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CHARACTERIZATION OF HISTORICAL MASONRY MORTAR FROM SITES DAMAGED DURING THE CENTRAL ITALY 2016-2017 SEISMIC SEQUENCE: THE CASE STUDY OF ARQUATA DEL TRONTO

MORTARS FROM ANCIENT TOWNS IN CENTRAL ITALY (40 characters)

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Abstract

Mortar quality is a fundamental parameter to take into account when studying the structural behavior of masonry, especially under seismic actions. Separation between the leaves of rubble masonry can occur, inducing the partial or total collapse of the construction. A good quality mortar is essential to delay/prevent the separation of leaves, but often, especially in ancient building with a cultural value, mortars have low binder capabilities.
The paper presents an experimental investigation on mortar specimens taken from buildings of a little municipality in Marche region, Arquata del Tronto, heavily damaged by recent earthquakes in Central Italy (2016-2017). Both diagnostic techniques as X-Ray diffraction, Fourier-Transform infrared spectroscopy and calcimetry, and mechanical test as compression tests were carried out in order to correlate the obtained values with the performance of the original masonry.

1. Introduction

The damage caused by the 2016-2017 Central Italy earthquakes to architectural heritage in the municipalities of Marche region were very high. In Arquata del Tronto, a small town in the province of Ascoli Piceno, the earthquakes caused collapses and damage of churches, monuments and cultural heritage, as well of buildings in small neighboring villages.

From the macro-seismic point of view the municipality of Arquata, as well as the other localities in the same area, was historically subjected to significant earthquakes interspersed with periods of seismic inactivity: as shown in table 1, in which only recent seismic events with a level of damage greater than or equal to the VI MCS are reported, it is possible to note that a long period of calm goes from the shock on May 12th, 1730 (VII-VIII MCS) to that on July 4th, 1916 (VII MCS).

Table 1. Recent earthquakes in Central Italy with a level of damage greater than or equal to the VI MCS [Locati et al., 2016; Albini et al., 2016]

MCS ≥ VI	Date	Epicenter
IX	January 14th, 1703	Valnerina
VII-VIII	May 12th, 1730	Valnerina
VII	July 4th, 1916	Sibylline Mountains
VI	April 7th, 1930	Sibylline Mountains
VI	December 19th, 1941	Sibylline Mountains
VI	January 29th, 1943	Sibylline Mountains
VI	October 3rd, 1943	Area of Ascoli Piceno
VI-VII	September 5th, 1950	Gran Sasso d'Italia
VI-VII	November 26th, 1972	Southern Marche
VI	September 19th, 1979	Valnerina
VIII-IX	August 24th, 2016	Area of Amatrice

The shock on August 24th, 2016 caused damage associated to the IX degree of the MCS. Although damage was more severe in the surrounding villages, only a few buildings collapsed in the main square, whereas all the others were damaged. With the event on October 30th of the same year (fig. 1) the scenario changed radically: Arquata was completely destroyed. The Italian Army and the firefighters started the debris removal and the realization of a *tabula rasa* in all the Arquata promontory.

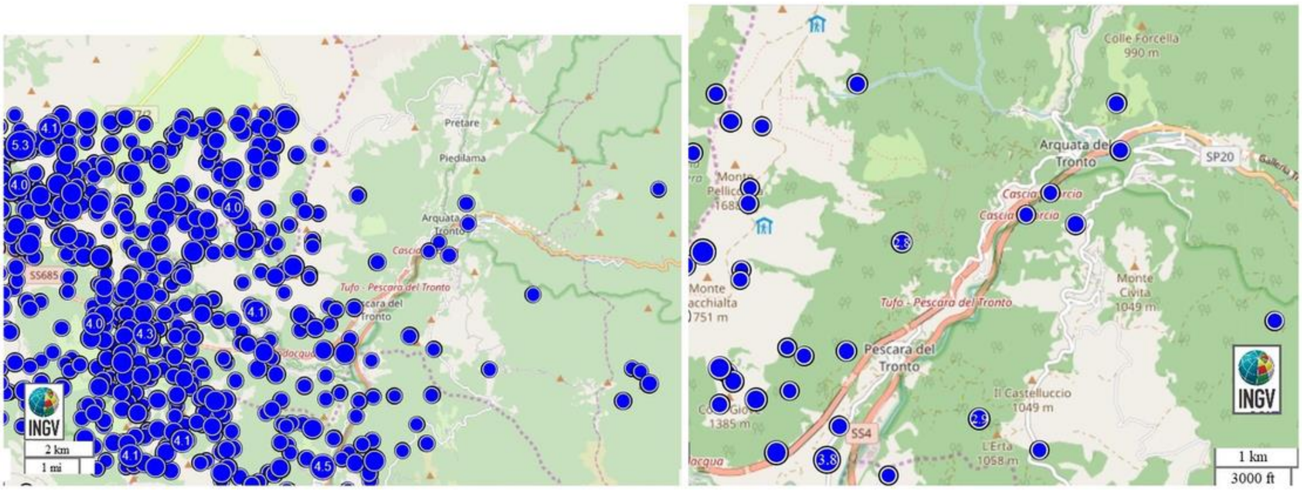

Fig. 1. Earthquakes registered, between 2016 and 2017, in the area surrounding Arquata del Tronto with magnitude higher than 2.5. The events of magnitude from 3.8 to 4.1 on October 30th, 2016 are shown. Left, larger scale; right, smaller scale (source: INGV[1])

[1] Data and results published on this website by Istituto Nazionale di Geofisica e Vulcanologia (http://www.ingv.it/) are licensed under a Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/). ISIDe Working Group at National Earthquake Center (http://cnt.rm.ingv.it/) benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri, Dipartimento della Protezione Civile.

The 2016 seismic sequence affected a portion of the Apennines characterized by the outcrop of turbiditic sandstones (Laga Flysch, Messinian), limestones and pelagic marly limestones of the Umbro-Marchigiana series (Mesozoic) (fig. 2). These lithologies are the most common construction material of the buildings erected until the sixties of the last century, as well as of all the monumental buildings as churches, castles, towers and convents. An in-depth study on the architectural heritage in the territory of Arquata del Tronto shows that the masonry structures follow a building practice which changed during time, entailing substantial variations of their load bearing capacity. Local materials were used for masonry, with differences between the zones north and south of river Tronto.

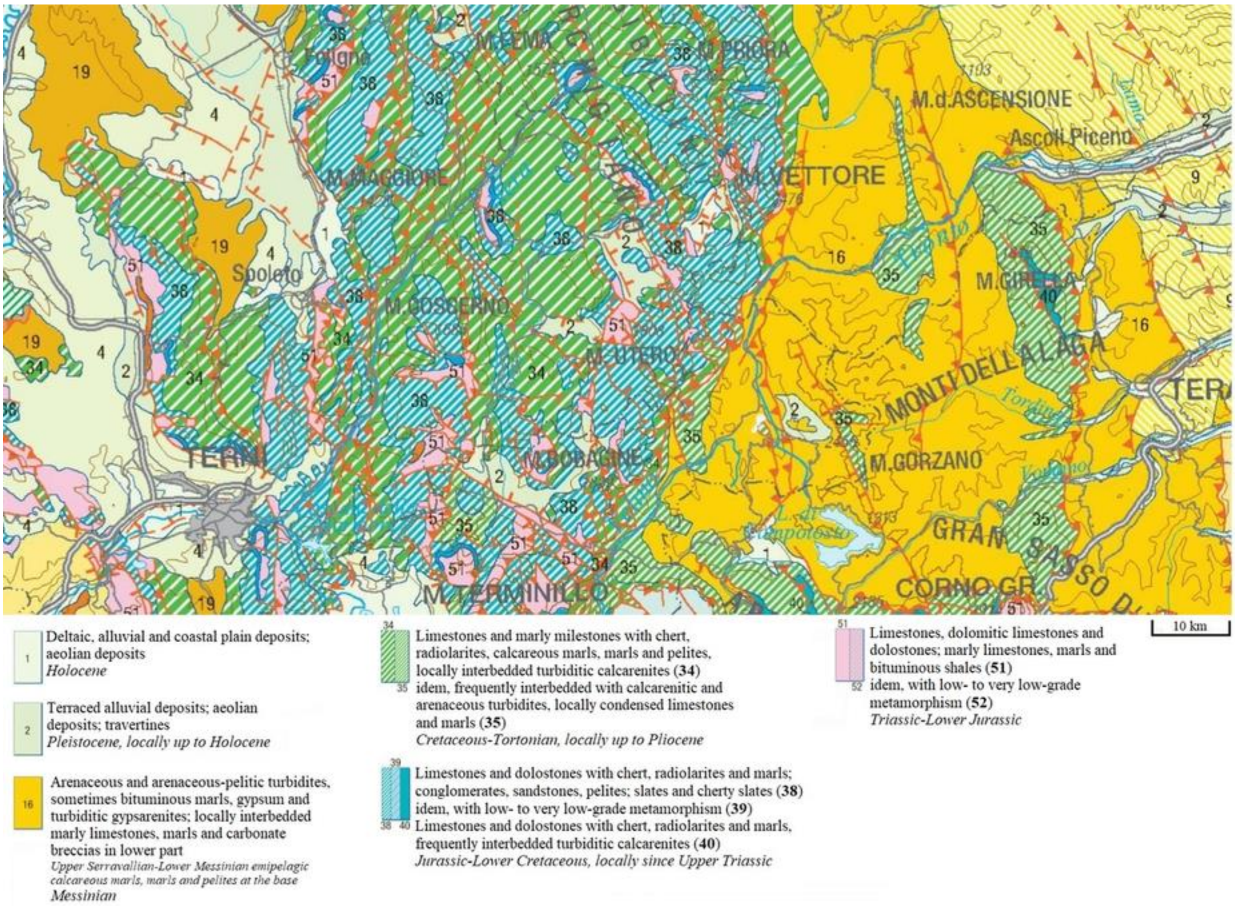

Fig. 2. Geological map (1:1000000) relative to Arquata del Tronto and surroundings (source: ISPRA[2])

The southern zone is characterized by sandstone mixed with river pebbles, with rare brick units, whereas the northern zone by limestones added to masonry. The masonry fabric consists of irregularly rough-hewed units and chips of natural materials. The mortar is poor of lime and particularly crumbly. Irregularities are compensated by plentiful mortar. A limited compliance of the horizontal orientation can be observed. Sometimes the horizontality of courses is provided by the insertion of brick wedges. The offset of head joints is nearly absent. Several buildings are in complete abandonment since decades, and some of them were near collapse already before the earthquake. At the same time there are inhabited buildings in normal maintenance conditions, where relatively recent interventions were carried out, with ring beams and roofs in reinforced concrete, in some cases with smooth rebars, not linked each other and without hoops. As already observed after

[2] www.isprambiente.gov.it.

the 1997 Umbria-Marche earthquake and the 2009 L'Aquila earthquake, these intervention, without a proper consolidation of the vertical structure, usually entailed widespread collapses.

Although it is aware that the seismic effects on structures depend on a plurality of factors, like the energy released by the earthquake, the geological characteristics of the site, the type of foundation, the original materials and techniques, but also the state of conservation of the buildings and possible maintenance actions occurred during the time [Guidoboni and Ferrari, 2009], developing a methodology to define mortar quality would be very useful to interpret the mutual relationship and the correlation between earthquake and damage. With this aim, a sampling campaign in Arquata and its neighboring villages was carried out, in order to chemically and mechanically characterize the mortar and correlate the obtained values with the performance of the original masonry.

2. Experimental setup or method

Twenty-four mortar samples have been collected, under the supervision of firefighters, from historical and monumental buildings located in different settlements within the municipality of Arquata del Tronto (table 2 and fig. 3). Sampling has been performed with care considering only bedding mortars from collapsed or partially collapsed buildings.

Table 2. Mortar samples from settlements within the municipality of Arquata del Tronto

Settlement	Sample ID
	1
Arquata del Tronto	2
	3
	4
	5
Borgo	6
	7
	8
	9
	10
Camartina	11
	12
	13
Faete	14
	15
	16
	17
Pretare	18
	19
	20
	21
	22
Trisungo	23
	24

During sampling, for each mortar specimen a record card has been filled with: date, location, type of building, point of sampling, sample quantity (estimated).

Fig. 3. Mortar sampling campaign in Pretare - St. Rocco Church (Arquata del Tronto)

Firstly, an inspection of the samples collected has been carried out, in order to remove possible impurities and to exclude samples that presented effects of external agents. The inspection has been made in laboratory, both with naked eye and a stereomicroscope Olympus SZX12 with digital image acquisition.

Possible contaminations could be due to the collapse of the structure itself, causing contact with other materials, or from subsequent contact with external agents (natural or anthropic). For instance, some mortar samples have been excluded from the analysis as they presented the formation of plants probably due to exposure to a humid environment.

Then, to evaluate grain size distribution the samples have been firstly roughly cracked in smaller pieces and successively they have been sieved. Different mechanical treatments have been performed in dry conditions and the material passing through the sieve has been weighted and recovered [Groot et al., 1996]. Particle-size analysis was carried out using the following sieves: 2.000, 1.000, 0.500, 0.250, 0.106, 0.063 mm.

The samples were analysed by X-Ray diffraction in order to evaluate the type of binder and aggregate. This technique allows identifying crystalline phases, while the presence of amorphous phases generates broad halos in the pattern.

A SmartLab Rigaku powder diffractometer, equipped with Cu kα radiation source and a graphite monochromator in the diffracted beam, operated at 40kV and 30 mA, has been used. X-Ray diffraction powder patterns have been acquired within the angular range 2-90 2theta at a step size of 0.04 and 12 seconds per step. In order to enhance the binder fraction the disaggregated mortars have been sieved at 63 μm and the powder obtained has been successively grinded in order to further reduce particles dimensions [Carrara and Persia, 2001; Cardinale et al., 2002]. Some samples have been analysed also after removal of larger inert coarser granule and refining the powders using an agate mortar [Chiari et al., 1993].

Analysis by Fourier-Transform Infrared Spectroscopy (FT-IR) was carried out on mortar samples ground in a agate mortar and then passed completely through a 125 μm sieve. A Perkin Elmer Spectrum 100 was used in ATR mode (Total Reflected Reflectance). For each sample two acquisitions were performed.

Calcimetry has been performed, using the gas-volumetric Dietrich-Fruhling method. The sample was ground manually with an agate mortar until it was completely passed through a 63 μm sieve, then dried into a thermobalance at 60 °C up to constant mass. The sample was treated with a reagent based on hydrochloric acid, which decomposes the carbonates present by CO_2 development, as regulated by UNI 11140: 2004. This technique allowed to evaluate with greater precision, compared to the analysis in FT-IR spectroscopy ATR, the quantity of carbonates present in the samples (uncertainty: ± 0.1%).

Soluble salt content was estimated by conductometric measurements. From the conductivity value of the solutions, the formula indicated in the DIMOS document, part II module 3, ICR, 1978 was applied, estimating the percentage of soluble salts present in the samples. Analysis of soluble salts (UNI 11087: 2003) was carried out as following: the sample was dried in an oven at 60 °C for about 24 h, then ground manually within an agate mortar until it was completely passed through a 125 μm sieve. The samples were weighed (95 mg up to 105 mg) and treated into a thermobalance at a temperature of 60 °C up to constant mass. 100 ml of bi-distilled H_2O, whose conductivity was previously measured, were added to the sample and placed in a flat-bottomed glass container. The container was hermetically sealed to prevent evaporation and slowly stirred for 2h; then residuals were left to deposit for about 30 min; finally, conductivity was measured with a XS Multiparameter, model PC 70 (resolution: 0.1 μS). The obtained suspension was then filtered (black band filter) and the solution was used for the measurements of the single ionic species by ionic chromatography.

Concentration of anions contained in mortar under study has been measured with a Metrohm Ion Chromatograph 761 Compact with chemical integrated Metrohm suppressor module (MSM) and METROSEP A Supp. 5 150/4.0 separation column. Injection volume was typically 1.5 ml and the loop volume was 20 μl. Sartorius 0.45 μm RC-Membrane PP-Housing filters were used to remove particles. Three repetition for each analysis were performed. The method of calibration curve with increasing concentrations of standards has been used to calculate the concentration of anions.

Prismatic specimens were obtained from field samples, the edges were measured, the top and bottom faces were covered with plaster and a compression test was performed. The tests were performed under displacement control at a speed of 0.54 mm/min. Strain was calculated dividing the relative displacement between the load cell and the base plate by the initial distance. The measurement was not taken directly on the sample because of the large size of the aggregate. For each sample, the stress-strain curve was elaborated. The normalized compressive strength f_m was determined multiplying the nominal strength f by the shape factor δ:

$$f_m = \delta\, f \qquad (1)$$

The shape factor δ, which accounts for the sample geometry, was calculated according to [BS EN 772-1:2011 + A1:2015, 2015].

Since no standard is available for the determination of the modulus of elasticity of masonry mortar, that recommended for concrete was used [ASTM C 469 – 02, 2002]. Thus, the modulus of elasticity E is given by:

$$E = \frac{S_2 - S_1}{\varepsilon_2 - \varepsilon_1} \qquad (2)$$

where:

S_2 = 40% of the nominal compressive strength f;

S_1 = stress corresponding to strain ε_1;

ε_2 = strain corresponding to stress S_2;

ε_1 = 0.00005.

As for the measurement of strain, the beginning of the test was identified when the load was monotonically increasing under a prescribed monotonically increasing displacement.

3. Results and discussion

3.1 Sieving process and grain size distribution

Particle-size distribution highlighted the preponderance of a fine fraction in mortar samples, especially those from Pretare, as shown in fig. 4.

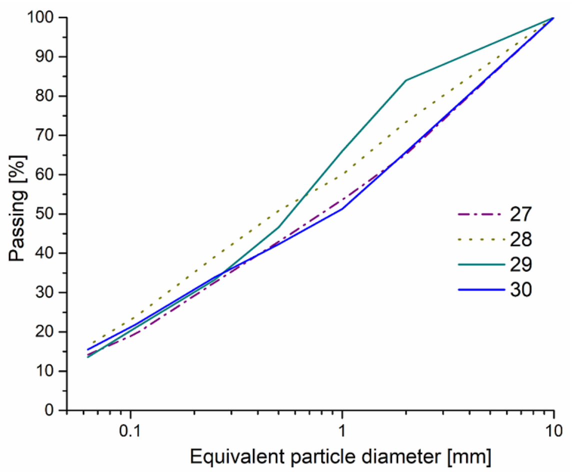

Fig. 4. Particle-size analysis

In some cases the finer fractions, smaller than 0.5 mm, constitute more than 40% of the entire aggregates.

3.2 X-Ray diffraction

In fig. 5 XRD patterns of mortars from Arquata del Tronto (1, 2, 3), Camartina (10, 11, 12, 13), Faete (14) and Trisungo (24) are shown. The samples from Arquata presented principally quartz, calcite, phyllosilicates, feldspars and dolomite, in particular in sample 2 and some traces of gypsum. Same phases were identified in the samples from Camartina, even if only traces of dolomite were present while gypsum was absent. Sample 11 from Camartina presented higher quantity of calcite with respect to the other samples. Material sampled in Faete revealed small quantity of calcite, being quartz the most abundant phase. The sample from Trisungo presented similar phases respect to those from Arquata but also gypsum and lower concentrations of calcite. It has to be noted that no crystalline phases related to hydraulic binders have been detected in all the samples investigated. X-Ray diffraction data could give important indication about binder and aggregates even if it should be considered that the detection limit of the technique is about 1 wt%.

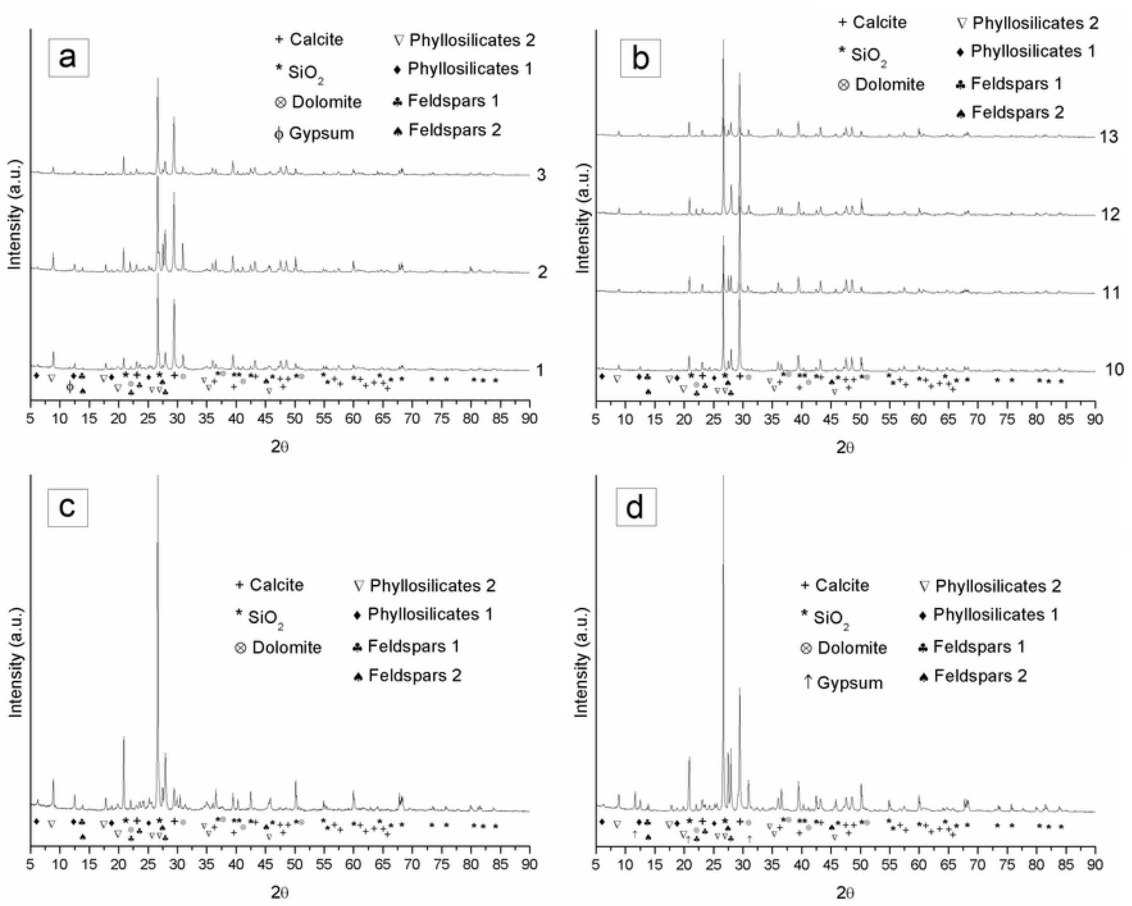

Fig. 5. XRD patterns of samples from a) Arquata del Tronto (1, 2, 3), b) Camartina (10, 11, 12, 13), c) Faete (14) and d) Trisungo (24)

Moreover, eventual non crystalline phases deriving from carbonation and hardening, as amorphous calcium silica gel (C-S-H), deriving from hydration of cement, could not be detected. In some samples large quantities of calcite have been detected being probably related in part to aggregate fraction [Chiari et al., 1992].

The dolomite recognized in the samples was probably used as aggregate, because peaks related to hydromagnesite and hydrated magnesium carbonate hydroxide have not been detected in the XRD patterns. The presence of hydromagnesite deriving from mortars with binders deriving from dolomite as precursor is still controversial [Montoya et al., 2003].

As just stated above and referring to the geological map, the analysis of the materials sampled are in agreement with the hypothesis that the construction materials were extracted around these small towns.

3.3 Fourier-Transform Infrared Spectroscopy, calcimetry, soluble salt analysis and dosage of anionic species

FT-IR analysis allowed to gain an overview of the composition of the mortars [Gulmini et al., 2015] and, relatively to carbonates, silicates and sulphates, the intensity of their stretching signals have been used to obtain a semi-quantitative evaluation (table 3).

Table 3. FT-IR results and percentage of carbonates in mortars analyzed from settlements within the municipality of Arquata del Tronto. The intensity of the stretching signals of carbonates, silicates and sulphates is indicated by the number of 'x'

Settlement	Sample ID	FT-IR CO_3^{2-}	FT-IR SiO_4^{4-}	FT-IR SO_4^{2-}	Calcimetry [% of carbonates]
Arquata del Tronto	1	xx*	xxx		26.5
	2	xx*	xx	(x)	21.1
	3	x	xx		16.5
Borgo	4	xxx			95.6
	5	xxx	xx		52.6
	6	xxx*	xx		51.9
	7	xxx	xxx		35.4
	8	xxx	xx**		32.9
	9	xxx	x**		62.2
Camartina	10	xxx	xx		50.0
	11	xxx	xx		50.9
	12	xxx	xx		44.5
Faete	13	xxx	xxx		36.9
	14	x	xxx		16.6
Pretare	15	xxx*	x		76.4
	16	xxx*	x		54.4
	17	xxx*	(x)		30.5
	18	xxx*	x		39.3
	19	xxx*	x		95.1
	20	xxx	x		76.7
	21	xxx	x		73.5
	22	xxx*	(x)		32.7
Trisungo	23	x	xx**		17.6
	24	x*	xxx	xx	11.0

* presence of dolomite, in addition to calcite
** presence of phyllosilicates, in addition to quartz

The most part of mortars collected show intense signals of carbonates, as confirmed by calcimetry: eighteen samples have a percentage of carbonates higher than 30%; eleven of them have a percentage well above 50% (table 3), indicating that the aggregate is partially made by carbonates. According to XRD results, in some specimens FT-IR analysis highlighted the presence of dolomite.

In regard to the soluble salt analysis by conductimetry, the mortars are characterized by percentages between 2 and 10%, with the exception of sample 24 (table 4).

Table 4. Percentage of Soluble Salts (SS) and concentration of anionic species (average value of three measurements and associated standard deviation) in mortars analyzed from settlements within the municipality of Arquata del Tronto

Settlement	Sample ID	Conductivity [µS]	SS [%]	F^- [ppm]	Cl^- [ppm]	NO_3^- [ppm]	PO_4^{3-} [ppm]	SO_4^{2-} [ppm]
Arquata del Tronto	1	62.1	4.1	-	2.11±0.12	2.64±0.36	-	2.18±0.21
	2	105.8	7.1	-	5.84±0.49	9.63±0.19	-	9.78±0.60
	3	62.5	4.2	-	1.07±0.07	-	-	1.72±0.25
Borgo	4	45.3	2.9	-	0.43±0.02	0.65±0.05	-	>0.5
	5	92.1	5.9	-	0.98±0.04	19.17±0.17	-	1.00±0.04
	6	54.3	3.4	-	0.57±0.11	0.45±0.05	-	0.90±0.17
	7	40.2	2.4	-	0.38±0.03	-	-	>0.5
	8	56.3	3.6	-	0.83±0.01	0.74±0.05	-	-
	9	82.5	5.2	-	1.08±0.16	13.56±1.22	-	-
Camartina	10	44.8	3.0	-	<0.25	-	-	<0.25
	11	52.0	3.4	-	<0.25	-	-	<0.25

Faete	12	49.5	3.2	-	1.50±0.06	3.57±0.34	-	<0.25
	13	57.4	3.8	-	0.54±0.11	0.76±0.05	-	<0.25
	14	67.5	4.4	-	2.43±0.31	3.10±0.56	-	-
	15	78.9	5.0	-	0.50±0.03	0.45±0.05	-	>0.5
Pretare	16	65.2	4.0	-	1.04±0.17	1.50±0.29	-	8.84±1.05
	17	125.4	8.3	-	0.33±0.01	0.30±0.20	-	0.51±0.13
	18	45.5	2.8	-	0.52±0.01	-	-	0.67±0.05
	19	61.1	4.1	-	0.50±0.07	1.15±0.20	-	0.92±0.10
	20	158.3	10.0	-	2.57±0.01	13.14±1.5	-	0.65±0.05
Trisungo	21							
	22	66.2	4.0	-	0.59±0.09	0.24±0.05	-	1.07±0.12
	23	93.5	5.9	-	5.00±0.05	13.70±1.79	-	3.87±0.64
	24	177.9	11.9	-	2.07±0.05	3.39±0.37	-	61.17±0.41

Concerning the concentration of the various anionic species (table 4), the following considerations can be made:

- the sulphates were present in low quantities, below 3 ppm (except for samples 2, 16, 23 and 24);
- the presence of chlorides in the samples is negligible: only two samples exceed 3 ppm (2 and 23);
- regarding nitrates there is a very heterogeneous situation, with values between 0,24 and 19,17 ppm;
- presence of fluorides and phosphates was not detected.

3.4 Compression tests

Some samples, although containing calcite, presented poor compactness and they could be easily fragmented. Mechanical tests have been performed on the samples that presented the highest compactness and in particular those that could be cut to a shape suitable for tests without fragmentation. Two specimens were obtained from sample 17, collected at Pretare. The prismatic samples, tested in compression, are shown in fig. 6.

Fig. 6. Cubic samples obtained from sample 17: left, sample 17.1; right, sample 17.2

Their dimensions are reported in table 5, along with the corresponding shape factor.

Table 5. Characteristics of the samples tested in compression

Sample	Weight (g)	Length (mm)	Width (mm)	Cross-section area (mm^2)	Height (mm)	Density (kg/m^3)	Shape factor (-)
17.1	154	49	54	2660	45	1284	0.821
17.2	149	50	55	2739	44	1235	0.816

It is mandatory to emphasise that these specimens were obtained from a sample having an above-average compactness compared to those collected in the municipality.

For sample 17.1, a first test was performed that did not reach failure, and a second test until failure. For sample 17.2, failure was reached at the first test. For each sample, the stress-strain curve is reported in figs. 7-8, along with a picture of the sample at the end of the test.

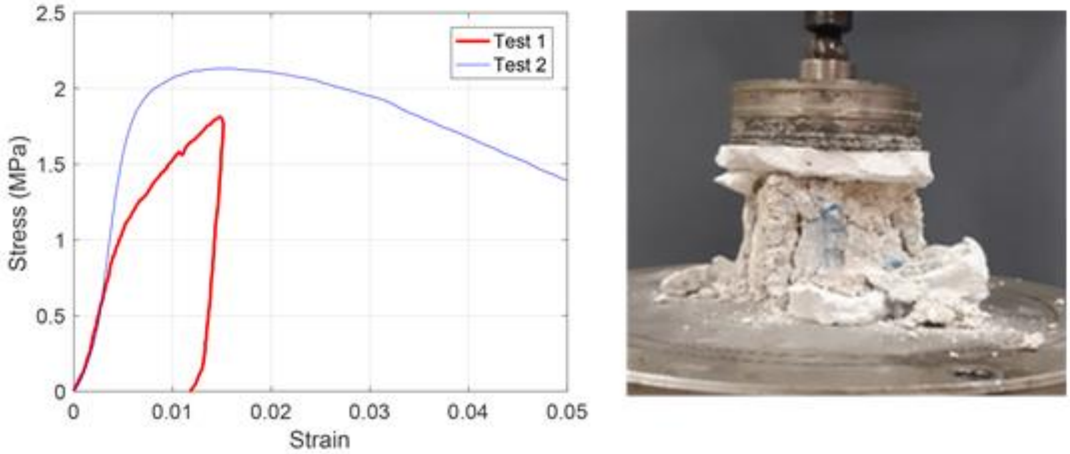

Fig. 7. Sample 17.1: left, stress-strain curve; right, sample at the end of the test

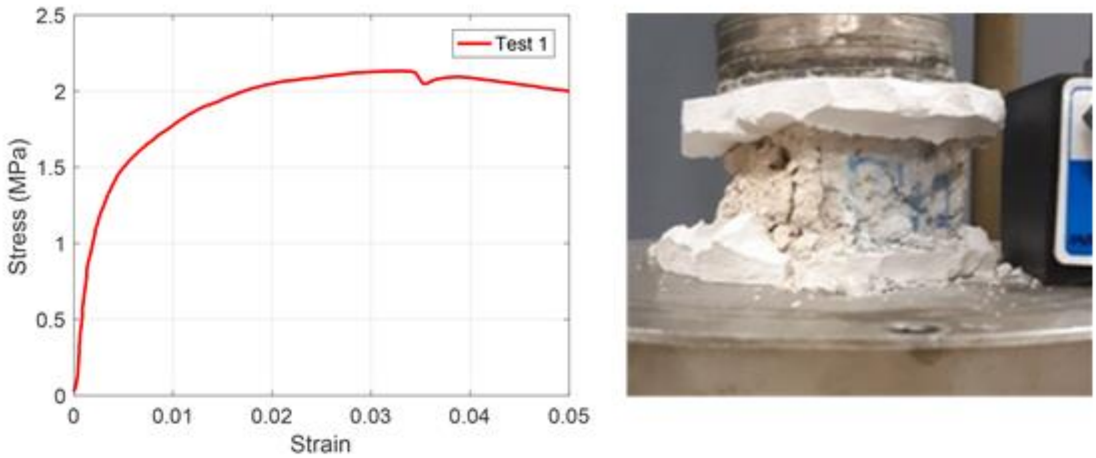

Fig. 8. Sample 17.2: left, stress-strain curve; right, sample at the end of the test

The normalized compressive strength f_m was calculated according to Eq. (1). The results are reported in table 6, where, for the test that did not reach failure:
F_{max} = maximum load;
σ_{max} = maximum stress;
ε_{max} = strain at maximum stress;
ε_r = residual strain;
and, for the tests that reached failure:
F_u = ultimate load;
f = nominal strength;
ε_f = strain corresponding to ultimate load.

Table 6. Results of compression tests

Sample	Failure	F_{max} (kN)	σ_{max} (MPa)	ε_{max}	ε_r	F_u (kN)	F (MPa)	f_m (MPa)	ε_f
17.1	No	5.0	1.88	0.015	0.012	-	-	-	-
	Yes	-	-	-	-	5.8	2.18	1.79	0.015
17.2	Yes	-	-	-	-	6.0	2.19	1.79	0.035

The two samples highlight an almost perfect match in terms of strength, but a significant difference in terms of strain at ultimate load. Such difference could be ascribed to sample scatter, to disturbance introduced during sample preparation or, more likely, to the fact that sample 17.1 underwent a first test before the failure one.
The strength value can be compared with the 60 values collected from literature in [Liberatore et al., 2014] for clay brickwork: there are six samples with a smaller strength (the smallest being 0.28 MPa). If the 42 sample of tuffwork in [Marotta et al., 2016] are considered, Arquata's samples are larger of just four values (minimum value 0.55 MPa). Additionally, it is worth emphasising that the current Italian building code [DMIT, 2018] prescribes a minimum strength of 2.5 MPa for ordinary loads (Sect. 11.10.2), and 5.0 MPa under earthquake loads (Sect. 7.8.1). Instrumental error of the load cell is declared by the manufacturer as ±0.5%, and the same error can be assumed for strength estimation.
Additionally, it is useful to emphasise that mortar deformation capacities are seldom reported, hence, enhancing the importance of data reported herein that is necessary for non-linear micromechanical modelling [Zucchini and Lourenco, 2007]. Instrumental error of the displacement transducer is ±1.0%, and the same error can be assumed for deformation estimation.

Finally, modulus of elasticity of masonry mortar, reported in table 7, presents a scatter greater than that of strength. Sample 17.1 has a modulus of elasticity nearly constant during the two tests. Observed values are very low compared to the seven in [Liberatore et al., 2014] all larger than 1 GPa. The worst combination of instrumental error in load cell and displacement transducer leads to a Young's modulus measurement uncertainty of ±0.6%.

Table 7. Modulus of elasticity

Sample	Failure	S_2 (MPa)	S_1 (MPa)	ε_2 (-)	E (MPa)
17.1	No	0.85	0.01	0.0038	223
	Yes	0.85	0.01	0.0033	258
17.2	Yes	0.85	0.04	0.0014	615

Conclusions

During 2016 and 2017 a dramatic sequence of seismic events heavily damaged small towns in the Centre of Italy in regions as Lazio, Abruzzo, Marche and Umbria, causing a large number of victims.

In this work the bedding mortars of some masonry partially or completed collapsed during earthquakes have been sampled in the surroundings of Arquata del Tronto and analyzed by different techniques.

X-Ray diffraction analysis revealed the use of lime mortars with the presence mainly of quartz and calcite and the presence of feldspars and phyllosilicates. In some cases dolomite has been identified. Some samples also evidenced the absence of the binder or its presence in traces. FTIR and Calcimetry confirmed the presence of carbonates and silicates and that of dolomite in some specimens, while other measurements revealed the presence of low concentrations of soluble salts.

Several samples presented poor mechanical characteristics and could be easily fragmented. Compression tests have been performed on two samples that showed higher cohesion and could be worked without fragmentation. The tests showed that the mortar, of presumed lime type from calcareous and dolomitic rocks, has poor mechanical behavior, with normalized compressive strength lower than 1.8 MPa, i.e. at the lower bound of the values reported in the literature, and significantly lower than the minimum strength prescribed by the code for new constructions in seismic prone areas (5 MPa). Similar results were found for the modulus of elasticity. This work evidences, through a multidisciplinary approach, some highlights on the bedding mortars used in these historical sites. The results of the analysis reported in this paper could be useful as support for future research, supplying information for establishing priorities of intervention for repairing and consolidation and also for reconstruction activities which would take into account construction materials of this ancient masonries. In the future a campaign of measurements could be carried out in order to design a sort of vulnerability map of masonries as aid for lawmakers, municipalities and experts.

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