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# OPERATIONAL ATLAS OF EXPOSED MORTARS AND CONGLOMERATES FOR INTERVENTIONS ON THE WIDESPREAD ARCHITECTURAL HERITAGE

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Sara Fasana, Marco Zerbinatti, Alessandro Grazzini, Federico Vecchio

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**Highlights**

Prepare an operational atlas of traditional mortars and conglomerates. Recover the historical technological knowledge of materials for exposed surfaces. Innovate traditional techniques and methods with *ad hoc* formulations. Encourage the use of materials compatible with common heritage buildings. Promote the methods of choice and action that prioritise circular construction.

**Abstract**

When it comes to Science Heritage, the availability of refined investigation techniques, an advanced knowledge of the characteristics of materials, the current technological capacity and the synergy of specialised operators, coordinated into multidisciplinary teams, guarantee, with the support of cutting-edge tools, excellent results for every conservative operation applied to monumental buildings of acknowledged interest. On the contrary, there are still strong limits to the likelihood that this excellence will reverberate on the multitude of interventions performed on widespread architectural heritage. The research project underway envisages the preparation of an operational atlas of reference for exposed mortars and conglomerates, based on the historical and technological knowledge of materials (particularly those available locally) complete with experimental data on constitution and performance, which is useful to support the development of compatible maintenance and conservation procedures.

**Keywords**

Mortars, Conglomerates, Mechanical behaviour, Maintenance, Innovative method, Operational atlas.

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## 1. INTRODUCTION

Historical mortars and conglomerates are a distinguishing element in the image of historic buildings; as such, they represent a key aspect in their conservation. In particular, the choice of material is an essential step in the correct orientation of any maintenance, recovery or conservation work, ensuring compatibility, effectiveness and durability over time [1]. The investigation methods used for the characterisation of historical mortar samples taken on-site (from monuments or buildings of high cultural and environmental value) are well established and widely documented in the literature. The direct aim of the investigation phases (Fig. 1) is to support, on a case by case basis, the specific formulation of the material used for integration (or, more rarely, replacement), be it for exposed surfaces, to support the finishing or to assist the load-bearing functions. That described is a

Fig. 1. *Serralunga di Crea, Sacro Monte, Chapel 1. A sampling of external render on the south façade (left); Sample 11 (top right); aggregates from disgregation of sample 11 (bottom right).*

fundamental moment in the design of each operation, in the case of buildings subject to specific protective measures. On the other hand, it is rarely implemented in the case of widespread architectural heritage, even though these buildings extensively characterise every local cultural- environmental system considered as the ambitus, on a par with elements of recognised monumental value (Fig. 2).

This critical aspect highlights the need to implement effective programmes aimed at the development of innovative instruments for coordinating research, in order to promote the sharing and dissemination of the most advanced knowledge so that it is accessible and applicable on a broader scale, involving and raising awareness among the numerous parties directly concerned with widespread heritage.

For the coordination and innovation of scientific research into the more general matter of Science Heritage, for example, a widespread research infrastructure, which is strategic for Europe, has been set up for some years now: it consists of a network of laboratories and state-of-the-art instrumental resources, physical and advanced digital archives, widely distributed throughout the territory. This platform, made available to the scientific and manufacturing community, makes it possible to support high-level research, supporting innovation and consequently the competitiveness of the reference market, by sharing cutting-edge instrumental resources in the new multidisciplinary field of cultural and natural heritage science [2]. Numerous projects respond to the need to integrate skills and effectively propagate knowledge, usually by creating “scalable” databases, the architecture of which increasingly makes use of the potential for interoperability with resources for the modelling of information related to spatial entities. [3–5]. Lastly, there are plenty of projects that focus on more specific research topics, such as the classification and characterisation of traditional building materials of historical and cultural interest: the knowledge of the historical and technological value of the materials used can represent a research


Fig. 2. *Serralunga di Crea, Sacro Monte, Chapel 1. Main façade (right) and damage at the base of the northern façade (left).*

strategy, to develop more efficient ways to use them and to refine conservation and restoration methods [6, 7].

None of these instruments, however, can effectively meet the requirements of "accessibility", "technology transfer" and extended applicability of results. The possibility that excellent research methods and results can significantly affect the quality of maintenance, conservation and recovery of widespread heritage is still generally very limited. The phases that govern their conduct, from the diagnostic project to the choice of material and its final application, are often affected by different and concomitant errors or shortcomings. This means that in a present in which the progress of knowledge is supported by the availability of refined investigation and analysis procedures and in a technological context which would make it possible to fulfil the production of very high-quality materials, it is becoming increasingly complex to operate in such a way as to limit the repetition of operations that soon turn out to be ineffective [8, 9].

The causes of these failures often depend on design shortcomings, which are then reflected in the subsequent phases with the choice and application of inappropriate materials.

From a theoretical point of view, it is necessary to fill the current gap between "knowing and doing" by disseminating the method and *applied technological documentation*. The current multiplication of responses on the market and the apparent availability of "new" and easy to apply products, must be supported by a solid and widespread *basic knowledge*.

In more general terms, it is necessary to work case by case to guide the choice towards materials which, while respecting (or approximating) the current regulatory requirements, reconcile the constitutional requirements (which derive from the intrinsic characteristics and are also expressed in the value of image), with the performance requirements (which take into account the complex characteristics of the substrate, e.g.: the weaving/construction of walls, expressed in behaviour): resulting in compatibility.

The complex methodological framework, the criticalities and the goals outlined, with reference to all the interventions on the existing heritage for conservation purposes, can similarly be applied to those aimed at the "innovation of existing elements", or to new constructions.

For example, we cannot overlook the fact that a wide range of currently available materials, formulated in response to the application of modern Bio-Eco compatibility assessment protocols, also draw extensively on technological knowledge already consolidated in ancient times. It is now widely recognised the intrinsic ability of materials (historically derived from the use of locally available raw materials) to meet "sustainability" criteria (ante litteram). In this case also, the "quality" of the product represents a necessary condition but is not sufficient to guarantee the "quality" of the interventions (there are no such things as "good" and "bad" materials, there are materials that are suitable for the specific case, which must be applied correctly): the expected effectiveness can be compromised by incorrect application cycles and, even before that, by the proven incompatibility of the material chosen with the characteristics of the "modern" supports to which they are to be applied.

It is on the basis of these reflections and the current state of the art that two main requirements are outlined.

The first, methodological: it is necessary to reconcile the knowledge of tradition with the know-how brought about by innovation. The second, of a practical application type: it is necessary to further the knowledge of historical mortars and conglomerates in order to accompany the results of the constitutional analysis (consolidated in terms of the method and with a good level of dissemination of the results) with those of the performance analysis, with particular reference to the mechanical behaviour.

This contribution outlines the methodological approach for setting up an operational tool, in the form of an atlas, for the current selection and application of traditional local mortars and conglomerates, in response to the first requirement. It illustrates the results of a phase of experimental tests for the mechanical characterisation of traditional mortars, in response to the second requirement.

## 2. FROM THE KNOWLEDGE OF TRADITIONAL TECHNIQUES TO THE DEVELOPMENT OF EFFECTIVE OPERATING METHODS AND SUITABLE APPLICATION SOLUTIONS

The investigations underway represent a specific development of the general topic of masonry surfaces in historical buildings, with particular reference to the renewed knowledge of historical materials and techniques. Previous research developed at the Department of Structural and Geotechnical Building Engineering (from now on DISEG, formerly Department of Building and Territorial Systems Engineering) of the Politecnico di Torino, on the general topic of masonry surfaces in historical buildings, has produced significant results, including the Permanent Collection in two sections, "Natural dyes and earth-based dyes" (prepared by G.P. Scarzella) and "Review of local sands and mortars". These researches were launched with the main goal of recovering and documenting materials, principles and operational criteria of tradition (on the basis of scientific knowledge) necessary and essential for the development of compatible procedures for conservation, by virtue of their documentary value and technological testimony, together with their recognised environmental cultural value. The materials exhibited in the two sections are organised into homogeneous territorial areas (also respecting the geopolitical subdivision of the pre-unification Italian territory).

The materials displayed in the two sections of the DISEG collections are arranged according to homogeneous territorial areas, in keeping with the need to document the wide variety of solutions and image values associated with the historically consolidated use of local materials, creating a solid conceptual basis for the subsequent definition of an Atlas.

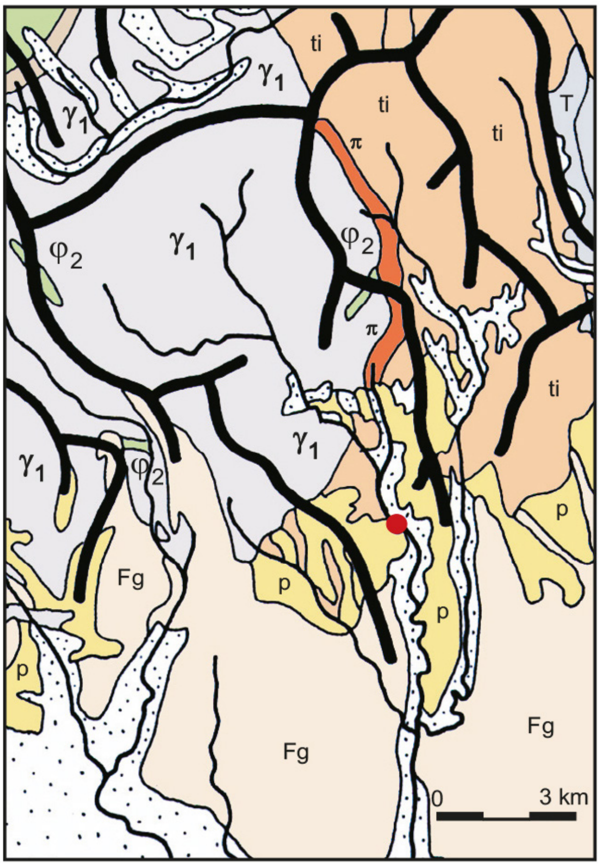
Also with reference to specific solutions prepared for conservation interventions on widespread heritage, each element of the rich collection is accompanied by samples of original materials (historical mortars or plasters collected on-site, also from study sites), samples of local sands sifted according to different grain size classes (Fig. 3) and the respective laboratory samples obtained from specific formulations (with the definition of appropriate grading curves).

The collection and cataloguing of local sands used historically are continuously increased, both with systematic procedures for territorial areas and with reference to further analysis for case studies dealt with gradually during research projects.

The knowledge acquired through the research mentioned in abstract form the basis for the definition of specific suitable and effective application solutions. Numerous experimental studies have been carried out for the

Fig. 3. *Sands from the DISEG permanent collection, sampled at (from left to right): Ostola creek, near Masserano; San Damiano, loc. Caminello; San Damiano, loc. Caminello, from a different geological stratification; Varaita creek, near Fontanile; Toce river, at Crevola d'Ossola.*

characterisation of historical mortars and conglomerates, including fatigue tests and thermo-hygrometric tests to identify, case by case, the most durable repair mortar compatible with a specific historical masonry. The experimental characterisation phase and the subsequent formulation of ad hoc mortars made it possible to effectively support the choice of the most compatible material in important restoration sites [10].



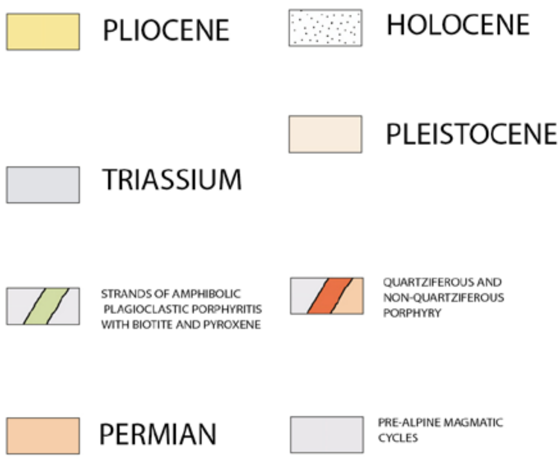




Fig. 4. *Masserano, Ostola creek; geological map and related key.*

## 3. METHOD AND STRUCTURE OF THE ATLAS

The methodological approach and the consolidated results of the research illustrated in paragraph 2 form the solid basis for the current in-depth study, which slots into the international scientific debate in an organic and dialectical way, sensitive to the topic of the characterisation of mortars as a specific and foundational phase for the activity of each restoration site [11–13].

The set of reference data (composition, grading curve, constitutional characteristics, experimental results for physical and mechanical characterisation, data on compatibility with different types of the substrate) will be progressively arranged into a methodological, operational and interactive tool, aimed at supporting the investigation phases and, consequently, at effectively guiding the choice of the most suitable material for the specific case, from the point of view of aesthetic, physical-chemical and mechanical compatibility. The deposit of georeferenced data, both with reference to the geographical location of the structures in our case studies and, particularly, the place of origin of the local material used historically and subject to analysis; or, again, to the location of historical and current quarrying sites. Such mapping, in relation to special cartographic levels, mainly geological, will make it possible to identify possible horizons common to different areas, favouring the use of materials similar to those historically quarried, even in the absence of sites that are still active (Fig. 4).

From an operational point of view, the architecture of the data in the atlas, and particularly the way in which its scientific and technological contents are consulted and

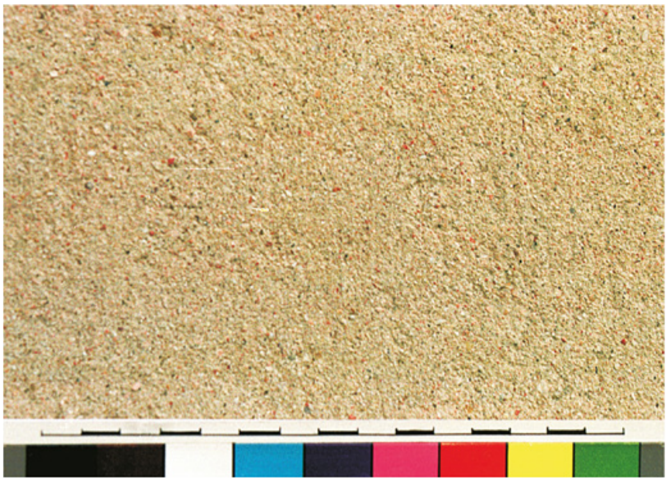


Fig. 5. *Image of an external render of the apse of a local church (see the red sand a) shown in Fig. 3, the sampling point of which is the red point on the map shown in Fig. 4.*

integrated, will allow different possibilities of interaction, also as a consequence of the characteristics of each intervention.

With particular reference to work on existing structures, from the methodological point of view there are four different operating methods (in relation to the possible boundary conditions) of "utility" (the language and coding used in the description of this paragraph are functional to the structure of the data architecture of the interactive tool):

A) interventions of excellence, with the possibility to:
- carry out in-depth diagnostic surveys;
- ormulate a suitable material ad hoc;
- define specific operational application methods.

In this case, an out-in-outnew-in procedure is developed:
- out: comparison and methodological support in choosing surveys, based on similar cases catalogued in the atlas;
- in: deposit of the knowledge gained from the case-study in question;
- outnew: support with the elaboration of the formulations ad-hoc;
- in: deposit and cataloguing of the innovative formulation produced for the case-study in question.

B) interventions with:
- the possibility to carry out diagnostic surveys based on a specific survey project;
- the need to use pre-formulated solutions and operational methods that have already been outlined;

In this case, an out-in-outchoose procedure is developed:
- out: comparison and methodological support in choosing surveys, based on similar cases catalogued in the atlas;
- in: deposit of the knowledge gained from the case-study in question;
- out-choose: support with the choice of the material, based on the specific formulations catalogued in the atlas.

C) interventions without:
- the possibility to carry out diagnostic surveys;
- and with the need to use premixed solution, resorting to defined executive methods;

In this case, an out-outchoose procedure is developed:
- out: identification of the most similar case among those catalogued in the atlas;
- out-choose: support with the choice of the material, based on the specific formulations catalogued in the atlas.

D) interventions without:
- the possibility to carry out diagnostic surveys;
- and with the possibility to use locally available materials mixed at the time of use by experts with full knowledge of the traditional techniques.

In this case, an out-out.in- outchoose procedure is developed:
- out: identification of the most similar case among those catalogued in the atlas;
- out.in (the atlas can be enriched with new case-histories);
- out-choose: support with the choice of the material, based on the specific formulations catalogued in the atlas.

Common to each type of utility will be the systematic deposit of documentation in the appropriate appendix: quali-quantitative, in cases A), B) and D), or qualitative only, in case C). The aim of this is to monitor the behaviour of the individual materials over time, in relation to the physical and environmental context of their application, which is conditioned by the implementation procedures.

The project of the operational scientific atlas is accompanied by an experimental research activity planned in the laboratory. Numerous mixtures of mortars characterised by a single aggregate distribution curve as project invariable are being formulated and packaged. The sand used is siliceous and comes from Pliocene deposits of the Tertiary Basin in Cisterna d'Asti. More precisely, they consist of Pliocene sediments. Asti Sands - Alternating sand - clay (Villafranchiano) and are more or less stratified yellow sands, with gravelly layers and marly, calcarenite and calcirudite intercalations; microfauna – in the marly interlayers – in Bolivina (Geological Map of Italy, 1:100,000, sheet 69). Material is taken from the Bricco Toni quarry. (http://193.206.192.231/carta_geologica_italia/tavoletta.php?foglio=69). The sand is wet sifted in the quarry so that it can be classified for industrial production purposes. In the laboratory, new sifting and mixing operations are carried out to ensure that the distribution of aggregates is always uniform.

Mixture variables are the types of binder and binder/aggregate ratios. 30 standardised specimens are produced for each type of mixture, and mechanical characterisation tests are carried out. The specific aim is to obtain numerical reference values for the different types of mortar, to be used with different types of substrate.

This provides a useful tool for operators already in the preliminary decision-making process of planning interventions.

## 4. TYPES OF MORTARS AND THEIR BEHAVIOUR: FROM THE FORMULATION OF THE MIXTURE TO PERFORMANCE CHARACTERISATION

Once a solid methodological basis has been established, the effectiveness of an operational tool requires simplified criteria, to guarantee its applicability, also modulated according to different levels of detail (potentially different for each situation). Similarly to the synthetic identification of the possible cases of intervention outlined in the previous paragraph 3, it is, therefore, necessary to accompany the atlas with multiple criteria for the classification of material, functional to the construction of a reference matrix to outline complex paths according to the different combinations that are possible. Sensitivity and preparation of all those involved, the specificity of the case, conditions and criticality of the context will help guide the approach, influencing the quality of the results achieved. A specific component of the atlas consists of a guide to the correct and unambiguous identification and classification of types of mortar and conglomerate, with the aim of outlining the variety and complexity behind said classification, also appropriately reconciling the legislative data. This is why it is essential to envisage the preparation of a "connection" that leads to the definition of a limited range of suitable solutions, among those available and is continuously harmonised and updated (The main lexical references used as terminology and definitions are referable to the standards in force in the sector, such as – by way of non-limiting example: UNI 10924:2001, UNI EN 1015:2007 and subsequent updates).

The specific aims of the research include the assessment of the mechanical characteristics (resistance to compression and flexion, dynamic elastic modulus and

Fig. 6. *DISEG Laboratory storage. Sets of mortar specimens of Group 1 (standard size, according to UNI EN 1015:2007).*

static elastic modulus) of mortars formulated with reference to traditional types of mortar among the most common and widespread in the historical building industry. Mortars were formulated and produced for a test campaign (Group 1): three sets of specimens (Fig. 6) were prepared (in two series: a - standard size 40x40x160 mm [according to UNI 1015:2007] and b - size 30x30x300 mm), respectively: set I) for 28-day tests; set II) for 120-day tests; set III) for the cataloguing and archiving of the material inventory that accompanies the atlas. The results of the tests carried out on this set of samples (28-day tests) are presented in paragraph 5 below.

Additional phases are currently being developed:

- characterisation of the second set of specimens, stored in an uncontrolled environment;
- packaging of the samples in Group 2;
- replica of two sets (IV) and (V) of samples from Group 1, for ageing in a climatic chamber (T and RH checked with cycles at pre-set intervals) and subsequently testing for mechanical characterisation, in order to compare the results obtained from the tests on set II (in an uncontrolled environment at 120 days).

At the end of Phase Two, when it is considered that the amount of experimental data available can be considered statistically significant, a specific transversal phase will be launched, aimed at verifying known methods for the dimensional reconfiguration of samples to undergo mechanical behaviour tests, for the comparison and validation of results [14].

## 5. THE EXPERIMENTAL RESULTS OF SET I

For each formulation of Group 1 mortars, test specimens of set I) underwent laboratory tests to determine the modulus of elasticity using an ultrasound device. The tests (ultrasound test is described by UNI EN 12504-4: 2005) were carried out both on standardised specimens and on specimens measuring 30x30x300 mm.

This non-destructive and repeatable survey allows various observations [15]; the flight times obtained were used to calculate the dynamic modulus of elasticity *Ed,* according to (1):

$$Ed = vm^2 \cdot \rho m \qquad (1)$$

where $vm$ is the mean propagation speed (m/s), ρm the mean density of the material considered (kg/m$^3$).

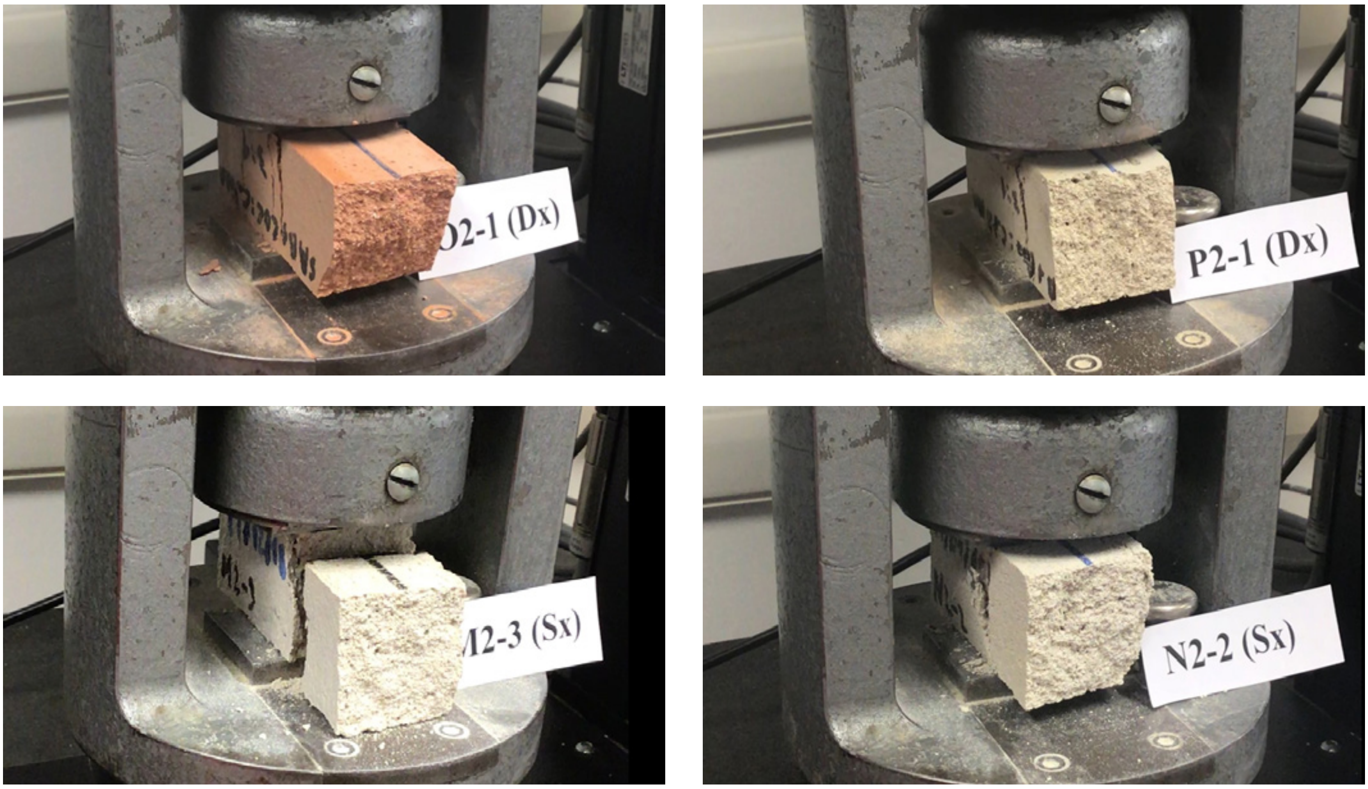



Fig. 7. *Samples of set I, Group 1 tested to compression resistance according to UNI EN 1015-11:2007.*

The set of samples with the highest mean *Ed* value consists of cement or cement and lime putty (category H), with the exception of samples for which the amount of lime putty is predominant compared to cement (H4 and H8). In general, the high speed of the formulations corresponding to categories H and O2 is probably due to the fact that the samples have a high density. On the other hand, the lowest absolute values of *Ed* were recorded by the specimens made with hydraulic lime (category G). Comparing the values of mortars G1 and G2 it was possible to see how the amount of hydraulic lime in the mixture influenced the *Ed* value; the aggregate/binder ratio influenced the density of the samples, which is directly proportional to *Ed*.

For a comparison with the experimental results of the elastic modulus, the flexion and compression resistance tests described in UNI EN 1015-11:2007 (Fig. 7) were also performed (first set of specimens) [16]. The results of the resistance to compression (Fig. 8), confirmed a tendency towards values already observed in the measurement of the dynamic elasticity modulus.

The first results of the flexion tests (performed with three substrates) on mortars G-H-I-L also confirmed the trend detected by the results of the remaining formulations, and therefore the mechanical characteristics previously obtained.

## 6. DISCUSSION OF THE RESULTS AND PROSPECTS

The elastic modulus of materials is of great importance, especially in the presence of coupled materials (e.g. in the case of plaster applied to masonry or mortar for bedding joints). As the mortar applied on-site starts to set and harden, it is inevitably subject to shrinkage, which can cause deformations (albeit controlled), only partially transmitted to the masonry. The coupling and the bond between the original masonry substrate and the restoration mortar inevitably create deformations of the materials when they are subject to different types of cyclic stress (thermo-hygrometric or mechanical) linked to their working life [17]. We know that the value of these deformations is proportional to the elastic modulus of the material; to prevent possible recurring problems, it is necessary for there to be adequate mechanical compatibility between the two materials [18]. In general, the results obtained with the test campaigns have confirmed the values expected for each group of mixtures; with reference to the most common types of masonry substrate [19, 20] of widespread heritage (bricks, mixed masonry such as listed or ordinary masonry in compliance with Savoy specifications) the first results obtained already offer the possibility to guide design choices.

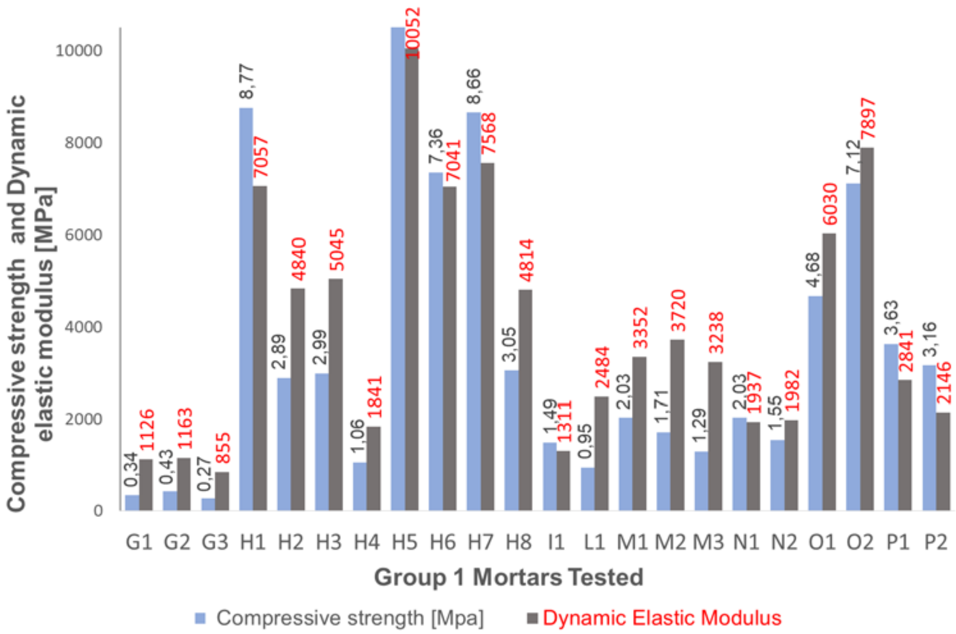



Fig. 8. *Medium values of compressive strength and dynamic elastic modulus for each mortar composition of set I, Group 1.*

As a second approximation, differences in binder and binder/aggregate ratios (e.g. mortar type G3, for the group of mortars with hydraulic lime) make it possible to refine the knowledge of the mechanical properties of a larger number of mixtures; in practice, this makes it possible to better approximate the behaviour of the pre-existing homologous material.

Given the importance of the requirement in question for the durability of any maintenance, conservation or consolidation work, the atlas under construction will be accompanied by reference values of the elastic modulus of the mortars investigated.

The framework of needs and contextual conditions, to which employees must refer, is complex and articulate: the effective coordination of knowledge is a strategic condition to ensure a high-quality level of work. The operational atlas is proposed as a methodological and practical tool, with the ambitious aim of helping fill the current gap between "knowing and doing" from the bottom up.

The set of data collected and arranged will be able to support the survey phases, and the choice and application of mortars and conglomerates to respond to the needs and critical issues of specific construction sites.

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