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A research about a method for restoration of traditional lime mortars and plasters: A staging system approach

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Abstract

Turkey is quite rich with historical buildings. Depending on various factors like time, increasing air pollution due to technological improvements of the present era together with insufficiency of inspection leads to the formation of damages on these buildings which are part of our historical heritage. Conservation of such buildings which are as important as historical documents should be the first and foremost target of any project. Where maintenance is insufficient, conservation and restoration attempts should replace it. What is necessary in restoration is the use of material which resembles the original material to the closest degree or, producing appropriate material which is compatible with the properties of the original material. The first dimension of the current problem is the insufficiency of resources while the second dimension stems from the lack of proper evaluation of the material to be used in conservation and restoration. This study defines the importance of mortars and plasters along with their history and the reasons of deterioration. In addition, it sets up the information flow of mortar and plaster within a systematic decision making process. The necessary experimental methods for the production of new repair mortar or plaster that can be used in determining the character analysis of original mortar and deterioration morphology are also analyzed. Thus, a method that can be used in the conservation and restoration studies is determined with this paper.

Keywords: Experimental method; Evaluation of restoration materials; Lime mortars; Lime plasters; Experimental techniques of materials; Reproduction of mortars; Design of repair mortars

1. Introduction

The number of different materials used in the historical buildings is limited. Generally, available regional materials had to be used due to necessity during the construction. What we name as traditional materials consist of stone, brick, wood, mortar and plaster. Among these, plasters and mortars are greatly affected by environmental factors and hence they are the ones that necessitate conservation and repair the most.

Besides their functional necessity during the construction of the building, mortars and plasters carry an aesthetic value depending on their architectural form and construction techniques. Even though mortars and plasters serve different purposes within a building, their deterioration morphology and conservation attempts should be analyzed together since they are basically made out of similar materials. Mortar is a structural material that keeps stone or brick together, which provides stability to the wall. On the other hand, plaster covers the façade of the building and preserves the material that constitutes the structure of the wall from external weather conditions. Thus, plaster is not a structural material, it only serves to protect the building's facade. While investigating the deterioration of mortar and plaster, which serve different functions, it is necessary to investigate if there is a decrease in their common and functional features (if there is any). For example, the difference in compression resistance and elasticity modulus between plaster and mortar is quite

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important. Furthermore, common properties or processes influencing each other like optimum water vapor permeability values, durability against acids or gas in the air, thermal dilatation and swelling by water are common important factors for both mortar and plaster.

Among the historical mortars that have come to survive until today, gypsum, lime and lime pozzolana have been used as binding materials. As aggregate materials, river sand, pebbles, brick pieces and powder have been used together with hay, horse hair and goat hair which have served as fibers. In our country, we encounter Horasan mortar with varying mixture ratios in buildings from Byzantion, Seldjuki and Ottoman periods. This type of mortar is as strong as concrete and is made by binding lime together with varying proportions of river sand and brick pieces/powder that are used as aggregates. Horasan mortar has been widely used in Ottoman buildings especially in those that belong to the 15th century and in the period that follows. In 18th and 19th centuries, lime mortar, named as ‘‘royal mortar’’ which was made of Italian pozzolana ‘‘poçlana’’, has been used. Lime mortar is actually composed of non-hydraulic lime, which is irresistant to water, when combined with pozzolana. In this way, hydraulic lime is formed which is hard and resistant to water at the same time. Hence, it is also known as Horasan concrete in history. Lime mortar made out of pozzolana and brick pieces have been named by the Romans as ‘‘opus cementicium’’ and they have continued to survive until today. In addition, these mortars have served to improve the cement technology of today. Toward the 20th century, the hydraulic quality of cement and its feasible use has been combined with positive features like low compression stress, high deformation capacity and porosity of lime mortar and as a consequence, lime–cement mortar production has begun. The first step in the evaluation of mortar and plaster used in historical buildings is the accurate determination of the original material used and the reasons that have led to deterioration. Table 1 briefly summarizes the deterioration causes of mortar and plaster.

2. The causes of deterioration on mortars and plasters used in historical buildings

It is possible to list the causes of damage in mortars and plasters as atmospheric effects, effects of use and production conditions and destructive effects of restoration. However, it is possible to group the most commonly observed causes of damage in two basic groups. Table 1 shows causes of damage and their types [1].

3. An evaluation of mortars and plasters produced for using in the restoration of historical buildings

Mortars and plasters used in historical buildings provide important and helpful information about the building technology of their historical period and they are as important as historical documents. Therefore, the evaluation analyses of original mortar and plaster during the restoration should be scientifically based. The work may require to include scholars with various professions such as art historians, restorators, physicians, chemists, biologists, engineers and architects within the same team during the analyses process from time to time. However, method determination practices that shall be used in applications on the subject matter have not been standardized. In addition, it is not possible to utilize all the experiments and the standards that check and control the quality of binding products and raw material applied on mortar and plaster analysis of historical buildings. The purpose of mortar and plaster analysis of historical buildings is not to make a quality control of the material used, but to determine the physical, chemical and mechanical properties. Therefore, it is required to provide the information that explains the current condition of the material as well as the factors that have led to the formation of the current situation of the material used in the building.

In order to be able to make the ideal repair mortar choice that will be used in the restoration of the historical buildings, it is necessary to know the properties of traditional mortar very well. Consequently, this should be compared with comparative mortars. After making such a comparison, production of a mortar that carries the advantageous properties of traditional and comparative mortar is possible. Since there is a lack of academic publication on this issue in our country, different problems in reaching the accurate and sufficient information are encountered. This leads to the use of incompatible material during the restoration process.

An experimental method that can be used in evaluating the analyses of traditional mortar as well as mortar and plaster that shall be used in restoration is suggested below. This method is composed of four basic phases. Phase I; Visual analysis and documentation, Phase II; Experimental research, Phase III; Evaluation of experiments made in Phase II in order to produce the repair mortar, Phase IV; Decision making on the appropriateness of the repair mortar (Fig. 1).

3.1. Phase I: Visual analysis and documentation

The first thing to do in a damaged historical building is visual analysis. It is necessary to observe where the original mortar is. Since there is a possibility that the building may have had more than one restoration, different materials and building techniques can be

Table 1
Some factors that cause damage to original mortar and plaster and damage types

Factor	Effect	Damage type
A. *The destructive effects of the environment*		
Acidic waters (with CO_2, SO_2) that come with rain or snow water	Dissolve the carbonates of lime binder	Adhesion and cohesion features of the mortar are decreased. Aggregates are decomposed
The continuity of freezing/thawing cycles	The bonds of the mortar among the binding aggregates are dissolved	Leads to the dissolution of the mortar
Exposion to extreme amount of water vapor (in case of fire)	The critical water vapor content the mortar can carry is exceeded	Leads to the hanging of the mortars in folds through decomposition
If the sand used in mortar has clay in content	The swelling of clay in a moisture environment, leading to internal stresses	Crumbling of the mortar is observed, regional swellings and draping are seen
Sea water, air pollution, use of dirty material	Anionic salt crystals i.e. chlorides, sulfates and nitrates are formed	Decomposition of the mortar, deep cracks and draping of the mortar are observed
Formation of plants	Especially some plant roots lead to the dissolution of the mortar	Biological decay, coloring of the mortar and dissolution
Existence of organic growth	With the formation of insects, the binding quality of the mortar is reduced	Microbiological decay and dissolution of the mortar
B. *The destructive effects of the repair mortars*		
Using more cement than lime	Formation of highly stiff mortar, cracking	Shrinkage cracks and diffusion of water through cracks, drapings due to different work
Salts that may come from the cement	Efflourescence on the surface of the mortar	The salts cause the efflourescence and lead to internal stresses
Adding synthetic resin (if it is too much)	The water and vapor permeability regime of the original mortar is deteriorated	Dissolution in the form of shells on the surface of the mortar

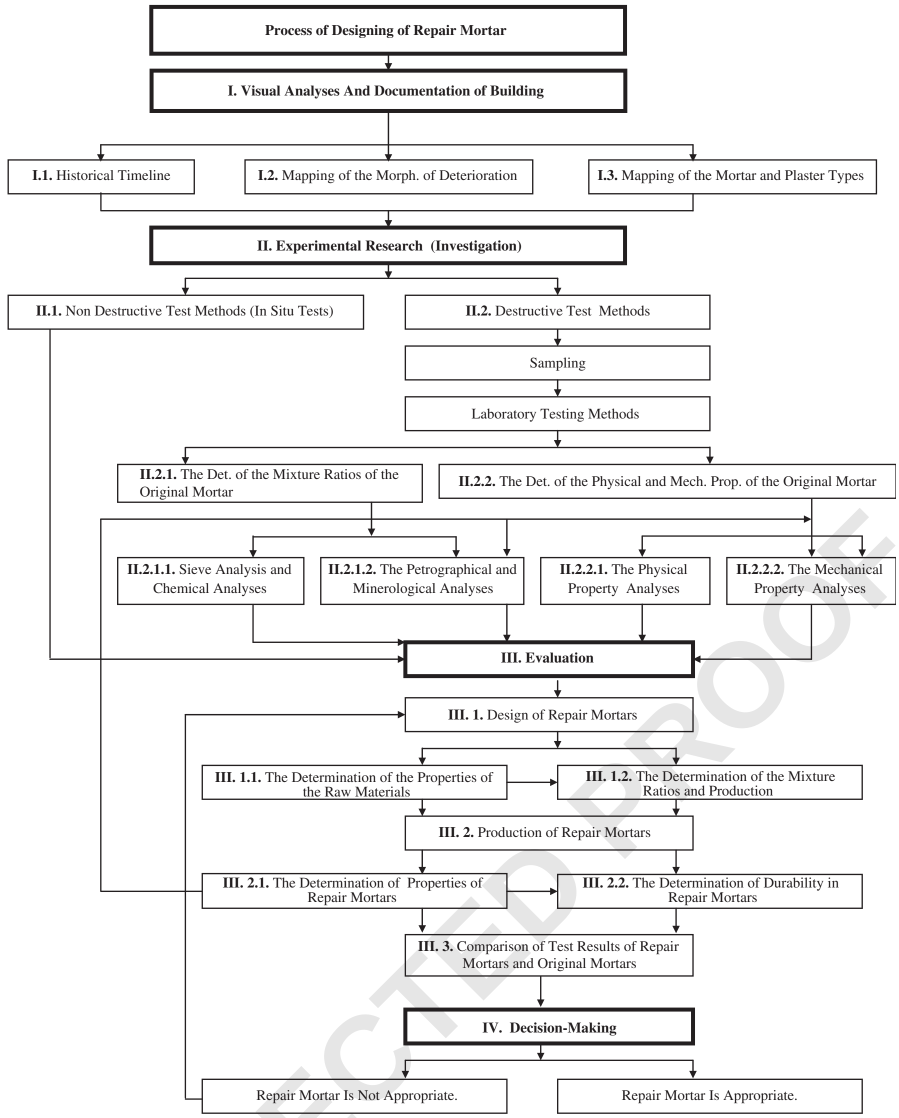

Fig. 1. A flow diagram that shows a suggested experimental method used in the process of designing of repair mortars and plasters.

found. Therefore, the original plaster or wall system should be determined by removing the layers that belong to the new period. While doing so, it is necessary to find and use the documents that are related to the building. After determining the original mortar and plaster, causes of damage and their types should be drawn to scale and their pictures should be taken in the light of visual analyses. The requirements of visual analysis and documentation are summarized in Table 2. In addition to these steps, factors that may lead to deterioration around the building should be analyzed and documented.

3.2. Phase II: Experimental research (investigation)

This phase consists of experimental systematique that can be followed during the determination of mortar performance and the production of repair mortar. The experimental work is composed of two groups: (1)in-situ/non-destructive tests, (2) laboratory/destructive tests. First, in order to make an in-situ examination, non-destructive tests are conducted on mortar and plaster which are found to be damaged during the observation. Consequently, in order to determine the mixture of the new repair mortar to be produced, samples should be taken and laboratory experiments should be made.

3.2.1. Non-destructive test methods (in-situ tests)

Besides visual data, non-destructive in-situ tests where necessary should be conducted which can provide information about the physical and mechanical properties of the mortar in order to determine the level of deterioration. Such experiments can be conducted with an attempt to remove any doubts about the damage determination encountered during the visual analysis. In

Table 2
Requirements of visual analysis and documentation

I. Visual analyses and documentation	
I.1. Historical timeline	Chronological ordering of the previous restorations by searching the historical documents
I.2. Mapping of the morphology of the deterioration	Mapping of the visually observed damages on drawings, making legends in accordance with damage types
I.3. Mapping of the mortar, plaster types	The drawing of the mortar and plaster types determined on the building by making a legend on the drawings

Table 3
Non-destructive experimental methods that can be applied on historical mortars [2]

II.1. Non-destructive experimental methods	
II.1.1. Determination of the amount of water absorption	With the help of "Carsten"-type test tube, the amount of water absorption is determined on the surface of the original mortar
II.1.2. Determination of the amount of humidity	The amount of humidity of the mortar is measured with the help of neutron sondage
II.1.3. Determination of hardness	With the help of a needle, the hardness of the mortar is evaluated in accordance with the Mohs hardness scala
II.1.4. Endoscopic examination	In order to see the thickness and the level of preservation of the mortar and plaster layers, a hole is opened in the material and a camera sent through the hole for observation [2]
II.1.5. Ultrasonic examination	By measuring the sound transfer speed which is sent from the ultrasonic device, homogeneity and micro-cracks are determined [2]

Table 4
Example for preparing a sample card

Sample no.	Location	Function	Timeline	Colour	Damage type

addition, they also constitute a sub-knowledge accumulation for the required laboratory tests. These methods are briefly explained in Table 3.

3.2.2. *Destructive test methods (in laboratory tests)*

Destructive test methods are used in order to design the mixture ratios of the original mortar and to find its current physico-mechanical properties. This information will help us produce the appropriate repair mortar. In order to conduct these experiments in a laboratory, samples should be taken from certain parts of the building in adequate amounts and dimensions with the help of a professional device in a very delicate and planned manner. These samples are collected from different parts of the building which are thought to be constructed or repaired in different time periods. In order to understand the behavior of the mortar underground and above ground, samples should be taken from different levels [3]. While taking samples, they should be collected from varying directions as well as from the structure and the surface layer of the building. In the process of taking samples, the photogrametric drawings prepared during the visual analysis phase which depict the mortar and damage types shall be useful. These drawings should show where each sample is taken from, and information cards that contain detailed data about the location of the samples should be prepared (Table 4).

3.2.2.1. The determination of the mixture ratios of the original mortar. Making a character analysis of the original mortar will serve to prepare the design criteria of the repair mortar that will be produced and help to design the current condition of the building. The list of experiments which shall be realized in making a character analysis is composed of minerology–petrography analyses, chemical analyses, physical and mechanical property tests (shown in Fig. 1). These experiments serve to find the necessary parameters in order to produce the material similar to the original one. Calculating the binder/aggregate ratio, determination of binder types, the dispersion of aggregate granulometry within the binder, the mineralogical definition of the aggregates, the presence of organic matter, its properties and its ratio are among the list of parameters that should be considered while producing the material that shall be used in the restoration of historical buildings [4].

Sieve analysis and chemical analyses: In determining the types of materials used as binders and aggregates and their mixture ratios within the original mortar, chemical and sieve analyses are made. If the binder in the original mortar is lime, sieve analysis is made after solving the mortar in acid. If the binder is soil, sieve analysis is made for the aggregate after it is dissolved in water. Sieve analysis is made in order to determine the grain dimension dispersion of the material used as aggregates. If there are additional fibrous additives like hay, it is revealed during the analysis. Calcination analyses are made in order to determine the type of the binder, presence of organic matter and their ratios of presence. Calcination is an experimental method by measuring the weight losses of the sample mortar through heating it in the oven at high temperatures. With the calcination tests, determination of humidity, water content, loss through heating and the content of organic matter are revealed. Carbonate determination test is made by heating the sample mortar at high temperatures and calculating the amount of loss.

Other experiments under the heading of chemical analyses are the analysis of salts disssolved in water. They are chloride (Cl^-) analysis, sulfate (SO_4^{-2}) and carbonate (CO_3^{-2}) analysis, nitrate (NO_3^-) analysis, protein analysis and saponifiable oil analysis. Through interpreting the qualitative (element-type determination) and quantitative (amount) determination in chemical analysis together with petrographic and X-ray data, the types of binders and aggregates are determined.

The petrographical and minerological analyses: Petrographical analyses are made in order to determine the mineral type and structure of the mortar's aggregate. The analysis of the mineral character in the sound part of the original mortar and analysis of the deformed mineral parts are made on samples which are prepared by taking a cross-section from the mortar. Other methods of analysis in determining the grain dimension, shape, location system, color, tissue and crystal structure are scanning electron microscope (SEM) and elemental dispersive analysis (EDAX). In addition, these features are examined also by X-ray diffraction. Additionally, with the ICP analyses minerals in the material are expressed in terms of chemical formulas.

3.2.2.2. *The determination of the physical and mechanical properties of the original mortar.*

The physical and mechanical property tests conducted for the original mortar should be done on the repair mortar samples as well. The results of these experiments are statistically evaluated and compared (Table 5).

3.3. *Phase III: Evaluation*

In the light of previously made visual and experimental analyses, the new mortar which is similar to the original mortar in appearance is designed in this phase.

Table 5
The physical and mechanical property tests

II.2.2.1.The physical property tests

Properties	Name of the testing techniques	Aim to define
Weight	Density (g/cm^3), Specific gravity (g/cm^3)	Composity, porosity
Water absorption ratio	Pressurized water absorption rate and ratio under atmosphere conditions (%), coefficient of capillary water absorption (g/cm$^2\sqrt{}$dak)	Visual porosity
Pore ratio and structure	Pore size distribution (porozimetry) measurement, porosity ratio (%), saturation degree measurement (%)	Real porosity and saturation properties related to its lifecycle durability
Water vapor permeability	Water vapor diffusion resistance factor test	Durability properties against wetting-drying cycles
Temperature resistance	Coefficient of thermal dilatation testing	Interaction property of original between new mortar

II.2.2.2. The mechanical property tests

Determination of	Aim to define
Compression strength (MPa), tensile strength (N/mm^2), flexural strength (N/mm^2)	Resistance against horizontal and vertical loads
Youngs' modulus (N/mm^2)	Ductility or brittleness property
Adhesion strength (N/mm^2)	Adhesion to different material
Determination of hardness, abrasion strength	The strength of stiffness and life cycle

Since the quantitative and qualitative results of the mixture ratios and the physico-mechanical properties of the original mortar has been calculated by making a statistical distribution of the experimental studies, it is appropriate to make design tests for the new repair mortar.

3.3.1. Design of the repair mortars

While producing the repair mortar, aesthetic concerns like structure and color compatibility should be taken into account together with physical and mechanical properties. The properties and the mixture rations of the present material should take place within the process of designing the repair mortar.

3.3.1.1. The determination of the properties of the raw material

It is necessary to know the type and size of the aggregates to be used in the newly produced mortar together with the chemical structure of the lime that will be used as a binder. In addition, having some information about the effects of the additives such as pozzolanic matter, silica fume, fly ash, white cement, acrylic and delicate balancing of their mixture ratios will help prevent any possible damage.

3.3.1.2. The determination of the mixture ratios and production. As a result of the chemical and sieve analyses made on the original mortar, mass ratios are calculated. Consequently, these results help to determine the amount of the present material that will be used in the mixture. Repair mortar samples should be made for testing. The first attempt may not be successful, therefore the results of multiple attempts are compared accordingly. The physical and mechanical properties of the new mortar that resembles the original one in color and structure are found with the help of experiments and are compared with the values of the original mortar. Lastly, the new mortar, whose physical and mechanical properties are compatible with that of the original one should be subject to a series of durability tests. These tests will help us to determine whether the use of new mortar is appropriate or not.

3.3.2. Production of repair mortars

After the determination of the mixture ratio and materials which are used to make repair mortar, sample mixtures are prepared and cast in steel casts at the laboratory conditions. Later, the physical and mechanical property tests are conducted on the produced repair mortar samples as shown in Section 3.2.2.2. Also, to determine the atmospheric condition resistance of repair mortars, durability tests must be conducted.

3.3.2.1. The determination of properties of repair mortars. In order to make a comparison between original mortar and repair mortar samples which were produced in the laboratory, physical, mechanical tests (in Table 5) and petrographical–minerological analyses must be conducted (in "The petrographical and mineralogical analyses").

3.3.2.2. The determination of durability in repair mortars. Experiments of durability are made in order to measure the resistance of the new mortar to the atmosphere conditions. In determining the durability of the mortar the following experiments should be made: wetting–drying, freezing–thawing and aging tests in the sodium sulfate decahydrade solution (salty solution). These experiments will give us information about the behavior of the new repair mortar under unstable atmosphere conditions. In other words, it will be possible to learn the new mortar's duration of life through the above-mentioned tests. If there is minimum or no damage at all on the new mortar as a result of these experiments, it is possible to decide that the durability of the new mortar is high and hence, its application is appropriate. The most important aspect of an ideal repair mortar is its durability to freezing and thawing cycles together with the durability against salt crystals dissolved in water against hydration and dehydration cycles [5].

3.3.3. Comparison of test results of repair mortars and original mortars

Comparison is made to determine the similarities between the characteristic properties of original mortar and repair mortar. In the comparison, depending on the places where the repair mortar is used, it can be given priority on some characteristic properties. The value of priority characteristic property of repair mortar must be closer to the original mortar' value. For the other property values, this similarity can be enough. In addition, durability test results of repair mortar are considered.

3.4. Phase IV: Decision-making

In conclusion, if expected characteristic properties are found in the repair mortar (in other words, enough similarities to the original mortar are obtained), mixture ratios are concluded and then decisions are made for application. If repair mortar's characteristic properties are not enough as expected, the design of the repair mortar (Section 3.3.1) should be reconsidered.

4. Results and suggestions

This study has tried to summarize a basic schema of the experimental methods that may be followed in order within the repairing process of the most important materials that have been used in the construction of the historical buildings: mortar and plaster. The lack of an existing standard with regard to repair mortar to be used in historical buildings requires the design of such a flow diagram as presented in this study. The suggested experimental method can be applied for every type of mortar or building. The repair mortars sold currently at the markets may be prepared and upgraded in accordance with the experiment results; in this way, use of ready-made repair mortar sold at the markets in plastic bags may facilitate the restoration process. At the same time, the flow diagram presented in this study sets up the study practice that may constitute a standard for obtaining a data archive that includes information about the diversity of the mortar in accordance with the time period in which they were made.

References

[1] Torraca G. Porous building materials—materials science for architectural conservation. International Centre For The Study Of The Preservation And The Restoration Of Cultural Property; 1981. p.64–6, 105–7.

[2] Croci G. The conservation and structural restoration of architectural heritage. Southhampton, UK, Boston, USA: Computational Mechanics Publications; 1998. p. 68–70.

[3] Güleç A. Bazı Tarihi ve Anıt Harç ve Sıvalarının İncelenmesi (Investigation of mortars and plasters in some historical buildings and monuments). Doktora Tezi (PhD Thesis), İTÜ Fen Bilimleri Enstitüsü (Institute of Science and Technology), İstanbul, 1992. p. 23–30, 33–5.

[4] Teutonico JM. A laboratory manual for architectural Conservators. ICCROM Publication; 1988. p. 73, 113–9.

[5] Weaver M, Matero FG. Conserving buildings—guide to techniques and materials. New York: Wiley; 1997. p.133–7.