Feasibility of Fiber-Reinforced Mortar for the Reconstruction of an Ancient Roman Temple

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SUMMARY: The imperial Roman temple, located on the site of the ancient city of Antiocheia ad Kragum in southern Turkey, has fully collapsed. The marble blocks that once formed the walls, columns, and superstructure are piled upon each other on the original platform. The exact cause for the collapse is unknown. Some damages could have occurred from earthquakes, soil settlements, religious wars, or microclimatic events.

The author and her colleagues have been approved to investigate the ruins of the temple in hopes of resurrecting it to its original structure. In order to do so, the conditions of the existing structural components and an evaluation of possible solutions to restore and improve the strength of the structure, needs to be considered. Some premature proposals of repair for some of the structural components of the building are: repointing the mortar joints of the foundation, repairing the cracks in the blocks with epoxy, drilled fiber bar reinforcement in columns, and potential fiber-reinforced mortar (FRM) joints for invisible parts of the load-bearing system.

This paper examines the feasibility of utilizing FRM to repair the temple's foundation as well as other load-bearing parts of the Temple. It involves a literature review regarding ancient Roman mortar formulations, a laboratory analysis of an authentic concrete sample of the Temple's platform, and a discussion of pros and cons of FRMs in ancient marble masonry applications with referrals to the author's ongoing experimental FRM research. The paper will summarize the up-to-date findings of this feasibility study.

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KEY-WORDS: historical preservation, structural, Fiber-Reinforced mortar

INTRODUCTION

The imperial Roman temple, located on the site of the ancient city of *Antiocheia ad Kragum* in southern Turkey, has completely collapsed and all of the marble blocks that once formed the walls, columns, and superstructure are piled upon each other on the original platform (Fig. 1a). The cause of the collapse of the structure is unknown, but some possible causes could be from earthquakes, soil settlements, damage occurred during religious wars, or simply, poor materials damaged by microclimatic events.

Fig.1. (a) Collapsed State of the Temple; (b) Partial Block Inventory; (c) Hypothesized Architecture

In 2004, the first author and her colleagues were invited by the regional government authorities to investigate the condition of the temple's ruins with the expected outcome of reconstructing the temple and revival of the architectural heritage. This project aims to merge engineering and archeology in order to understand the original design and the construction technology employed at the time; the condition and capacity of the remaining structural elements and materials; and to design an appropriate reconstruction scheme. A three-year project is awarded to the first author by the National Science Foundation (NSF) to address all of the above and other related research questions. Other sponsors such as Harvard University Loeb Library Foundation and University of Nebraska Layman and Research Council Awards also support this project. Once this investigation phase is complete, the reconstruction stage will be launched. The predicted start for this phase is the summer of 2010.
The current phase of the project involves investigative work to successfully design appropriate and feasible repair and strengthening materials, and a reconstruction scenario by: 1) dismantling the mound of blocks and cataloguing the inventory (Fig. 1b); 2) architectural and structural assessment of the remaining blocks; 3) analysis of the mortar samples from the temple; and 4) analytical research to determine the plausible causes of the initial collapse.

In the summer of 2007, the project team started moving the blocks which were stacked on the original platform to be placed on an adjacent field (Fig. 1b). About 90 blocks were moved in the 2007 season, and this will be continued over the next few summers. Before each block was moved, it was measured, sketched, and surveyed *in situ*. Each block is assessed with care to determine the way the original structure looked architecturally, to understand the block's role, and to assess the possibility of employing the block in the reconstruction. Current block inventory suggests that the Temple was *prostyle* with four columns in the front, and with the estimated proportions, a three-dimensional rendering is prepared by the team (Fig. 1c). The column capitals of the Temple are in the Corinthian order (Fig.2a), and a pediment block that once stood atop the entry way of the temple was discovered (Fig.2b). This pediment was relatively well preserved and depicts the bust of a male in the manner of the god Apollo flanked by winged victories. Based on the assessments of the archeologists in the team, the details of the carvings on the bust, and other sculptural elements, it has been predicted that the temple likely belonged to the Severan Dynasty of the Roman Empire roughly the early 3rd century A.D. (Erdogmus, Hoff and Townsend, 2007[3]).

Fig. 2. (a) Corinthian column capital from the temple; (b) Relieved sculpture on Temple's pediment

An important consideration in this project is the assessment of existing materials to be able to design and propose the most appropriate repair and reconstruction program. According to findings to date, the Temple has white marble dry masonry walls and superstructure; and rubble and marble masonry with mortar joints is used for the platform and the foundation walls (Fig. 3). The research team thinks that there may be a vaulted room below the platform, however, the dismantling and excavation is not advanced enough validate this suspicion. If there is a vaulted room, however, the materials would be similar mortar and marble.

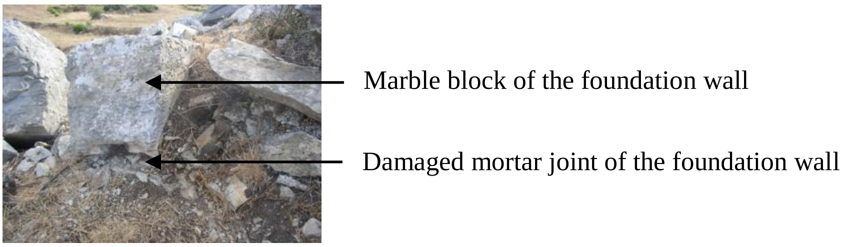

Fig. 3. Foundation wall where the crumbled mortar chunks are found

Based on the material inventory so-far recovered, it is clear that the blocks seem to be in need of repair and strengthening, and the mortar needs to be replaced with stronger material to revive the Temple. While the reconstruction program is not yet designed and further study is needed, potential repair, reconstruction and strengthening techniques considered include the following:

1. Development of appropriate repair mortars for the strengthening and the reconstruction of the platform and the foundation walls (and perhaps the vault that is yet to be found): Innovative fiber-reinforced mortar (FRM) will be considered

2. Epoxy injections in the cracks: regular and fiber reinforced epoxy will be considered

3. Drilled or hoop reinforcement for marble column drums: fiber-reinforced polymer bars or ties will be considered.

This paper studies the first of these repair methods and scrutinizes the feasibility of using FRM in the repair of the temple's foundation walls and the platform.

The anatomy of the authentic mortar must be determined to design the method of repair and reconstruction. During the investigations up to date, the researchers were able to recover a sample of the mortar used in the foundation walls, which were also observed to be in poor condition. An analysis of this mortar sample is carried out and the literature on Roman mortars and the advancements in fiber-reinforced cementitious systems are studied to assess the feasibility of the proposed repair method. This paper reports the up-to-date progress of the project. The combination of discussion on historic mortars versus innovative FRMs along with the analysis results on the material sample will bring the authors' research team to the point where they can start developing the appropriate and efficient, yet innovative repair materials, potentially those reinforced with fibers.

LITERATURE REVIEW

Historical Mortars

The literature is not in agreement with regards to when the first form of mortar was created. Many think that Egyptians were the first to create mortar, but according to the Hellenic Cement Industry Association (HCIA)[4]; it dates back to 7000 B.C. and was found in south Galilee, Yiftah El, in Israel and it consisted of a mixture of lime combined with water, sand, and stones. It appears, however, the earliest known use of lime mortar in Ancient Egypt was in 4000 B.C. (Ringbom *et. al.* [10]). Until then, there are reports of clay mortar with sand, water, and stone aggregates in small pyramids located along the west bank of the Nile, which date back to about 26th- 25th century B.C. (Winston [13]). The large pyramid in Giza, Egypt (2500 B.C.), however, is reported to employ mortar made of lime or gypsum (HCIA). Regardless of when the first mortar was created, it was certainly adopted and widely used in the Roman Empire. The renowned buildings of the Roman Empire located in Europe and Africa were built using variations of lime mortars. Over the many years in which lime mortar was used, the aggregates and other additives vary according to time period or region, yet use of lime in the binding matrix stays common. Other forms of mortar that were used included mortar with bitumen and gypsum. Lime mortars were used until about the 19th century, after that Portland cement became the dominant material in cementitious mixtures.

Around 500 B.C. pozzolana mortar is developed, which is a lime based mortar with volcanic ashes. The ashes allow the mortar to harden underwater, resulting with hydraulic cement. The Romans were well known for using various materials in combination with the lime binder, and they began to improve the pozzolana mortar. Instead of using the volcanic ashes they would use crushed terra cotta; this addition would allow aluminum oxide and silicon dioxide into the mix. The strength of this mix was lower than that of the pozzolana mortar, but it was denser and presented better resistance to water penetration (Ringbom *et.al.* [10]). Romans are accredited for inventing "opus cementicium", the first form of concrete, yet there is no one consistent story of how it was invented among scholars (Acun *et. al*. [1]). Vitruvius reports that Romans discovered how volcanic ashes harden under water forming natural hydraulic cement, which may very well be how Romans discovered concrete and pozzolana mortar (Vitruvius [12]).

Lechtman and Hobbs [6] state that in Vitruvius' Ten Books on Architecture, a method for designing the mix of lime mortars according to the significance of the structure is suggested. Vitruvius suggests a pozzolana/terra cotta mortar, which was a reddish-brown color, for structural applications. The mix should be 1 part lime to 3 parts pozzolana, and for structures underwater the ratio should be 1:2. According to Lechtman and Hobbs, this mortar proportion was adopted for almost all of Rome's structures and lasted many years. Mack [7] states that generally the historical mortars that he has studied were 1 part lime to 3 parts sand by volume, with the inclusion of other aggregates such as crushed marine shells (another source of lime), brick dust, clay, natural elements, pigments, and even animal hair. A study of lime mortars and plasters in Turkey states that a variation of lime mortar named *Horasan Mortar* was found in the remains of ancient Roman structures in Anatolia.

Horasan mortar is believed to have been common amongst the Byzantine, Seldjuki, and Ottoman periods. This particular mortar is as strong as concrete and is made by binding lime together with varying proportions of river sand, brick pieces or powder that are used as aggregates (Acun *et. al.* [1]).

The ancient city of *Antiocheia ad Kragum*, where the Temple studied in this article is located was founded in the 1st Century A.D. by Antiochus IV of Commagene and the temple is predicted to have been built during the 3rd century A.D. during the Severan Dynasty. Given this time period along with the history of Roman architecture and construction technology, it is certain that the mortar used in the Temple is a type of lime mortar. Based on visual inspections, the Temple's mortar agrees with both Acun's and Mack's synopsis of Roman lime mortar in Turkey. Vitruvius' suggestion of the mortar being a reddish-brown colour, however, contradicts with our grey mortar sample. Although our specimen seemed to have some reddish specs in it, it is believed to be the colour of an aggregate, possible brick pieces or terra cotta.

ANALYSIS OF SAMPLE MORTAR

Historical Mortar Analysis Method

In historical preservation projects, first the authentic mortar must be studied in order to design a compatible yet effective mortar mixture. There are numerous methods for the analysis of historic mortars such as: Acid Dissolution, Wet Chemical and Sieve Analysis, Petrographical and Minerological Analysis, Scanning Electron Microscope (SEM) with Elemental Dispersive analysis (EDAX), Optical Microscopy, X-Ray Diffraction (XRD), Thermal Analysis (DTA and TGA), Visual, Physical, and Mechanical Testing. All of these methods offer a certain set of information and with the use of more than one method, better results can be achieved. The wet chemical analysis and the Petrographical analysis are American Society of Testing Materials (ASTM) standard methods, and thus the first one is selected as the preliminary analysis method in this preliminary phase of project. After the chemical analysis, a sieve analysis is also carried out to identify the types and sizes of the aggregates. While not comprehensive, this set of analyses provides enough information to start an understanding of the mortar's composition and with the results of this analysis, further directions of the project will be determined.

The authors worked with a specialist firm, Virginia Lime Works, to carry out the wet chemical analysis. The general process that was used is as follows:

- A mortar sample with a diameter of about 1 inch (2.5 cm) is weighed and crushed. (Two more samples are tested to provide adequate analysis of the mortar. However, the study is ongoing and the analysis of these samples cannot be included in this manuscript)
- The mortar was then dissolved in a 3:1 water to Muriatic acid solution
- After all of the lime was dissolved, the aggregates that remain in the solution are weighed and the lime binder to aggregate ratio is determined
- The aggregates are then sieved through different size sieves; this is known as the Sieve Analysis. This process helps to determine the different sizes of aggregate used in the mortar, and the data collected from this process is shown in a chart of sand sizes.

- At the end of the series of tests, the following are reported: the dry weights of the materials, the sand size chart, and the colour of the mortar with respect to Munsell scale. A dry weight composition of the original mortar in terms of sand to lime proportion, and any general observations noticed during the test are also reported.

The results of the Temple's mortar sample analysis are presented in the following section.

Temple Mortar Sample Analysis Results

The wet chemical analysis of the mortar presented the following information:

- The mortar is light grey in colour comparable to Munsell 2.5Y-8/1 to 7/1.
- The original weight of the sample was 15.71g.
- After being exposed to the soluble acid the following weights were determined:
  - Weight of sand: 9.26g
  - Weight of fines (the particles that are left in the pan after the sieving process, noted as pan in **Fig.** 4): 7.85g
  - Soluble Fraction Weight (Lime): 4.60g
- The colour of the sand (Munsell based): 2.5Y-7/1 to 6/1
- The colour of the fines (Munsell based): 2.5Y-7/2
- The Proposed Original Mix (dry weight ratio): 2.42:1 sand and fines to lime

The aggregates' analysis reveals a wide spectrum of sizes, as shown in Table 1 and Fig. 4.

Table 1. Aggregate Analysis Results

Sieve Label	0	4	8	16	25	50	100	200	Pan	
Sieve size (mm)	0	4.75	2.36	1.18	710UM	300UM	150UM	75UM	pan	TOTAL
Sample (grams)	0	1.05	1.51	1.88	1.29	1.95	1.12	0.39	0.07	9.26
Percent	0.0%	11.3%	16.3%	20.3%	13.9%	21.1%	12.1%	4.2%	0.8%	100.0%

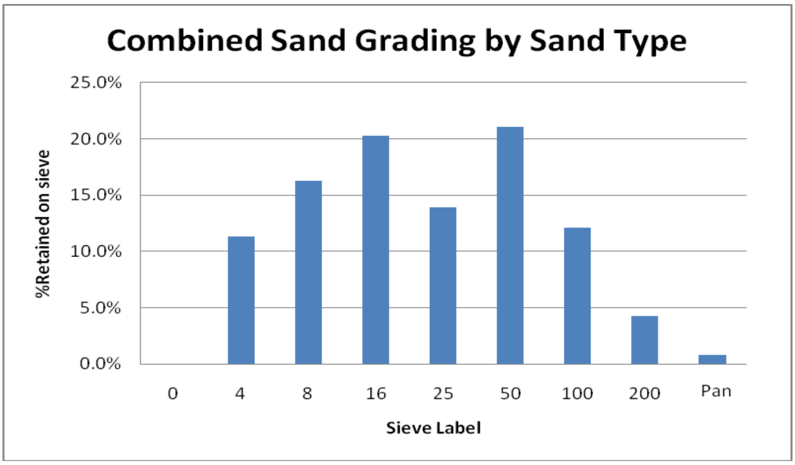

Fig. 4. Temple Mortar Aggregate Size Analysis Results

The toughness of the mortar from the temple was assessed with a preliminary scratch test, and presented high stiffness; however it crumbles under impact. This is typical of mortars with high lime content and no pozzolana/cement. During the chemical analysis process, it was noted that the sample broke down very fast and in a violent manner when immersed in the acid solution. Not only did the sample include regular lime, but it was also noticed that some under-burnt limestone was present. Since the limestone aggregate and under-burnt stone aggregates may have been understood as lime content, the aggregate to binder ratio may have been affected such that the lime content may even be lower than the reported 2.42:1 ratio. It is also possible that the initial aggregate sizes may be larger, because some of the limestone was dissolved by the acid. It is observed that the aggregate is a mixture of various mineralogical sources, including possibly limestone, sandstone, and granite. These extra portions of lime are probably why the sample was so violent during the chemical process, as nearly the entire material was reactive to acid, and not only the binder material as intended.

The analysis of this sample shows that the composition of Temple's mortar is relatively poor, but consistent with the reported compositions of Roman mortars in Mack [7]. Our proportions of dry mixture is 2.42:1 sand/fines to lime and Mack reports 3:1 sand volume to lime. The reason of the difference may be local variations or the fact that some of the aggregates in our mixture may be dissolved in the acid and the actual proportion may be closer to 3:1. The materials that Acun *et. al.* [1] stated about Ancient Roman mortars in Turkey having a binding matrix with lime and having varying proportions of river sand and brick pieces/powder as aggregate, is very similar to the ones discovered at our site as well. Therefore, it can be preliminarily reported that the lime mortar observed in the Temple strongly resembles *Horasan* mortar.

REPAIR MORTARS

In considering repair mortar, there are a few rules that should be followed. Maurenbrecher [9] provides the following criteria for developing a repair mortar.

- Mortar should not be stronger than needed for the structural strength and durability requirements of the masonry
- Water absorption and vapour transmission rates should be similar to the existing masonry units and mortar.
- The new mortar should have little shrinkage.
- The new mortar should be resistant to frost and salts as required by environmental exposure.
- The new mortar should match the existing masonry unit and mortar expansion properties due to thermal and moisture effects.
- The new mortar should match the existing masonry in colour and performance.
- The new mortar should be practical in preparation and application to encourage a high level of workmanship.

As discussed previously, one of the repair/strengthening/reconstruction ideas currently considered is the development of novel materials that are compatible with the authentic materials but are stronger against tensile loads and environmental effects. The novel idea proposed here is to use fiber reinforcement in the repair of the foundation walls, platform, and if one is discovered, in the vault of the lower chamber. The feasibility of this idea, however, must be studied carefully. The authors are concurrently conducting an extensive experimental program to study FRMs, a literature review and the assessment of authentic materials to reach a conclusion about feasibility. A brief discussion of FRMs is provided below.

Fiber Reinforced Mortar

In the field of FRC, many studies have been performed to evaluate how the type of fibers such as glass, steel, synthetic, organic, etc. in relation to their various sizes, affect the characteristics of concrete. The authors' research team has been evaluating FRM mixtures for masonry applications and has been comparing the findings to the better studied fiber-reinforced concretes (FRC). Mainly polyvinyl alcohol (PVA) fibers have been studied by the team so far. In a previous publication by the first author, (Skourup *et. al.* [11]) the team discovered that all tested PVA FRMs showed an increase in post-crack ductility, toughness and energy absorption compared to plain mortar. This is aligned with the FRC studies reported in the literature. For instance, Lawler *et. al.* [5] demonstrated that a concrete mix including both micro (smaller than 0.25 inch) and macro fibers (0.25 inch- 2.5 inch) increased the strength, toughness, and flow ability of concrete while reducing constrained shrinkage. The research team studied micro and macro fibers alone and also hybrid fibers. From an aesthetic feasibility point of view, it was also determined that the macro fibers had a tendency to project out of the joints, causing an unappealing appearance but micro fibers do not present this problem; thus micro-fiber-only mixtures work better for masonry applications.

Another problem that must always be addressed in masonry applications is the bond between unit and mortar. This is an issue repeatedly discussed in the literature for regular mortar and unit combinations (Maurenbrecher *et. al.* [9]). With FRMs, there is a potential that the bond may be worsened, and it must be tested and optimized. In previous tests performed by the first author and her team (Skourup *et. al.* [11]), it has been evident that the more fiber included in the mortar mixture the drier the mixture becomes, which decreases bond strength. It is the lack of moisture available in the mixture that causes the mortar not to bond well with the units; therefore in the design of the repair mortar, there should be an adjustment of water applied to the mixture. Preparation and curing techniques must also be optimized to achieve maximum possible bond strength. For example, preliminary studies for both the PVA and corn fibers show that wet or pre-soaked fibers present a potential to increase the bond strength. This part of the optimization study is still ongoing and since enough statistical data is not yet gathered, definite conclusions about curing techniques and optimization are avoided herein. However, if such optimization is achieved, it is predicted that bond strengths comparable to or higher than regular mortar-unit bonds will be possible.

A study by Drdacky and Michoinova [2] who looked at a typical lime mortar composition reinforced with horse and goat hair fibers show that use of fibers are very effective in achieving better volumetric stability of lime mortars, and supports the authors' findings and claims.

With such encouragement from the preliminary work on FRMs, the authors are considering using FRM in the repairing of the structural platform of the Temple as well as the invisible portions of the load-bearing components. The temple's site is by the Mediterranean Sea.

During the months of March to October the site experiences drastically hot weather, ranging between 32˚C and 38˚C degrees. It rains and floods some during the period of November to April, and is humid year-round; therefore moisture and high temperature are environmental effects that must be considered in repairing and strengthening the Temple. There is no snow in the area and the lowest temperatures are about 15˚C, so frost protection is rather irrelevant. There is aggressive vegetation growth at the collapsed and un-maintained temple site, which has aggravated the damage on the materials. Another consideration for the Temple's revival is that the site has endured seismic activity in the past and may face such effects again in the future.

For all of these strength, stability and material performance issues, it is evident that the revived system must have increased strength, ductility and toughness. A strong foundation and platform is necessary to survive earthquakes and environmental effects. The authors' study of micro and macro PVA fibers in Portland cement mortar has proven that there is an increase in the flexural strength, toughness and post-crack behavior of the mortar if fibers are added, however for optimum benefits for each mortar-fiber- masonry unit combination, further studies and optimization is needed.

When assessing FRM feasibility in historic repairs and reconstructions, it is considered to be successful based on preliminary results. The idea proposed by the authors is such that the binding matrix can be one that closely matches the make-up (composition, color, etc...) of the authentic mortar, and the addition of fibers can boost the mechanical and durability characteristics.

CONCLUDING REMARKS

This project is an extraordinary opportunity to contribute to revival of ancient architecture. The authors' engineering team are studying the feasibility of using fibers in lime based mortar in order to repair the structural system of the Temple located on the ancient site of *Antiocheia ad Kragum*. The parts of the system that will need strengthening and repairing using mortar include: the foundation walls, the platform, and if one is found, the vault of the underground chamber.

Preliminary findings show that the authentic mortar of the Temple is of a relatively poor make-up with a high lime concentration and various sizes and qualities of aggregates. There are no traces of strong binders such as cement or pozzolans. The site inspections, especially the cracks and material deformations on the marble units also suggest that the structure has seen at least one forest fire after the collapse and years of weathering. Any reconstruction attempt will necessitate a mortar mixture that is of similar look, and have similar chemical composition to match the reconstruction of historical architecture rules, but needs a way to boost the structural capacity. Current findings including the authors' previous work on FRM point out that use of FRM may just be the recipe to solve this dilemma. In the next phase, as more samples from the Temple are analyzed an a clear identification of the mortar is finalized, imitation mortar with similar compositionwill be prepared and various types, sizes and volume fractions of fibers will be tested. An adjustment of water content in the mortar will be evaluated in order to create a better bond between the units and the mortar.

BIBLIOGRAPHY

[1]ACUN, S., ANGOLU, N.- *The Evaluation of Lime Mortars and Plasters with the Purpose of Conservation and Restoration.* Building and Environment, Vol. 41, 9, September 2006, 1223-1230.

[2]Drdácký, M. F., and Michoinová, D. (2006). "Lime Mortars with Natural Fibres." Proceedings, Workshop on In Situ Evaluation of Historic Masonry and Wood Structures.

[3]ERDOGMUS, E., HOFF M., TOWNSEND, R. (2007). Engineering Assessments in Preparation for the Reconstruction of the Imperial Temple in Antioch, Rough Cilicia Archeological Conference, University of Nebraska-Lincoln.

[4]HELLENIC CEMENT INDUSTRY ASSOCIATION. History of Cement and Concrete. www.hcia.gr/3a.html

[5]LAWLER, J. S., ZAMPINI, D., and SHAH, S. P.-*Microfiber and Macrofiber Hybrid Fiber-Reinforced Concrete*. Journal of Materials in Civil Engineering, Vol. 17, 5, 2005, 595-604.

[6]LECHTMAN, Heather and HOBBS, Linn. -*Roman Concrete and the Roman Architectural Revolution*. Ceramics and Civilization Volume 3: High Technology Ceramics: Past, Present, Future, 1986; and Vitruvius, Book II:v,1; Book V:xii2

[7]MACK, Robert C., FAIA, SPEWEIK, John P.- *Repointing Mortar Joints in Historic Masonry Buildings.* Preservation Briefs. Ch. 2, Washington, D.C., October 1998.

[8]MAURENBRECHER, A. H. P., SUTER, G. T., TRISCHUK, K., and FONTAINE, L.- *Contribution to Pointing Mortar Durability In Historic Mortars Characteristics and Tests*. Proceedings of the RILEM International Workshop.2000, 361-369.

[9]MAURENBRECHER, A. H. P.- *Mortars for Repair of Traditional Masonry*. Practice Periodical on Structural Design and Construction, Vol. 9, 2, 2004, 62-65.

[10]RINGBOM, S., HALE, John, Heinemeier, Jan, Lancaster, Lynne, Lindroos, Alf,- *Dating Ancient Mortar.* American Scientist Online. Vol. 91, 2003.

[11]Skourup, B., and Erdogmus, E. (2008). "Mechanical Characteristics of PVA Fiber-Reinforced PCL Mortars for Masonry Applications" under review for publication in the ACI Materials Journal.

[12]VITRUVIUS. (1960). Translator: MORGAN, M.H. *Ten Books on Architecture*. Dover Publications.

[13]WINSTON, Alan.- *Egypt's Ancient, Small, Step Pyramids.* Jan 02, 2005. http://www.touregypt.net/featurestories/smallstep.htm