, maintenance, recovery and restoration of such buildings is regulated by PPTR, resolution n.176 of 16/02/2015, to give guidelines about operations on dry-built manufacts. Trulli are also recognised of an important cultural relevance, as Alberobello entered the list of UNESCO World Heritage Sites in 1996, as “an example of traditional human settlement, the use of territorial resources, representative of a culture, or the interaction of man with the environment, especially when it has become vulnerable because of irreversible transformations”. Even though these legal interventions and recognitions, it is still of paramount importance to intervene with policies of local development, all the while respecting pre-existences and through promotion of requalification/restoration. This work focuses on the study of natural stones employed in the construction and restoration of trulli, masserie and churches, two of which fall in the classification of “rural buildings”. The work of G. Ruggiero provides a general schematic of these fabrications (figure 1.2):

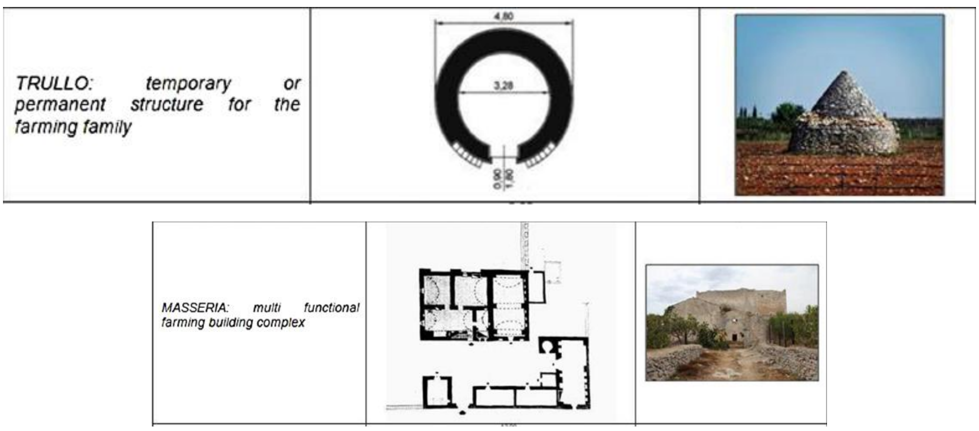

Figure 1.2: Schematics of typical rural buildings in Itria Valley [Ruggiero G., 2019].

A full census of Apulian rural buildings has been made, and total number of items and density over the territory has been computed, as in table 1.2:

Table 1.2: The counting of rural architectonic elements in all of Apulian region, and marked in yellow those referring to Murgia dei Trulli/Itria Valley [G. Ruggiero, 2019].

	Dwellings								Operation, storage and trasformation buildings										
PPTR Landscape areas	Masserie	Casini	Torri	Ville	Trulli[a]	Pagliari	Lamie	Other minor dwellings	Stalle	Ovili	Iazzi e poste	Porcilaie	Colombaie	Frantoi	Palmenti e cantine	Molini	Neviere	Other opera-tional buildings	Total
Gargano	378	10	41	10	(3)	3	1	1	1	/	77	/	/	3	/	2	/	6	536
Monti dauni	754	25	3	3	(4)	/	/	/	1	/	2	/	/	/	/	8	/	26	826
Tavoliere	1396	23	23	35	(6)	/	/	21	4	1	96	/	1	2	/	/	/	31	1639
Ofanto	296	5	10	9	(1)	/	/	/	/	/	34	/	/	2	1	1	/	3	362
Puglia centrale	603	358	301	220	(1)	1	27	/	1	/	36	/	1	11	11	/	/	2	1573
Alta murgia	1041	55	11	26	(7)	/	63	/	2	/	137	/	/	/	/	/	/	4	1346
Murgia dei trulli	1388	173	26	82	38(26) + 12	/	13	/	/	3	7	/	/	22	3	3	1	2	1761
Arco jonico tarantino	602	108	46	13	2 (1) + 1	1	17	/	/	8	22	/	1	11	1	1	/	5	838
Campagna brindisina	437	63	11	31	(4)	/	/	/	/	/	9	/	2	3	9	/	/	2	571
Tavoliere salentino	1180	244	31	113	1	/	4	/	/	/	9	1	6	13	/	/	/	/	1602
Salento delle serre	439	222	33	48	(1)	1	/	/	/	/	/	/	1	6	5	/	/	1	757
Apulia region	8514	1286	536	590	68(54 + 14)	6	125	22	9	12	429	1	12	73	30	15	1	82	*11811*

[a] The values in brackets () refer to dwellings denominated by the IGM as caselle or casette.

As made evident by the table, 1761 elements are censed in Itria Valley, out of 11811 total, which compared to the areal extension of the region (1662.3 km^2, calculated in QGIS) gives a density of about 1 element/km^2, which is the highest of all of Puglia. Depurating the value of the elements that are not either trulli or masserie, the density becomes 0.85 elements/km^2, as summarised in table 1.3:

Table 1.3: The density of rural buildings in Itria Valley, calculated through the work of G. Ruggiero and QGIS.

	n. of elements	Surface (km^2)	Density
Considering all	1761	1662.3	1.05
Only trulli and masserie	1426		0.85

Going beyond the mere counting of elements, this work can give a perspective of the use, and with it the importance in construction and restoration, of natural stone in this territory: it is documented that the construction material employed by farmers to build their trulli was almost always available in the agricultural fund, since it had already been removed by the massaro or by who would farm there. Such stone clusters are known as specchie (from Latin speculae), and traditionally served as landmarks for delimiting funds and territories [Marzulli M., 2019]. This clarifies the origin of building material for trulli, as opposed to those used for bigger buildings, such as masserie and churches: the higher amount of material makes it impossible to raise enough fabric from local clusters of stone, so they would definitely have to resort to surrounding quarries, even though the precise location is difficult to be assessed, as in the case of the restoration of the bell tower of “Chiesa Madre” in Noci [La Viola F., 2016].

1.3 NATURAL STONE OF ITRIA VALLEY

Trulli are dry-built constructions, with rock chunks left in place without the aid of cement mortar. As mentioned before, the origin of lithic material for the construction of trulli is most likely piles of rocks (specchie, as in figure 1.3), or other immediate sources. Yet this may not always be the case, as trulli have a long history and a multitude of uses: the most ancient documented trullo of Puglia is referred to in the Conversano Code, and dated 971 D.C. Other ancient buildings have been found in Castellaneta, as the initial layout of San Bartolomeo in Padula Church, dated as belonging to the end of IX Century. San Nicola dei Greci Church, now restored, has roof covering made of chiancarelle [Marzulli M., 2019]: this may prove that the source of natural stone for the construction of trulli is quite varied. On the other hand, trulli builders, or mastri trullari, became a professional figure and are still renowned in the territory, operating exclusively on trulli building and restoring. Building materials were obtained directly from the fund, so it would have to be surfacing material, and raising stones would have the second end of making farming easier [D’Aurea V., 2008].

Figure 1.3: A specchia on the left, and chiancarelle from Palmisano quarry in Alberobello.

Quarrying and extraction activities are a fundamental resource for Puglia: Italy is the first producer of stone materials in the world, and Puglia is the third region in Italy as for quantity of extracted material, and among the first ones for quality. [Micheletti F., 2021].

Apulian natural stone has a very high degree of compactness, very good values of flexural strength, elastic modulus and good resistance to wear phenomena, all the while showing very low levels of water absorption. They also present an attitude to being polished, which brings out many aesthetic values, such as colourful veins like those of Filetto Rosso di Fasano. It is customary to name such polishable, strong and compact limestones "Marmi di Trani", or Trani marble, even though it is improper.

The basin of extraction of Trani marble is quite vast, and historically relevant, as this territory has always been a centre of commerce and export of stone materials across the Mediterranean. For this reason, the activity of quarrying has been flourishing in other basins too, like those of Itria Valley, leaving many historical pits, now abandoned and reclaimed by nature, as well as in-activity quarries, which still supply the induct of civil construction and architecture. Going deeper in detail, the of limestones that emerge in the area of Itria Valley are divided into three main series: Altamura limestone, Bari limestone and Mola limestone. These limestones are diversified based on the presence and number of specific fossils, like Rudists and others. Namely, Bari limestone sometimes presents, on the superior detrital part, stratifications (chiancarelle) that allow to quarry this material as slabs [from the analysis of Chart n.190, Carta Geologica d'Italia, ISPRA].

Some quarries, both historic and in-activity, along with cultural heritage sites, have been mapped in QGIS 3.14, and are shown in figures 1.4 to 1.8.

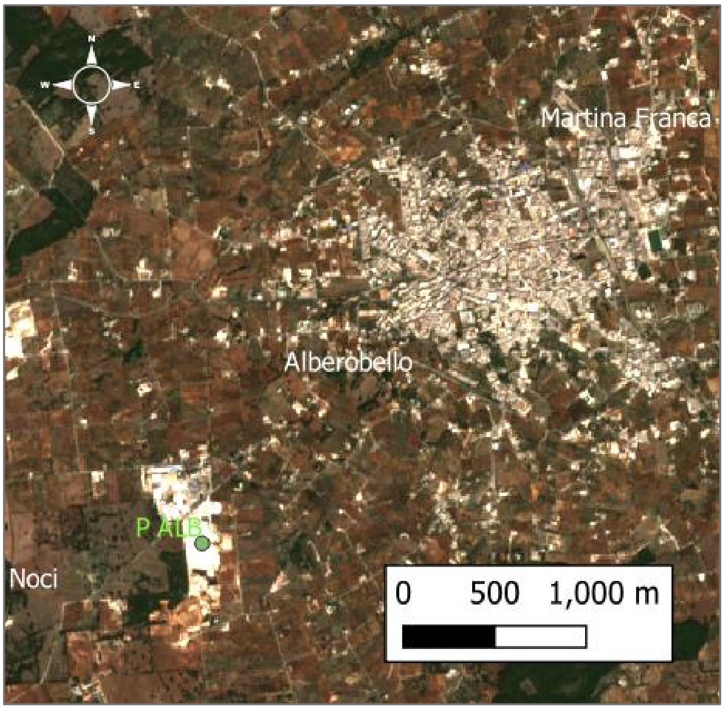

Figure 1.4: Palmisano quarry, near Alberobello, with codename P ALB, is in activity.

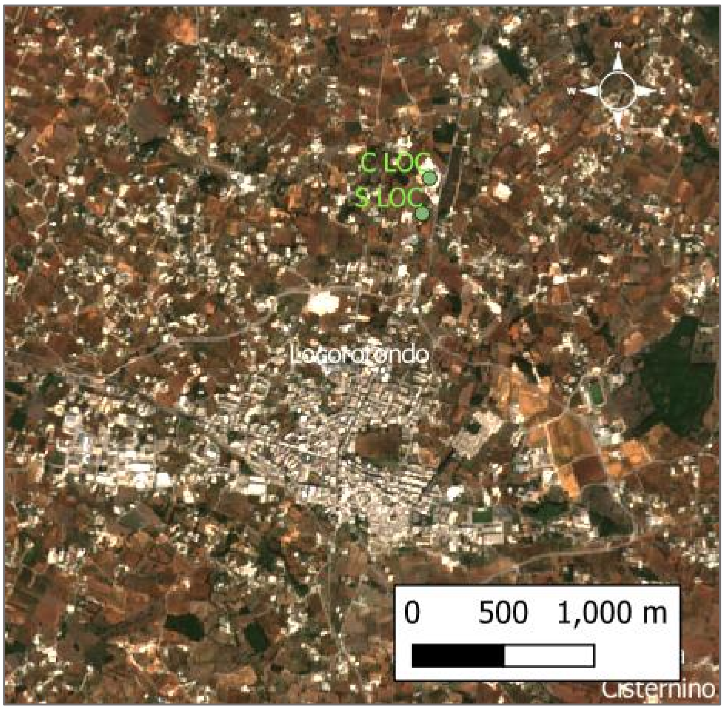

Figure 1.5: Calella quarry, near Locorotondo, is in activity, while the nearby historic quarry is abandoned. The quarries are coded respectively C LOC and S LOC.

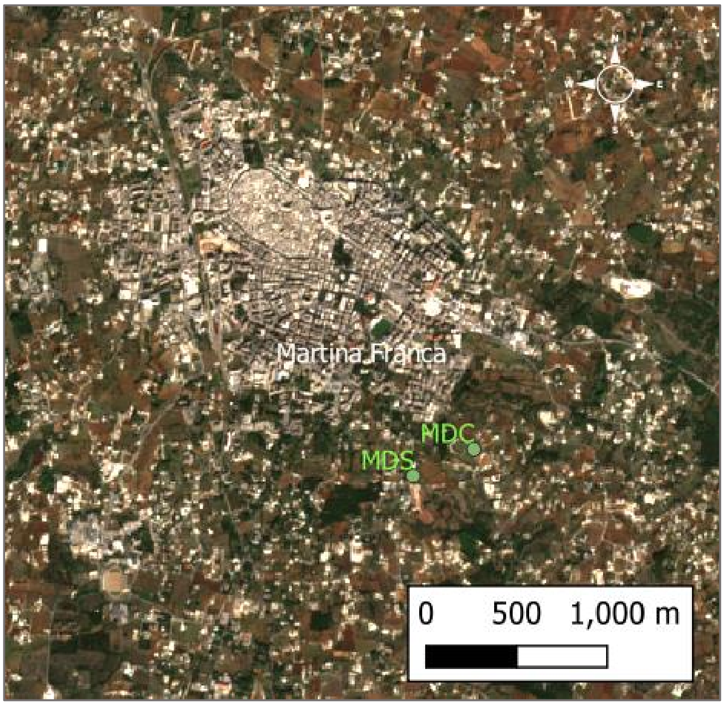

Figure 1.6: Placed in an outer district of Martina Franca, the Monte del Duca historic quarries are both abandoned. One of them is the actual site of the quarry, and is coded MDC, while the other one, MDS, is a stripping site.

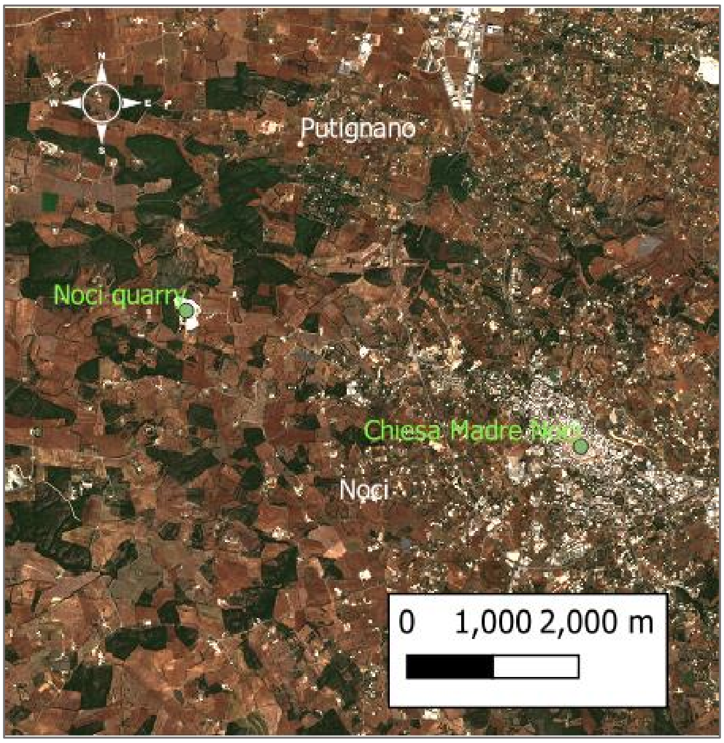

Figure 1.7: The quarry of Noci, in activity (code Noci Cava), and the belltower of “Chiesa Madre” in Noci (code Noci Camp).

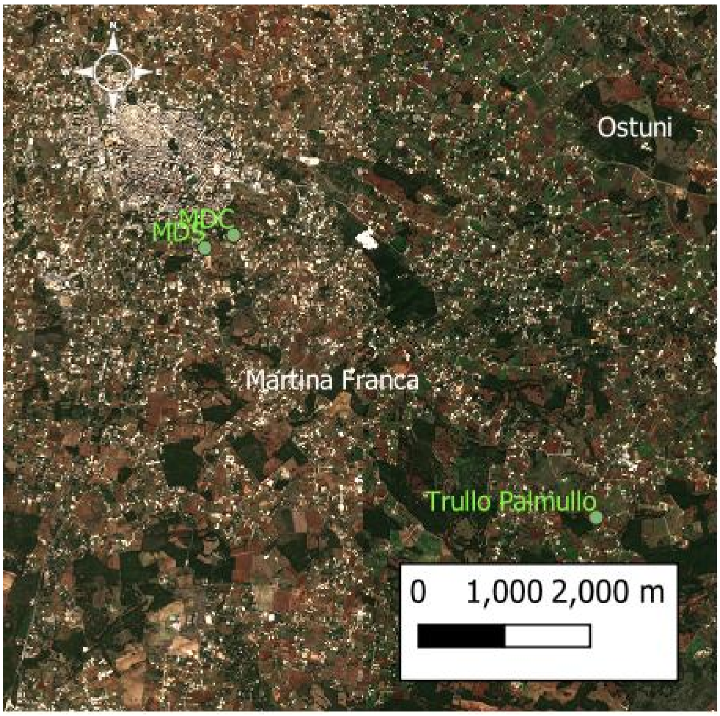

Figure 1.8: The origin of material tested, in the area of Martina Franca: the embankments of Monte del Duca and Trullo Palmullo, with code T. PALM.

The many materials collected and analysed in the course of this work have uncertain geological origins. Stone from Palmisano Alberobello quarry is sold as chiancarelle, but it has been observed that chiancarelle are no longer extracted: the material quarried is actually named “chianche segate” [Marzulli M., 2019]. Chiancarelle should be considered as an historical building material, that was typically taken from available local sources, and rarely quarried. As of now, their employment in construction is exclusively focused around the restoration of trulli; for this scope, stone is either bought from quarries or taken from specchie, depending on the needs and the project of the restorer. Other materials are also commonly adopted for these restorations, such as Albanian limestone, which has been observed to be less porous and less susceptible to biologic attacks from mold or lichens, thus remaining whiter for a longer period of time, and marking clear the difference in the kind of materials used.

Other materials, like those coming from historic quarries such as Locorotondo and Monte del Duca, come from sites of extraction of which the geological features are uncertain. Since Altamura limestone outcrops on almost the entirety of the study area, it is unclear whether such stones could be classified as coming from Bari or Altamura series; to clarify this point would give interesting insight about these materials, as it will be explained later, through the study of thin section specimens.

As for the material coming from the belltower of “Chiesa Madre” in Noci, the works of restoration [La Viola F., 2016] have brought up that the possible source of the original materials is rather hard to assess: they have been classified as Altamura limestone, but no further information is given.

What results from this is a collection of materials of which only geographical source is determined with certainty. One of the goals of this work will be to classify them on the base of their mineralogic and petrographic properties, to determine their geologic origin, a starting point to frame their mechanical features and allow confrontations between different materials, with a multidisciplinary approach.

2. GEOLOGICAL FRAMEWORK

To understand the geological setting of Itria Valley, and to discuss the mechanical properties studied by some authors it is useful to present an in-depth analysis of the geological processes that lead to the formation of the Apulian platform, the diagenetic mechanisms involved and an overview of what can be found in the study area. The goal is not only to highlight some criteria to differ from one lithotype to another, but also to present how the geological characterization of natural stones is quite difficult to assess, and the way it is reported in geological maps, only available at a very large scale of representation, gives almost univocal indications. Since it was observed, through on-site tests on relevant buildings spread in the area, that mechanical properties seem to differ sensibly depending on the geographical position of the site of investigation, suggesting that either stones with distinct properties were employed, or that ageing occurred in ways that affected materials differently.

This chapter goes through a brief history of Apulian geology, and then, with a zoom in, is going to focus on the more restricted territory of Itria Valley, as identified in the previous chapter.

2.1 THE GEOLOGICAL PROCESSES THAT LEAD TO THE FORMATION OF PUGLIA

The Apulian platform faces a scenario in which the African plaque pushes against the Euro-Asian one, determining the formation of the Alps chain starting from the beginning of the Cretaceous, and later (about the geological epoch between Oligocene-Miocene) the rise of the Apennines. The platform originated before these events, in an arch that spans from Palaeozoic to Mesozoic, a period in which the platform plays a role of passive continental escarpment, promoting the development of large shallow areas [Channel J.E.T. et al., 1979]. The continuous accumulation of sediments caused a constant subsidence.

Such subsidence gradually led even relatively high areas to drop below sea level. These conditions play an important role in the accumulation of thick layers of carbonate particles, all favoured by the high degree of precipitation of carbonate and the abundance of sea life and vegetal organic rests, made up of calcium carbonate as well. Gradual transformation to limestone of carbonatic accumulations – mainly muddy sediments – led to the formation of a sedimentary series, the thickness of which reaches several kilometres. The continuous growth of the sedimentary platform would compensate the subsidence, and the space created by the lowering of the depositional surface was filled at the same pace by the settling of carbonatic sediments. This way, the conditions of inter-oceanic platform would remain constant through time, promoting the formation and development of carbonatic reefs [Lavenziana R., 2016].

Because of a global process of lowering of the sea level, by the end of Cretaceous the Apulian platform emerged and became a wide continental setting, mainly subjected to karstification, and in such way unable to promote the accumulation of substantial layers of carbonatic sediments.

The growth of the Apulian platform happened both before and during the convergence of African and Euro-Asian plaques; such movements led to the closure of oceans in between the plaques, and later involved directly the Apulian platform, which saw its margins shaped by Alps and Apennine orogenesis. A deep marine basin separated this plaque from the rest of southern Italy: the lagonegrese-molisano basin. Here, clay sediments, along with silico-clastic carbonates from deep sea (having different origins: part from the carbonatic platforms, part from African continental areas) would find a good depositional environment. Starting from Miocene, there was a series of overlays: first the Apennine chain over the lagonegrese-molisano basin, then both overlapped over the central portion of the Apulian platform, progressively shaping the southern Apennine chain [Lavenziana R., 2016].

Figures 2.1 and 2.2 show the evolution of the formation of the chain-pit-foreland system, composed of southern Apennine chain, Bradanic pit and Apulian foreland.

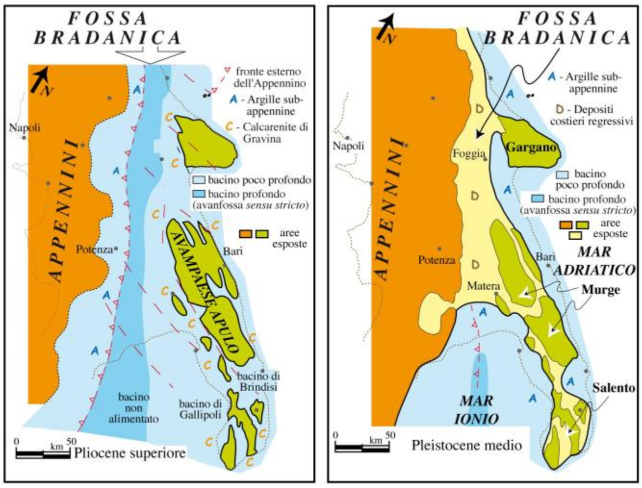

Figure 2.1: Evolution of the palaeographic setting in southern Italy, from upper Pliocene to middle Pleistocene [Tropeano M. et al., 2002].

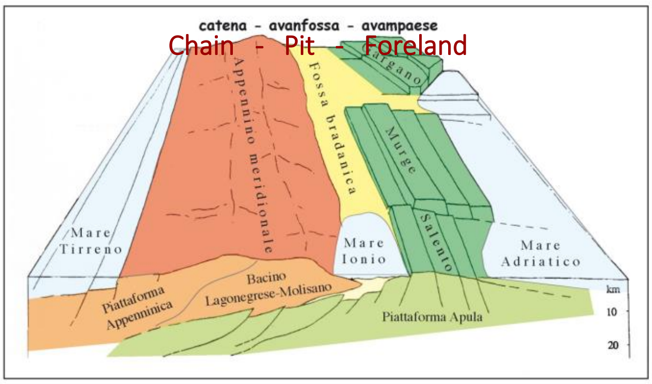

Figure 2.2: Apulian platform in Mesozoic, displaying the chain-pit-foreland system [Funiciello R. et al., 1991].

2.2 A GEOLOGIC OVERVIEW OF ITRIA VALLEY

The Chart 190 from Carta Geologica d'Italia (C.G. d'I.), on a scale 1:100000 (figure 2.4), named Monopoli, is occupied by the largest part by a Mesozoic limestone series, which is found in literature as "Murge Limestone", showing little to no variation with nearby coeval areas [from Carta Geologica d'Italia, chart 190 "Monopoli", 1971]. This group of limestones, which derive from a mainly detrital sedimentary environment, are well stratified, so much so that it is possible to split it into three lithostratigraphic units:

- Bari limestone: developed between Turomanian and Cenomanian, it outcrops in a quite widespread area. It is composed of a thick series of limestone layers; most of them are detrital, with various colorations, and presenting a variety of fossils, both vegetal and animal (namely limestone algae, and sometimes big gastropods). The base of this formation does not emerge, even out of the study area, but the total depth is estimated to be around 2000 m. The top (about 100 m thick) is made of detrital slab-like limestones, chiancarelle. The upper contact of Bari limestone is Altamura limestone, and the transition is often accompanied by a limestone breccia, sometimes the thickness of ten meters. Overall, it can be assessed that this variety of limestone deposited in a coast platform environment, and for a period in a lagoon environment, as shown by the presence of Ophtalmididae and Ostracoda.
- Mola limestone: formed in the same geologic age as the Bari limestone, it surfaces in the northern part of the chart, and is mainly constituted by a fine grain detrital sediment, with remains of Rudistae and Cisalveolina Fallax. The thickness of this formation is about 15 m.
- Altamura limestone: the period of formation is Senonian, so posterior to Bari and Mola limestones (Senonian includes the age spanning from Maastrichtian to Coniacian), this formation is distinguished from Bari limestone for an angular discrepancy, an abundance of different fossils – Ippurites and Radiolites – and the presence of reddish encrusting calcium carbonates. The sedimentation environment is the same as previous formations, and the thickness is, though difficult to assess precisely, inferior to that measured elsewhere, because of a lack of grey dolomites, which characterise the upper part of the formation.

The compendium of C.G. d'I. brings up the applications as construction materials in the segment dedicated to Applied Geology: here is mentioned the importance of chiancarelle as ornamental stone, employed in the covering of trulli and other monuments/rural buildings. On the other hand, the bottom of Altamura limestone series is more common in road building and rarely as ornamental stone. Figure 2.3 displays the succession of limestone formations in Itria Valley, including the names of ornamental stones extracted at different depths.

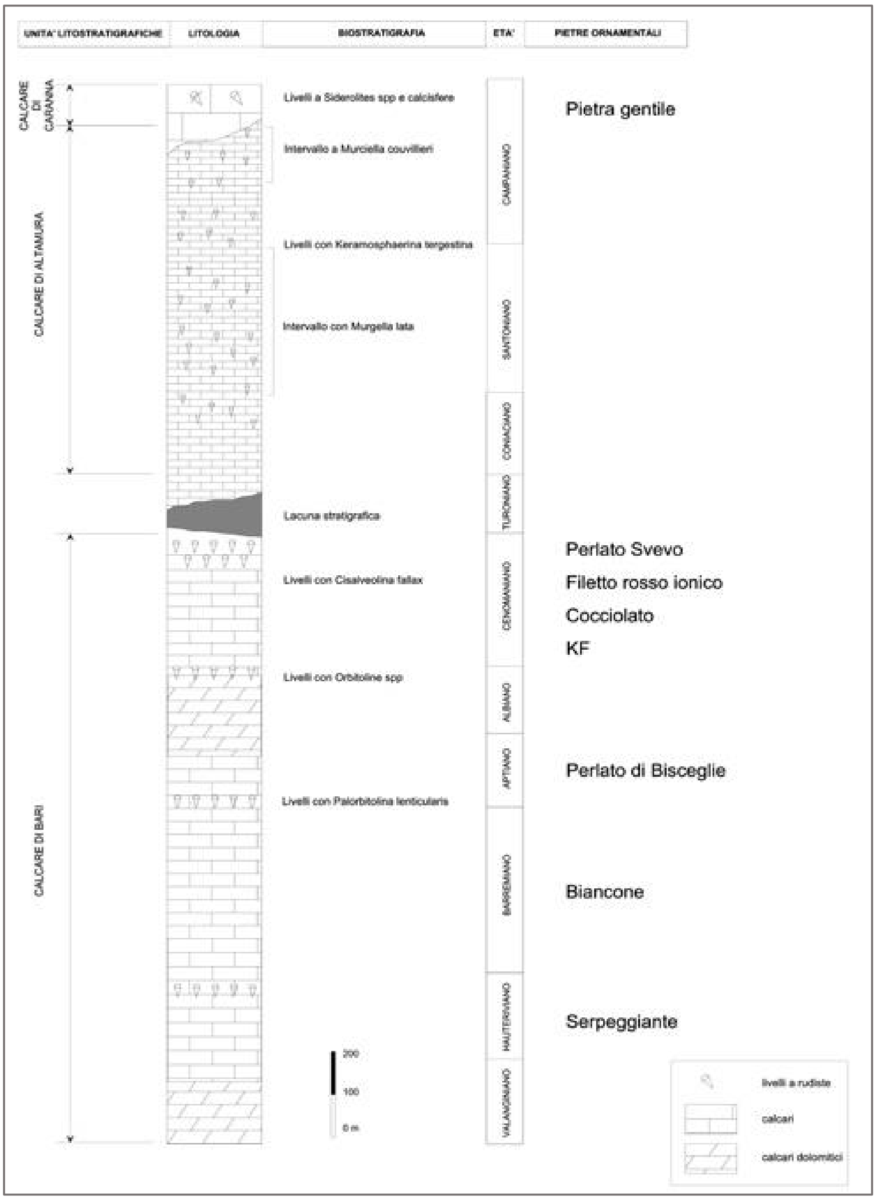

Figure 2.3: The alternance of limestones and dolomitic limestones in a stratigraphic log of Murgia dei Trulli, the periods of formation and the names of ornamental stones [Reina A. et al., 2005].

The figure shows how ornamental stones are almost all concentrated at the top of Bari limestone, especially in the first 200 m. Here can be found the most famous varieties of chiancarelle and ornamental stones, such as Perlato Svevo and Filetto Ionico; along with Cocciolato they will be used in the next chapter as a reference to confront the values obtained with lab tests, since it is extracted in the area of Fasano and Ostuni. The Altamura variety is transgressive to the Bari limestone, and a stratigraphic gap is often found, which origin is not better specified.

In the next page, figure 2.4 shows Chart 190 from C.G. d'I., which frames the study area of this work.

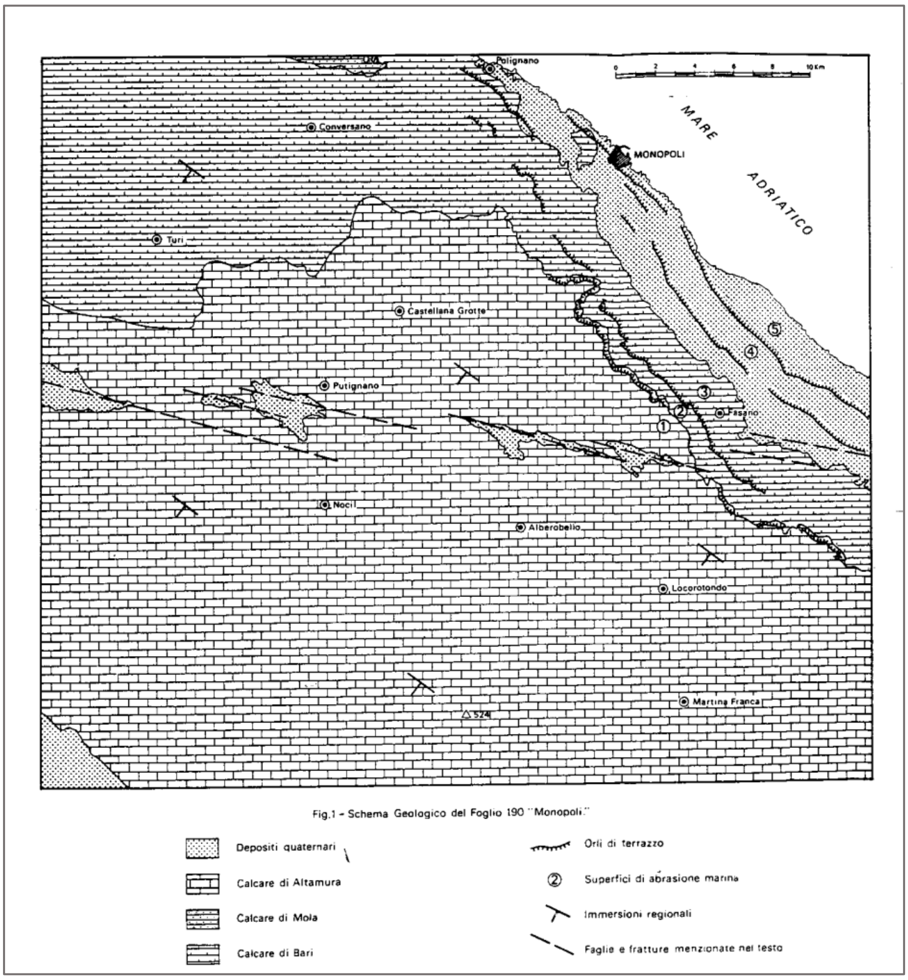

Figure 2.4: The grayscale version of Chart 190. This view clearly shows how the main area of interest (the municipalities of Noci, Martina Franca, Locorotondo, Alberobello) completely fall inside a zone in which Altamura limestone surfaces. It is also clear how this formation lays on the top of Bari limestone, which surfaces around Fasano (main site of Filetto Rosso Ionico extraction).

The geologic map indicates that in almost all the study area of Itria Valley the series that outcrops is that of Altamura, while Bari limestone does so in the northern region of the chart. Recent studies [Reina A., 2005] showed that chiancarelle are found in the Altamura limestone series, too: they are observed to constitute the base of the series, and are classified as strongly stratified stromatolitic limestones, sometimes affected by karstification.

This could explain how rural buildings like trulli may be built with chiancarelle even in areas where Bari limestone doesn’t outcrop.

2.3 THE ORNAMENTAL STONES OF THE BARI LIMESTONE SERIES

Palmisano Alberobello quarry market their product as ornamental stone and chiancarelle, allegedly extracting from Sannicandro level of the Bari limestone series [Maggiore M., 1978]; in the area of Itria Valley, layers of ornamental stones are found in this level, namely Filetto Rosso, Perlato Svevo and Cocciolato. Their geologic features are displayed in the following paragraphs.

2.3.1 FILETTO ROSSO

The extractive area of Ostuni and Fasano is characterised by the use of local stone, which constitute the material of construction of most historical monuments of the cities. Filetto Rosso quarries lie on a NW-SE line, by the Selva di Fasano, and the layers of extraction belong to the series of Bari limestones (dated Cenomanian-Turonian) [Lavenziana R., 2016].

Filetto Rosso is a prestigious variety of natural stone: it has good mechanical characteristics, such as consistency and compactness, a good degree of workability and a pleasing aesthetic look (as seen in figure 2.5).

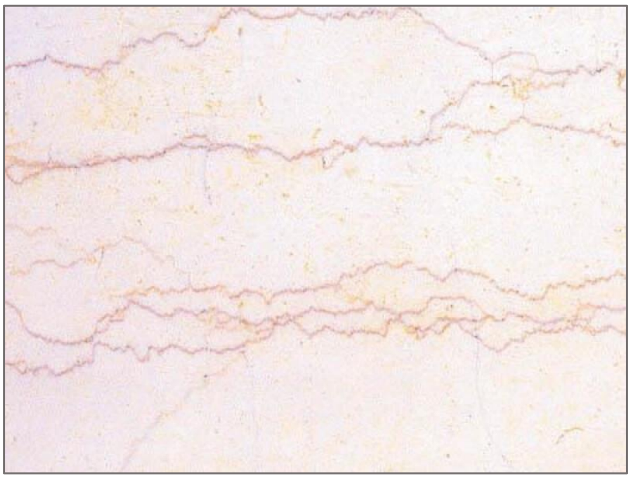

Figure 2.5: Filetto Rosso di Fasano, presenting the typical red veins, on a beige-havana background. This material was selected as a confrontation with the testing samples because of the location of extraction and the applications as ornamental stone [picture from Cotecchia V. et al., 1982].

Macroscopically, it is a micritic limestone, with medium-coarse grain, numerous sparitic formations and reddish stylolites. On a microscopic scale, it is classified as biopelmicrite with grain-sustained texture.

The rock is made out of bioclasts - mainly algae fragments and Oftalmididae and Miliolides – pellets and intraclasts [Maggiore M., 1983].

2.3.2 PERLATO SVEVO

Perlato Svevo is extracted from the basin of Trani, around Ruvo di Puglia. It stands out for its high yield both at quarrying and processing stage. Other than its pleasing chromatic appearance, with a soft background hue and a fossil decoration (figure 2.6), it shows very good mechanical characteristics: the flexural strength is higher than regional average [Cotecchia V., 1982].

Figure 2.6: The most common use of this material is interior decoration, even though the mechanical qualities mentioned before make it suitable for other applications [Cotecchia V., 1982].

This stone is a pseudo-brecciated limestone, with macrofossil fragments and yellowish micritic clasts, with more intense veins. Microscopically, it can be classified as biomicrosparite with grain-sustained texture. The stone is constituted by accumulations of Rudistae and rests of Echini in a micritic matrix or in a sparitic cement. The structure is intensely recrystallized [Maggiore M., 1983].

2.3.3 COCCIOLATO

Cocciolato (figure 2.7) has good workability and technological features and presents itself as a peculiar-looking ornamental stone. It is commonly employed as an interior material, but its qualities make it versatile and adapt for many purposes. The best way to show its ornamental potential is by polishing, but other techniques are employed too [Cotecchia V., 1982].

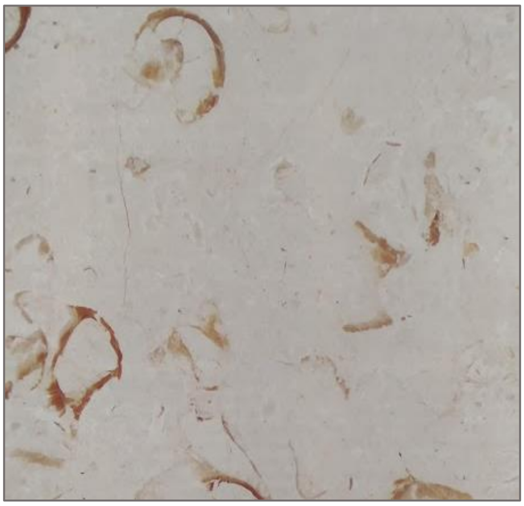

Figure 2.7: Cocciolato is a quite different material from the average ornamental stone product from Puglia, showing a light background tonality in which a good many fossils are set rather like casually placed gems; some of these fossils are quite large in diameter and size [Cotecchia M., 1982].

Cocciolato is a fine grain limestone, white or rosé, with macrofossils (Gasteropodes or Rudistae) and a dense network of irregular reddish stylolites. Microscopically, it is classified as an intrabiomicrite with grain-sustained texture. The stone, which has undergone a bland process of recrystallization, is made out of big macrofossils, such as Ostracoda, Oftalmididae, Algae and rarely Foraminifera, dipped in a micritic matrix. Sparite fills the shapes of primary voids inside the shells of Rudistae and Gasteropodes. Stylolites are often found, and are highlighted by reddish, thin clay films [Maggiore M., 1983].

2.4 THE ORNAMENTAL STONES OF THE ALTAMURA LIMESTONE SERIES

The material coming from the area of Noci and from Trullo Palmullo is of unknown origin; considering that trulli were usually built as a temporary residence, and had to be dismantled quickly, it is unlikely that the materials employed would be extracted in quarries, as other sources were available at much lower costs (see chapter 1.3). The stones from the Noci quarry could belong to either Bari limestone series or Altamura, the precise location of extraction is unknown. This is confirmed by studies performed during the restoration of “Chiesa Madre” of Noci and its belltower, which have shown how building materials of the entire church could have several possible sources.

Other materials employed in this work, such as those coming from Cava Storica Locorotondo and Monte del Duca, are of uncertain origin.

Altamura limestone is seldom used as ornamental stone [C.G. d'I., 1971], but there is a variety that is employed, and it will be examined in the coming paragraph.

2.4.1 PIETRA GENTILE

Pietra Gentile (figure 2.8) belongs to the series of Altamura limestone, but is found to outcrop in a formation named Caranna limestone, in the area around Ostuni, Caranna, Carovigno and Cisternino (see Chart 190 as reference). This variety of limestone is often quarried as building material, but its mechanical characteristics, which make it easy to process, leave some space for applications as ornamental stone too, although its high porosity makes it very susceptible to alterations caused by environmental factors [Laviano R., 2006].

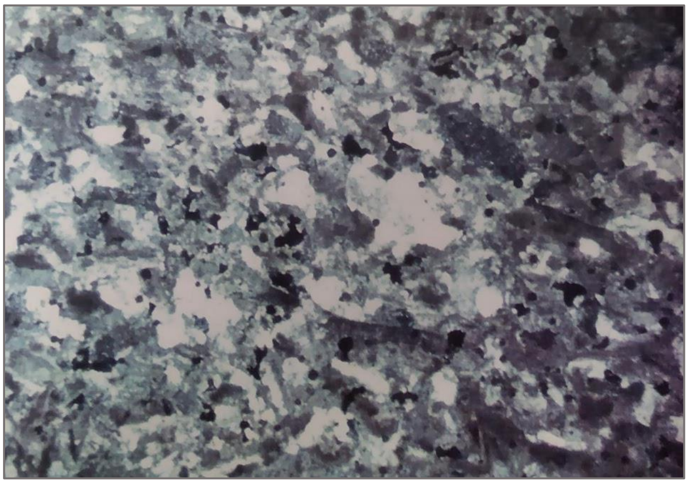

Figure 2.8: Caranna limestone as observed through microscope in thin section [Fiorucci A., 1992].

Pietra Gentile is a very fine calcarenite, coloured white and gypsum-like. The fossil content is not easy to discern because of the intense recrystallisation, except for shells of Rudistae and rare Miliolides. The recrystallisation indicates that the content of sparite is very high [Fiorucci A., 1992]. Given the very high content of $CaCO_3$, determined through XRD tests [Fiorucci A., 1992], this material can be classified as a pure limestone.

3. MECHANICAL PROPERTIES FROM LITERATURE

The widespread use of natural stone as ornamental or building material, depending on the quality (both aesthetic and practical) of it, and the intense activity of quarrying in Puglia, makes for a large quantity of works and studies, and provides a solid reference to understand the expected behaviour of natural stones. This chapter is going to cover some relevant articles and publications, which will constitute a foundation to determine where the results of laboratory testing falls into, thus framing these materials and classifying them on the base of their physical and mechanical features.

Also, some aspects related to a link between geologic traits and mechanical response are going to be investigated, using Filetto Rosso di Fasano, Perlato Svevo and Cocciolato from Bari limestone series and Pietra Gentile from Altamura limestone series as reference.

3.1 MECHANICAL CHARACTERISTICS OF BARI LIMESTONES

The limestones of Murge present themselves as micritic or granular, often laminated, and with organic traces of Rudists, alternated with dolomitic limestones formed during Cretaceous [Ricchetti G., 1975].

The eligibility as ornamental stone derives from an observation of singenetic and diagenetic treats, which influence technical characteristics. It has been observed through XRD that chemical and mineralogic composition is almost unchanged in several stones, but small variations in chemical composition can still cause large gaps in mechanical response [Maggiore M., 1983]. This point will be discussed and explored further, with the use of thin-section observations, to analyse the chemical composition of stones and their mineralogy, as well as correlation diagrams, to prove whether there is a link between petrographic factors and some mechanical properties, such as flexural strength and UPV. Other parameters, like density (both real and apparent) and water absorption, can be observed to give a more complete frame and characterization of these stones, and form a reference to confront specimens (tables 3.1 and 3.2):

Table 3.1: It has been observed that W.A. values between 0.15% and 2.6% are typical of these kinds of poorly absorbing stones, and justify their hardness [Maggiore M., 1983].

Filetto Rosso				
Real density (kg/m^3)	Apparent density (kg/m^3)	Porosity ρ (%)	Compactness (-)	Water absorption W.A. (%)
2710	2650	2.3	0.977	0.62

Perlato Svevo				
Real density (kg/m^3)	Apparent density (kg/m^3)	Porosity ρ (%)	Compactness (-)	Water absorption W.A. (%)
2700	2660	1.5	0.985	0.37

Cocciolato				
Real density (kg/m^3)	Apparent density (kg/m^3)	Porosity ρ (%)	Compactness (-)	Water absorption W.A. (%)
2700	2620	3.0	0.970	0.83

Table 3.2: The values of compressive strength and static elastic modulus, as well as that of flexural strength [Cotecchia V., 1982].

Filetto Rosso		
Uniaxial compressive strength σ_A (MPa)	Flexural strength σ_f (MPa)	Elastic modulus E (MPa)
136.31	17.16	31381

Perlato Svevo		
Uniaxial compressive strength σ_A (MPa)	Flexural strength σ_f (MPa)	Elastic modulus E (MPa)
135.33	16.67	26477

Cocciolato		
Uniaxial compressive strength σ_A (MPa)	Flexural strength σ_f (MPa)	Elastic modulus E (MPa)
131.40	11.77	28930

About the values in tables 3.1 and 3.2, it was observed that in the work of Maggiore et al. the number of samples on which testing was performed was very low, and the dispersion of results is too high to consider those values reliable. The only values considered are those that couldn't be found elsewhere, specifically those contained in table 3.1. On a side note, these values are the results of testing procedures that are not explained in depth by the authors, and should be referred to only as background framework for the outcome of laboratory tests.

Additionally, what is stated in table 3.1 about water absorption and its link to mechanical properties needs to be addressed: values higher than 2% are commonly considered as high, as opposed to what Maggiore states. It is possible that this was to consider that, on average, such stones all have quite high water absorption factors and that, related to that average, such values should be considered low.

It was determined [Maggiore M., 1983] that a direct comparison between physical characteristics and compression strength is difficult to observe, given the variability of natural stones samples (the unpredictability in the orientation of discontinuities compared with the orientations of loads plays a determining role). It still was possible however to find a reverse proportionality between compression strength and water absorption. In chapter 6, other variants are considered, to investigate whether trends exist for other configurations of mechanical properties.

3.2 MECHANICAL CHARACTERISTICS OF ALTAMURA LIMESTONE

During the works for S.P. 48 Taranto – Statte, a few km south-west of Martina Franca, Altamura limestone was found and studied [Carroccia G., 2012]. As for Pietra Gentile, direct literature data could not be found, but it is indicated to be comparable, from a mechanical point of view, to a variety of Gravina limestone, named Carparo Bianco. The information gathered is displayed in the following tables 3.3 and 3.4.

Table 3.3: The main technical properties of Altamura limestone, as reported from the analyses conducted for the works of S.P. 48 [Carroccia G., 2012].

Altamura limestone		
Uniaxial compressive strength σ_A (kg/cm^2)	Real density (kg/m^3)	Porosity ρ (%)
37.36	2540	4

Table 3.4: Carparo Bianco is a material often used in the building of houses and the front of churches, and its properties can be compared to those of Pietra Gentile [Cherubini C., 2007].

Carparo Bianco			
Apparent density (kg/m^3)	Real density (kg/m^3)	Water absorption W.A. (%)	Porosity ρ (%)
1890	2750	15.4	11.3

Although data comes from different sources and the same properties are not covered for all the materials, a comparison between the limestones from Bari and Altamura series can highlight some interesting differences:

- All the varieties of limestones fall into a relatively wide range of density: if Carparo Bianco, which has a very high value of porosity (11.3%) is not considered, the minimum is 2540 kg/m^3 (samples of Altamura limestone from S.P. 48 works) and the maximum is 2710 kg/m^3 (Filetto Rosso); considering Carparo Bianco however shows that natural stone can present relevant variations.
- From these considerations, Altamura limestone is found to perform significantly worse than Bari limestone; such a gap in performances could derive from a number of factors, but is not surprising: notes from C.G. d'I. suggest that Altamura limestone is not a variety exploited because of its high mechanical properties, but mostly as inert in concrete.

4. ON-SITE TESTS

Before the beginning of this work of thesis, ultrasonic pulse velocity measures were performed on churches and buildings of Itria Valley that were considered significant. The scope of the investigation of was to monitor, through non-invasive tests, the properties of stone material coming from buildings of cultural interest, and to correlate the measures with observations regarding degradation and weathering.

The buildings under investigations are in Noci, Locorotondo and Martina Franca, and the results of measurements are displayed in table 4.1.

Table 4.1: The locations and values of UPV measurements. Measurements were collected with exponential transducer with a natural frequency of 33 kHz.

City	Building	Location	Average UPV (m/s)
Noci	S. Chiara church	FRONT	3640
		PORTAL	2240
	Chiesa Madre	FRONT	2450
		PORTAL	2290
		BELLTOWER	3200
Locorotondo	La Greca church	EASTERN WALL	2200
	S. Giorgio church	FRONT	1550
		LATERAL EXTERNAL WALL	2100
Martina Franca	Trullo Palmullo	BASE	2520
		CONE	1990
	S. Martino basilica	EASTERN FRONT	1930

The values of UPV present a maximum of 3640 m/s and a minimum of 1930 m/s. This is possibly due to the different sources of stones: as exposed in chapter 3, the technological features of natural stone can vary depending on geologic origin.

The following figures 4.1 to 4.4 were taken during the measurement campaign, and show the on-site procedures for the acquisition of UPV data.


Figures 4.1 and 4.2: Measurements on the portals of “Chiesa Madre” and S. Chiara of Noci.


Figures 4.3 and 4.4: Measures on the lateral external wall of S. Giorgio church in Locorotondo and the cone of trullo Palmullo in Martina Franca.

The UPV measurements can give some information about the mechanical behaviour of the material: a stiffer and less porous stone shows higher values of UPV, just as is the case with any mechanical wave. The dynamic elastic modulus is directly correlated to UPV by means of equation 4.1, valid in the case of unconfined or limited medium [Santamarina J.C. et al., 2001]:

$$UPV = \sqrt{\frac{E}{\rho}} \tag{4.1}$$

Where:

- UPV is the ultrasonic pulse inside stone, in m/s
- E is the dynamic Young modulus, un Pa
- ρ is the density of the material, in kg/m^3

While it is true that the density of the stone is not easily available on site, and would require sampling to be assessed with precision, this formula is expressly formulated for sampled material, and measures can be conducted knowing precisely all the parameters needed. At that point, further correlations can be employed to determine the static elastic modulus, like the one in equation 4.2 [Rzhevsky Y. et al., 1971]:

$$E_S = \frac{E_D - 0.97}{8.30} \tag{4.2}$$

Which is often used in the assessment of the static Young modulus during preliminary phases of projecting.

The case of an on-site investigation is more complex than this though, since the medium cannot be considered limited. A relation still exists (equation 4.3), but other parameters are needed [Santamarina J.C., ,2001]:

$$UPV = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad (4.3)$$

Where:

- M is the dynamic elastic modulus of the medium in confined conditions, in Pa
- ν is the Poisson modulus of the material, dimensionless

The formulas to calculate the dynamic elastic modulus of the medium work in the case of p-waves (direct waves of compression), and not with surface waves, which are those detected in an indirect method survey. There is a link between compression and superficial waves though [Bellopede R., 2006], as shown in equation 4.4:

$$UPV_p = 1.5 \cdot UPV_s \qquad (4.4)$$

This way, the dynamic Young modulus can be assessed from on-site measures, as in table 4.2. The other parameters needed to perform the calculations, density and Poisson modulus, can be estimated for a first assessment; in this case, considering the range of density for limestones is about 2400 to 2700 kg/m^3, as it was found in chapter 3. For compact limestones from both Bari and Altamura series this value is close to the upper limit.

Table 4.2: a basic knowledge of the stone characteristics allows to estimate the Young modulus directly on-site, using equation 4.2. In this case, ν=0.35 and ρ=2700 kg/m^3.

City	Building	Location	Corrected UPV (m/s)	Dynamic E (GPa)
Noci	S. Chiara church	FRONT	5460	50.2
		PORTAL	3360	19.0
	Chiesa Madre	FRONT	3675	22.7
		PORTAL	3435	19.8
		BELLTOWER	4800	38.8
Locorotondo	La Greca church	EASTERN WALL	3300	18.3
	S. Giorgio church	FRONT	2325	9.1
		LATERAL EXTERNAL WALL	3150	16.7
Martina Franca	Trullo Palmullo	BASE	3780	24.0
		CONE	2985	15.0
	S. Martino basilica	EASTERN FRONT	2895	14.1

5. MATERIALS STUDIED AND LABORATORY TESTS

This section is dedicated to the exposition of all procedures and tests executed in laboratory environment, starting with the preparation of samples from material delivered from the sources seen in chapter 1.

5.1 STONE SPECIMENS

5.1.1 MATERIAL FOR SCREENING TESTS

A first shipment of material, partly recovered on site, but which revealed inadequate for proper cutting: European normative specifies, for each test, the requisites of dimensions and shape for the specimens, and the first batch of material couldn’t suffice, since the volume of stone wasn’t enough to get a numerous population and have a statistical description of results. This first group includes specimens from:

- Palmisano Alberobello quarry, taken on site (shown in figure 5.1)
- Calella Locorotondo quarry, taken on site (figure 5.2)
- Historic Locorotondo quarry (figure 5.3)
- Monte del Duca quarry and embankment (figure 5.4 and 5.5)
- Trullo Palmullo, Martina Franca (figure 5.6)

The first group of stone material did not undergo all the tests performed on the second group: the test of flexural strength was not performed, since the prerequisites of the norms are the condition to compare the properties of different specimens, and the specimens were too much different, even after cutting, from the indications about shape and dimension. These samples were then used as a preliminary source of investigation, to proceed with systematic testing with the second group.

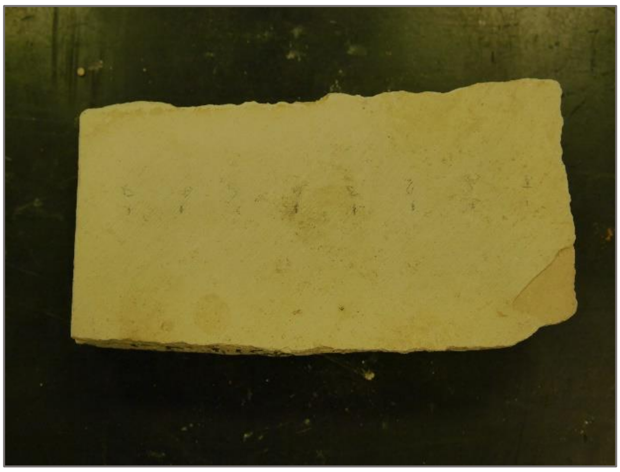

Figure 5.1: The stone block from Palmisano Alberobello quarry. Dimensions: approx. 25 x 10 x 5 cm.

Figure 5.2: A stone chunk taken from Calella Locorotondo quarry. Dimensions: approx. 15 x 10 x 5 cm.

Figure 5.3: The stone block from the historic Locorotondo quarry. Dimensions: approx. 25 x 15 x 15 cm.

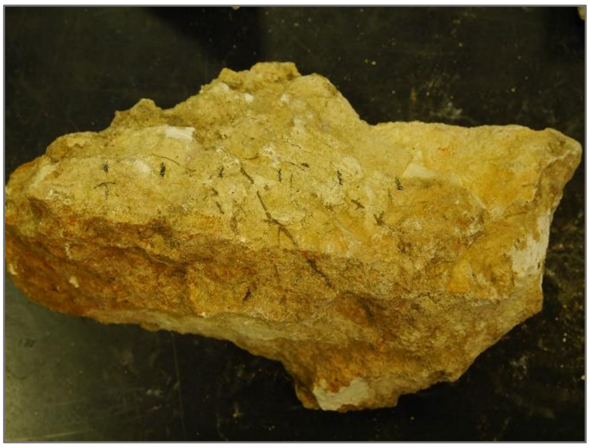

Figure 5.4: A stone chunk from the historic quarry of Monte del Duca, Martina Franca. Dimensions approx. 30 x 15 x 15 cm.

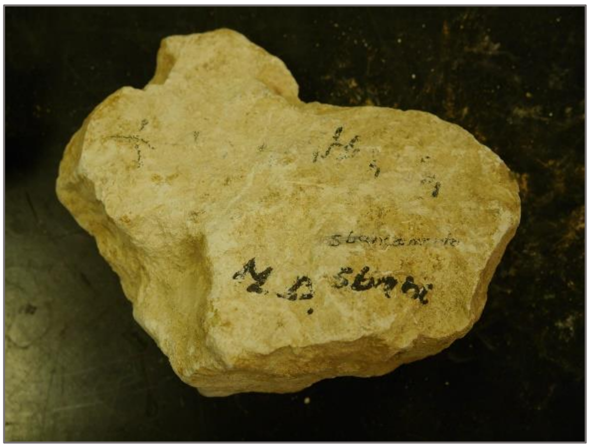

Figure 5.5: The rock chunk from the embankment near Monte del Duca historic quarry, Martina Franca. Dimensions: approx. 20 x 20 x 10 cm.

5.1.2 MATERIAL FOR SYSTEMATIC TESTS

The second group of material was collected to improve statistical representativity and in conformity with the directions of the normative, giving priority to the flexural strength test. When possible, as is the case of Palmisano Alberobello quarry, stone samples were delivered already cut, and in consistent number; in the other cases, stones were sent in the form of blocks, which needed to be cut. The second group includes material coming from:

- Palmisano Alberobello quarry (figure 5.7)
- Quarry of Noci (figure 5.10)
- Belltower of Noci (figure 5.11)
- Trullo Palmullo, Martina Franca (figure 5.12)

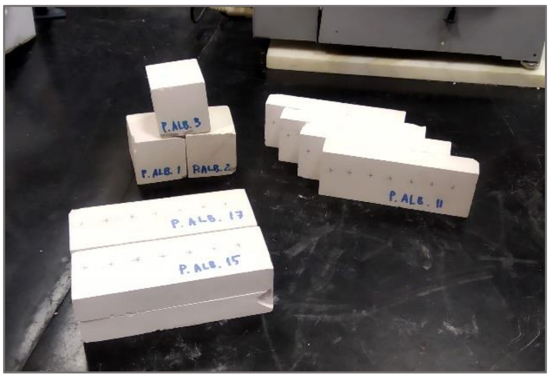

Figure 5.7: The materials from the Palmisano Alberobello quarry. The shipment consists of 10 cubes (5 x 5 x 5 cm) and 20 bars (15 x 5 x 3 cm).

The rest of the material was delivered in the form of blocks and chunks, which were cut as shown in the following figures 5.8 and 5.9:

Figure 5.8: The cut of stone from Trullo Palmullo, to get bars.

Figure 5.9: The result of cutting the stone chunk from Trullo Palmullo.

The final results after cutting are displayed in figures 5.10 to 5.12:

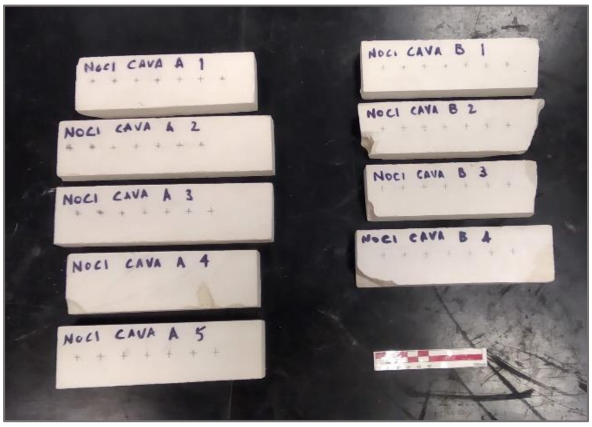

Figure 5.10: Two blocks came from the quarry of Noci, so the specimens were named A and B.

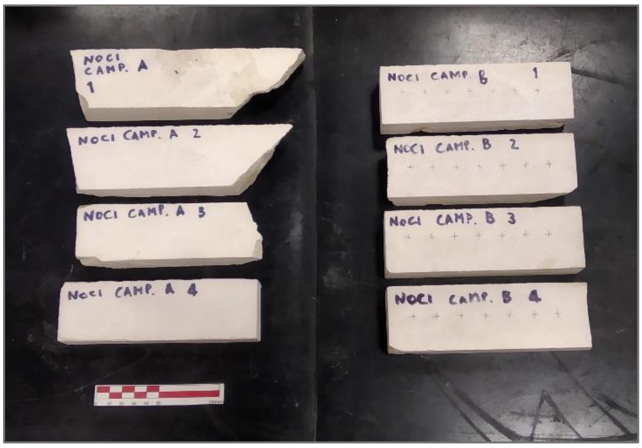

Figure 5.11: Two blocks came from the belltower of “Chiesa Madre” of Noci. The samples named A are from a chunk that was allegedly in place before the restoration of 2019. The ones named B were sawn out of a block of debris from the restoration.

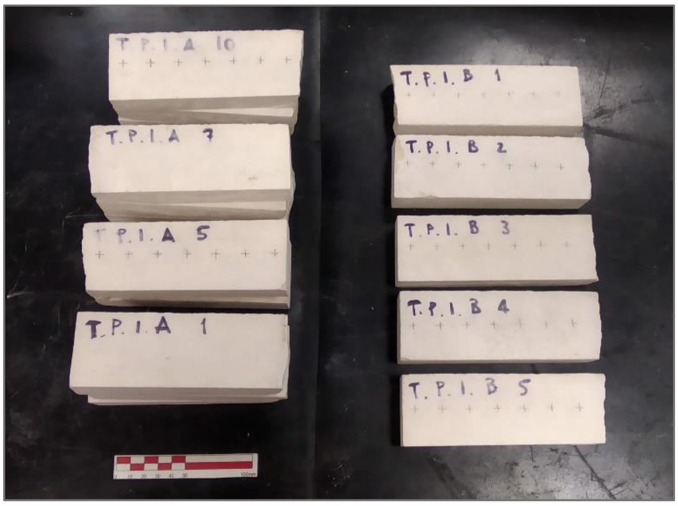

Figure 5.12: The chianca from Trullo Palmullo showed signs of intense weathering on one side (figure 5.13), and was massive enough to give 12 specimens from side A, and 5 from side B.

Figure 5.13: The chianca from Trullo Palmullo. Side A shows evident signs of weathering and possibly lichen attack, while side B doesn’t. This is due to the way the stone was set up in the cone of the trullo.

5.2 MACROSCOPIC ANALYSIS OF THE STONE SAMPLES

Through simple visual analysis, it is already possible to recognise some distinguishing traits in the stone specimens (figure 5.14):

- Palmisano Alberobello quarry: specimens present evident fossil rests, which could give indications during the microscope observation (figure 5.14.c).
- Noci quarry: the chunks coming from Noci, and some sawn specimens, show sparse black spotting; those could possibly be Mn oxide traces, although the fact that they can be easily scratched from the stone may suggest they are in fact traces of lichen or mold attack (figure 5.14.a). An observation of the spotting was performed through scanning-electron-microscope (SEM), but it didn't give satisfying results to confirm either supposition. The material showed a very brittle behaviour in the phase of sawing, so much so that 2 specimens were damaged and had to be discarded (figure 5.14.b).
- Trullo Palmullo: the stone is intensely weathered on its side A, as shown in figure 5.13: a lichen formation is recognisable, and the black spots could be mold. It was observed, through experience with these materials, that the formation of a weathered layer on the surface of the stone could enhance the properties of it. The laboratory tests of water absorption and open porosity could help proving this. The sawn specimens also show what could be interpreted as signs of stratification.

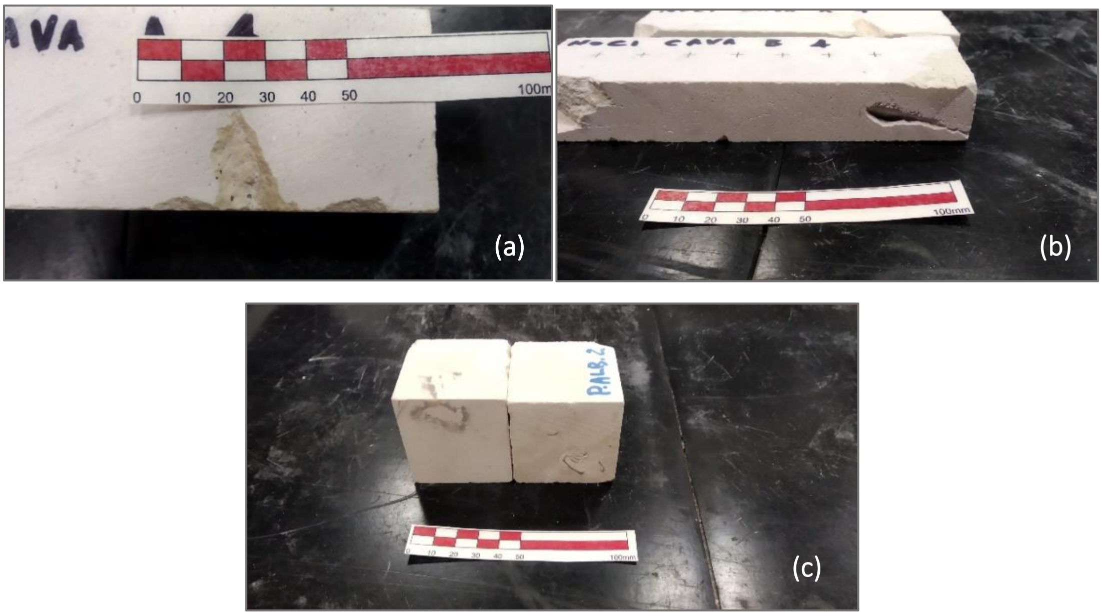

Figure 5.14: The visibly recognisable traits of the samples.

5.3 ULTRASONIC PULSE VELOCITY (UPV) MEASURES

UPV measures were conducted on all the specimens produced and delivered, except for the cubic elements from Palmisano Alberobello quarry. The reference for the testing procedure and the requisites of specimens, in terms of shape and dimension, is the European standard EN 14579. The indications include:

- The frequency of transducers should fall between 20 and 250 kHz. The ones used for these tests had a natural frequency of 33 kHz.
- Table B.1 of EN 14579, about the influence of specimen dimensions on impulses transmission indicates, for sound speed propagations of about 3500 m/s and a natural frequency of transducers of 54 kHz, the smallest admissible lateral dimension of the test specimen to be 65 mm. This could not be respected, as the bars have lateral dimension of 50 mm.

The tests were conducted using the indirect transmission method, in which the transducers shall be placed at growing distances, along a line on the surface of the specimen. This method was used in order to confront these measures with those collected on site (chapter 4). The transmission times recorded are then plotted on a graph showing their relation to the distances separating the transducers, like what is shown in figure 5.15 [EN 14579]:

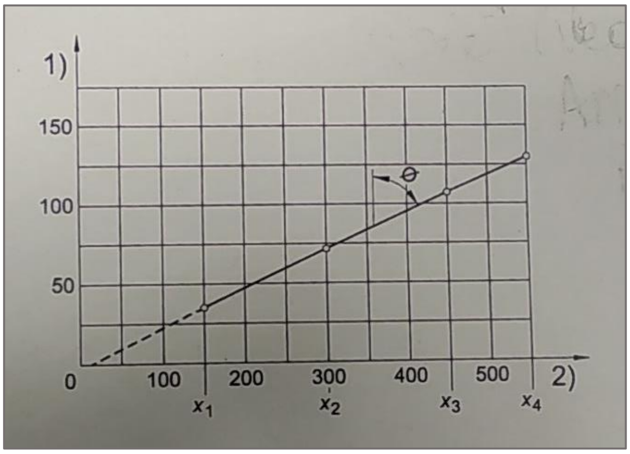

Figure 5.14: Figure A.1 from EN 14579 shows the graph for the reconstruction of the sound propagation speed of the material in the indirect testing method. The slope of the linear regression is the reciprocal of the medium UPV.

The apparatus used to carry out the tests is a Proceq Pundit model PL200, with exponential transducers with a natural frequency of 33 kHz (figure 5.15). Pundit PL200 includes a working station, to visualise and monitor the quality of the acquisition of data and connection wires to attach to the transducers.

Figure 5.15: The apparatus for the acquisition of UPV measures includes the PL200 working station, connection wires and exponential transducers (33 kHz).

The procedure of the test (figure 5.16), according to the prescriptions of the norm, involves:

- Marking the specimen: this allows to precisely position the transducers. Markings were drawn with a pencil with a step of 2 cm, with a total of 7 marks per specimen. The first mark is the one dedicated to the transmitting transducer, while the receiver moves on the remaining 6. This means that the graph (see figure 5.14) consists of a linear interpolation of 6 points.
- Acquisition of UPV measures: the PL200 working station makes this process automatic, including the interpolation between values. The only manual operation consists of giving the input to register the value of first arrival time, recognisable on the working station screen, as it corresponds to the beginning of first wavelet. To give a precise input, reducing the on-screen visualization of noise, the values of voltage and gain can be adjusted.

Figure 5.16: The procedure of UPV measure acquisition.

5.4 WATER ABSORPTION AT ATMOSPHERIC PRESSURE TESTS

Water absorption tests were carried out on all the specimens, excluded the 20 bars from Palmisano Alberobello quarry. In their place, the cubes were used. The measures have been executed according to the European norm EN 13755. Water absorption at atmospheric pressure gives an information about the attitude of a stone sample to absorb water, and a measure of its porosity in terms of weight percentage. The indications of the norm specify the procedure of the test, for which the following symbology will be useful:

- m_d is the mass of the dry specimen, in grams.
- m_s is the mass of the saturated specimen (after immersion in water until constant mass is reached), in grams.
- WA is the water absorption at atmospheric pressure, expressed as a percentage.

The specimens are required to be have an apparent volume of at least 60 ml and have a surface/volume ratio between 0.08 and 0.20 mm^{-1} [EN 13755]. That prescription is respected with cubic and bar specimens, as in both cases the ratio is equal to 0.12 mm^{-1}.

The apparatus needed to perform the tests consists of:

- A ventilated oven capable to maintain a temperature of (70 $\pm$ 5) °C.
- A desiccator (figure 5.17), to cool the specimens until room temperature (20$\pm$ 5) °C is attained.
- A tank with flat base, to immerse the specimens in (20 $\pm$ 10) °C.
- A weighing instrument with an accuracy of 0.01 g (figure 5.18).

Figure 5.17: The desiccator, to store the specimens and keep them dry while reaching room temperature.

Figure 5.18: The weight scale with accuracy of 0.01 g.

To perform the test, the first step is drying the specimens to constant mass at a temperature of 70 °C. Constant mass is reached when the difference between two successive weighings at 24 hours interval is not greater than 0.1% of the mass of the specimen [EN 13755]. Until they reach room temperature, the specimens should be kept in a desiccator. The last measure of weight is m_d.

After the phase of drying, specimens are immersed in 20 °C water, free of impurity such as dissolved air (which could affect density). After 48 hours the specimens are quickly wiped and weighted within one minute, to be then immersed again for 24 more hours. The procedure is to be repeated until constant weight is attained. The result of the last measure of weight is m_s, the mass of the saturated specimen.

The coefficient of water absorption, WA, is calculated with the following expression (equation 5.1):

$$WA = \frac{m_s - m_d}{m_d} \cdot 100 \qquad (5.1)$$

The norm prescribes that results are to be expressed as a percentage to the nearest 0.1%.

5.5 OPEN POROSITY TESTS

As for water absorption at atmospheric pressure tests, open porosity measures were conducted on all the specimens, except for the bars from Palmisano Alberobello quarry. For this procedure, the normative reference is the European standard EN 1936. The meaning of an open porosity measure is similar to that of water absorption: both of them are an esteem of the attitude of the material towards absorbing water, and both are expressed as percentages; the difference between them is that while WA is a measure of porosity in weight percentage, open porosity is a measure in volume percentage. The norm specifies the procedures to follow, and to express the results the following symbology is adopted:

- m_d is the mass of the dry specimen, measured in grams.
- m_h is the mass of the saturated specimen measured by means of a hydrostatic balance, measured in grams.
- m_s is the mass of the saturated specimen, measured in grams.
- pO is the open porosity, measured as a percentage.

The requirements to the specimens, in terms of shape, volume and surface/volume ratio are the same as in water absorption tests (see chapter 5.3), and as in the case of WA tests, specimens satisfy those conditions, having a surface/volume ratio of 0.12 mm^{-1} and volume at least 60 ml.

The apparatus needed to perform the testing procedure consists of [EN 1936]:

- A ventilated oven capable to maintain a temperature of (70 ± 5) °C.
- A desiccator, to cool the specimens until they reach room temperature.
- An evacuation vessel which can maintain a pressure of (2.0 ± 0.7) kPa and allow gradual immersion of the contained specimens (through a Venturi pump) (figure 5.19).
- A weighing instrument which has an accuracy of at least 0.01% of the mass to be weighted, also capable of weighing the specimen in water (hydrostatic balance of figure 5.20).

Figure 5.19: The evacuation vessel in action, maintaining the void inside the glass bell.

Figure 5.20: The hydrostatic balance: the specimen is put on a support immersed in water, and the weighting scale measures.

The first step to perform the test is to dry the specimens until they reach constant mass, at a temperature of 70 °C. Constant mass is reached at the same conditions specified in chapter 5.3. To allow the specimens to cool down until they reach room temperature, while assuring they stay dry, a desiccator is used. The last recorded mass of the specimen, when constant mass is attained, is m_d.

The following passage requires to store the specimens in an evacuating vessel, and to lower the pressure to 2 kPa for a duration of 2 hours. After that, water is gradually added to the vessel, at a pace such that the specimens are completely immersed in no less than 15 minutes. The pressure is then brought back to atmospheric level, by shutting off the pumping system. After 24 hours the specimens are weighted in the hydrostatic balance first, then quickly wiped and weighted again on the weight scale. The measures taken are respectively m_h and m_s.

The coefficient of open porosity, pO, is calculated with the following expression (equation 5.2):

$$pO = \frac{m_s - m_d}{m_s - m_h} \cdot 100 \tag{5.2}$$

The value of pO has to be expressed as a percentage to the closest 0.1%.

5.6 FLEXURAL STRENGTH UNDER CONCENTRATED LOAD TEST

Flexural strength testing in a destructive procedure, so it was the last one performed on the specimens. The samples that went through that test were all the bar specimens. The measures have been executed according to the European standard EN 12372. To interpret the results of the tests the following nomenclature is proposed by the norm:

- R_{tf} is the flexural strength of the specimen, in MPa.
- F is the breaking load, in N.
- a is the load rate, indicated in MPa/s.
- V is the loading rate, in N/s.
- The dimensions of the specimen and of the testing apparatus are indicated as:
  - l: distance between supporting rollers, in mm.
  - b: width of the specimen, in mm.
  - h: thickness of the specimen, in mm.
  - L: total length of the specimen, in mm.

The specimens are required to have the surface in contact with the rollers either sawn, honed or polished; the samples used for the test were sawn. As for the dimensions of the specimens:

- The thickness should be between 25 and 100 mm; in this case, h is 30 mm.
- The width should be between 50 mm and three times the thickness of the specimen, and in no case should b < h; in this case b is 50 mm.
- The total length of the specimen should be equal to six times the thickness; in this case, L is 150 mm, so the indication is not respected thoroughly, yet the dimensions are still acceptable.

The apparatus to perform the testing procedure consists of [EN 12372]:

- A linear measuring device, with accuracy of at least 0.05 mm (digital gauge).
- A ventilated oven, capable of maintaining a temperature of (70$\pm$ 5) °C.
- A balance capable of measuring the specimen to an accuracy of at least 0.1% of its weight.
- A testing machine of appropriate force, in accordance to EN 12390 and calibrated according to the standards of EN 12372.
- A device for applying loads on the specimen by a centre-point load (figure 5.21.a). It consists of two rollers (supporting rollers) and one upper roller (applying the load), centred exactly in the middle between the supporting rollers (figure 5.21.b).
- A room which can be maintained at a temperature of (20$\pm$ 5) °C.

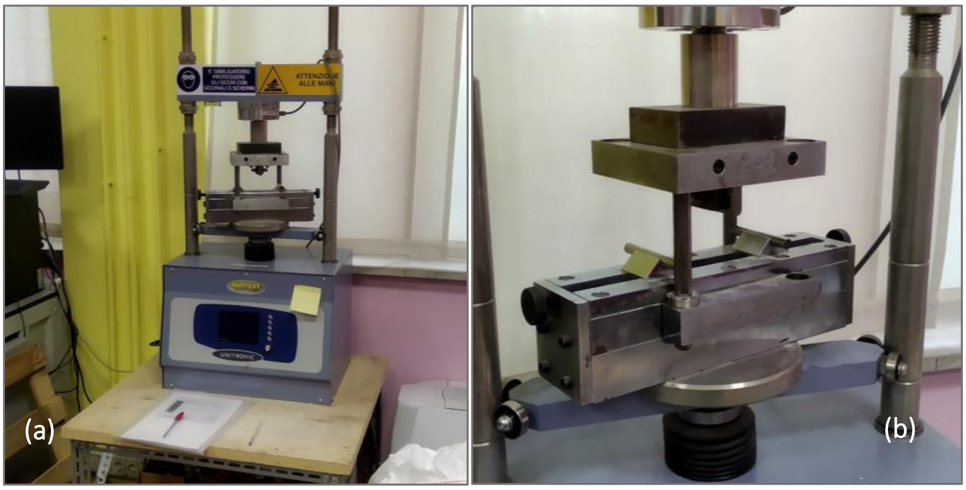

Figure 5.21: The machine to load the specimens, (a). On the right (b) a detail of the loading cell and the rollers.

To perform the test, the specimens must be dried until they reach constant mass (see 5.3), and then cooled to the room temperature of (20$\pm$ 5) °C. After this, the following procedure should be performed within the following 24 hours.

The specimens then have to be quickly wiped, to remove any loose grits from the surface in contact with the rollers. The loading roller is centred in the middle of the specimen, and the loading starts. The load is incremented uniformly at a rate of (0.25$\pm$ 0.05) MPa/s, until the breakage occurs. The breaking load is rounded to the nearest 10 N; if the loading rate is needed in N/s, the following expression (equation 5.3) can be used [EN 12372]:

$$V = \frac{2abh^2}{3l} \tag{5.3}$$

The results of the test are expressed by calculating the flexural strength R_{tf}, through equation 5.4:

$$R_{tf} = \frac{3Fl}{2bh^2} \tag{5.4}$$

The result has to be expressed in MPa, to the nearest 0.1 MPa, and if the fracture occurs more than 15% of the distance of the rollers (l) from the middle of the specimen and/or flaws (fissures or veins) are present, it should be reported.

5.7 ACCELERATED AGEING

To model the behaviour of a possible on-site variant of the material examined with the previously described tests, and so to confront the technological properties of the stone samples before and after weathering, two different procedures of accelerated ageing were carried out. This however was only possible to perform on 10 bar specimens, coming from Palmisano Alberobello quarry. After the conditioning, tests of UPV and flexural strength are performed on the specimens, following the procedures described respectively in chapter 5.1 and 5.4.

5.7.1 THERMAL SHOCK

The specimens selected to perform thermal shock were 5 bars from the Palmisano Alberobello quarry group, and were coded P. ALB. 24 to P. ALB. 28. The procedure followed and the requisites of the stone samples are indicated in the European norm EN 14066. The potential strength loss and changes in other characteristics are determined following the procedures prescribed in EN 12372 (flexural strength) and EN 14579 (UPV measures).

The apparatus needed to perform thermal shock is:

- A ventilated oven capable of maintaining a temperature of (70$\pm$ 5) °C.
- A tank with flat base.
- A weighing instrument with an accuracy of at least 0.01% of the mass to be weighed.

After drying the specimens in a ventilated oven at 40 °C for a week, the specimens are let to cool down until reaching room temperature of (20$\pm$ 5) °C. At this point the process of cycling begins; the specimens are subjected to changes of temperature according to the following procedure: (18$\pm$ 1) hours in the ventilated oven at a temperature of 70 °C, immediately followed by (6$\pm$ 0.5) hours completely submerged in 20 °C water [EN 14066]. Enough room must be left between the samples, to allow the action of sudden temperature change not to be influenced by the proximity of a near specimen. The procedure described constitutes one cycle.

After 20 cycles the specimens are dried to constant mass in a ventilated oven at 70 °C. At this point further testing is performed, and all the variations are monitored.

5.7.2 THERMAL AND MOISTURE CYCLES

The procedure followed to perform thermal and moisture cycles is not completely in accordance with what is prescribed by the European reference standard, EN 16306, however the majority of the precautions taken come directly from it. A source to plan the execution of the test is a work performed on limestones from Sardegna, to simulate Mediterranean climactic conditions in a faithful way and model the ageing of the material [Sitzia F. et al., 2020]. Testing was performed on 5 bar specimens from P. ALB. group. As for the samples of thermal shock, tests of UPV and flexural strength were performed, following the indications of chapters 5.1 and 5.4.

The apparatus needed is the same described by EN 16306 for bowing evaluation, and consists of:

- A non-corrosive bath of sufficient capacity to hold the required number of samples. The samples must receive constant moisture from one side, and be exposed to cyclic heating on the other (figure 5.22.a).
- A 5 mm filter cloth, made of either polyester or PTFE, to maintain a constant level of moisture and a stable support for the specimens.
- Heating panels of sufficient size and number to provide a constant and uniform heat flow, heating a black reference plate from 20 °C to 80 °C at a rate of 30 °C per minute; in this case, an infrared (IR) lamp (figure 5.22.b).
- A black reference plate, according to EN ISO 4892 – 1:2000, to establish the maximum temperature of 80 °C. The plate has to be connected by a thermocouple to a high stability temperature and process controller.
- An infrared thermometer to measure the surface temperature of the specimens.
- A ventilated oven capable of maintaining a temperature of (70$\pm$ 5) °C.

The temperature and process controller employed is a programmable thermoregulator, TM-95 from Thermosystems s.r.l., and is set to perform heating cycles of 12 hours, with the steps of table 5.1 and as shown in the graph of figure 5.23.

Table 5.1: The steps used to program the heating cycles.

Step	Duration (hours and minutes)	Temperature (°C)
1	00:15	30
2	00:45	50
3	01:00	70
4	01:00	80
5	00:30	80
6	02:30	20

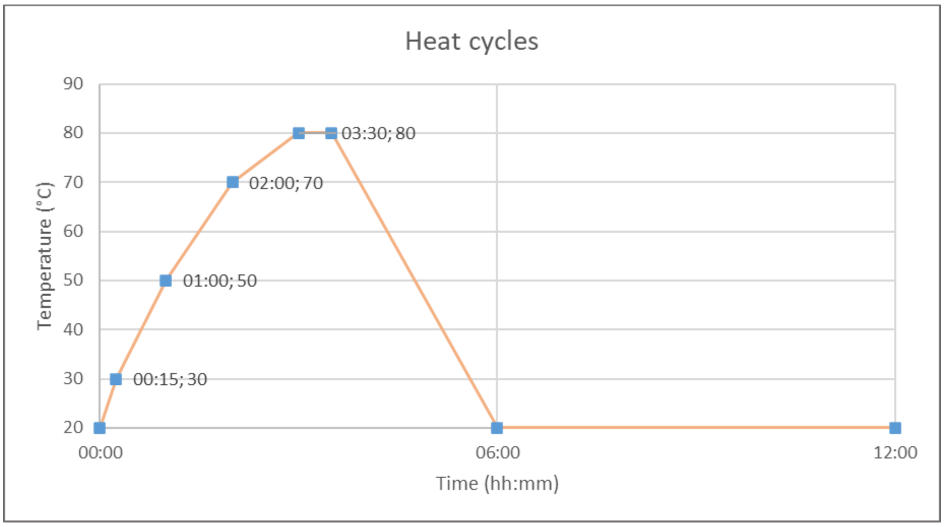

Figure 5.23: The heating cycle programmed on the TM-95 thermoregulator takes 12 hours to complete, and is split in two parts: the first one brings the specimens to the temperature of 80 °C to then lower it to 20 °C; the second one maintains the specimens at 20 °C for 6 hours to recover from the heat stress, and to start with the following cycle.

By analysing the climactic conditions of the area of Bari and Noci, it was observed that in the months of June, July and August the air temperature reached a maximum of 30 °C (35 °C in August) in the years 2019/2020. On the base of this consideration, since the temperature inside the ageing cell is ~ 3 times the air temperature measured, it is estimated that each cycle simulates 3 days of ageing. Considering the effect of humidity, which is constant and near to 100%, the effect could be considered as doubled, so the final estimation is that 50 cycles simulate about 300 days, corresponding to the effect of 4 years of effective summer conditions (June, July and August). Figure 5.22 shows the most important components of the apparatus to perform the cycles:

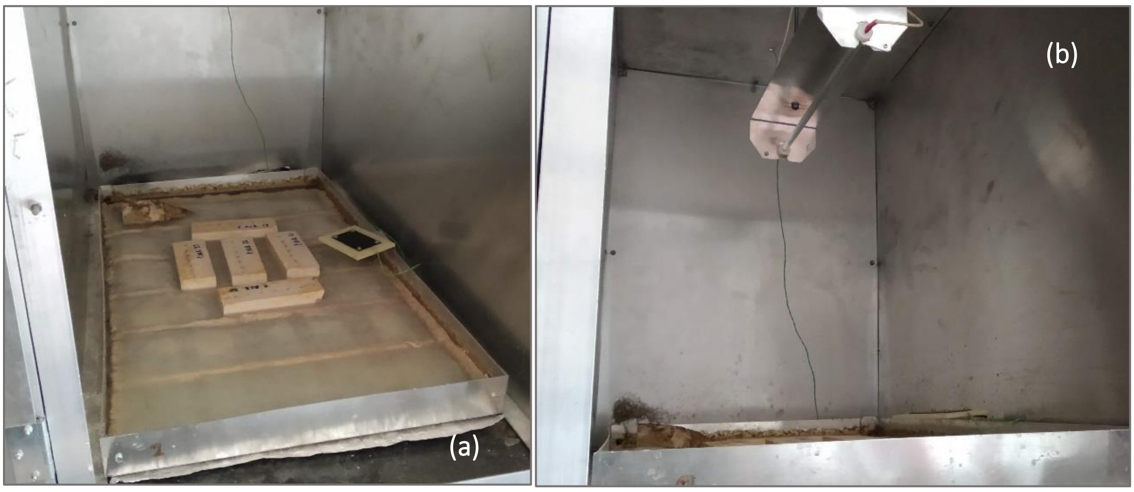

Figure 5.22: The ageing chamber (a) and the IR lamp (b).

5.8 PETROGRAPHIC ANALYSIS

The analyses were conducted on 6 thin sections, namely:

- P. ALB., from Palmisano Alberobello quarry.
- Noci Cava A and B, from the quarry of Noci.
- Noci Camp A, from the original stone block of the belltower of Noci “Chiesa Madre”.
- Noci Camp B, from the material employed for the restoration of the belltower.
- TPIA and TPIB, from Trullo Palmullo, Martina Franca.

The scope of the analyses was to search for relevant fossils, in order to classify the limestones as coming from Bari or Altamura series, and to perform a Folk classification. To carry out the examination, the following apparatus is needed:

- Polarizing optical microscope and a digital camera to visualise the images on a PC (figure 5.24).
- Thin sections of the specimens prepared accordingly with UNI-Normal 14/83, with a thickness of about 30 μm (figure 5.25).

Figure 5.24: The optical microscope, the digital camera and the PC to visualise and analyse images.

Figure 5.25: The thin sections.

To perform a classification with Folk methodology, the following figure 5.26 was used as reference [Folk R., 1962]:

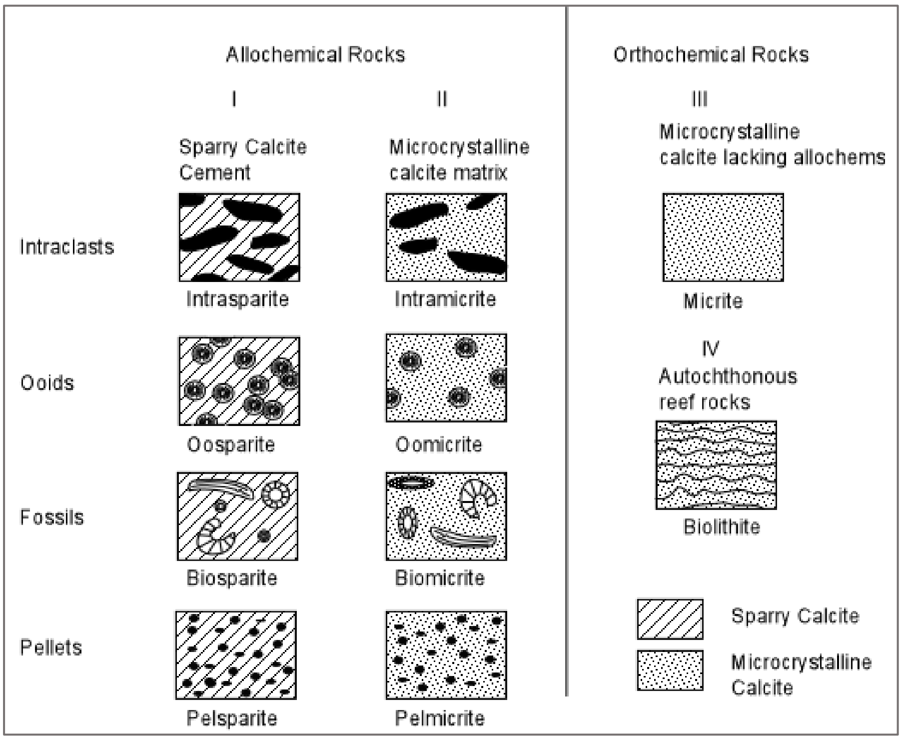

Figure 5.26: Folk classification is based on the presence and quantity of orthochemical component (micrite or sparite) and of allochems: these are diversified as intraclasts, ooids, fossils and pellets.

Based on the nature and quantity of allochems, Folk classification describes two main classes, each divided into four sub-classes, indicated by a prefix:

- Intra-, for intraclasts, which are irregular fragments.
- Bio-, for fossils.
- Oo-, for oolites, rounded calcite concretions.
- Pel-, for pellets, elliptic structures.

The discrimination between micritic or sparitic orthochemical cement is based on relative abundance: if more than 2/3 of the cement is micritic, the limestone is classified as *prefix*-micrite, and vice versa in the case of sparite. The determination of the nature of cement, as the identification of allochemicals, is conducted by microscopic observation.

6. RESULTS AND ANALYSES

This chapter is focused on the presentation of the results of laboratory tests, starting from the preliminary testing on stone samples, described in chapter 5.1. The analysis of these results is going to be used as reference to understand whether systematic tests on the second group of specimens gave acceptable and reliable results.

6.1 SCREENING TESTS

These specimens went through ultrasonic pulse velocity, water absorption and open porosity tests, and the results are summarised in table 6.1:

Table 6.1: The collected results of all tests performed on the specimens from the first group of stone samples.

Group	ID	UPV average (m/s)	WA (%)	WA average (%)	pO (%)	pO average (%)
Calella Locorotondo	C. LOC 1	2403	5.9	5.8	-	15.3
	C. LOC 2		5.6		15.3	
Monte del Duca quarry	M.D.C 1	3226	6.0	6.0	17.3	17.3
Monte del Duca stripping site	M.D.S 1	2381	6.5	5.6	-	-
	M.D.S 2		4.7		-	
Palmisano Alberobello	P. ALB 1	2474	3.8	4.9	11.8	11.2
	P. ALB 2		3.3		10.5	
	P. ALB 3		5.4		-	
	P. ALB 4		6.2		-	
	P. ALB 5		5.6		-	
Trullo Palmullo	T. PALM 1	2840	4.3	4.4	11.8	11.8
	T. PALM 2		4.4		-	
Historic quarry Locorotondo	S. LOC 1	2250	5.6	4.8	15.8	15.4
	S. LOC 2		5.1		14.9	
	S. LOC 3		5.0		-	
	S. LOC 4		5.4		-	
	S. LOC 5		4.4		-	
	S. LOC 6		4.7		-	
	S. LOC 7		3.5		-	
	S. LOC 8		4.9		-	

Blank spaces in table 6.1 are due to untested specimens. Flexural strength tests were not performed on this group of stone samples, since they could not be cut adequately to respect the prescriptions of EN 12372 (see chapter 5.7).

6.2 SYSTEMATIC TESTS

This section is going to present the results to the tests of UPV, WA, open porosity and flexural strength on all the specimens presented in chapter 5.2. The results are divided into groups, based on the origin of the stone material.

6.2.1 PALMISANO ALBEROBELLO QUARRY

To characterise material coming from Palmisano quarry in Alberobello, tables 6.2 and 6.3 summarise the results of the tests:

Table 6.2: The results of the tests on the specimens of Palmisano quarry in Alberobello.

ID	UPV (m/s)	R_{tf} (MPa)
P ALB 9	2303	12.3
P ALB 10	2273	13.6
P ALB 11	2244	-
P ALB 12	2251	13.3
P ALB 13	2273	12.3
P ALB 14	1913	12.0
P ALB 15	2318	12.6
P ALB 16	2160	9.9
P ALB 17	2174	14.1
P ALB 18	2174	14.2
ID	WA (%)	pO (%)
P ALB 1	4.8	14.7
P ALB 1	4.8	14.7
P ALB 2	5.5	17.3
P ALB 3	3.3	10.4
P ALB 4	4.2	13.5
P ALB 5	3.0	9.4
P ALB 6	5.4	16.6
P ALB 7	4.7	14.4
P ALB 8	4.7	14.6

Table 6.3: Mean values and standard deviations of the results from the tests performed on P. ALB. specimens.

Test	Mean	Standard Deviation
UPV (m/s)	2210	117
WA (%)	4.4	0.89
pO (%)	13.9	2.75
R_{tf} (MPa)	11.4	4.21

Specimen P. ALB. 11 has a blank space under R_{tf} because of an incorrect execution of the test.

6.2.2 QUARRY OF NOCI

Tables 6.4 and 6.5 show the results of the tests on the 9 specimens cut from two chunks of stone coming from the quarry of Noci:

Table 6.4: The results of the tests on the specimens from the quarry of Noci.

ID	UPV (m/s)	WA (%)	pO (%)	R_{tf} (MPa)
Noci Cava A 1	1939	2.2	10.0	17.2
Noci Cava A 2	2251	2.4	10.2	15.5
Noci Cava A 3	1972	2.2	9.8	17.9
Noci Cava A 4	1923	2.0	8.9	19.2
Noci Cava A 5	2071	2.5	10.7	16.1
Noci Cava B 1	2422	2.0	8.8	17.0
Noci Cava B 2	2357	1.8	8.0	17.2
Noci Cava B 3	2333	2.3	9.7	16.7
Noci Cava B 4	2422	1.9	8.2	17.6

Table 6.5: Mean values and standard deviations of the results from tests performed on Noci Cava specimens.

Test	Mean	Standard Deviation
UPV (m/s)	2190	210
WA (%)	2.2	0.23
pO (%)	9.4	0.94
R_{tf} (MPa)	17.1	1.05

The two blocks show a sensible difference in UPV, but a rather uniform distributions of values in flexural strength, water absorption and open porosity tests. For this set of specimens, a correlation was found (figure 6.1) between WA and R_{tf} by considering Noci Cava A 3 and Noci Cava A 4 outliers.

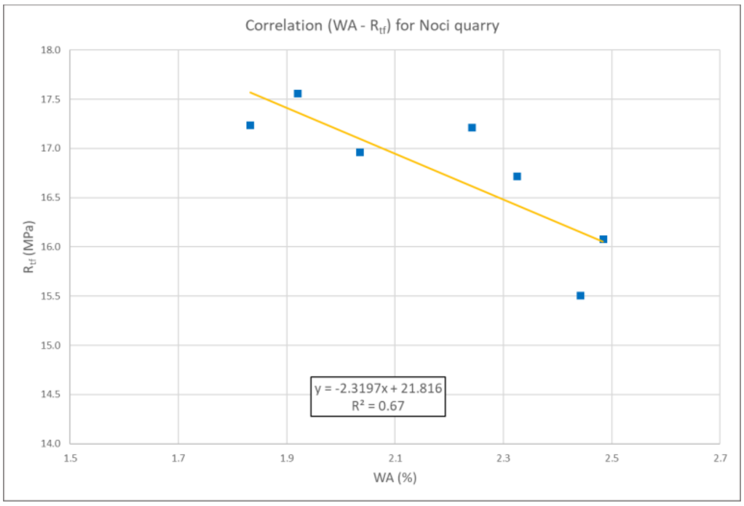

Figure 6.1: The correlation shows a decreasing trend of R_{tf} with the growth of WA. The correlation coefficient R = 0.81.

6.2.3 BELLTOWER OF NOCI A

The stone chunk from which this series of specimens were cut was an original part of the belltower of Noci “Chiesa Madre”. The results of the tests are reported in tables 6.6 and 6.7:

Table 6.6: The results of the tests on the specimens from the belltower of “Chiesa Madre” of Noci.

ID	UPV (m/s)	WA (%)	pO (%)	R_{tf} (MPa)
Noci Camp A 1	2194	2.9	-	11.5
Noci Camp A 2	2201	4.0	-	14.7
Noci Camp A 3	2181	3.6	12.2	-
Noci Camp A 4	2236	3.3	11.0	16.0

Table 6.7: Mean values and standard deviations from tests performed on Noci Camp A specimens.

Test	Mean	Standard Deviation
UPV (m/s)	2200	210
WA (%)	3.4	0.46
pO (%)	11.6	0.88
R_{tf} (MPa)	14.1	2.29

The blank space of Noci Camp A 3 in R_{tf} is due to an incorrect development of the test. Noci Camp A 1 and 2 were not tested for open porosity.

6.2.4 BELLTOWER OF NOCI B

The second chunk of stone from the belltower of Noci “Chiesa Madre” was employed during the restoration of 2019, and is indicated as coming from a quarry near Carovigno (BR). The results of the tests are reported in tables 6.8 and 6.9:

Table 6.8: The results of the tests on the restoration material of “Chiesa Madre” of Noci.

ID	UPV (m/s)	WA (%)	pO (%)	R_{tf} (MPa)
Noci Camp B 1	2215	2.5	12.1	21.9
Noci Camp B 2	2303	2.6	12.1	21.7
Noci Camp B 3	2265	2.4	11.9	26.0
Noci Camp B 4	2222	2.7	12.3	16.5

Table 6.9: Mean values and standard deviations from tests performed on Noci Camp B specimens.

Test	Mean	Standard Deviation
UPV (m/s)	2250	40
WA (%)	2.6	0.11
pO (%)	12.1	0.18
R_{tf} (MPa)	21.5	3.90

6.2.5 TRULLO PALMULLO

The chianca from Trullo Palmullo was sawn into 17 specimens: 12 of them are sawn out of an intensely weathered area (see chapter 5.2). The results of the tests performed on them are shown in the following tables 6.10 and 6.11:

Table 6.10: The results of the tests on the specimens from Trullo Palmullo, interior chianca from the cone, part A.

ID	UPV (m/s)	WA (%)	pO (%)	R_{tf} (MPa)
TPIA 1	2071	5.0	13.5	15.7
TPIA 2	2108	4.4	12.0	15.1
TPIA 3	2053	3.8	11.0	14.2
TPIA 4	2365	4.2	11.9	19.0
TPIA 5	2349	3.9	11.4	19.2
TPIA 6	2310	3.4	10.4	19.6
TPIA 7	2105	8.7	19.4	10.6
TPIA 8	1777	8.6	19.4	8.6
TPIA 9	1923	7.9	18.1	12.5
TPIA 10	1867	7.1	16.9	15.5
TPIA 11	1907	6.9	16.1	15.5
TPIA 12	1977	6.4	15.7	15.4

The sample TPIA 8 broke in an unexpected way during flexural strength test, but the result of that measurement seems to correlate well with those of UPV and WA, so it was not considered as outlier.

Table 6.11: Mean values and standard deviations from tests performed on TPIA specimens.

Test	Mean	Standard Deviation
UPV (m/s)	2070	192
WA (%)	5.9	1.96
pO (%)	14.6	3.34
R_{tf} (MPa)	15.1	3.35

For this set of samples, two trends of correlation were found, and are shown in figures 6.2 and 6.3:

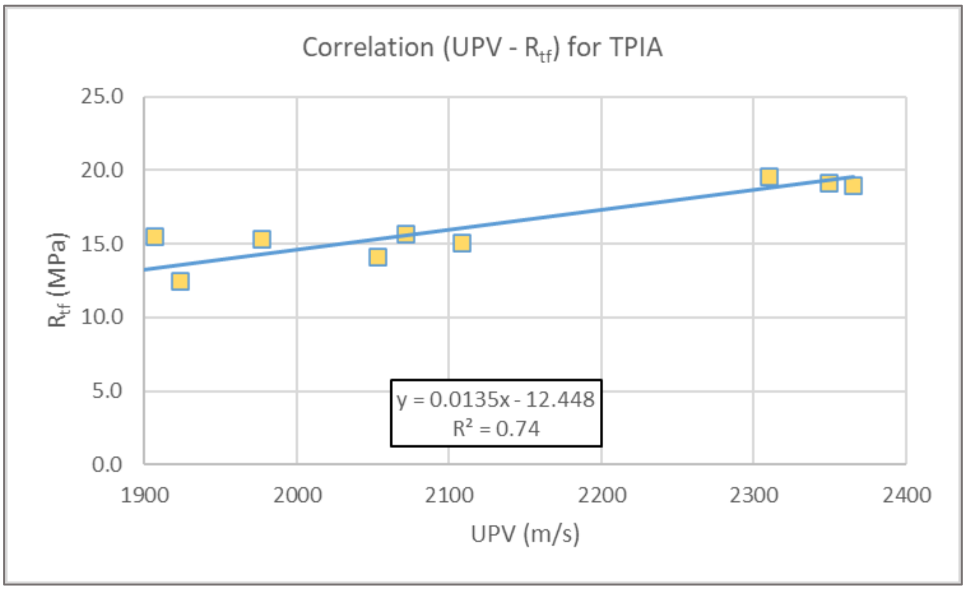

Figure 6.2: The correlation between UPV and R_{tf} shows a clear growing trend, meaning that a stiffer material (one with higher pulse velocity) from this stone sample will likely show a higher resistance to flexion. Sample TPIA 7 was considered an outlier, since part of it was too slender to perform correctly during the test. The correlation coefficient R = 0.86.

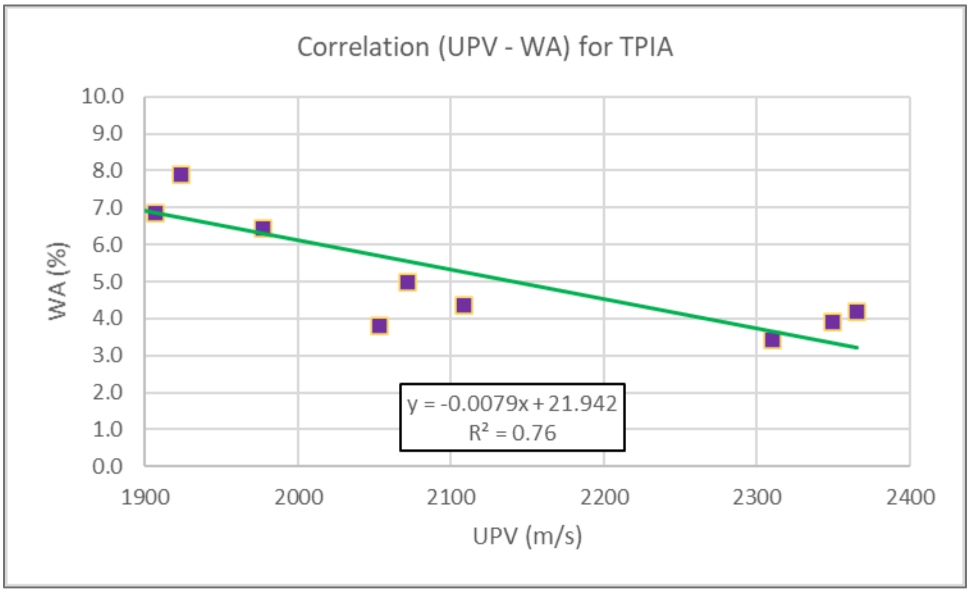

Figure 6.3: Comparing the performances of specimens out of UPV and WA tests, the correlation shows a clear decreasing trend. This is reasonable, since a stiffer material is likely to be less porous, therefore less prone to absorb water. Again, sample TPIA 7 was considered an outlier. The correlation coefficient R = 0.87.

One more analysis was performed on the chianca from Trullo Palmullo: after reconstructing it, assembling the bars to recreate the original shape of the stone, the spatial distribution of values was examined. Figure 6.4 shows how the specimens were reassembled:

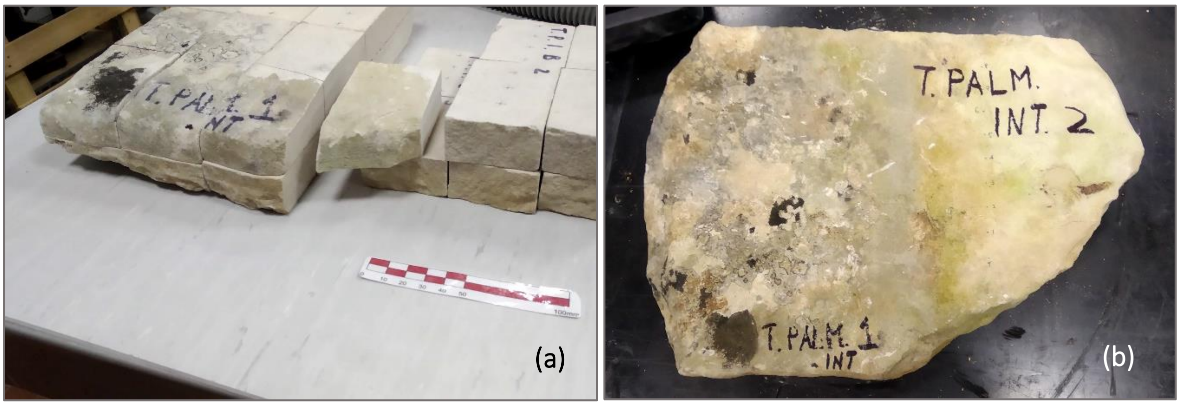

Figure 6.4: The reconstructed chianca (a), and the whole stone (b).

It is possible to observe, from table 6.10, that there seems to be a distribution in the properties of the stone, especially evident in UPV measures and R_{tf}: table 6.12 shows how the samples can be distinguished into four main areas:

Table 6.12: The coloration is meant to divide the specimens into their respective area:

- Green: above average UPV, above average R_{tf}
- Yellow: average UPV, average R_{tf}
- Orange: below average UPV, average R_{tf}
- Red: below average UPV, below average R_{tf}

ID	UPV (m/s)	Mean UPV (m/s)	R_{tf} (MPa)	Mean R_{tf} (MPa)
TPIA 1	2071		15.7	
TPIA 2	2108	2080	15.1	15.0
TPIA 3	2053		14.2	
TPIA 4	2365		19.0	
TPIA 5	2349	2340	19.2	19.3
TPIA 6	2310		19.6	
TPIA 7	2105		10.6	
TPIA 8	1777	1935	8.6	10.6
TPIA 9	1923		12.5	
TPIA 10	1867		15.5	
TPIA 11	1907	1920	15.5	15.5
TPIA 12	1977		15.4	

Figures 6.5 to 6.7 show the positions of the bars inside the stone:

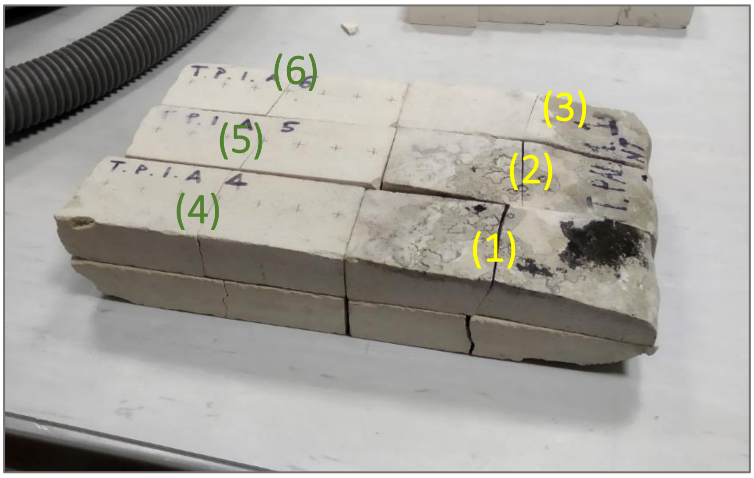

Figure 6.5: The upper layer of the chianca includes samples TPIA 1 to 6, while the lower one contains TPIA 7 to 12. The numbers in yellow brackets indicate the specimens TPIA 1, 2 and 3 and those in green TPIA 4, 5 and 6.

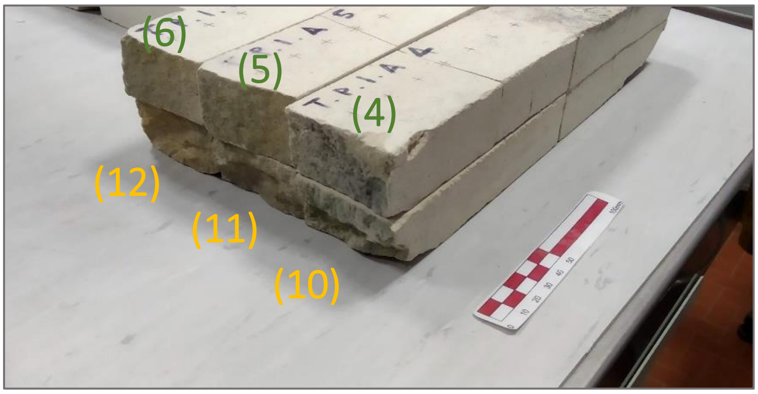

Figure 6.6: The back side of the chianca, and specimens TPIA 10, 11 and 12 indicated by the orange numbered brackets.

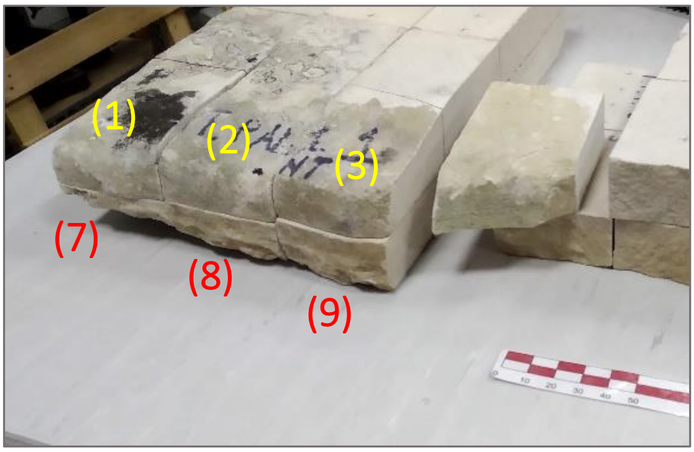

Figure 6.7: The front side of the chianca, and specimens TPIA 7, 8 and 9 in red brackets.

The results of the tests performed on the second set of specimens from the chianca of Trullo Palmullo are summarised in tables 6.13 and 6.14:

Table 6.13: The results of the tests on the specimens from Trullo Palmullo, interior chianca from the cone, part B.

ID	UPV (m/s)	WA (%)	pO (%)	R_{tf} (MPa)
TPIB 1	2414	3.0	9.9	10.7
TPIB 2	2422	2.4	8.9	20.0
TPIB 3	2244	4.9	13.9	14.0
TPIB 4	2373	2.7	9.4	21.4
TPIB 5	2251	5.4	14.4	12.5

Specimens from part B of the stone exhibit higher values of UPV and lower WA and pO, possibly due to the lack of superficial weathering.

Table 6.14: Mean values and standard deviations from tests performed on TPIB specimens.

Test	Mean	Standard Deviation
UPV (m/s)	2340	87
WA (%)	3.7	1.38
pO (%)	11.3	2.64
R_{tf} (MPa)	15.7	4.70

Considering all of the specimens from the chianca, the following correlation (figure 6.8) can be found:

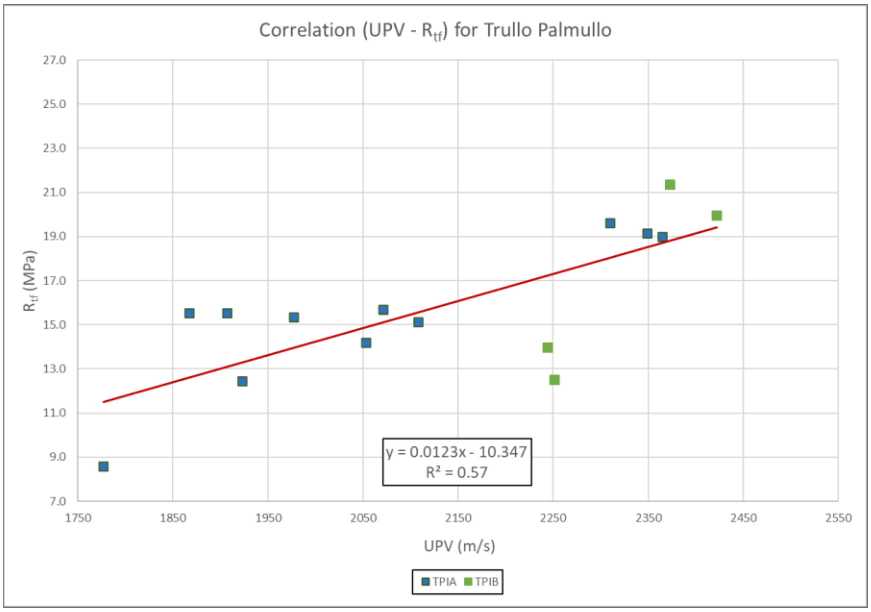

Figure 6.8: Increased UPV values are correlated with increased flexural strength of the specimen. Specimens TPIA 7 and TPIB 1 were considered outliers. The correlation coefficient R = 0.75.

6.3 ACCELERATED AGEING

Two methodologies of accelerated ageing were performed on specimens from the group of Palmisano Alberobello quarry (see chapters 5.8.1 and 5.8.2). After the cycles of ageing, the samples were analysed with visual observation, UPV measures and flexural strength tests. The following paragraphs report the results.

6.3.1 VISUAL OBSERVATION

To perform a correct visual evaluation of the changes in appearance of specimens, the European normative EN 16140 was followed. Figures 6.9 and 6.10 show the visual changes that could be recognised.

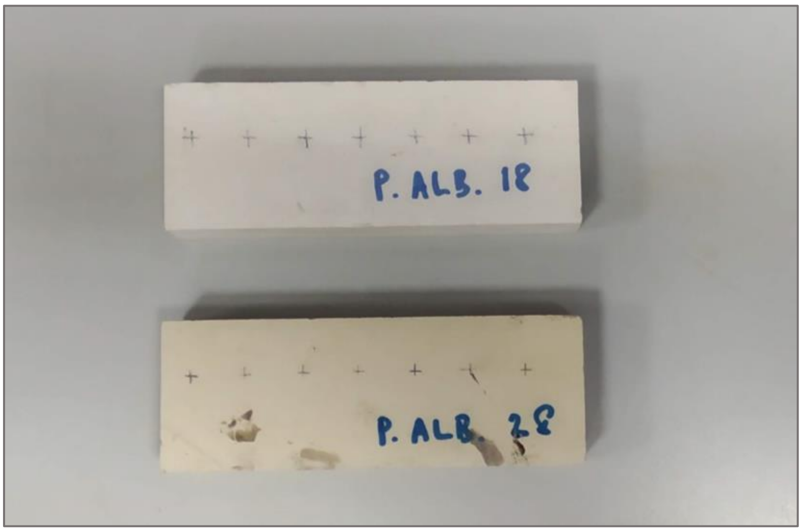

Figure 6.9: Thermal shock cycles affected the coloration of the specimens, revealing an havana grading. No fracturing or detachment is observable.

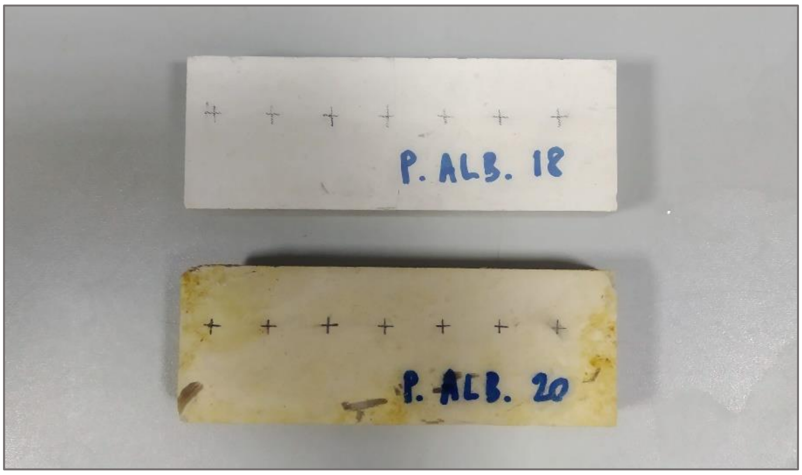

Figure 6.10: The specimens on which cycles of temperature and moisture were performed show staining after ageing.

6.3.2 UPV MEASURES

The results of UPV measures and the statistic interpretation of them, for both sets of specimens, are reported in tables 6.15 and 6.16.

Table 6.15: The results of UPV measures on thermal shock aged specimens.

ID	UPV (m/s)	Mean UPV (m/s)	Standard Deviation (m/s)
P. ALB. 24	2310	2290	116
P. ALB. 25	2310		
P. ALB. 26	2090		
P. ALB. 27	2077		
P. ALB. 28	2258		

Table 6.16: The results of UPV measures on specimens aged with thermal and moisture cycles.

ID	UPV (m/s)	Mean UPV (m/s)	Standard Deviation (m/s)
P. ALB. 19	2280	2290	39
P. ALB. 20	2244		
P. ALB. 21	2341		
P. ALB. 22	2258		
P. ALB. 23	2310		

6.3.3 FLEXURAL STRENGTH TESTS

The results of flexural strength tests, on both sets of specimens, are reported in tables 6.17 and 6.18.

Table 6.17: The results of flexural strength tests on thermal shock aged specimens.

ID	R_{tf} (MPa)	Mean R_{tf} (MPa)	Standard Deviation (MPa)
P. ALB. 24	15.3	13.7	1.22
P. ALB. 25	12.8		
P. ALB. 26	12.4		
P. ALB. 27	13.4		
P. ALB. 28	14.6		

Table 6.18: The results of flexural strength tests on thermal and moisture cycles aged specimens.

ID	R_{tf} (MPa)	Mean R_{tf} (MPa)	Standard Deviation (MPa)
P. ALB. 19	13.9	13.4	1.15
P. ALB. 20	13.5		
P. ALB. 21	13.1		
P. ALB. 22	14.8		
P. ALB. 23	11.7		

6.4 PETROGRAPHIC ANALYSIS

The observations were carried out on 5 thin sections, namely:

- P. ALB. from Palmisano Alberobello quarry.
- Noci Camp A, from the belltower of Noci "Chiesa Madre".
- Noci Camp B, from the material employed in the restoration.
- Noci Cava A, from the quarry of Noci.
- TPIA, from Trullo Palmullo.

For each section, the observations aimed at the identification of relevant fossils and a classification with Folk methodology. The microscope was set to have crossed polarizers, so that pores could be easily distinguished from any formation, as they would appear black.

Macroscopic observations of the samples were performed as well (see chapter 5.3), and served as reference to understand whether microscopic traits can be linked to macroscopic ones, and possibly influence the mechanical response of the material.

6.4.1 PALMISANO ALBEROBELLO QUARRY

Figure 6.11: In this thin section, a fragment of fossil shell can be observed, possibly from a Bivalve. Additionally, Foraminifera and algae rests. The bioclastic fraction appears very badly preserved, and it is difficult to assess the nature of fossils. For Folk classification, this limestone is a biomicrite, with 10 – 20 % of bioclasts.

6.4.2 QUARRY OF NOCI

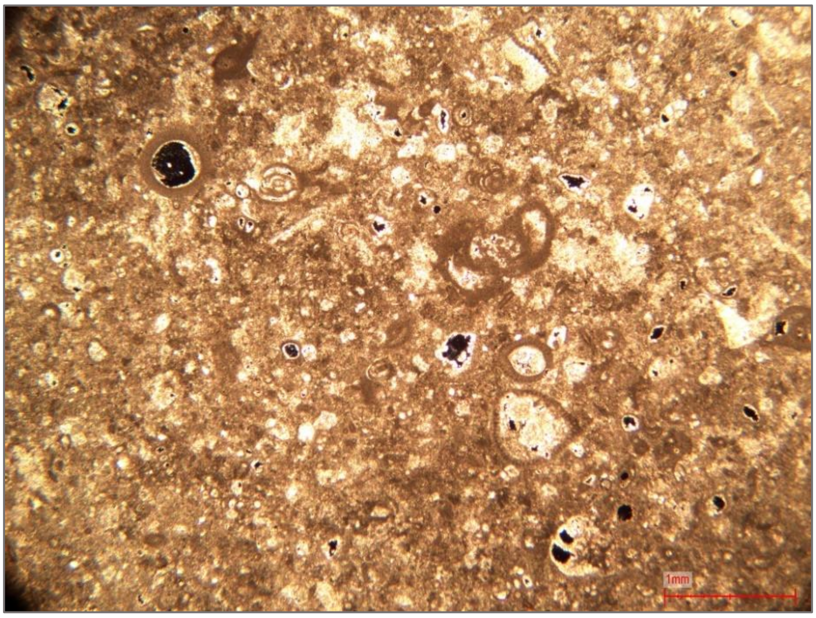

Figure 6.12: The thin section from the quarry of Noci shows an increase in the presence of ooids, and the presence of algae colonies, possibly Heteroporella Lepina, and Alveolinidae. These algae were recognised in limestones from the bottom of Altamura limestone, during the search for Perlato Svevo sites of extraction [Reina A., 2005]. For Folk classification, this limestone is a biopelmicrite, with more than 50 % of bioclasts.

6.4.3 BELLTOWER OF NOCI A

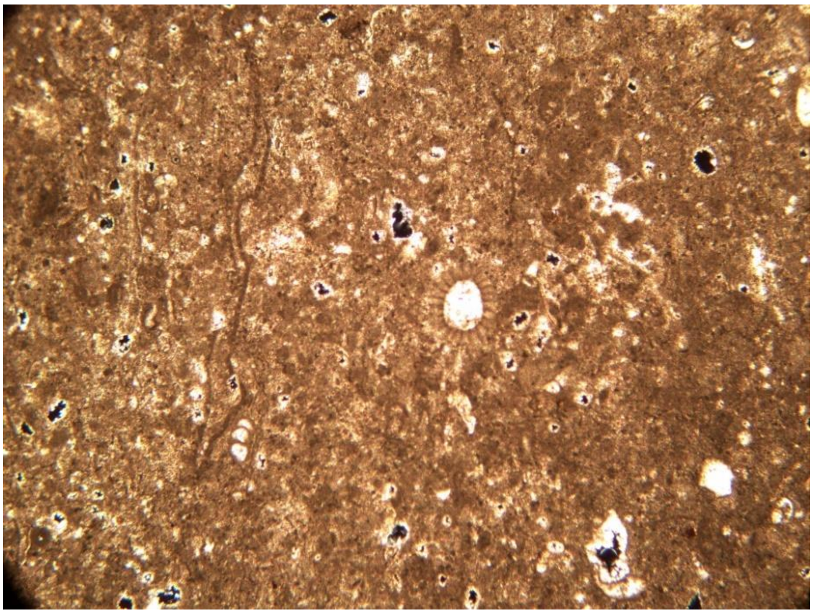

Figure 6.13: In this thin section from the original stone block from "Chiesa Madre" belltower, calcareous algae and Bivalvia were observed. Their presence was noted during the works for the restoration of the belltower, too [La Viola F., 2016]. For Folk classification, this limestone is a biomicrite, with 30-40 % of bioclasts.

6.4.4 BELLTOWER OF NOCI B

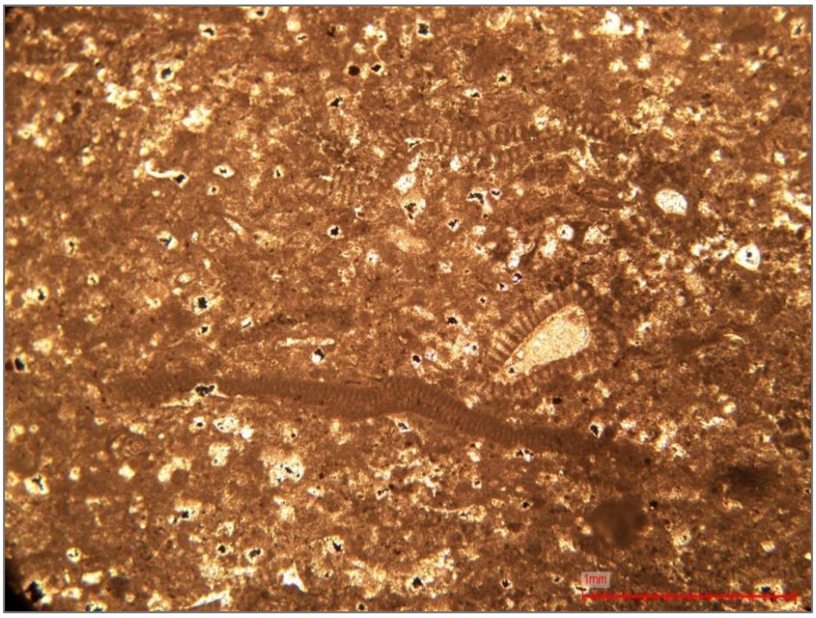

Figure 6.14: In this thin section from the material employed for the restoration of the belltower of "Chiesa Madre", algae (Heteroporella Lepina) can be observed, along with recognisable Foraminifera. For Folk classification, this limestone is a biopelmicrite, with more than 50 % of bioclasts.

6.4.5 TRULLO PALMULLO

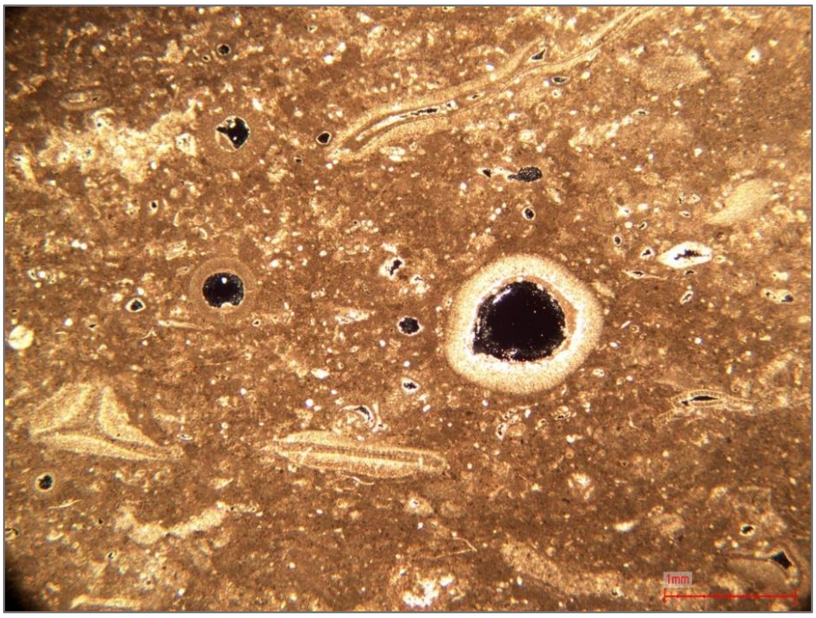

Figure 6.15: Trullo Palmullo exhibits a different population of fossils, seldom with a compressed shape: Alveolinidae and algae could be recognised, and bioclast concentration is about 45 – 50 %. For Folk, this limestone is a biomicrite.

7. DISCUSSIONS AND CONCLUSIONS

This chapter is going to give an in-depth analysis of the results from laboratory tests, a comparison of them with on-site investigations, and draw conclusions and further achievable objectives to this research, with the perspective of protection of Cultural Heritage in Itria Valley.

7.1 DISCUSSION OF LABORATORY TESTS RESULTS

Table 7.1 summarises the mean values of tested properties for each group of stone samples:

Table 7.1: A report of means and standard deviations of the properties tested in laboratory for each group of specimens.

Group	UPV (m/s)		WA (%)		pO (%)		R_{tf} (MPa)	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
P. ALB.	2210	117	4.4	0.89	13.9	2.75	11.4	4.21
Noci Cava	2190	210	2.2	0.23	9.4	0.94	17.1	1.05
Noci Camp A	2200	210	3.4	0.46	11.6	0.88	14.1	2.29
Noci Camp B	2250	40	2.6	0.11	12.1	0.18	21.5	3.90
TPIA	2070	192	5.9	1.96	14.6	3.34	15.1	3.35
TPIB	2340	87	3.7	1.38	11.3	2.64	15.7	4.70

As a first analysis, the results of UPV measurements can be compared with those recorded on-site (table 4.1), and the results of screening testing (table 6.1).

7.1.1 COMPARISON WITH SCREENING TESTS

To confirm whether systematic testing was performed in a reliable way, UPV values from Palmisano Alberobello quarry are sensibly lower, 2210 m/s against 2474 m/s, but not so much to render the two materials incomparable; this is possibly due to rock variability: Palmisano Alberobello shows high standard deviations in each test. The graph in figure 7.1 shows how the values obtained through screening tests fall out of the boundaries set by mean ± standard deviation of the results of systematic testing. About WA and open porosity, the same considerations can be drawn: WA and pO are reasonably similar, and standard deviation is high, due to high variability of the stone.

For Trullo Palmullo, UPV are sensibly higher in the material from the first group, 2840 m/s against 2070 m/s and 2340 m/s from TPIA and TPIB. This is possibly due to the high variability in the origin of the material. The same can be observed for WA and open porosity.

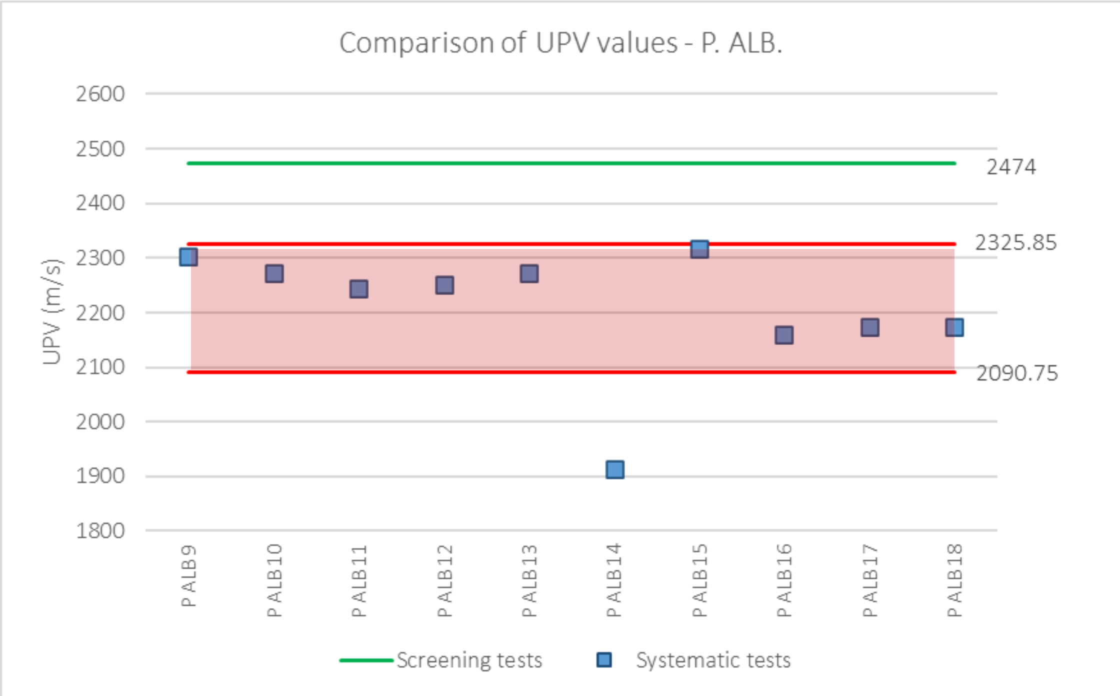

Figure 7.1: By comparing the results of systematic UPV tests on P. ALB. specimens with those obtained through screening procedures, it can be observed how the materials have sensibly different UPV properties, but not so much to make them incomparable, taking into account that the standard deviation for screening tests is estimated as 10 % of the mean (2474 m/s).

7.1.2 COMPARISON WITH ON-SITE MEASUREMENTS

Values taken in Noci show significant variation, with a maximum of 3640 m/s (S. Chiara Church front) and a minimum of 2240 (S. Chiara Church portal). The material from the front of the church cannot be compared with any values recorded in laboratory tests, and it is safe to assume that it is a completely different material from those studied in this work. The material from the portal however shows UPV measures that are very close to those of Noci Camp A, which are specimens sawn from an original stone block from the belltower of Noci "Chiesa Madre". This could mean that these materials may have common origin, but to assess it with certainty other studies (both historic, about the construction of the churches, and about other properties of the material) should be conducted. It is interesting to see how the values recorded in the belltower of Noci "Chiesa Madre" give very different readings from those obtained in laboratory: the material of the on-site investigation exhibits a UPV value of 3200 m/s, against 2200 m/s from laboratory testing. Such a significant gap can be interpreted as material in different areas of the belltower is likely to come from different sources.

From the comparison between on-site measurements and the materials coming from Trullo Palmullo, UPV measures are not comparable; this is likely due to the very high variability of origin of material used in the construction of trulli (see chapter 1.3).

7.1.3 COMPARISON WITH KNOWN ORNAMENTAL STONES OF PUGLIA

To put these materials in perspective with those already studied and presented as literature (see chapter 3), it is useful to look back on tables 3.1 and 3.2.

As seen in table 3.1, WA of ornamental stones is always < 1 %, while the materials tested always exceed 1 % (ranging from a minimum of 2.2 for Noci Cava to a maximum of 5.9 for TPIA). What seem to be comparable are the values of R_{tf} from table 3.2: samples from the quarry of Noci have R_{tf} = 17.1 MPa, against 17.16 MPa of Filetto Rosso. However, it could not be determined by microscopic observation whether stone from Noci quarry belongs to the same series of limestones as Filetto Rosso; also, the material doesn't present the characteristic red veins on a macroscopic level.

Stone from Palmisano Alberobello quarry is characterised by rests of fossils, visible to the naked eye, and has a R_{tf} = 11.4 MPa, which is comparable to the value of Cocciolato, 11.77 MPa. These similarities, along with the knowledge that the quarry extracts from level Sannicandro, at the top of Bari limestone series, allows to consider this material as Cocciolato.

7.2 RESULTS OF PETROGRAPHIC OBSERVATIONS

The fossils observed during microscopic observations did not allow to define the geologic origins of samples, since guide fossils could not be identified. The presence of Heteroporella Lepina is not enough to link these materials directly to those found in studies for Perlato Svevo sites [Reina A., 2005]. However, the presence of fossils and bioclasts could be quantified, to characterise how quantity and dimensions of them can influence the mechanical response of the specimens (table 7.2):

Table 7.2: This table summarises the results of flexural strength of the samples and relates them to the quantity and average dimensions of fossils found with microscopic observation.

Group	R_{tf} (MPa)	Fossils percentage	Fossils average dimensions (mm)	Fossils maximum dimensions (mm)
P. ALB.	11.4	10 to 20 %	0.13	2.0
Noci Cava	17.1	50 %	0.8	2.3
Noci Camp A	14.1	30 to 40 %	0.4	0.8
Noci Camp B	21.5	50 %	0.05	2.5
Trullo Palmullo	15.5	45 to 50 %	0.12	2.3

The average fossil dimensions were used in these considerations, since fossils with maximum dimensions were too less common in the samples, and cannot be considered representative of fossil population. It can be observed how materials with higher percentage of fossil allochems and bigger dimensions of them tend to exhibit higher values of R_{tf}.

The specimens of material from the restoration of the belltower of "Chiesa Madre" of Noci (Noci Camp B), however, show a value of average dimension of fossils much below average (one order of magnitude), compared to other materials, yet this limestone has the highest R_{tf} of the entire population of samples. Further microscopic observations revealed that this thin section is characterised by numerous accumulations of recrystallised sparitic calcite, in dimensions comparable with the average of fossils in other samples.

If these sparitic re-crystallisations can be assumed to improve the mechanical response of the material, then this can explain why samples from Noci Camp B have higher values of R_{tf}.

7.3 OBSERVATIONS ON THE AGEING CYCLES

The expected outcome of accelerated ageing was a loss in mechanical characteristics, however results of thermal shock and thermal/moisture ageing cycles, reported in tables 6.15 to 6.18, show how specimen did not suffer a decrease in performance, not in sound speed propagation nor flexural strength. It was observed on biomicritic limestones that cycles of accelerated ageing cause strong decay in mechanical characteristics, mainly because of the rock fabric and texture, which favour moisture retention. In particular, biomicrites showed a loss of $\sim$ 19% in point load strength [Sitzia F., 2020].

The average values of UPV and R_{tf} are slightly higher than those of non-aged samples; there are two possible interpretations of this, either of which can be explored further with more in-depth studies:

– The specimens were not affected by ageing, meaning that this material shows a resistance to weathering.
– The specimens did not show a decrease in performance because the ageing cycles were too short and too little aggressive to affect these materials in a significant way. It is possible that 50 cycles could be more indicated, as the effects of weathering seem to become more apparent with longer exposures [Guler S. et al., 2021].

7.4 CONCLUSIONS

The objective of this work was to characterise natural stone coming from Itria Valley, as it represents an essential component in Cultural Heritage: a deeper knowledge of it is key for a correct implementation of restoration actions and for the choice of the most adequate materials.

Several sources of material were tested and analysed, both on-site and in laboratory, and the observations performed on them have been promising:

- The characterisation allowed to recognise quite confidently one of the materials as Cocciolato, through a multidisciplinary approach.
- The trends of correlation that were found show how different physical-mechanical properties can be linked, to extrapolate information about the material even from on-site tests, like UPV measurements.
- The “reconstruction” of the chianca from Trullo Palmullo allowed to assess how the technological properties of these materials are variable, even inside a single stone, depending on the state of weathering and the position of samples inside the whole stone.
- It was observed in this study that as numerosity and dimensions of bioclasts increase, so do mechanical performances. Future studies could explore further the relationship between number and dimension of fossils in a limestone and their impact on mechanical properties.
- Accelerated ageing, both with thermal shock and thermal/moisture cycles, did not affect the specimens as it was expected, possibly because of a resistance of the material to weathering, or due to the fact that ageing procedures were not aggressive enough; possible future studies could investigate further.

The observations, analyses and conclusions produced in this work will serve as a base for further researches to promote the Cultural Heritage of Itria Valley and its natural stone. The results of this laboratory analysis could be a reference for the next publication of “Natural Stone and Cultural Heritage”, focused on Itria Valley.

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