# Influence of thick mortar joints on the early and late mechanical behaviour of Byzantine constructions

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## Abstract

Stack-bond prisms built with joints 40mm thick, reproducing the type of masonry used for the Byzantine Basilica of St. Vitale in Ravenna (Vth Cent. AD) were tested under compression by the authors at different time of curing (28, 60, 90, 180, 365 days). The results show a high influence of the joint thickness on the mechanical behaviour of the masonry, particularly at an early age.
The use of thick joints in brick and stone masonry seems to prove that the Byzantine masonry was an „intelligent“ material highly suitable to react towards possible stresses occurring during the structure long life-span, e.g. allowing for large soil settlements without the development of important crack patterns.

## 1 Introduction

The authors are carrying out an experimental research on Roman and Byzantine brick masonries built with thick mortar joints. The aim of the research is to understand the role of these joint in the mechanical and structural behaviour of these masonries. Romans have used variable thickness of the joints from very thin (2 mm) to very thick; this last feature was also a characteristic of many Byzantine buildings in the East or West of Europe. Some explanation have been given by the historians concerning eventual economical reasons as spearing the use of bricks or obtaining lighter structures. Nevertheless a building technique

applied for more than 700 years certainly deserves a technological explanation. In fact the use of thick mortar joints was frequent in the case of constructions laying on subsidizing soils and/or in seismic areas. Therefore the authors assume that this technique, beside being more economical has also scientific motivations. A previous study on site and in laboratory on the composition of the material used for the thick joints of Byzantine masonries has shown clearly its peculiar behaviour. In fact this material can be called conglomerate or even concrete rather than mortar, since the size of its aggregates reaches values which can be found rather in a modern concrete than in a normal mortar for joints (Baronio [1]).
Once that conglomerate has been studied by the authors from the chemical, physical point of view, new conglomerates have been reproduced based on the studied composition and their mechanical behaviour has been periodically detected during the time of curing up to 365 days (Baronio [1]).
Then stack bond prisms were built with mortar joints 40mm thick and a thickness ratio brick/joint of 1/1, reproducing the technology used in St. Vitale in Ravenna a Byzantine Basilica built in the V cent AD. The mechanical behaviour in compression of the prisms was studied at different ages (28, 60, 90, 365 days). A parallel study was carried out in Stuttgart (Falter [2]) on the behaviour of the same type of mortar in joints of variable thickness.
On site flatjack tests have been carried out for comparison on the masonry of St. Vitale.

## 2 A case history: St. Vitale in Ravenna

The Basilica of St. Vitale in Ravenna, a Byzantine monument built between 526 and 547 A.D. (Figure 1) has been since a long time the object of archeological studies, stylistic criticism and studies carried on by historians with the aim of chronological and typological classification. St. Vitale architecture has several connection with the Byzantine buildings realized in the same years in Istanbul (Hagia Sophia) and in Greece (Mainstone [3]). The masonries of St. Vitale are built with large Julianean bricks (310x510x40mm dimension) and very thick mortar joints, being the ratio mortar/brick thickness 1/1 as very frequently is found in Byzantine buildings in Italy, Turkey and Greece [Deichmann [4]), [Mark [5]).

Figure 1: View of the church of St. Vitale in Ravenna

This aspect gives the Byzantine walls a peculiar appearance with evident horizontal strips. The reason for using thick joints is not yet clear to the

Figure 2: The thick mortar joints of St. Vitale

researchers. According to the recognized influence of the mortar joint on the mechanical behaviour of the masonry, thick joints should mean low strength of the masonry. Figure 2 shows a detail of the masonry of St. Vitale. The material can be considered a conglomerate rather than a mortar due to the max dimensions of the brick pebbles and of the other aggregates which can reach a value >16mm. The largest fraction is mainly composed by crushed bricks; in fact there is an important presence of bricks (50%) in the largest and medium sizes while the percentage of brick dust is decreasing in the small sizes (Binda [6]). The quantification of the binder, of the brick and of the other aggregate could only be made by microscopic observation since the adhesion of the brick to the binder was very strong and no other chemical or thermal separation could be made. The chemical analyses show the presence of aggregates which are partially siliceous and partially calcareous and of a binder based on hydrated lime. The soluble silica 0.33% is low in the large fractions of the aggregates and significant (13.15%) in the small fractions with dimensions below 0.075mm. The petrographic-mineralogical analyses confirm the results of the chemical ones on the composition of binder and aggregates and also show the presence of new formation products between binder and brick pebbles; this could mean the possibility that a pozzolanic reaction between lime and bricks occurred after the construction of the masonry.

In Table1 the size intervals of the aggregates are reported.

| Particle Size [mm] | Amount [%] | Calc.+Sil [%] | Brick [%] |
|---|---|---|---|
| 16 ÷ 6 | 10 | 5.0 | 5.0 |
| 6 ÷ 3 | 17 | 8.5 | 8.5 |
| 3 ÷ 0.075 | 73 | 65.7 | 7.3 |
| | 100 | 79.2 | 20.8 |

Table 1: Dimensions and size intervals of aggregates used for the new conglomerate

In order to study the mechanical behaviour of the original masonry and its state of stress, flat jack tests were carried out on site. The difficulty of applying this test to the Byzantine masonry is represented by the thick joints. The test was in fact developed to be carried out on what is considered a normal mortar joint in Italy, i.e. a joint 10mm thick ([Rossi [7]). Therefore it had to be decided how to position the jacks and to control whether this application was successful in the special case. The tests were carried out according to the ASTM Code (ASTM [8], [9]) with some modifications, due to the special application: (i) the cuts were made with an eccentric saw in the mortar joints just at the contact surface with the bricks (Figure 3), (ii) three extra measurements were carried out beside the four suggested by the Code, (iii) the measurements in the case of the double flatjack were carried out automatically by applying to the wall LVDTs connected to a portable computer, so that the stress-strain curve could be directly controlled during the test.

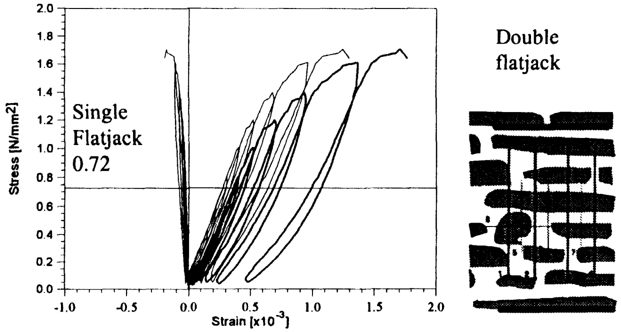


Figure 3: Flatjack test on a wall of St. Vitale

This first test was mainly done to understand: (i) the stress value at the bottom of one of the loadbearing walls, (ii) the stress-strain behaviour of the masonry. The single flatjack test gave an average stress of .72 $N/mm^2$. Figure 3 reports the vertical and horizontal stress-strain plot. Unfortunately at 1.4 $N/mm^2$ a local damage appeared on the upper and lower mortar joints and the test was stopped at 1.7 $N/mm^2$ since the upper jack was badly deformed. In Figure 3 the value of the calculated stress is reported showing that the masonry can easily carry the service load. The peak stress can be supposed around 3.0 to 4.0 $N/mm^2$ since the max deformation measured is only 1.2 $x10^{-3}$; this value probably means that the applied stress is still far from the peak stress value.

# 3 Experimental research on masonry prisms

In order to study the development of the mechanical properties at different ages, a series of 12 stack bond prisms were built with the reproduced mortar and a joint thickness of 40mm. The prisms were subject to increasing load from the first day up to the day of testing and cured at 20°C and 65% R.H. At different ages they were subject to the compression test up to failure and their behavior was investigated.

## 3.1 Mortar and brick properties

Following the results of the experimental study carried out on the conglomerate joints of San Vitale a similar material was reproduced as in the mentioned above experiments ([Binda [10]).

In order to compare the new results with the results obtained previously in Milan ([Baronio [1]) and Stuttgart ([Falter [2]) the mortar composition and the grain size distribution of the aggregate was kept constant as much as possible.

In Table 1 details of the percentage and type of aggregates in various size intervals are given. The ratio binder/aggregate of the mix was 1:3. The workability test was carried out according to the Italian Code (10UNI 8020-11/1979 [11]) and the average value was 60%.

Sets of three specimens of dimension 40mmx40mmx160mm, were prepared in coincidence with the preparation of the prisms, cured in the same climatic room and submitted to the flexural and compression tests at different age of curing in order to compare the results with the ones obtained previously and have information on the mechanical strength of the mortar used for these prisms.

The values of one set of mortar specimens subject to compression and flexural tests are plotted in Figure 4. They show that the flexural strength of the material is increasing up to 90 days then it is reaching an apparent steady state, while the compressive strength is still increasing at 360 days.

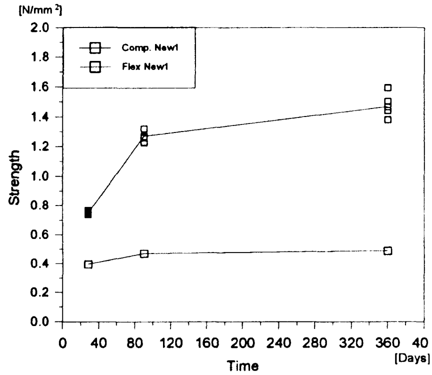


Figure 4: Compression and flexural strength of conglomerates

The carbonation test was carried out on the fractured surfaces of the remaining portions soon after the mechanical tests. The bricks used for the stack-bond prisms were produced on purpose with ferrous clays adding quartz sand fired at a temperature of 950°C; they have a bulk density of 1500-1600 $kg/m^3$ and a total absorption of 20-23%.

The mean compression strength was 14.16 $N/mm^2$, the Poisson ratio 0.14, the Young modulus 4650 $N/mm^2$. The brick dimensions, 510x310x40mm, were chosen similar to the dimensions of the bricks of St. Vitale in Ravenna. Subsequently the bricks were cut into the following dimension: 310x310x40mm in order to obtain prisms with an acceptable dimension according to the codes.

### 3.2 Preparation and curing of the prisms

12 stackbond prisms were prepared and submitted, starting from 24h after the preparation to slowly increasing loads. The prisms were made with four brick courses and three conglomerate joints (Binda [2]) 45mm thick. The height of the masonry specimens 5min after they were built was 290mm; so the prism dimension was at the preparation 310x310x290mm.

Three timber molds were used to contain the joints. After 24 hours the specimens were demolded and cured for different times (28,60,90,365 days) at 20°C and 65% R.H. The loading program was applied daily step by step simulating the dead load increasing during the construction as it happens in a very thick wall or in a large pier built by two masons. The load step corresponded to the weight of three bricks, that is 30daN. The load was

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increased up to the corresponding stress value of 0.15 N/mm$^2$ and the corresponding vertical and horizontal displacements were measured (Binda [6]). A further increase of the load was impossible due to the lack of a better equipment in the climatic room.

## 4 Evaluation of the results

Table 2 reports the name and the age of the prisms at the moment the compressive test was carried out. The specimens were all capped with gypsum and tested under a servocontrolled hydraulic MTS press of 250tons which operated under displacement control.

| Name | SB2.1 | SB2.2 | SB2.3 | SB2.4 | SB2.5 | SB2.6 | SB2.7 | SB2.8 | SB2.9 |
|---|---|---|---|---|---|---|---|---|---|
| Days | 28 | 28 | 28 | 60 | 60 | 90 | 90 | 365 | 365 |

Table 2: Name and age of the tested prisms

Two Teflon sheets were placed between each contact face of the prisms and the steel plates of the machine. Loading was carried out monotonically after some loading-unloding at the first stress increments, at a rate of 1 μm/s, unloading at a rate of 25 μm/s. A schema of the measurements carried out with LVDTs (Linear Variable Displacement Transducer) and CPDTs (Clamp on Point Displacement Transducer) on the prisms is given in Figure 5. Only two faces of the prism are represented in the figure, being the other two measured in a symmetric way. The aim was to have more knowledge on the differential behaviour of mortar and bricks and on their influence on the masonry behaviour.

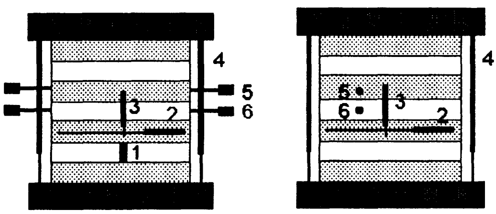

Figure 5: Measuring device schema.

Figures 6a, b,c,d report the stress-strain plots obtained respectively for the 28, 60, 90 and 365 days.. The stress-horizontal strain curves are given for the mortar and the bricks, as measured by LVDT5 and LVDT6. Surprisingly the peak stress of the specimens at the different ages is very similar ranging from a minimum of 3.5 to a maximum of 4.7 N/mm$^2$ and apparently not depending on the age as it happens for the mortars.

Concerning horizontal displacements much larger strains occurr undoubtedly in the mortar joints starting at very low stress values at early age (0.4 to 0.8 N/mm$^2$). The difference decreases with the age always remaining the mortar deformation higher than the brick one, as it is well known. The values of the vertical displacements reported in Figure 6 were measured by the LVDT4s between the platens of the machine.

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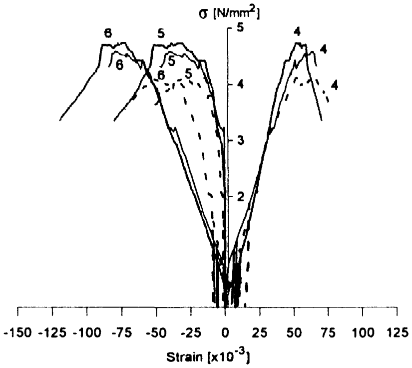


Figure 6a. Stress-Strain plots of prisms SB2.1, SB2.2, SB2.3 (28 days)

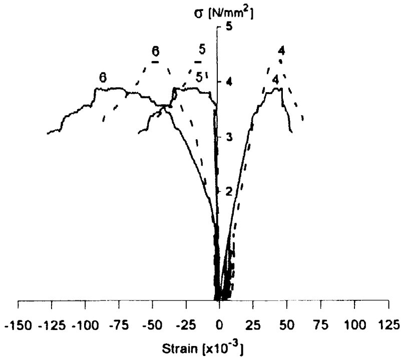


Figure 6b: Stress-Strain plots of prisms SB2.4, SB2.5 (60 days)

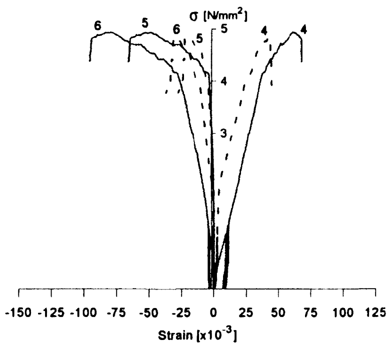


Figure 6c: Stress-Strain plots of prisms SB2.6, SB2.7 (90 days)

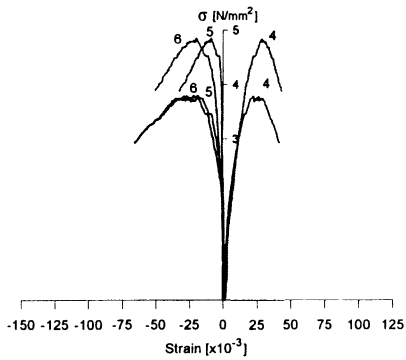


Figure 6d: Stress-Strain plots of prisms SB2.8, SB2.9 (365 days)

In order to understand better the role played by the mortar joints also the vertical displacements were measured on the joint itself. Since it was difficult to fix the small CPDT1 (Clamp on Point Displacement Transducer) to the joint and it gave too much scatter in the measurement due the weakness of the joint, LVDT3 was fixed between two bricks as shown in Figure 5. Figure 7a,b comparing the deformations measured by LVDT4 and LVDT3 shows how much the mortar deformation is influencing the masonry deformability in the cases of 28 and 90 days of age. This is not so much evident at a late age.

LVDT2 was also applied to one of the bricks at each face of the prism in order to control the reliability of LVDT5 which was not directly applied on the specimen; the results show that the two measurements give approximately the same results. Large horizontal displacements start in the brick at the 75% of the peak stress at 28 and 60 days, and at the 50% of the peak stress at 90 and 365 days.

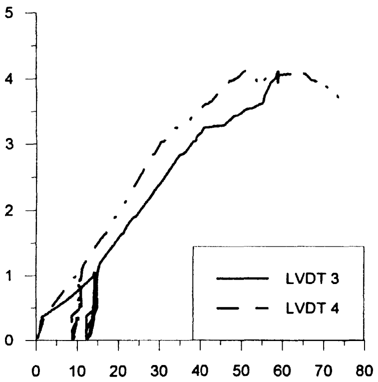


Figure 7a: Stress-Strain plots of prisms SB2.2

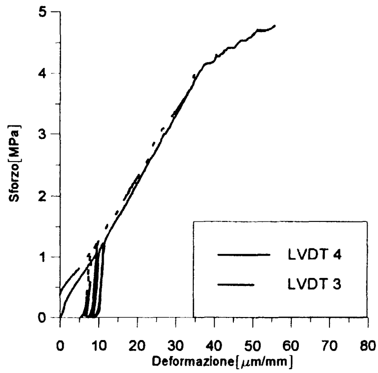


Figure 7b: Stress-Strain plots of prisms SB2.6

Figure 8 shows the strain values measured at: (i) the peak stress, (ii) the onset of cracking for the different ages. A quick decrease of the (i) values can be noticed from 28 to 365days, while values (ii) tend to increase with the age.

Finally Figures 9a,b show the variation of the elasticity modulus with the stress values at the different ages. The stiffness of the wall is increasing with the age even if the strength does not seem to be so much influenced by the age at least up to 1 year. Fig.9 also means that the stiffness increases much more as the mortar carbonation proceeds to become much higher in a long time (Figure 3).

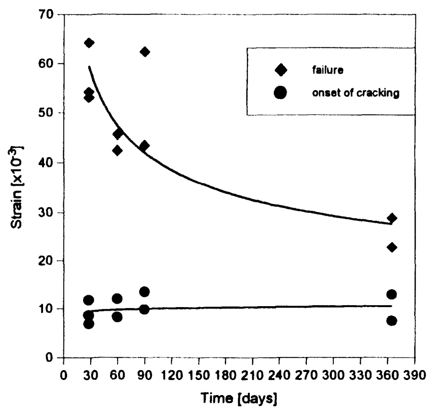


Figure 8: Vertical deformation value at onset of cracking and at failure at different age.

The formation of the first cracks in every joint and brick were also surveyed and gave the following results: (i) at an early age the cracks appear in the mortar joints at very low load value and in the brick at much higher value, (ii) at the age of 365 days the formation of cracks occurs in the mortar joint and in the bricks at higher load values, tendentially before in the bricks.

This difference explains very well the large displacements measured for the early age specimens. The fact that the first cracks occurr in the mortar joints explains also the bilinear behaviour of the 28 days specimens appearing in Figure 6 and more clearly in Figure 7.

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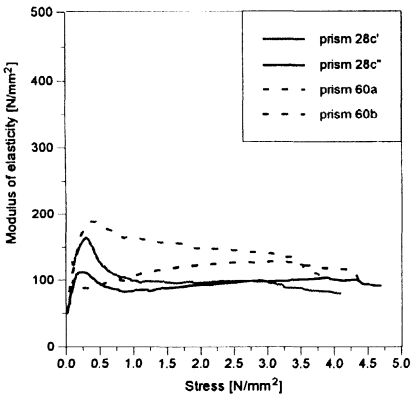


Figure 9a: Tangent modulus against stress variation of prisms at 28 and 60 days.

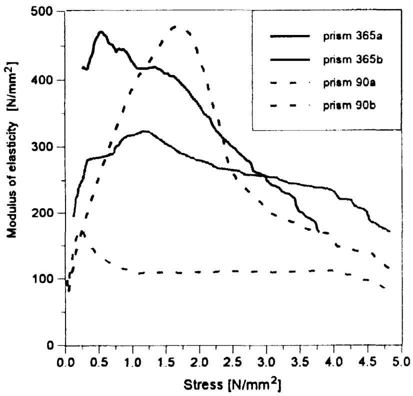


Figure 9b: Tangent modulus against stress variation of prisms at 90 and 365 days.

Figure 10: Failure of mortar joints in compression

In fact the changement in slope of the stress-strain curve occurs when the first cracks appear with loss of the carbonated layer of mortar as it can be seen in Figure 10.

# 5 Conclusions

The results of the experimental research carried out on prisms with thick mortar joints and on site on the walls of the Basilica of St. Vitale in Ravenna, allow for some first conclusions.

- the use of thick joints was probably made in the Bizantine architecture because the experience had shown that thick joints allowed large deformation decreasing as the material hardened but so slowly that soil settlements were allowed without causing important cracks;
- at an early age, the well known mechanism of failure due to the tensile strength exerted by the mortar on the bricks under compression was retarded due to the high deformability of the mortar;
- large deformations could take place at an early age under high stresses, but the overall strength of the material was not decreased and the wall could bear its weight and the dead load without failure.

Overall the Byzantine masonry proved to be an "intelligent" material highly suitable to react towards possible stresses occurring during the structure long life-span.

The results show that investigation is essential to understand the behaviour of ancient building materials.

Further research is being carried out on site and in laboratory in order to develop new knowledge expecially on the effect of the variation of the mortar composition and of the aggregate size and dimension on short and long term behaviour of these masonries.

## 6 Acknowledgements

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