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THE «MACIGNO» SANDSTONE FROM MATRAIA AND PIAN DI LANZOLA QUARRIES (NORTH-WESTERN TUSCANY, ITALY). A COMPARISON OF PHYSICAL AND MECHANICAL PROPERTIES

Abstract - Within the framework of a research program devoted to quantify the natural stones quarried in the Garfagnana and Lunigiana areas (north-western Tuscany, Italy) in terms of quality, a careful study of the «Pietra di Matraia» and «Pietra di Pian di Lanzola» with respect to physical and mechanical properties was performed according to European Standards/Norms indications.
The studied stones have been locally employed as building materials and as decorative stones from prehistoric times until today. They belong to the Macigno Formation (Upper Oligocene to Lower Miocene) that crops out extensively in the Northern Apennines and consists of grey to bluish-grey, well-consolidated, fine- to medium-grained, poorly to moderately sorted siliciclastic sandstones, with quartz, feldspar and micas.
«Pietra di Matraia» and «Pietra di Pian di Lanzola» are to be regarded as heavy and compact arenitic arkoses, characterized by both low values of porosity and water absorptions at atmospheric pressure, unaffected by freeze-thaw cycles, with an high strength for compression, flexure and impact stress.
Sandstones from the Matraia quarry show lower values of porosity and water absorption as well as a significantly higher value of flexural strength under concentrated load than those obtained on «Pietra di Pian di Lanzola» samples.

Key words - Sandstones, building materials, physical properties, mechanical properties, Tuscany, Italy.

Riassunto - *L'arenaria «Macigno» delle cave di Matraia e di Pian di Lanzola (Toscana nord-occidentale, Italia). Un confronto di proprietà fisiche e meccaniche*. Nell'ambito di un programma di ricerca rivolto a quantificare la qualità delle pietre estratte in Garfagnana e Lunigiana (Toscana nord-occidentale, Italia), è stato eseguito, in accordo con le indicazioni fornite dalle Normative Europee, lo studio delle proprietà fisiche e meccaniche della pietra di Matraia e della Pietra di Pian di Lanzola.
Da tempi preistorici fino ad oggi, le rocce in esame sono state impiegate localmente come materiali da costruzione e come pietre da decorazione. Queste rocce appartengono alla Formazione Macigno (Oligocene sup. - Miocene inf.) che affiora ampiamente nell'Appennino settentrionale e consiste di arenarie silico-clastiche, di colore variabile da grigio a grigio-bluastro, ben consolidate, di granulometria da fine a media, da scarsamente a moderatamente classate, con quarzo, feldspati e miche.
La «Pietra di Matraia» e la «Pietra di Pian di Lanzola» sono rocce pesanti e compatte classificabili come areniti arcosiche, caratterizzate da bassi valori di porosità e di assorbimenti d'acqua a pressione atmosferica, non gelive, con un'elevata resistenza a compressione, flessione ed urto.
Le arenarie prelevate nella cava di Matraia mostrano più bassi valori di porosità e di assorbimento d'acqua e più alti valori di resistenza a flessione sotto carico concentrato rispetto a quelli ottenuti su campioni prelevati dalla cava di Pian di Lanzola.

Parole chiave - Arenarie, materiali da costruzione, proprietà fisiche, proprietà meccaniche, Toscana, Italia.

Introduction

From prehistoric times until today, the «Macigno» sandstones from Matraia (MT) and Pian di Lanzola (LN) quarries were widely used as building material and decorative stones in the Garfagnana and Lunigiana areas (north-western Tuscany, Italy). A lot of stele statues, great parish churches, small country churches, street paving-stones and buildings in small mountain villages, architectural and ornamental pieces in great monumental buildings were built with these natural stones.
From the geological point of view, the rocks from MT and LN are sandstones belonging to the «Macigno» Formation (Upper Oligocene to Lower Miocene) that crop out extensively in the Northern Apennines of Italy, from Pontremoli to the Chianti area, with some occurrences in the southern Tuscan region (Fig. 1).
Chemical, mineralogical, petrographic and sedimentological features of the «Macigno» sandstones have been reported in several papers (Cipriani, 1958, 1961; Gazzi, 1965; Cipriani & Malesani, 1972; Valloni, 1978; Reutter *et al*., 1980; Deneke & Gutnther, 1981; Cipriani *et al*., 1985; Valloni *et al*., 1991; van de Kamp & Leake, 1995; Bargossi *et al*., 1998; Morandi & Tateo, 1998; Dinelli *et al*., 1999; Franzini *et al*., 2007) and a complete catalogue of publications on the Lunigiana «Macigno» sandstones can be found in the interesting monograph published by Di Battistini & Rapetti (2003).
As one can deduce from the scientific literature, the «Macigno» sandstones generally consist of well-consolidated, fine- to very coarse-grained, poorly to moderately sorted siliciclastic rocks made up of sub-angular detrital grains of quartz, plagioclase, K-feldspar, chlorite s.l., mica-like minerals (muscovite/illite and minor biotite), with minor amounts of rock fragments (< 10% by volume), including granites, felsic volcanites and metavolcanites, low to medium metamorphic-grade rocks, ophiolites, quartz veins, limestones and shales. Carbonates occur as both detrital clasts and authigenic

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cement. Mixed-layer chlorite/smectite and subordinate illite/smectite phases, as well as minor and sporadic kaolinite may be present as clay minerals. Neoformed pumpellyte, illite, epidote and chlorite have also been described, indicating an incipient metamorphic process.

The purpose here is to investigate the physical and geomechanical properties of the MT and LN production, in the framework of the researches devoted to improve the knowledge of the engineering properties of these largely employed sandstones.

The properties studied according to European Standards/Norms (EN) indications include: real and apparent density, open and total porosity, water absorption coefficient by capillarity, water absorption at atmospheric pressure measured before and after freeze-thaw cycles, compressive and flexural strength measured before and after freeze-thaw cycles, rupture energy, abrasion resistance and Knoop hardness.

Since several authors (Bell, 1978; Dobereiner & De Freitas, 1986; Ulusay *et al.*, 1994; Bell & Lindsay, 1999; Plachik, 1999; Jeng *et al.*, 2004; Tamrakar *et al.*, 2007) have shown that the chemical, mineralogical and petrographic features may affect the physical and mechanical behavior of sandstones, their influence was also evaluated in this research.

Sampling and analytical methods

A total of 10 fresh rock samples were collected from two working quarries opened near the villages of Matraia (Matraia quarry, samples MT1-MT6) and Pontremoli (Pian di Lanzola quarry, samples LN1-LN4) (see Fig. 1).

XRF analysis was used to determine major chemical elements on powdered bulk samples (Franzini *et al.*, 1975). Loss on ignition (LOI) and CO_2 were determined at 950°C on powders previously dried at 105 ± 5°C and through calcimeter method (Leone *et al.*, 1988), respectively. The difference between LOI and CO_2 contents was ascribed entirely to H_2O^+.

Mineralogical analysis was carried out through XRPD of the total sample (random powder diffractogram) and the < 4 μm fraction (diffraction diagram of oriented aggregate). The nature of the clay minerals was examined on oriented aggregate slides after treatment with Mg^{2+} and K^+ solutions. The Mg^{2+} saturated specimens were measured in both air-dried (AD) and ethylene glycol-saturated (EG) states, while the K^+ saturated specimens were measured at room temperature as well as after heating at 100, 300 and 550°C.

To observe the petrographic features (EN 12407 and EN 12670) of the studied sandstones, at least one covered thin section was prepared for each sample.

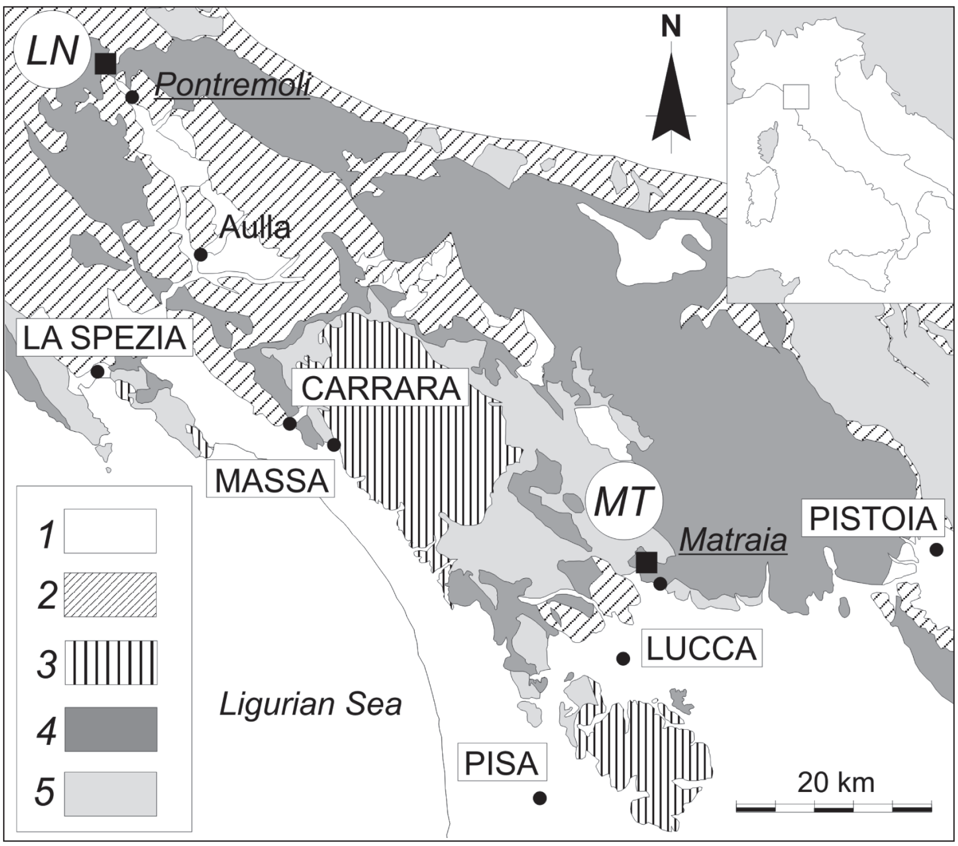

Fig. 1 - Simplified geological map of the north-western Tuscany. 1 = Quaternary and Pliocene; 2 = External and internal Ligurian Units; 3 = Tuscan metamorphic Units; 4 = Macigno Formation belonging to the Tuscan non-metamorphic Unit; 5 = Pre-Oligocene sequence of the Tuscan non-metamorphic Unit. ■ = sampling sites of the «Macigno» sandstones: Matraia (MT) and Pian di Lanzola (LN) quarries.

All standard test pieces used for measuring physical and mechanical properties according to European Standards/Norms (EN) were obtained by cutting to size only two samples MT6 and LN1.
Determination of real and apparent densities, and total and open porosities was performed according to EN 1936 indications. Water absorption coefficient by capillarity was measured on a specimen surface with normal orientation of the water-rising axis with respect to the existing planes of anisotropy (EN 1925). Water absorption by total immersion at atmospheric pressure was measured both before and after 48 freeze-thaw cycles (EN 12371) according to EN 13755. Compressive strength and flexural strength under concentrated load were measured on specimen with normal orientation of the load axis with respect to the existing planes of anisotropy both before and after 48 freeze-thaw cycles (EN 12371), according to EN 1926 and EN 12372 indications, respectively. Rupture energy, i.e. the resistance of a stone to fail under impact, was measured according to EN 14158. Abrasion resistance was carried out by abrading the face of a specimen through wide wheel abrasion test (EN 14157). Knoop hardness was measured following the EN 14205 indications.
All the original data of the studied samples can be found online at the website: http://www.dst.unipi.it/min.

RESULTS AND DISCUSSION

Petrography, mineralogy and chemistry

The new chemical, mineralogical and petrographic data collected in the present study on six samples from MT and four samples from LN are in good agreement with those previously reported by several authors (Cipriani, 1958, 1961; Gazzi, 1965; Cipriani & Malesani, 1972; Valloni, 1978; Reutter *et al.*, 1980; Deneke & Gutnther, 1981; Cipriani *et al.*, 1985; Valloni *et al.*, 1991; van de Kamp & Leake, 1995; Bargossi *et al.*, 1998; Morandi & Tateo, 1998; Dinelli *et al.*, 1999; Di Battistini & Rapetti, 2003; Franzini *et al.*, 2007).
From the petrographic point of view, the studied sandstones are medium- or fine-grained rocks, moderately sorted with angular to sub-angular detrital grains and grey to bluish-grey in colour.
Table 1 reports the simplified modal compositions of the examined sandstones; sporadic limestone grains and carbonate cement are grouped in the «calcite» class.
At least 200 points were counted for modal analysis using Gazzi-Dickinson's method that lowers compositional variation depending on grain size (Ingersoll *et al.*, 1984). Data of Table 1 show that samples from MP and LN are composed principally of quartz and plagioclase with subordinate K-feldspar. The total contents of quartz and plagioclase range from 35.5% (sample LN3) to 43.8% (sample MT1), and from 16.9% (sample MT4) to 28.8% (sample LN1), respectively. Quartz/Feldspar ratio is 1.14 ± 0.10 and it is rather constant in all examined samples. The remaining detrital minerals consist of phyllosilicates (mica-like minerals and chlorites s.l.), accessory minerals such as zircon, garnet, apatite, epidote, pyrite and spinels, and a fine-grained, clay-rich intergranular material that in Table 1 is indicated as silicatic matrix. Carbonates, consisting essentially of calcite, occur as sporadic limestone fragments and authigenic cement. The total carbonate content ranges from 3.8% (sample LN1) to 8.5% (sample LN3) with an average content of about 5%. Granites, low

Tab. 1 - Simplified modal composition and grain size of the Macigno sandstones from Matraia (MT) and Pian di Lanzola (LN) quarries.

Sample	Qz	K-f	Pl	Phyll.	Cc	Am	Rf	Ma
MT1	43.8	8.5	23.5	8.5	5.3	< 0.1	2.6	7.8
MT2	38.8	10.6	25.5	8.8	4.7	0.5	1.4	9.7
MT3	38.5	12.9	24.6	9.4	4.7	< 0.1	3.5	6.4
MT4	37.9	14.5	16.9	8.9	7.3	0.8	4.0	9.7
MT5	38.0	13.3	22.7	7.2	5.0	0.6	3.3	9.9
MT6	38.2	13.3	20.2	7.5	5.2	1.7	3.5	10.4
Mean	*39.20*	*12.18*	*22.23*	*8.38*	*5.37*	*0.60*	*3.05*	*8.98*
St. Dev.	*2.28*	*2.21*	*3.18*	*0.86*	*0.98*	*0.63*	*0.93*	*1.55*
LN1	40.2	8.3	28.8	9.1	3.8	< 0.1	1.5	8.3
LN2	39.0	11.4	22.4	9.0	4.8	1.0	3.8	8.6
LN3	35.5	8.5	22.0	11.9	8.5	< 0.1	3.4	10.2
LN4	38.4	8.6	24.3	12.9	5.7	2.9	2.9	4.3
Mean	*38.28*	*9.20*	*24.38*	*10.73*	*5.70*	*0.98*	*2.90*	*7.85*
St. Dev.	*2.00*	*1.47*	*3.12*	*1.98*	*2.02*	*1.37*	*1.00*	*2.51*

Qz = quartz; K-f = K-feldspar; Pl = plagioclases; Phyll. = mica-like minerals and chlorites s.l.; Cc = calcite including sporadic limestone fragments and authigenic cement; Am = accessory minerals; Rf = non-carbonate rock fragments; Ma = silicotic matrix.

to medium metamorphic rocks (phyllites and schists) and minor amount of felsic volcanics, gabbro, diabase and serpentine are the prevalent lithic fragments. Mafic silicates present in gabbro and diabase fragments are generally altered to chloritic material, while feldspars are variably altered to sericite.

According to the Dickinson's classification (1985) all the studied sandstones are arkosic arenites (Fig. 2).

Computer-assisted image analysis was successfully used to derive quantitative textural data on quartz grains of these rocks. This method provides in a relatively short time a large number of different measurements such as grain size, particle shape and 2D orientation of particle main axes. Area (A), perimeter (P), major (D) and minor diameter (d), and orientation of the quartz particles were measured. From these measurements some petrographic parameters are derived according to Russ & DeHoff (2000) such as equivalent diameter (D_e), form factor (FF), sphericity (S) and elongation (E). The detailed definitions of the petrographic parameters used in this work are reported in Appendix A.

Table 2 reports the mean values and the standard deviations of some petrographic parameters of quartz grains derived from quantitative textural data measured on samples from MT and LN.

All derived shape-factors of quartz grains are very similar for the «Macigno» sandstones from each sampled quarry. As far as equivalent diameter, form factor, sphericity and elongation were concerned, mean values range from 0.08 mm (sample LN3) to 0.13 mm (samples LN1 and LN2), from 0.80 (samples LN1 and LN2) to 0.88 (sample LN3), from 0.81 (sample LN4) to 0.85 (samples MT2, MT3 and MT4) and from 0.67 (sample LN4) to 0.74 (samples MT2 and MT3), respectively. In particular, samples MT6 and LN1, used for measuring physical and mechanical properties according to European Standards/Norms (EN), show similar values of equivalent diameter, form factor, sphericity and elongation.

The chemical analyses obtained on bulk rock samples are reported in Table 3.

As expected on the basis of the mineralogical and petrografic data, the chemical compositions show a small range of variation. According to van de Kamp & Leake opinions (1995), the high silica, alumina and alkalies contents are probably due to degradation of rocks belonging to a pre-existent granitic basement whilst the MgO and Fe_2O_3 high contents can be accounted by mafic and ultramafic rocks. From the CO_2 measured values, the major carbonate content of the analysed rocks can be estimated about 9% by weight (sample LN3).

As previously reported by Franzini *et al.* (2007), XRPD study on oriented aggregates of < 4 µm fraction reveals that the phyllosilicate fraction (Phyll. and Ma classes of Tab. 1) of the «Macigno» sandstones from Pian di Lanzola quarry consists of major chloritic material made up of discrete chlorite (Chl) and chlorite/smectite mixed-layers (Chl/S) and, subordinately, micaceous materials (mica-like minerals), with biotite as minor phase. No substantial differences were found in the examined samples from Matraia quarry.

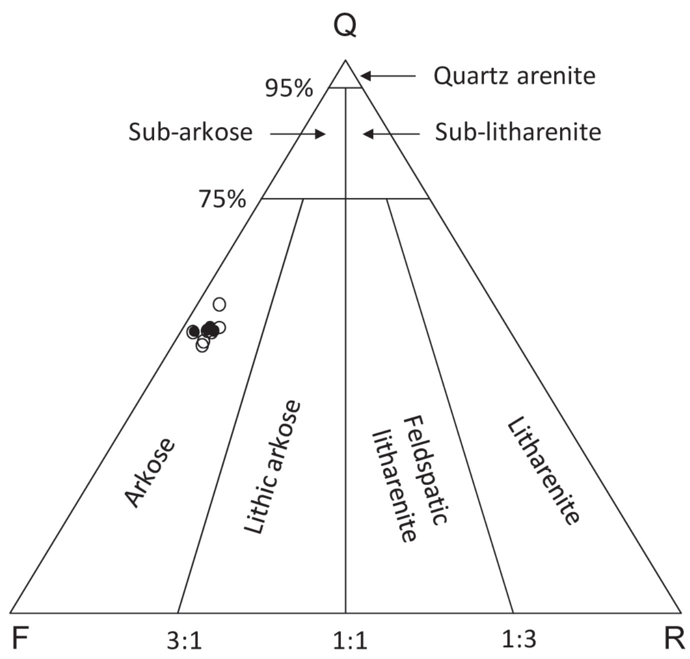

Fig. 2 - QFR ternary diagram showing the compositions of the «Macigno» sandstones studied in this work in the classification of Dickinson (1985). Q = quartz; F = feldspars; R = rock fragments.

Tab. 2 - Calculated petrographic parameters of the quartz grains in the «Macigno» sandstones from Matraia (MT) and Pian di Lanzola (LN) quarries.

Sample	D_e (mm)	FF	S	E
MT1	0.11 ± 0.07	0.82 ± 0.19	0.84 ± 0.11	0.72 ± 0.18
MT2	0.10 ± 0.05	0.86 ± 0.15	0.85 ± 0.10	0.74 ± 0.18
MT3	0.11 ± 0.06	0.86 ± 0.15	0.85 ± 0.10	0.74 ± 0.17
MT4	0.11 ± 0.07	0.83 ± 0.18	0.85 ± 0.11	0.73 ± 0.18
MT5	0.12 ± 0.07	0.81 ± 0.19	0.84 ± 0.11	0.72 ± 0.18
MT6	0.12 ± 0.08	0.81 ± 0.19	0.84 ± 0.11	0.72 ± 0.18
LN1	0.13 ± 0.09	0.80 ± 0.20	0.83 ± 0.11	0.71 ± 0.18
LN2	0.13 ± 0.09	0.80 ± 0.21	0.83 ± 0.11	0.71 ± 0.18
LN3	0.08 ± 0.07	0.88 ± 0.26	0.83 ± 0.12	0.71 ± 0.19
LN4	0.09 ± 0.08	0.84 ± 0.28	0.81 ± 0.13	0.67 ± 0.21

D_e = equivalent diameter; FF = form factor; S = sphericity; E = elongation.

Tab. 3 - Chemical composition of the «Macigno» sandstones from Matraia (MT) and Pian di Lanzola (LN) quarries.

Sample	H_2O^+	CO_2	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	$Fe_2O_3^*$
MT1	2.60	2.28	2.56	7.07	13.35	60.40	0.11	2.62	4.61	0.45	0.06	3.89
MT2	2.40	2.09	2.42	6.89	13.86	59.99	0.13	2.71	4.61	0.50	0.06	4.34
MT3	2.20	2.00	2.08	5.52	13.32	64.50	0.12	2.54	3.44	0.40	0.05	3.83
MT4	2.03	3.45	2.12	5.81	12.46	61.23	0.10	2.59	5.93	0.43	0.07	3.78
MT5	2.37	2.83	2.29	3.25	12.15	66.04	0.13	2.45	4.24	0.48	0.06	3.71
MT6	2.38	2.30	2.50	3.27	12.05	67.17	0.14	2.30	3.61	0.48	0.06	3.74
Mean	*2.33*	*2.49*	*2.33*	*5.30*	*12.87*	*63.22*	*0.12*	*2.54*	*4.41*	*0.46*	*0.06*	*3.88*
St. Dev.	*0.19*	*0.55*	*0.20*	*1.69*	*0.74*	*3.08*	*0.01*	*0.14*	*0.89*	*0.04*	*0.01*	*0.23*
LN1	1.79	2.25	2.53	4.66	13.38	64.89	0.12	2.56	3.68	0.44	0.08	3.62
LN2	2.02	2.43	2.63	5.35	14.90	62.58	0.13	2.39	3.21	0.50	0.07	3.79
LN3	2.12	3.96	2.37	4.50	13.21	57.83	0.10	3.22	8.35	0.45	0.11	3.78
LN4	2.08	1.64	2.51	5.59	14.06	62.56	0.11	2.96	4.05	0.43	0.06	3.95
Mean	*2.00*	*2.57*	*2.51*	*5.03*	*13.89*	*61.97*	*0.12*	*2.78*	*4.82*	*0.46*	*0.08*	*3.79*
St. Dev.	*0.15*	*0.99*	*0.11*	*0.53*	*0.77*	*2.97*	*0.01*	*0.38*	*2.38*	*0.03*	*0.02*	*0.13*

* = total iron expressed as Fe_2O_3.

Physical and mechanical properties

Water absorption, densities and porosities

The range of water absorption by total immersion at atmospheric pressure (A_b) is small, it extends from 0.26 to 0.34% on specimens from Matraia quarry and from 1.03 to 1.13% on specimens from Pian di Lanzola quarry. Instead, it is clear that an appreciable difference of open pore spaces is present among the rocks from the two quarries. The average value of water absorption determined on fourteen specimens from Matraia quarry (0.29 ± 0.02% by weight) is lower, about a third, than the value obtained on seven specimens from Pian di Lanzola quarry (1.09 ± 0.04% by weight).

After 48 freezing and thawing cycles, the values of water absorption of the «Macigno» sandstones from Matraia (MT) and Pian di Lanzola (LN) quarries have a little change for the worse, testifying a good resistance of these sandstones to natural decay processes due to frost action.

The mean value of real density (ρ_r) measured through an automatic He-pycnometer on six dried powders of MT6 sample (2710 ± 10 kg/m^3) is rather similar to that obtained on six dried powders of LN1sample (2720 ± 10 kg/m^3). Measured values of the real density are in good agreement with mineralogical data.

Apparent density (ρ_b), i.e. the mass of solid particles per the total volume of rock, is one of the basic properties of a stone, and it is rather influenced by both specific gravities of the rock-forming minerals and the amount of void spaces. As can be seen from Table 4, the range of apparent densities of the tested specimens is small, from 2669 to 2685 and from 2615 to 2625 kg/m^3, respectively, for specimens from Matraia and Pian di Lanzola quarries. All the samples have high density according to Anon. (1977).

Like water absorption, total (P) and open (P_0) porosities, i.e. respectively, the ratio between the volume of open and closed pores and the apparent volume of the specimen, and the ratio between the volume of only open pores and the apparent volume of the specimen, are useful to assess the durability of stone, specially its resistance against progressive deterioration under exposure to severe climate, and leaching due to prolonged seepage of water. As can be seen from Table 4, the «Macigno» sandstones from Matraia and Pian di Lanzola quarries have rather low porosity and the average values of total and open porosity determined on fourteen specimens from Matraia quarry ($P = 1.3 \pm 0.1\%$ and $P_0 = 0.8 \pm 0.1\%$ by volume) are lower, about a third, than the values obtained on seven specimens from Pian di Lanzola quarry ($P = 3.7 \pm 0.2\%$ and $P_0 = 2.9 \pm 0.1\%$ by volume).

Water absorption coefficient by capillarity

On six specimens with normal orientation of the axis of water rising with respect to the existing planes of anisotropy of MT6 sample from Matraia quarry and on six specimens of LN1 sample from Pian di Lanzola quarry in the same way oriented, the water absorption coefficient by capillarity (C1) (EN 1925) was measured.

It is clear from Figure 3 that the values of water absorption coefficient by capillarity form a straight lines about until 48 hours and that the angle of inclination deter-

Tab. 4 - Main physical and mechanical properties of the Macigno sandstones from Matraia (MT) and Pian di Lanzola (LN) quarries.

Commercial name	Pietra di Matraia					Pietra di Pian di Lanzola				
Geological formation	Macigno sandstone					Macigno sandstone				
Petrographic name	Arenitic arkoses					Arenitic arkoses				
Quarry	Matraia (MT)					Pian di Lanzola (LN)				
City/Province	Capannori/Lucca					Pontremoli/Massa				
Country	Italy					Italy				
Physical and mechanical properties	**n.**	**min.**	**max.**	**mean**	**s**	**n**	**min.**	**max.**	**mean**	**s**
Real density (kg/m^3)	6	2700	2720	2710	10	6	2700	2730	2720	20
Apparent density (kg/m^3)	14	2669	2685	2676	4	7	2615	2625	2619	4
Open porosity (vol. %)	14	0.7	0.9	0.8	0.1	7	2.7	3.0	2.9	0.1
Total porosity (vol. %)	14	0.9	1.5	1.3	0.1	7	3.5	3.9	3.7	0.2
Water absorption at atmospheric pressure (wt. %)	14	0.26	0.34	0.29	0.02	7	1.03	1.13	1.09	0.04
Water absorption at atmospheric pressure (wt. %) after 48 freezing and thawing cycles (according to EN 12371)	14	0.27	0.35	0.31	0.02	7	1.10	1.18	1.15	0.03
Water absorption coefficient by capillarity ($g/m^2\ s^{0.5}$)	6	1.083	1.333	1.220	0.086	6	2.777	3.208	2.991	0.149
Uniaxial compressive strength (MPa)	8	124.51	154.35	142.1	11.8	7	111.05	150.09	136.1	12.1
Uniaxial compressive strength (MPa) after 48 freezing and thawing cycles (according to EN 12371)	20	102.27	155.17	132.2	14.4	7	107.20	135.74	123.1	10.4
Flexural strength (MPa) under concentrated load	10	22.52	26.85	24.7	1.6	10	14.16	15.72	15.0	0.5
Flexural strength (MPa) under concentrated load after 48 freezing and thawing cycles (according to EN 12371)	10	23.11	26.98	25.0	1.5	10	14.55	15.74	15.3	0.4
Impact resistance, rupture energy (J)	6	10.9	11.8	11.4	0.3	6	9.2	9.7	9.4	0.3
Abrasion resistence (mm)	6	18	19	19.0	0.5	6	21	22	21.5	0.5
Knoop hardness HK (MPa)	3	3486	3634	3574	78	3	3198	3607	3449	219
HK_{75}/HK_{25}	3	2.2	3.0	2.6	0.6	3	2.9	5.0	4.0	1.5

n. = number of specimens; min. = minimum value; max. = maximum value; mean = average value; s = standard deviation.

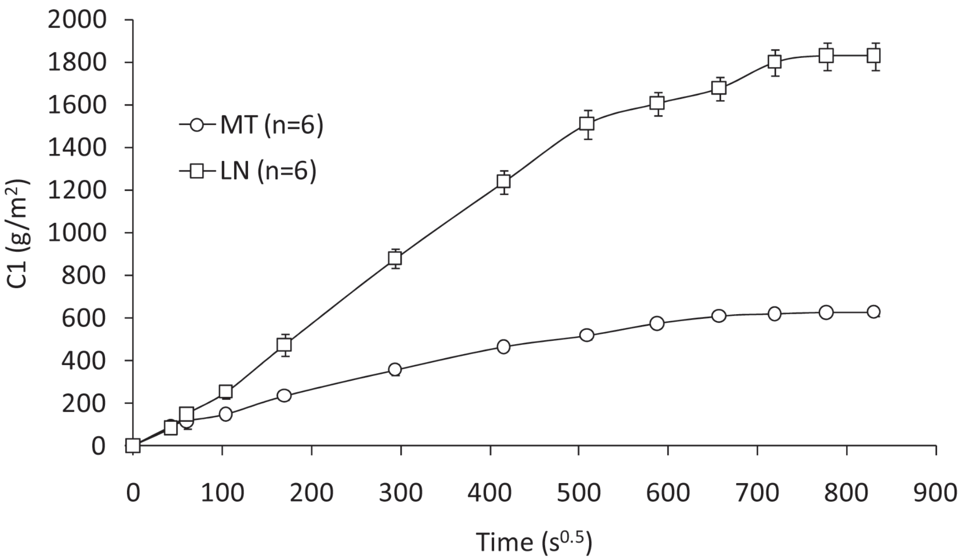

Fig. 3 - Mean trend of water absorption coefficient by capillarity during the measuring time expressed as square root of seconds.

mined on MT specimens is lower than the angle of inclination on LN specimens. It stands for larger pores of the specimens from Pian di Lanzola quarry than those from Matraia quarry.

Strength, rupture energy, abrasion resistance and hardness

«Macigno» sandstones from Matraia and Pian di Lanzola quarries were tested in compressive strength both before and after 48 freeze-thaw cycles measuring specimens with normal orientation of the load axis with respect to the existing planes of anisotropy.

Compressive strength, i.e. the load per unit area at which a cubic specimen of stone will fail in a simple compression test, is useful to select the stone suitable for various purposes and to predict long term performance.

The range of uniaxial compressive strength varies between 124.51 and 154.35 MPa, with a mean value of 142.1 MPa on specimens from Matraia quarry and between 111.05 and 150.09 MPa, with a mean value of 136.1 MPa on specimens from Pian di Lanzola quarry (Tab. 4).

All tested rocks are very strong sandstones according to the strength classification of Anon. (1977).

After 48 freeze-thaw cycles, the sandstones underwent scanty but appreciable reductions when compared with their dry equivalent samples (Tab. 4). These reductions in strength vary respectively from 7% to 10% for Matraia and Pian di Lanzola samples.

Samples of sandstones from Matraia and Pian di Lanzola quarries also were subjected to a process of deformation normal to the axis of existing planes of anisotropy when a moment is applied normal to its axis. The flexural strength is a property useful to find the suitable thickness of slabs used for load bearing applications like tabletops, park benches, kitchen tops, etc.

Flexural strength varies between 22.52 and 26.85 MPa on specimens from Matraia quarry and between 14.16 and 15.72 MPa on specimens from Pian di Lanzola quarry (Tab. 4). The mean value of flexural strength measured on samples from Matraia quarry (24.7 MPa) is significantly higher than the mean value measured on samples from Pian di Lanzola quarry (15.0 MPa).

After 48 freeze-thaw cycles, the sandstones from Matraia and Pian di Lanzola quarries did not underwent appreciable reductions when compared with their dry equivalent samples (Tab. 4).

The resistance of sandstones to fail under impact was measured on six specimens for each examined quarry according to EN 14158. This property is useful to determine resistance of the stone to failure under impact when exposed to rough usage, as occurs on steps, flooring, warehouses, and so on.

The range of impact resistance varies between 10.9 and 11.8 J, with a mean value of 11.4 J on specimens from Matraia quarry and between 9.2 and 9.7 J, with a mean value of 9.4 J on specimens from Pian di Lanzola quarry (Tab. 4).

As would be expected, there is a significant relationship between the impact resistance and the flexural strength, and little less the compressive strength.

Abrasion resistance of the examined sandstones to mechanical wearing, grinding, scraping or rubbing away of stone surfaces by friction or impact, or both, can be useful to evaluate the resistance of stone when used as steps, flooring, pavements of buildings, traffic like road, airports, railway stations, etc.

As can be seen from Table 4, the range of abrasion resistance of the tested specimens show very little variations considering samples from same quarry, it extending from 18 to 19 mm on specimens from Matraia quarry and from 21 to 22 mm on specimens from Pian di Lanzola quarry. Instead, it is clear that an appreciable difference of resistance is present in the rocks from two sampled quarries. The average value of abrasion resistance determined on six specimens from Matraia quarry (19.0 ± 0.5 mm) is lower that the value obtained on six specimens from Pian di Lanzola quarry (21.5 ± 0.5 mm).

The indentation resistance was determined by a Leitz durimeter, which measure the Knoop microhardness. An average of 40 readings by using a load of 1.96 N was taken from three samples for each sampled quarry. The property is useful to assess the type and quantity of the various mineral constituents of the stone and to evaluate the bond strength that exists between the mineral grains.

The range of values for Knoop hardness (HK) measured on samples from Matraia quarry extends from 3486 to 3634 MPa, with an average value of 3574 MPa, whilst that on samples from Pian di Lanzola quarry varies between 3198 and 3607 MPa, the average value being 3449 MPa.

As can be seen from Table 4, the HK_{75}/HK_{25} ratio determined on specimens from Matraia quarry (2.6 ± 0.6) is lower than that obtained on specimens from Pian di Lanzola quarry (4.0 ± 1.5). It stands for presence of higher quartz/matrix ratio of the samples from Pian di Lanzola quarry respect to the samples from Matraia quarry.

Conclusions

The examined rocks are sandstones belonging to «Macigno» Formation that are quarried in the north-western Tuscany from two working quarries opened near the villages of Matraia (Matraia quarry) and Pontremoli (Pian di Lanzola quarry) about 70 km away the one from the other.

These sandstones are medium- or fine-grained, moderately sorted with angular to sub-angular detrital grains, and grey to bluish-grey in colour. They contain principally quartz (35.5-43.8 vol. %), plagioclase (16.9-28.8%) and K-feldspar (8.3-14.5%). The remaining detrital minerals consist of phyllosilicates (7.2-12.9%), accessory minerals (< 0.1-2.9%) and silicatic matrix (4.3-10.4%). Carbonates, consisting essentially of calcite, occur as sporadic limestone fragments and authigenic cement (3.8-8.5%). The lithic fragments are scarce (1.4-4.0%). Accordingly, all these studied sandstones are classifiable as arkosic arenites.

The main physical and mechanical properties of the studied sandstones are summarised in Table 4 and they can be compared with those obtained on other sandstones of the Northern Apennines.

Synthetically, the physical and mechanical data, measured according to European Standards/Norms (EN), indicate that the examined sandstones from the north-western Tuscany extractive districts are to be regarded as stones:

– heavy and compact, on the basis of the values of apparent density (2615-2685 kg/m^3) and total porosity (0.9-3.9 vol. %);
– characterized by both low open porosity (0.7-3.0 vol. %) and a low degree of water absorption at atmospheric pressure (0.26-1.13 wt. %);
– with high strength for both compression (> 110 MPa), flexure (> 14 MPa) and impact (> 9 J) stress, if compared with other sandstones;
– un-affected by freeze-thaw cycles.

Compared to samples from Pian di Lanzola quarry, the sandstones from Matraia quarry are top-level stones showing a lower value of porosity and water absorption as well as a significantly higher value of flexural strength under concentrated load. In fact, the mean values of porosity, water absorption and flexural strength measured on samples from Matraia and Pian di Lanzola quarries vary, respectively, from 1.3 to 3.7 vol. %, 0.29 to 1.09 wt. % and 24.7 to 15.0 MPa.

Overall, the physical and mechanical characteristics explain the durability of these sandstones to natural and artificial decay processes, confirming their suitability for use as building material and decorative stone. Collected data were used here to compare the engineering properties of the «Macigno» sandstone from Matraia and Pian di Lanzola quarries and they will represent, in the near future, an interesting starting point to understand how the physical and mechanical properties affect the durability of this stone in a number of differing environments and use conditions.

Appendix A
Definition and determination of petrographic parameters

A1. Equivalent diameter

The equivalent diameter (D_e) was calculated with the following formula:

$$D_e = \sqrt{(4 \cdot A/\pi)}$$

where A is the area of the particle plane.

A2. Form factor

The form factor (FF) of the grain is defined as

$$FF = 4 \cdot \pi \cdot A/P^2$$

where A is the area of the particle plane, and P is the perimeter of the particle plane.

A3. Sphericity

The sphericity (S) of the grain was calculated by using the following formula:

$$S = D_e/D$$

where D_e is the equivalent diameter of the particle plane and D is the major diameter of the particle plane.

A4. Elongation

The elongation (E) of the grain is defined as:

$$E = d/D$$

where d and D are the minor and the major diameter of the particle plane, respectively.

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