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Use of Perlite as a Pozzolanic Addition in Lime Mortars

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ABSTRACT

The consciousness of a sustainable construction process requires awareness about production of construction materials. Considering the high cost and the negative environmental effects of cement, which is widely used in contemporary building construction, it becomes clear that there is a need in research of alternative binding materials. Pozzolanic lime mortars, which are among the oldest construction materials, have gradually been used less and less due to their long term strength development although they have high durability.

Since there is plenty of perlite reserves of in Turkey, it is necessary to research the possibilities of using it in the field of construction materials. The aim of this study is to invent a hydraulic cementitious material which is not soluble in water and which has efficient strength.

As result, the utilization of perlite as a pozzolanic activity in lime mortars ensures the strength requirements. But perlite-lime mortar did not show enough strength against freezing due to its high water absorption, since the number of open pores it contains is more than the closed ones. So, perlite-lime mortar can be successfully applied in historical buildings instead of classical lime mortars. On the other hand, mechanical properties of perlite-lime mortar are sufficient as an inner partition bricks.

Keywords: Pozzolanic activity, perlite, lime mortar.

INTRODUCTION

The use of pozzolanic materials is significant in terms of energy efficiency and environmental effects in cement industry and the durability and life cycle costs of reinforced concrete buildings. Pozzolans are used in mortar and concrete production thanks to their advantages such as low hydration temperature, high last strength, low permeability, high sulphate resistance and low alcali-silica reactions.

Lime mixed with pozzolanic additions has been used extensively in the past as mortars for the construction of historical and traditional buildings. Mortar/plaster or concrete produced by the mixtures of lime and calcinated clay supplied from ground or broken clay tiles, known as Horasan, was extensively used in Roman, Selchuk and Ottoman Buildings in Turkey.

Therefore, analogous materials should be used in today's interventions on the historic buildings in order to assure compatibility of the restoration mortars to authentic ones. One of the major problems of selecting the appropriate pozzolan used as a pozzolanic addition in restoration mortars is its reactivity. The use of high reactive pozzolans as an additive to lime mortars produces hydraulic, durable mortars with sufficient mechanical strength, similar to historic ones. Today, mixtures of portland cement and pozzolan are used in concrete to help alleviate the energy crisis and to achieve specific technical benefits like lower permeability, reduced heat of hydration, reduced alcali-aggregate expansion, reduced concrete drying shrinkage, higher strengths at later ages and increased resistance to attack from sulfates in seawater or from other sources [1-4].

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In terms of the national reserves of perlite, Turkey comes third in the world after the US and Greece [5]. This is the major reason for the research of perlite as a construction material.

Since Turkey is rich in volcanic tuff, certain tuff is used in the form of pozzolan by local cement factories and is added to the cement in the production of Portland cement [6].

Perlite is a volcanic glass with acidic character, composed of 3-10% crystallized minerals, including obsidian particles as well. It has the quality of thermal expansion which results in lightness and porous structure. Expanded perlite is used as plaster, concrete aggregate and insulation material in the construction sector. However, since the production of expanded perlite is a labor-intensive process, it can be argued that perlite should rather be used raw with its pozzolanic quality.

Erdem et. al. [6] studied in use of natural (raw) perlite as a pozzolanic addition in producing blended cements. According to their research; despite the early strength losses, the use of perlite in blended cements will be beneficial since the improvements in the grinding efficiency by the perlite and availability of it will help reduce the portland cement consumption, and therefore, cost and CO_2 emission.

Although there are limited studies on the use of expanded and raw perlite as a cement additive, there is almost no study on its use together with lime mortar.

The purpose of this study is to explore if the perlite has pozzolanic reactivity or not. And then, determine utilization of perlite-lime mortar as a building material. Thus, physical properties, dimensional stability and mechanical properties of lime-pozzolan mortar with perlite as the pozzolan material are analyzed.

2. Pozzolanic Activity Reactions

Pozzolanic reactions are those that occur in response to the combining of pozzolanic materials and $Ca(OH)_2$ (slaked lime) in a moist environment. These reactions can produce materials with hydraulic binding quality similar to portland cement hydration products.

Pozzolanic materials are silicates containing high levels of SiO_2 and Al_2O_3, with irregular crystal structures. They can dissolve in alkali environments with high pH levels under the impact of OH^- ions. The dissolution process begins with the absorption of the OH^- ions that come out of the reaction of Portland cement or lime with water. As a result, the coordination number/level of the silica atom on the surface of the silicate increases, its connection to the oxygen atom below weakens and silicic acid begins to emerge:

$$SiO_2 + 2H_2O \rightarrow Si(OH)_4$$

$$Si(OH)_4 + OH^- \rightarrow Si(OH)^-_5$$

$$Si(OH)^-_5 + OH^- \rightarrow Si(OH)^-_6$$

The negative charges of $Si(OH)^-_5$ and $Si(OH)^-_6$ that materialize as a result of the weakening of the ties inside the silica atoms on the surface can be neutralized with Ca^{++}, K^+ and Na^+ ions. Since the Ca^{++} ion is absorbed with greater force, it is the first to neutralize the negative charges. Some part of the negative charges can be neutralized by the other alkali ions (K^+ and Na^+). Calcium silicates materialize with the Ca^{++} exchanging places with H^+:

$$Si(OH)^-_5 + Ca^{++} \rightarrow CaO\ .\ SiO_2\ .\ 2H_2O + H^+$$

$$Si(OH)^- + 2Ca^{++} \rightarrow 2CaO\ .\ SiO_2\ .\ 2H_2O + 2H^+$$

3. EXPERIMENTAL

3.1. Raw Materials

In this study, the components of the mortar lime, perlite, sand and water are defined as the raw materials.

Quicklime (CaO), which is used as a binder in the production of mortar, was slaked with 2.3 kg of water per kilogram to obtain hydrated $Ca(OH)_2$ and stored in moist condition for 15 days until it is used. It was sieved from 600 µm sieve in order to remove unslaked particles if there is any. During the preparation of the sample, the amount of water that existed within the slaked lime was determined and reduced from the water added to the mixture. The density of the slaked lime was determined as 2.39 g/cm^3 with an experiment conducted in accordance with TS 639 [7].

As a pozzolanic material, the residue remained in the filters as the by-product of the process of expanding raw perlite was used. It was supplied from İzmir Etibank Perlite Enterprise. Perlite was grinded to a maximum grain size of 0.3 mm. The grinding process was conducted for 20 hours per 3 kg perlite, in a steel grinder. It was then sifted through a 90 µm sieve with 8% maximum residue which is in accordance with TS 25 [8]. The gradation of perlite used in the mortar is shown Table 1. After grinding Blaine fineness of perlite was measured in accordance with TS 24 [9]. The chemical analysis results, ignition and moisturation losses, densities, and the results for Blain fineness experiments of perlite are given in Table 2.

Table 1. Gradation of perlite

Sieve No (µm)	% residue
212	19,96
125	40,79
90	17,48
-90	21,77
Total	100,00

Table 2. Specifications of perlite and sand, and the limit values for pozzolan according to TS 25

	TS 25	Raw perlite	Standard sand
SiO_2 (%)	≥70	74.41	92.1
Al_2O_3 (%)		12.60	2.02
Fe_2O_3 (%)		0.80	0.43
MgO (%)	≤5.0	-	0.03
SO_3 (%)	≤3.0	-	0.07
Na_2O (%)	-	3.08	0.93
K_2O (%)	-	4.40	1.3
CaO (%)	-	-	0.2
Loss on ignition (%)	≤5	3.79	0.55
Loss on moisturation (%)	≤10	0.25	-
Density (g/cm^3)	-	2.38	2.36
Blain fineness (cm^2/g)	≥3000	5044	-

The sand used as aggregate met the requirements specified on TS EN 196-1 [10]. Its chemical analysis and its density determined with the experiment conducted in accordance with TS 699 [11] are given in Table 2. The water was supplied from the city water distribution system of Istanbul which does not contain any harmful materials.

3.2. Preparation of Experiment Samples

While the samples were prepared, first dry sand was mixed with perlite, and slaked lime and water were added to the mixture later. The mortar was mixed with electric mixer for three minutes to provide a homogeneous blend. The mortar was produced with the materials listed in Table 3, in accordance with TS 25. In order to analyze the effect of curing time, three sample groups were prepared (7-day, 28-day, and 91-day).

3.3. Pozzolanic Reactivity

The pozzolanic activity of perlite was evaluated based on TS 25. According to the TS 25, at least three mortar samples were prepared by mixing slaked lime, standard sand and pozzolan (perlite) having the weights shown in Table 3. After molding, mortar samples were covered top prevent evaporation and cured moist environment (at T=23±2 °C and RH= 90%) for 24 hours. Then they were cured at 55 °C for six days. After removing from the oven and cooling at desicators for four hours, the samples were tested for their 7th day flexural and compressive strengths according to the TS 25 and results shown in Table 4.

Table 3. Proportions of the ingredients of Perlite-lime mortar

	Defined values in TS 25	The values according to TS 25
Slaked lime	150 g	150 g
Pozzolan	2 x 150x (density of pozzolan/density of slaked lime)	2x150x (2,38/2,39) = 298.99 g
Aggregate (standard sand)	1350 g	1350 g
Water	0.5 x (150 + pozzolan weight)	0,5x (150+298,99) = 224.50 g

Table 4. Results of the Pozzolanic Activity Experiment

	Flexural strength (N/mm2)	Compressive strength (N/mm2)
Min. value defined in TS 25	1	4
Average value of perlite-lime mortar	2.99	10.50

Since the effects of the parameters of perlite/water ratio and curing temperature have already been studied in previous research [12], our aim here is to investigate the influence of curing time on pozzolanic activity. Thus, samples were prepared to be cured under 55 °C for 7, 28 and 91 days (‘P-55-7’ for 7 days cured; ‘P-55-28’ for 28 days cured; ‘P-55-91’ for 91 days cured).

3.4. Experimental Techniques

Testing of Physical Properties

Twelve samples were used to measure specific weight, density and visible porosity; and three samples were used to measure capillary water absorption, water absorption and freezing-thawing. Physical properties tests were determined accordance with TS 699 [13].

Testing of Dimensional Stability

Before curing, each three-sample group (for 7, 28 and 91 days curing periods) were measured. After curing 7, 28 and 91 days periods samples were measured again at T=23±2 °C and RH= 90%. And then two measurements for each sample have been compared.

Testing of Mechanical Properties

At every age (7, 28 and 91 days), six samples were used to measure flexural strength and twelve samples were used to measure compressive strength. If the strength of a sample differed by >10% from the average strength of the total sample, the strength value was discarded and one more sample was tested.

Ultrasound velocity was measured using the commercial device WTW-DIGI EG-c2. Elasticity modulus theoretically calculated by using ultrasound transition time and ultrasound velocity.

4. RESULTS and DISCUSSION

4.1. Evaluation of Physical Properties

Specific Weight

Figure 1 shows that the specific weights for the samples cured for 7 and 28 days are equal, while it is lower for the samples cured for 91 days. This is likely to be an outcome of the hydration reaction that occurred within the body of the sample. Porosity emerges as a result of the reaction between lime and carbon dioxide, which yields to the production of carbonate reaction and water. The separation of water from the body of sample results in porosity. On the other hand, as the C-S-H gels create a porous structure, the specific weight decreases.

As it is well known, the decrease of specific weight means the increase of porosity level and the decrease of strength and heat conductivity. The decrease specific weight due to the emergence of silicate structure leads to an increase in the level of porosity but it does not result in a decrease in strength. As illustrated in Table 5, specific weight values of perlite-lime mortar rest between those of the lower limit value of concrete and the higher limit value of brick.

Density

Figure 2 shows that the density is increased depending on the curing time. It was result of the increase of the continuation of silicate reactions throughout the curing period. As shown in Table 5, the density of perlite-lime mortar is even lower than the lower limit value for brick.

Porosity

Figure 3 shows that the porosity increased 20% by the end of 28th day and 100% by the end of 91st day, in comparison to the 7th day. Cerny [13] indicates that the C-S-H gels, which are the products of pozzolanic reaction, maintain a porous character. With the emergence of porous C-S-H structures as a result of the use of the existing water within the body of the sample in the ionization and silicate reactions, the increase in porosity continues.

Capillary water absorption

Figure 4 shows that the capillary water absorption coefficients for the samples cured for 7, 28 and 91 days decrease according to the curing time period. Against to the increase of porosity over time, the decrease in capillary water absorption could be explained as follows: Arandiyogen et. al. [14] suggest that both the porosity and the properties of the pores transform with carbonate reaction. The number of pores smaller than 0.03 micrometer decreases. This, in turn, reduces the Blain fineness of lime mortars. While porosity decreases around 10%, the distribution of pore size changes toward smaller pores.

On the other hand, as Mavi [15] suggests, the average capillarity level of lime mortar with a binder/aggregate ratio of 1125/2700 is 0.053 cm/√min. The capillary water absorption levels of the samples in our study are lower than this value (0.03370 – 0.03241- 0.03023 cm/√min).

High levels of capillarity for materials used as building blocks or mortar in walls could result in the rising of ground water. Similarly, it results in the absorption of rain in building facades. The vaporization of capillary water results in effloresance.

Table 5. Comparison of the values of specific weight, density and water absorption for various construction materials **[16]** and the perlite-lime mortar cured for 7, 28 and 91 days

Materials	Specific weight	Density (g/cm^3)	Water absorption (%)
Brick	1.2 - 1.8	2.5 - 2.7	8 – 18
Hard Stones	2.5 - 2.7	2.5 - 3.0	0 – 1
Soft Stones	2.0 - 2.5	2.5 - 2.7	1 – 3
Cement concrete	1.8 - 2.4	[*]	1 – 8
Wood	0.4 - 0.8	1.54	too much
Steel	7.9	7.9	0
Perlite-lime mortars 7/28/91 days	2.0 – 2.0 – 1.89	2.22 – 2.27 – 2.35	6.73 – 7.44 – 10.06

Water absorption under atmospheric pressure

Figure 5 shows the results of the water absorption experiment. The absorption levels of 28 days samples are 11% higher than those of the 7 days samples; and the levels for 91 days samples are 50% higher than those of the 7 days samples. Among the 7, 28 and 91 days samples, the increase in water absorption ratio related to the porosity development at the same periods.

As seen in Table 5, the water absorption level of perlite-lime mortar is between the higher and lower limit values for brick.

Visible porosity and freezing- thawing

Figure 6 shows that the level of visible porosity increases 15% on 28th day and 54% on 91st day , in comparison to the level on 7th day. The ratio of visible porosity to porosity gives the saturation level of the object. The saturation level informs whether or not the pores of sample are open. The characteristics of pores determine the durability against freezing. If the saturation level is below or equal to 80%, the material does not deform even if the water that penetrates the pores within the body of the sample expands 10% after it freezes. Nevertheless, the samples used in this study have given saturation levels higher than 80%.

During the freezing-thawing tests, the samples started to crumble after 21st recurrence for those cured for 7 days, after 23rd recurrence for those cured for 28 days, and after 24th recurrence for those cured for 91 days. Therefore, it can be argued that the durability of the perlite-lime mortar used in this study against freezing-thawing is low.

It is determined the perlite-lime mortar did not show enough strength against freezing due to its high water absorption, since the number of open pores it contains is more than the closed ones.

4.2. Evaluation of Dimensional Stability

According to Akman [17], although drying shrinkage lasts for five or six months, the significant portion of it occurs in the first month; hence, the experiment was held for a month. Thus, dimensional stability of perlite-lime mortar samples was measured during one month.

It is known that the drying shrinkage values are low/ zero for pozzolanic mortars. With the results of accurate measurements and ocular inspections, there was no drying shrinkage observed and all samples had the dimensional stability.

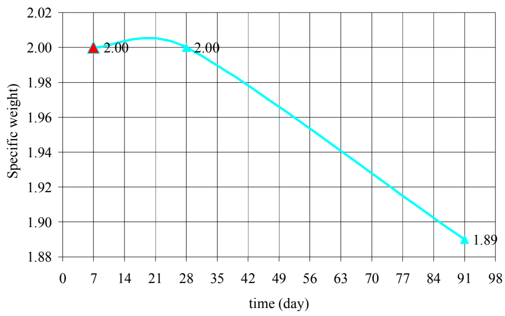

Fig.1: specific weight

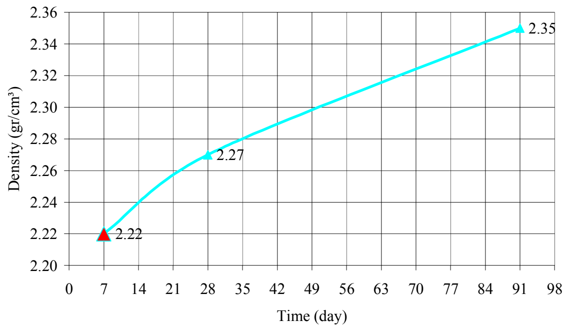

Fig.2: density

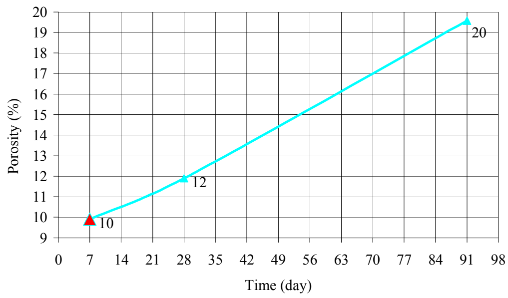

Fig.3: porosity

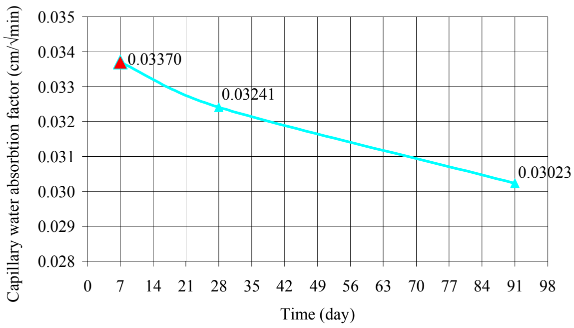

Fig.4: capillary water absorption

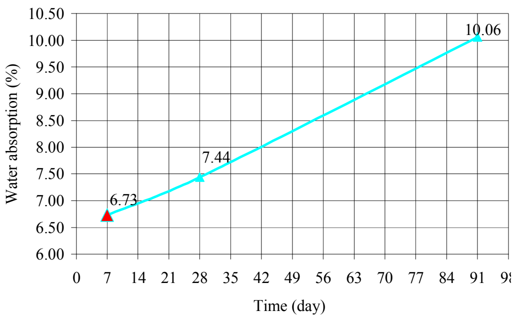

Fig.5: water absorption

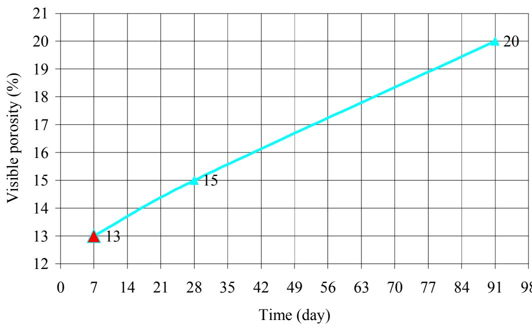

Fig.6: visible porosity

4.3. Evaluation of Strength

a. Evaluation of the compressive and flexural strength tests

Shown in Figure 7, compressive strength of the samples cured for 28 and 91 days are 30% and 65% higher than that of the sample cured for 7 days, respectively. Similarly, flexural strength of the samples cured for 28 and 91 days are 25% and 37% higher than that of the sample cured for 7 days, respectively. Both of the tests indicate that the strength increases along the curing time.

The changes in the flexural strength/compressive strength ratios of the samples are shown in Figure 8. Considering that this ratio is 0.1 for fragile materials, it is obvious that the sample cured for 91 days is fragile.

Illustrating compressive strength-porosity relationship as shown in Figure 9, the samples showed an increase in porosity and compressive strength. The C-S-H structures that materialize within the samples increase compressive strength and porosity percentage.

The comparison of the compressive strength levels of the samples used in this study with construction materials such as brick, natural stone, concrete, aerated concrete and cement could give some ideas as to the possible uses of this material.

- It is found that the compressive strength of the perlite-lime mortar samples is higher than 0.5 MPa, which is the minimum value defined for lime mortar.
- The comparison of the compressive strength values of perlite-lime mortar with those of mortar cements as listed in TS 22-1 ENV 413-1 [18] indicates while 7 days cured samples fulfill the limit values for MC 12.5 and MC 22.5, the 28 days cured samples fulfill the limit values for only MC 5 and MC 12.5.
- The perlite-lime mortar samples do not match the strength values defined for natural stone walls in TS 2510 [19].
- According to TS 453 [20], the average compressive strength values for aerated concrete construction elements are 2.5-7.5 N/mm^2. The samples of all curing durations have reached the average compressive strength durability levels defined for the aerated concrete elements.
- The samples reached the average levels of compressive strength defined for hollow bricks in TS 705 [21].

b. Evaluation of ultrasound velocity and elasticity module experiments

Since the data are interdependent and parallel, the dynamic elasticity module results are evaluated here but the ultrasound velocity results are not given. As it is shown in Figures 11 and 12, ultrasound velocity and elasticity modules decrease parallel to the curing period.

Since the elasticity module value for lime mortars in general is between 5.2 and 11 kN/mm^2, the perlite-lime mortar used in this study shows a high level of elasticity module, hence they can be considered as rigid materials. Figure 10 shows that the more the curing duration lasts, the less the elasticity module gets; which results in fragility.

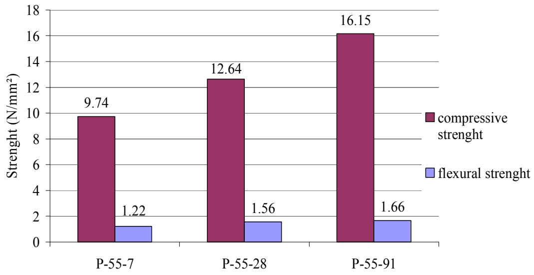

Fig 7: Flexural – compressive strength

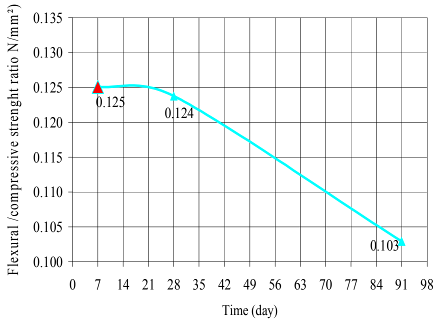

Fig 8: Flexural – compressive strength ratio

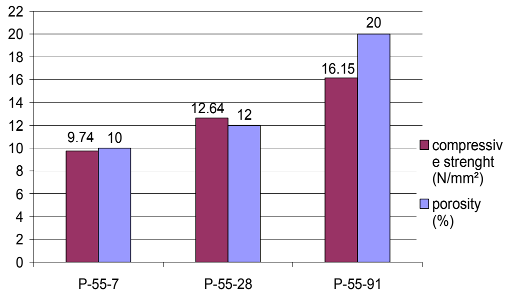

Fig 9: Compressive strength - porosity comparison

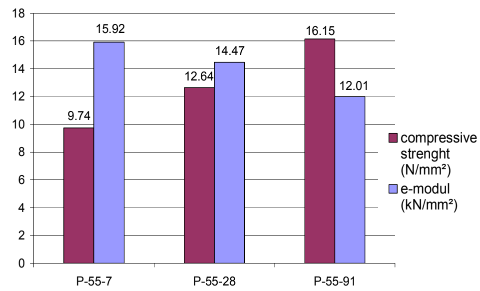

Fig 10: Compressive strength-elasticity modules comparison

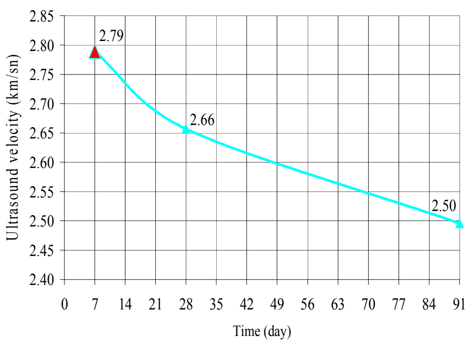

Fig 11: Ultrasound velocity

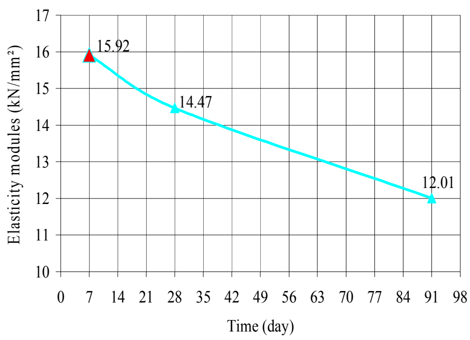

Fig 12: Elasticity modules

5. CONCLUSIONS

From the point of view of reconstruction of historical buildings, the most important result of the experimental work done in this paper is that a significant increase of strength of the mortars was achieved on the basis of the lime material basis, without using cement that was never used in buildings older than about 100 years.

Perlite, the pozzolanic admixture chosen in this work for the improvement of mechanical properties of lime plaster was found to play a very positive role in this respect. In addition the most physical properties of newly designed lime-pozzolan mortar were found to be either comparable or even better than the respective properties of the classical lime mortars.

On the basis of above findings, we can conclude that perlite-lime mortar can be successfully applied in historical buildings instead of classical lime mortars. On the other hand, mechanical properties of perlite-lime mortar are sufficient as an inner partition bricks. Nevertheless I believe that there is still a great potential for further improvement in hygric properties of perlite-lime mortars.

A very prospective investigation can be done for instance: heat absorption quality, reactions while curing inside water as well as sodium sulfide solution, effects of water repellent and super-plasticizer additives.

Acknowledgements

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