13th International Brick and
Block Masonry Conference
Amsterdam, July 4-7, 2004

# Creep Deformation of Lime-based Repair Mortars. The Effect of Aggregate Size.

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## Abstract

In this paper an experimental study concerning the shrinkage and creep deformations of lime-based mortars is presented. The parameters studied were the different binding systems and the maximum size of the mortars' aggregate content. Apart from time-dependent deformations, compressive and flexural strength, and dynamic modulus of elasticity were measured at 28 and 90 days. The results showed that the presence of coarse aggregates reduces significantly the creep deformations, even in the cases when they do not contribute to the strength development of the mortars. The higher deformations were exhibited by net lime mortars in comparison to those with hydraulic type binders.

## Key words

Shrinkage, creep, lime mortar, coarse aggregate.

## 1. Introduction

The time-dependent behaviour of masonry under sustained loading has been studied experimentally and analytically even from the decade of the 70's (Lenczner and Salahuddin, 1976; Shrive and England, 1981; Schubert, 1982). However, it was after the collapse of the Pavia Civic Tower in 1989 and the Noto Cathedral in 1996 (Binda et al, 1992 and 2003), that the creep phenomenon and failure due to long-term deformations of ancient heavy masonry drew the attention of the researchers (Anzani, 1993 and 1999; Papa and Taliercio, 2003), who much contributed to understanding the evolution of the damage, the synergetic effects and predicting the failure by modelling the creep of historic masonry. This is of particular importance for the safety of a great part of monumental structures, such as castles, towers or other tall and voluminous constructions.

As it is known, roman and Byzantine masonries have been built with thick mortar joints (30 to 50mm), which constitute a significant part of their total mass. The mortars were based on lime and contained coarse aggregate (natural or crushed brick) of good gradation. They could be characterised as old lime-based concrete (Papayianni, 1999). The role of these coarse aggregates in the strength and the long-term behaviour of ancient mortars is the question anticipated in this paper. Previous experiments measuring creep deformations of masonry models with traditional bricks thick lime-based mortar joints (Karaveziroglou et al, 1989) showed that creep deformations are very high in comparison to those of concrete or cement-based materials.

## 2. Experimental Part

The long term behaviour of lime-based mortars which are used for repair of historical masonry was studied by measuring shrinkage and creep deformations of them. Three

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series of compositions (R1, R2, R3) were manufactured which differed in the maximum size of their aggregate. In all of them the selected aggregate gradation was even but in R1 the max size of the grains was up to 4mm while in R2 an R3 it was up 8mm and 12mm respectively.

Each of R1, R2, and R3 was consisted of compositions corresponding to seven different based on lime binding systems which are shown in Table 1. The combinations of binders were chosen according to binding materials found by the analysis of ancient mortars dated from Roman and Byzantine period (Bugini and Salvatori, 1993; Papayianni and Stefanidou, 2001).

Compressive ($f_{mc}$) and flexural strength ($f_{mfl}$) were also measured at 28 and 90 days following ASTM C117-80, ASTM C 293-79 respectively. Prisms of 40x40x160mm were used for all tests. A total number of 380 specimens were tested. For the shrinkage and creep deformations the apparatus of Fig.1 was used that is a small model of that prescribed in ASTM C 512-82 method. Similar apparatus was previously used by other researchers (Karaveziroglou et al, 1995).

*Table 1 Composition of the lime-based mortar tested*

| Binding System | Proportions (by mass) for R1, R2, R3 compositions 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Hydrated lime | 1 | 1 | 1 | 1 | 1 | 0.8 | 0.8 |
| Pozzolan | 1 | 1 | - | - | 0.5 | 1 | 0.8 |
| Brick powder | - | - | - | 1 | 0.5 | - | - |
| Cement | - | - | - | - | - | 0.2 | 0.4 |

| Aggregates | Proportions (by mass) for R1, R2, R3 compositions R1 (1-7) | R2 (1-7) | R3 (1-7) |
|---|---|---|---|
| Sand (0-4mm) | 6 | 3.6 | 3 |
| Coarse sand (4-8mm) | - | 2.4 | 1.2 |
| Coarse aggregates (8-12mm) | - | - | 1.8 |

In the series $R1_2$, $R2_2$ and $R3_2$ half of the aggregate content was replaced by crushed bricks of corresponding max. size

*Figure1. Apparatus for the measurement of creep deformation*

## 2.1. Materials

The hydrated lime used as main binder was powder in airtight bags. As pozzolan a natural pozzolanic material emanating from island Milos was used after grinding so as the residue on 45μm sieve to be less than 10%. The pozzolanic activity index tested according ASTM C 311-83 was found above 5 MPa.

Brick dust, coming from milling brick fragments was also used. The pozzolanic activity index of it was 1,2 MPa. The use of brick powder was widely used in ancient mortars.

However, the old one has been found (from the analyses of old mortar) much more active in relation to its pozzolanicity (Baronio and Binda, 1997).
Low in alkalis white cement type was used for two compositions (Nr 6 and 7) in small percentages 10% and 20%. Natural river aggregates were used whose suitability was previously tested. Their gradations for each of R1, R2 and R3 series were selected to be even. For composition no.2 half of the aggregate was replaced by crushed brick of similar gradation.

## 2.2. Mixtures and Curing

The proportions of the constituents are shown in Table 1. The ratio of binder to aggregate was kept for all compositions 1: 3 which often found in historic masonry between the brick or stone pieces (Papayianni and Tsolaki, 1995).
The criterion for the water demand was the expansion according to flow table test, ASTM C230-83, to be 15± 1 cm. The mortar mixtures were cast carefully in the moulds without any mechanical compaction. The homogeneity of the mass of the mortar prisms was checked by using ultrasonic sonometer before any test. The recommended mixing procedure for preparation of mortars was followed (prEN 459-2:1997). All specimens were kept in a controlled room at a temperature of 20±2ºC and 90±5 rel. humidity, up to the age of testing. At the 90-d age a number of specimens was placed with the relevant apparatus in a chamber of temperature 21±1º C and relative humidity 55-60% for starting the shrinkage and creep tests.

## 2.3. Testing

Eight specimens (40x40x160mm) were tested in flexure for each one of compositions and for each age of testing. After that the two parts of them were crushed in compression.
Therefore, the mean values were estimated. For the measurement of creep deformations three specimens of each composition at the age of 90 days were loaded with the 40% of the counterpart mean value of the 90-d compressive strength. In some mortar specimens of net lime compositions an early failure was noticed and the creep testing stopped.

# 3. Results and Discussion

The mean values of compressive ($f_{mc}$), flexural strength ($f_{mfl}$) and dynamic modulus of elasticity $E_{md}$ are given in Table 2. In relation to the aggregate maximum size it could be said that generally the coarse aggregate does not contribute to the strength of the mortars (composition R2, R3) who's the binding system consist of hydraulic binders. Especially the strength of R3 hydraulic type mortars presents in some cases a significant decrease up to 30% in comparison with those ones of R1. However, for the mortars of non hydraulic character (Code Nr 3, 4) the coarse aggregates contribute to the strength increase. The higher strengths were achieved with the addition of 20% (by mass of binders) cement. Strength of the same level was also developed by the mortars of compositions (Code Nr 1, and 2) with binding system lime + pozzolan. The addition of crushed brick in replacement of aggregate (composition no.2) has influenced positively the strength development.
It must also be commented that the flexural to compressive strength ratio is very high comparatively to that of cement based mortars (from 0.40 to 0.60).
The estimated $E_{md}$ values based on ultrasonic wave velocity ranged from 12 to 20 GPa. Although the reliability of this indirect way of $E_{md}$ measurement is questioned they indicate that this elastic characteristic of lime based mortars is very low in comparison to that of conventional cement mortars (from 25 to 30 GPa).
The record of the shrinkage deformations were made with precisions of 0.01mm. The volume change of the prism divided by the initial volume of it was estimated by

measuring the three dimension of it every time. The evolution of the phenomenon was plotted in fig. 2 to 8. Although, there are some differences in composition of the mortar mixtures such as small variations in water content, total content in fines by which shrinkage is affected, it seems that by the coarse aggregate the volume deformation is limited.

The lower volume change was observed at mortar compositions with Code Nr 6 and 7 and was about 1% while for the other ones it ranged from 1,5 to 2%. It could also be said that the addition of cement contributed to this limitation.

Creep deformations were recorded in μstrain after the subsfraction of the mean value of the linear deformation due to shrinkage. The loading machine was checked by time to time (by using an inserted load cell) to keep the imposed load equivalent to 40% of the corresponding mortar's strength. Deformations were plotted in figs 9 to 15. The final values for all compositions except for the Code Nr 3 ranged between 2000 and 4000 μstrain or they were around 3000μstrain. The lower ones were exhibited by the compositions containing cement (around 2000 μstrain) and the higher ones were developed by mortar compositions of net lime binder (from 11000 to 12000μstrain). Comparing the R1 with the R2 and R3 compositions it was obvious that the coarse aggregate reduced the creep deformations even in the cases they did not increase the strength.

*Table 2 Mechanical characteristics of lime-based mortars*

| Comp. No. | Flexural strength, MPa | | | | | | Compressive strength, MPa | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 28-d | | | 90-d | | | 28-d | | | 90-d | | |
| | R1 | R2 | R3 | R1 | R2 | R3 | R1 | R2 | R3 | R1 | R2 | R3 |
| 1 | 1.97 | 1.20 | 1.40 | 3.00 | 2.30 | 1.70 | 3.80 | 3.50 | 2.70 | 5.80 | 4.60 | 3.80 |
| 2 | 3.90 | 2.00 | 2.40 | 7.20 | 4.50 | 3.20 | 7.40 | 5.60 | 4.80 | 11.0 | 8.00 | 6.20 |
| 3 | 0.18 | 0.21 | 0.40 | 0.16 | 0.23 | 0.32 | 0.25 | 0.37 | 0.38 | 0.33 | 0.46 | 0.48 |
| 4 | 0.58 | 0.81 | 0.85 | 1.40 | 1.60 | 1.10 | 1.00 | 1.30 | 1.70 | 2.00 | 2.90 | 1.80 |
| 5 | 1.10 | 1.20 | 1.29 | 2.10 | 1.70 | 1.30 | 2.60 | 2.00 | 1.80 | 3.80 | 4.00 | 2.90 |
| 6 | 1.90 | 1.20 | 1.00 | 2.40 | 2.60 | 1.60 | 4.50 | 2.90 | 1.90 | 5.80 | 5.60 | 3.50 |
| 7 | 2.10 | 2.20 | 1.26 | 4.70 | 4.00 | 2.30 | 4.80 | 4.80 | 2.80 | 6.70 | 6.60 | 5.80 |

| | Emd, GPa | | |
|---|---|---|---|
| | 90-d | | |
| | R1 | R2 | R3 |
| 1 | 16.8 | 15.0 | 15.6 |
| 2 | 16.2 | 15.5 | 14.3 |
| 3 | 11.5 | 16.6 | 19.7 |
| 4 | 9.1 | 10.9 | 16.2 |
| 5 | 9.2 | 15.2 | 19.1 |
| 6 | 15.1 | 17.9 | 13.9 |
| 7 | 19.4 | 20.0 | 15.7 |

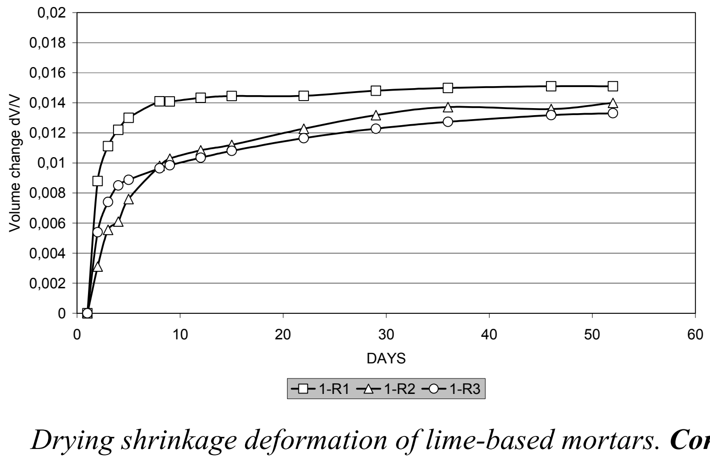


*Fig.2 Drying shrinkage deformation of lime-based mortars.* ***Composition 1***

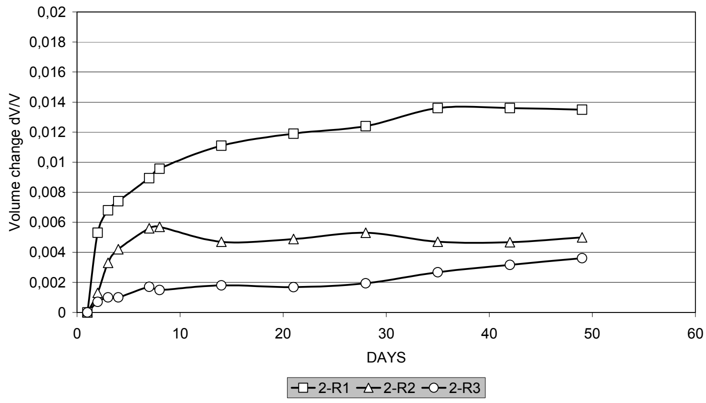


*Fig.3 Drying shrinkage deformation of lime-based mortars.* ***Composition 2***

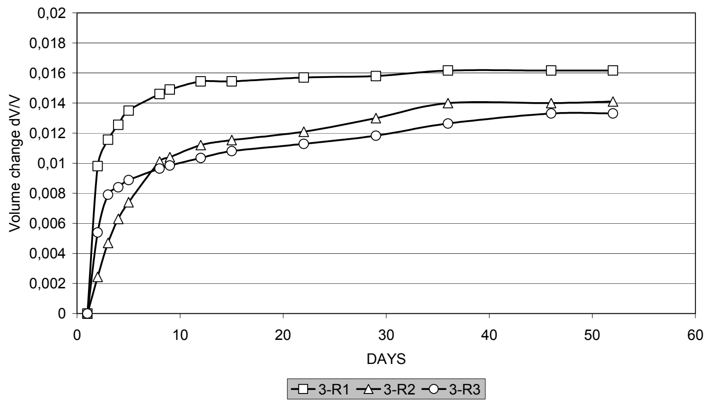


*Fig.4 Drying shrinkage deformation of lime-based mortars.* ***Composition 3***

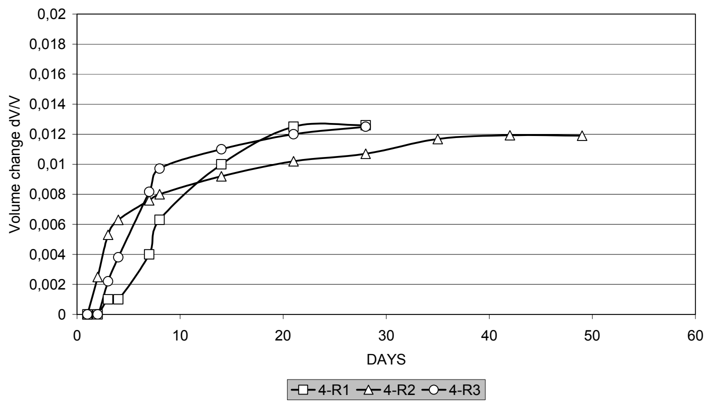


*Fig.5 Drying shrinkage deformation of lime-based mortars.* ***Composition 4***

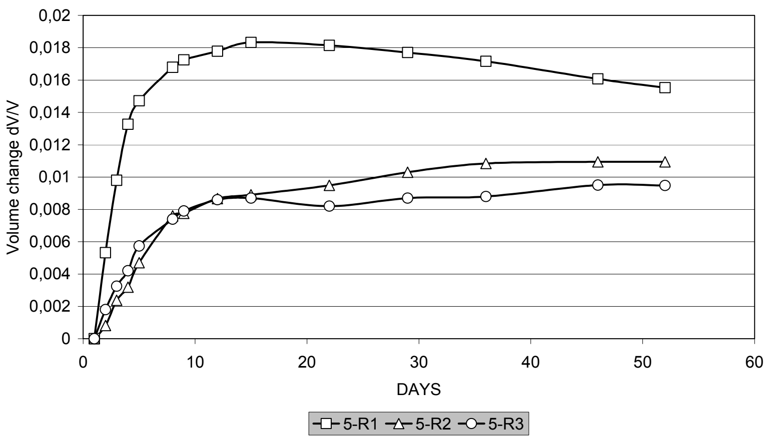


*Fig.6 Drying shrinkage deformation of lime-based mortars.* ***Composition 5***

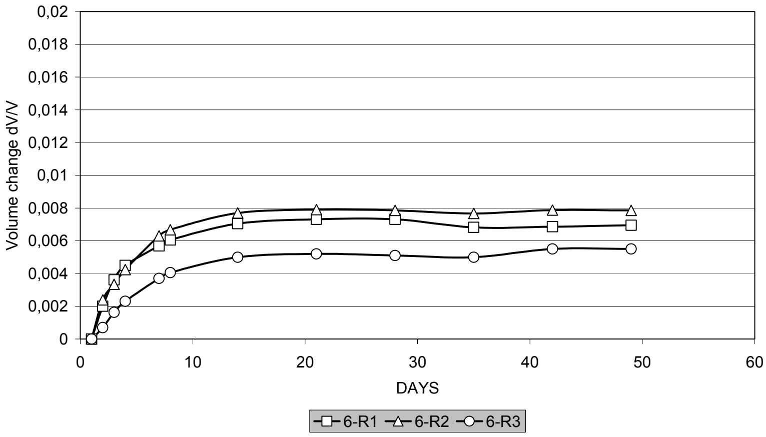


*Fig.7 Drying shrinkage deformation of lime-based mortars.* ***Composition 6***

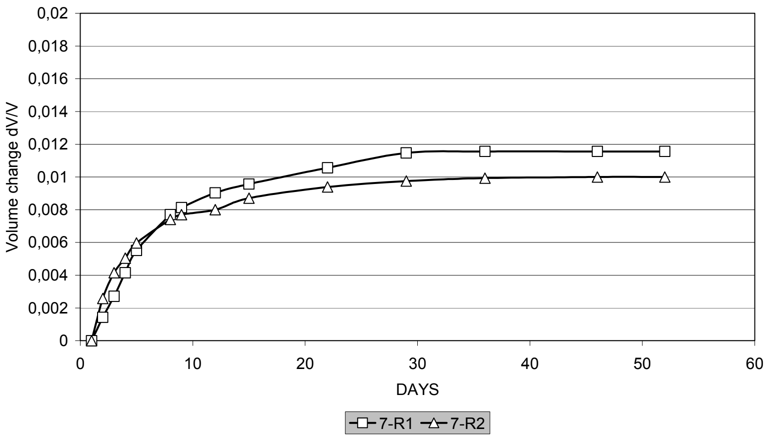


*Fig.8 Drying shrinkage deformation of lime-based mortars.* ***Composition 7***

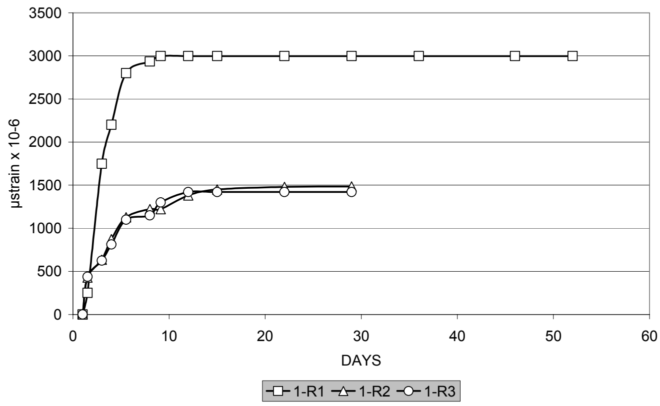


*Fig.9 Creep deformation of lime-based mortars.* ***Composition1***

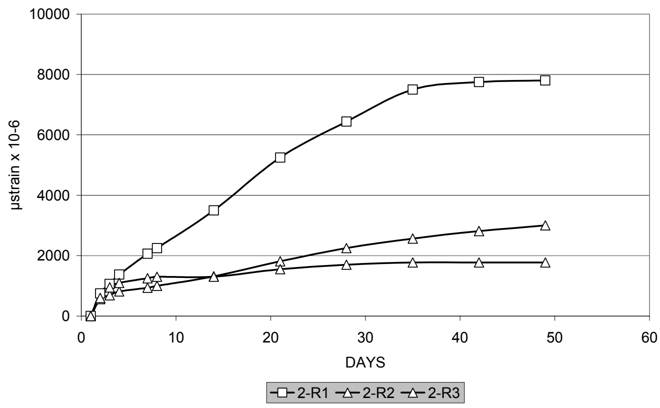


*Fig.10 Creep deformation of lime-based mortars.* ***Composition 2***

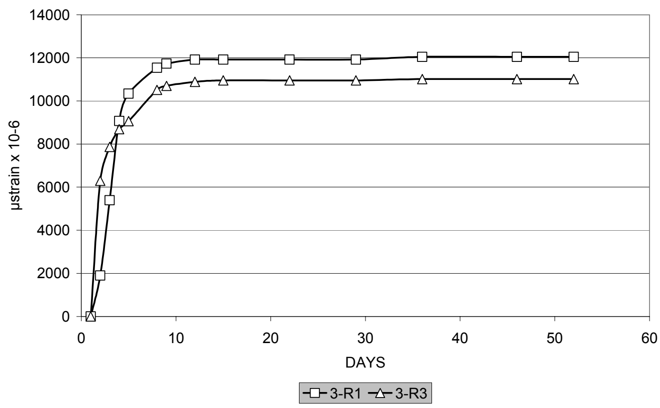


*Fig.11 Creep deformation of lime-based mortars.* ***Composition 3***

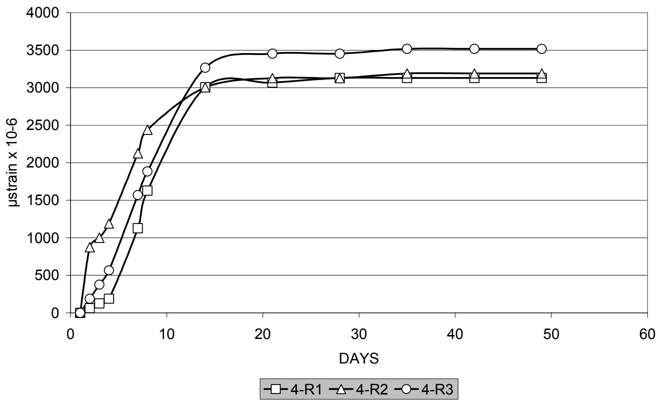


*Fig.12 Creep deformation of lime-based mortars.* ***Composition 4***

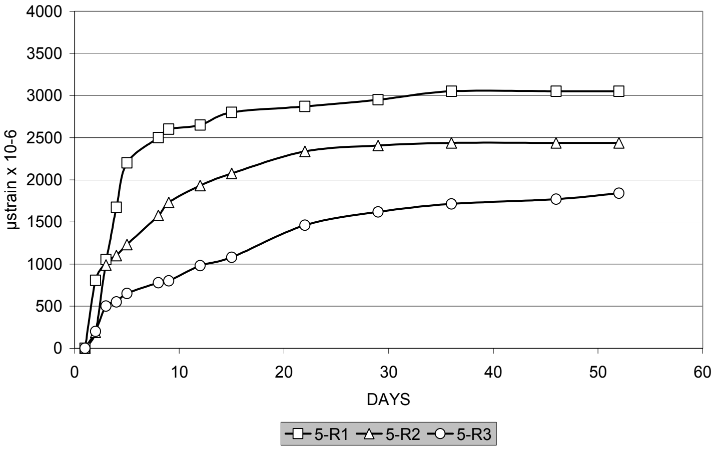


*Fig.13 Creep deformation of lime-based mortars.* ***Composition 5***

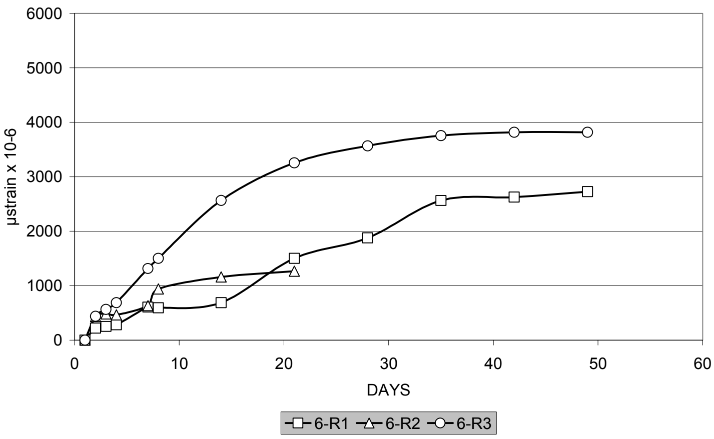


*Fig.14 Creep deformation of lime-based mortars.* ***Composition 6***

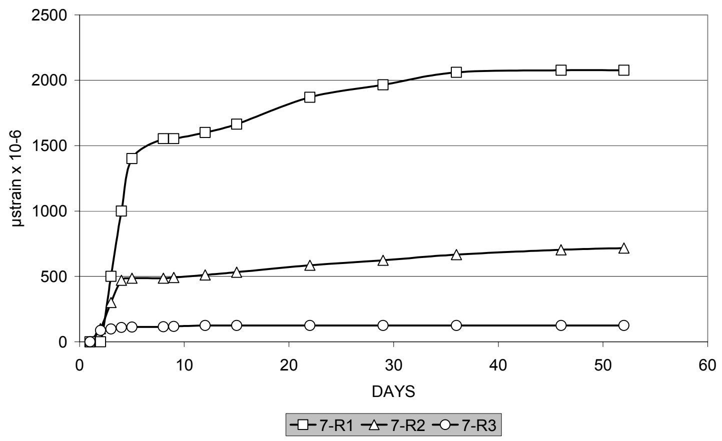


*Fig.15 Creep deformation of lime-based mortars.* ***Composition*** *7*

## 4. Conclusions

The lime-based mortars presented higher shrinkage and creep deformations than those of cement based mortars. In particular, net lime mortars exhibited creep deformations up to 12000 μstrain loaded with 40% of their strength. The mortars with hydraulic components developed lower creep deformations 2500-3000 μstrain. The presence of coarse aggregate in the mortar mixture contributes to the considerable (up to 70%) reduction of the long term deformations. This is in agreement with what has been found by analysing the collapsed piers of the Noto Cathedral, where the mortars' aggregates were very fine (Binda et al, 2003).
In the case of lime based mortars the strain – time curves showed that in short relatively time (10-15 days) the final values of deformations were achieved.
It seems that the construction of the old castles or massive structures by using mortars joints with pebbles or coarse aggregates in their mass is quite justified.
Furthermore, it is suggested the repair mortars for deep pointing or for reconstruction parts of old masonry to include coarse aggregate as the old ones.

## 5. Acknowledgements

The author acknowledges the students Asterios Dimitriou and Dimitrios Boulgouras of the Civil Engineering Department of Aristotle University of Thessaloniki for their participation in carrying out the laboratory work.

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