THE MECHANICAL BEHAVIOUR OF HISTORIC MASONRY STRUCTURES

R. Hayen[1], K. Van Balen[2] and D. Van Gemert[3]

Abstract

With the development of cementlike mortars, as early as the 19th century, the main aim of the scientific research was orientated towards the development of high strength hydraulic binders. With the change in strength and deformability of the mortar, the characteristics of the masonry composite changed dramatically. While a historic masonry structure generally is known as a rather strong, but deformable structure, the new masonry structures were increasingly brittle in nature. However, the loss of deformability was ignored within their quest for high strength mortars and structures.
In order to achieve a better understanding and adequate modelling of the mechanical behaviour of historic masonry structures, our current research focuses on the influence of the mortar characteristics on the behaviour of the composite masonry structure. Most commonly the brick/mortar interaction, imposing in general a triaxial state of compression on the mortar within the masonry joint, is denoted as the main reason for the specific visco-plastic behaviour of the composite.
Besides a detailed analysis of the brick/mortar interaction in and around a mortar joint by means of full-field optical methods, the influence of the mortar characteristics on the overall mechanical behaviour (compressive strength, Young's modulus, development of lateral strains, etc.) of the masonry composite is currently studied in depth.
The main results of the ongoing study are represented. The link with test results concerning the mechanical behaviour of mortars in both uni-axial and triaxial compression is made and the influence of the brick/mortar interaction on the overall mechanical behaviour is situated.

Key Words

historic masonry, lime mortar, mechanical behaviour, visco-plastic deformation

1. Introduction

The main objective of the ongoing study is to understand the differences in material behaviour of the composite masonry constructed with different mortar types; e.g. hydrated or hydraulic lime, cement or hybrid mortars. While historic masonry,

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constructed with a lime mortar, generally has a lower strength than nowadays cement-based masonry, the possibility of the former to adapt to settlements is extraordinary and still not well understood (Sahlin 1971). A better understanding of the brick-mortar interaction in masonry, therefore, is a necessity.
Masonry is a composite material, built up of brick or natural stone units and a mortar as binder matrix. Both composing materials are different in nature. Both brick and natural stone can be considered as an elastic brittle material with a certain compressive strength and some tensile strength, which is often considered only one tenth of its compressive strength. Mortar is generally also considered an elastic brittle material, however, with a much higher deformability with regard to the brick or natural stone units. Due the composite nature of masonry and the important difference in deformability of the composing materials, the stresses and strains will be divided in a complex manner between the brick units and mortar matrix, if masonry is subjected to an external loading (Sacchi 1983). Most common masonry is loaded by the dead load of the structures it bears. The vertical loads result in a horizontal confining pressure on the mortar inside the horizontal joint, as the mortar tries to move out horizontally from between both bricks due to its elevated deformability. Equilibrium in the composite masonry results in horizontal tensile stresses in the brick (Figure 1).

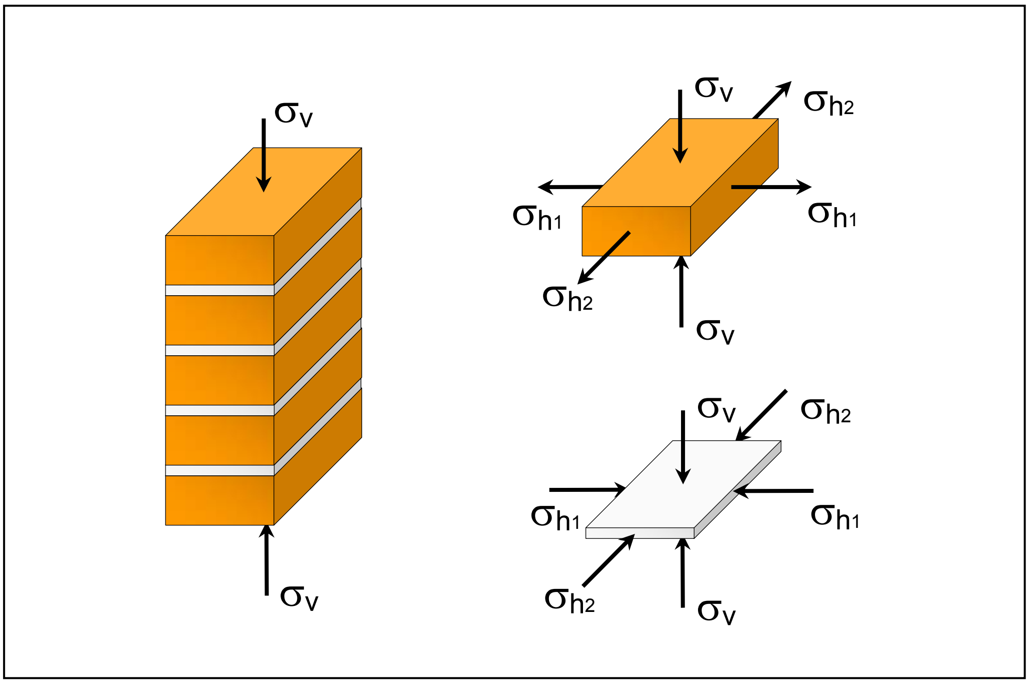

Figure 1: Stress distribution in the composite masonry

While in uniaxial compression mortars can generally be considered as a quasi-elastic brittle material, the mechanical behaviour of a mortar in triaxial compression, a state of compression one would expect to be present within the masonry joint, changes dramatically (Hayen 2003). In such conditions a mortar is no longer brittle in nature, but a mere visco-plastic material with an evident change in failure mechanism. While in conditions of no or only a limited horizontal confinement the mortar fails as a results of the occurrence of a network of fine vertical cracks, the formation of the vertical cracks will be inhibited as the horizontal confinement increases and failure will more likely lead to an overall compaction of the mortar. The presented research focuses on the study of the presence and the importance of such a confinement of the mortar through the careful measurement of the vertical and horizontal strains within brickwork masonry,

while in the mean time the necessary data are collected for the evaluation of the overall mechanical behaviour of the masonry composite, which will be discussed here.

2. The materials

2.1. The mortars

In order to understand the influence of the mortar strength and deformability on the overall mechanical behaviour of the masonry composite four different mortars were examined: a low strength lime putty mortar, a pre-blend natural hydraulic lime mortar, a lime-cement mortar and a high strength cement mortar.

For the natural hydraulic lime mortar UNILIT 35, a commercially available pre-blend lime mortar from HD System - Tassullo (Italy), is chosen. This pre-blend is composed of a natural hydraulic lime in combination with a calcareous sand. The maximum grain size of the sand is about 3mm. The pre-blend is distributed on the market as an all-round lime mortar, amongst others meant for the use as a mason and pointing mortar. The main hydraulic phase of the natural hydraulic lime binder, used for the production of the pre-blend, is dicalciumsilicate (C_2S) (Gödicke-Dettmering 1997), which confirms the characterisation of the binder as a natural hydraulic lime. Furthermore, according to EN 459-1 the binder is classified as a moderately hydraulic lime NHL 2 (at the utmost limits of the classification) or NHL 3.5.
For the production of the putty lime, the lime-cement and the cement mortar two types of binder were required; lime putty and cement. As for the putty lime binder RASOCAL from CORI (Italy) was chosen. This putty lime is obtained as a rather pure calciumhydrate lime paste, which has been slaked for a period of at least several months. Hence, its production process closely resembles the historical slaking technique of keeping the burnt limestone submerged in water for a long period of time. As for the cement a CEM I 42.5R was chosen, in order to obtain a very strong and quick setting cement mortar.

Except for the pre-blend hydraulic lime mortar, the general mortar composition (binder/aggregate ratio, aggregate type and water content) of the three other mortars

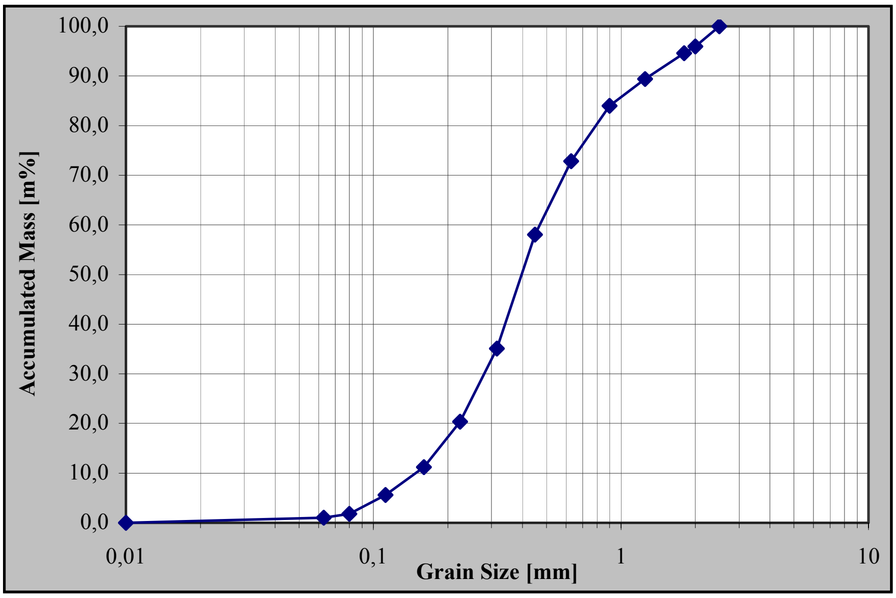

Figure 2 Grain size distribution of the SBS sand

needed to be determined. The binder/aggregate ratio was set to 1:3 in volumetric proportions for all three mortars. In order to produce the lime-cement mortar an equal volumetric proportion of lime putty and cement was used to formulate the binder mixture. The corresponding weight proportions of the different binder types, the aggregate and the added water are represented in Table 1.
The sand used for the production of these mortars is a coarse silicate sand from SBS Rijkevorsel (Belgium) with a maximum grain size of about 2.8mm. The grain size distribution of the sand is represented in Figure 2.

Table 1 Mortar compositions

Mortar / Binder	Lime Putty [m%]	Hydraulic Lime [m%]	Cement [m%]	Sand [m%]	Water [m%]
Putty lime	22.3	-	-	71.9	5.8
Natural hydraulic lime	-	87.5	-	-	12.5
Cement	-	-	18.2	70.0	11.8
Lime-cement	10.9	-	6.3	73.0	9.8

For each type of mortar the tensile and compressive strength were determined according to EN 196-1. However, in order to obtain as much information as possible on the mechanical behaviour of the mortar the compression tests were performed strain controlled (at a strain ratio of 2.5mm/min) in stead of stress controlled as defined by the mentioned standard.
A test set-up by means of vertical and horizontal Linear Voltage Differential Transducers (LVDT) was designed to determine both the Young's modulus and the Poisson ratio. Eliminating the effects of unwanted displacements within the test bank itself, the test sample is mounted in a frame to which 4 vertical and 2 horizontal LVDT's are mounted to measure the displacements. From these data the Young's modulus was consequently determined from the displacements in between 20 and 60% of the maximum strength. The results are represented in Table 2.

Table 2 Mechanical characterisation of the mortars at an age of 28 days (mean value and standard deviation in between brackets)

Mortar Type	f_t [MPa]	f_c [MPa]	E_v [MPa]
Putty lime mortar	0.52 (0.03)	0.79 (0.09)	96 (36)
Hydraulic lime mortar	1.34 (0.11)	4.47 (0.28)	-
Cement mortar	5.81 (0.35)	19.47 (1.23)	3325 (1643)
Lime-cement mortar	0.79 (0.05)	1.68 (0.07)	235 (189)

2.2. The brick

The single leaf brick masonry was constructed using the Spanish Red brick from Terca, Wienerberger; a red hand-moulded brick produced from pure Campinish old quaternary clay at a temperature of at least 1060°C. The mean dimensions are 188mm by 88mm by 48mm (Module 50).
The mechanical characterisation of the brick is of high importance in order to study its influence on the mechanical behaviour of the masonry composite. Hence, the compressive strength, the tensile strength and the Young's modulus were determined. The compressive strength of the brick has been determined by means of three different test set-ups: i) on cylindrical samples (Ø 48mm by 45mm height), ii) on simple cubes (40mm by 40mm by 40mm) and iii) on a stack bond of 3 cubes each 40mm by 40mm by 40mm in size. In each case the vertical alignment of the brick was regarded upon

positioning the drilled brick samples within the test set-up. The frame, designed for the characterisation of the different mortar types, was used again in order to measure the deformations of the cubic and stack bond samples.
The main objective for using a stack bond of 3 cubes is to minimise the influence on the overall mechanical behaviour of the frictional effect on the bottom and top surfaces of the brick specimen in contact with the test platens. Earlier studies (Binda 1998) demonstrate that such a set-up works successfully and reveals a more uniform stress and strain distribution within the central brick cube. While the test set-up with a single cube generally reveals a failure pattern forming two intersecting pyramidal structures, the stack bond set-up reveals most of the time an obvious, straight vertical crack through the middle brick complying the objective of the test set-up. Due to the absence of the strengthening effect, as a result of the restraining effect at the bottom and top surface in contact with the platens, the mean compressive strength and Young's modulus of the stack bond set-up reveals somewhat lower results (Table 3).

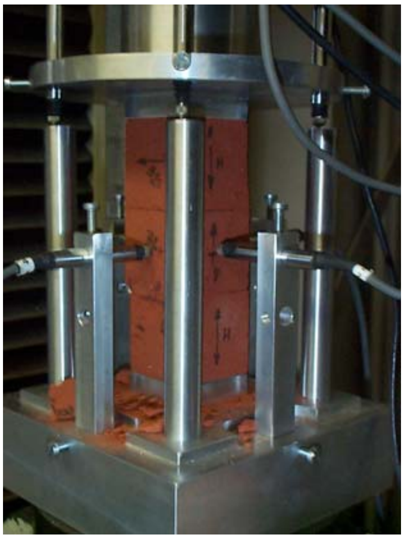

Figure 3 Test set-up for the determination of the vertical and horizontal displacements on a stack bond of 3 cubic samples (40mm x 40mm x 40mm)

In order to determine the Young's modulus and to obtain some information on the horizontal displacements upon failure of the brick, the deformations of the brick sample were measured using 8 LVDT's. Four LVDT's were placed vertically, while 4 horizontal LVDT's (positioned two by two diametrically on each side of the sample) measured the horizontal deformations. The obtained values for the Young's modulus, determined by means of a linear regression of the stress-strain data in between 20% and 60% of the maximum compressive stress, are represented in Table 3. A representation of the test set-up, measuring the vertical and horizontal displacements, is given in Figure 3.

Table 3 Mechanical characterisation of the Spanish red brick (mean value and standard deviation in between brackets)

Test	f_c / f_t [MPa]	E_v [MPa]
Compression		
cylinder	7.02 (1.48)	-
simple cube	9.97 (2.24)	1314 (256)
stack bond	7.66 (0.99)	1193 (114)
Tension		
3-point bending	3.12 (0.47)	-
Brazilian splitting	0.88 (0.23)	-

In addition also the tensile strength in both a 3-point bending test and a Brazilian splitting test was determined, according to NBN B15-214 and NBN B15-218, respectively. The occurrence of vertical cracks within the brick, as a result of the brick/mortar interaction within the masonry composite, determined the orientation of the brick specimen within the test set-up (see Figure 4). The brick sample was placed as such to provoke the tensile stresses within the test set-up along the prevailing direction of tensile forces within the masonry unit in the composite structure. The 3-point bending test revealed a much higher value for the tensile strength of the brick (see Table 3) in respect to the Brazilian splitting test.

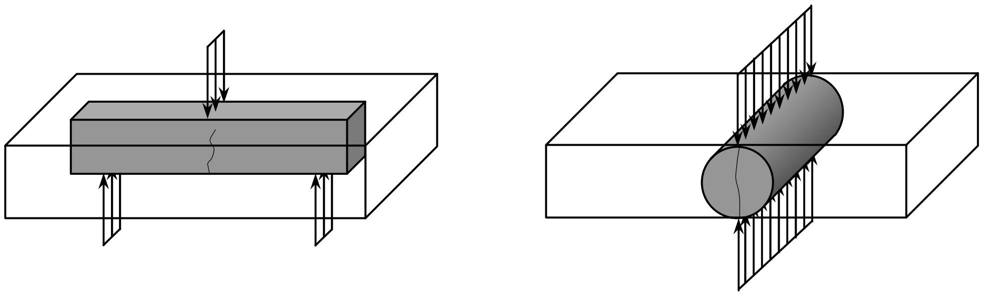

Figure 4 Orientation of the brick samples within the 3-point bending test (left) and the Brazilian splitting test (right).

2.3. The masonry

For each mortar two single leaf masonry walls were constructed in order to obtain a minimal statistical confirmation on the observed compressive strength and mechanical behaviour of the brickwork. The mean dimensions of the walls are 600mm by 607mm by 188mm (one brick thickness). The main structural bond of the single leaf masonry walls is Flemish closed off with a Dutch corner on the left (orientation of the brickwork in respect to the front surface of the wall, represented on the 2nd drawing from the left in Figure 5) and an English corner on the right. The mean width of the mortar joints is about 10 to 15mm.

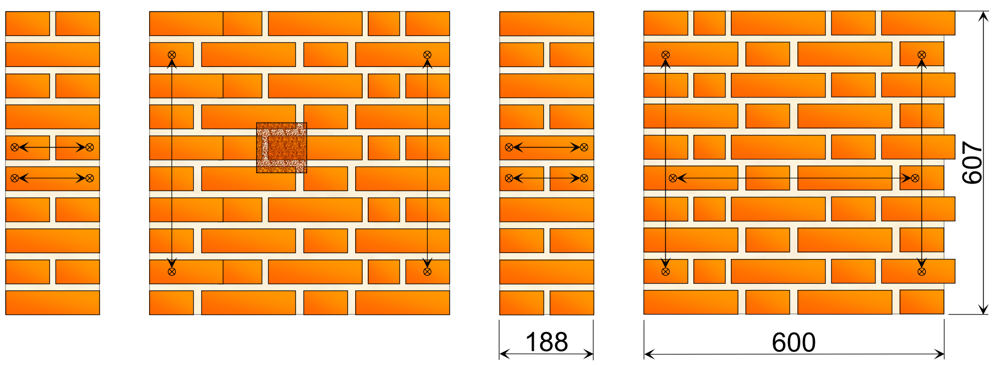

Figure 5 Schematic representation of the brickwork walls

The samples were constructed in the laboratory and were kept inside for about 1 week at an average temperature of about 18 to 20°C. Thereafter, the brickwork walls were moved outside under a protecting shelter, protecting the masonry samples from direct rain. They were kept outside for their respective curing periods during the months December through February.

While for the brickwork masonry with cement mortar a curing period of 28 days is satisfactory, a longer curing period is needed when using a lime putty or a natural

hydraulic lime as a binder. A minimum curing period of 90 days was regarded upon testing the brickwork masonry with both the putty lime mortar and the natural hydraulic lime mortar. The actual curing periods for each of the masonry samples are summarised in Table 4. At the moment of writing the masonry samples with the lime-cement mortar were not tested yet. Therefore, the lime-cement mortar samples are not mentioned in Table 4 as well as in the discussion on the test results.

Table 4: Curing periods

Mortar Type	Curing Period [days]
Putty lime mortar	110 days - 109 days
Hydraulic lime mortar	92 days - 92 days
Cement mortar	32 days - 48 days

3. Test set-up

The compression tests on the single leaf masonry walls consisted of a sequence of loading and unloading cycles in order to examine the elastic and/or plastic behaviour of the masonry structure. At each step the loading path was controlled at a strain rate of 0.1 mm/min, while the unloading path was controlled at a descending rate of 100 kN/min until a remaining load of 25 kN was reached. At the end of each loading and unloading phase the load was kept constant for a period of one minute. After each loading/unloading cycle the compression load was increased with 250 kN until failure occurred. Hence, loading steps of 250 kN and 500 kN were acquired for both the hydraulic lime mortar and the cement mortar samples, while only the 250 kN cycle could be achieved in the case of the putty lime mortar samples.

The deformations of the brickwork structure were measured using a series of LVDT's, mounted directly onto the brickwork (see Figure 5). Four LVDT's measured the vertical displacements of the masonry structure, placed two by two near to the corners of the front and the back surface. The horizontal displacements were measured with a total of 5 LVDT's. One horizontal LVDT was placed at the back surface crossing almost the entire width of the wall, while the other four LVDT's were placed two by two at either side of the wall. The wall's edges consist of alternating brick courses of a stretcher followed by two heathers with a mortar joint in between. Therefore, one of the LVDT's is mounted across one stretcher brick, while the other LVDT is mounted on a neighbouring brick course crossing the mortar joint from header to header brick. All of the horizontal LVDT's are positioned more or less at mid height.

The average base length and the accuracy of the different LVDT's are summarised in Table 5.

Table 5: Average base length and accurcay of the LVDT's

LVDT position	Average Base [mm]	Accuracy [mm]
Vertical	425	± 12.5
Horizontal, along backside	400	± 12.5
Horizontal, sideways header bricks	120	± 5
Horizontal, sideways stretcher brick	120	± 5

During the compression test the local displacements and the brick/mortar interaction were analysed in detail over an area of about 100mm by 100mm on the front surface of the wall. Use was made of a full field optical method based upon video grammetry. A set of four small LVDT's was placed around this area in order to evaluate the

measurements from the full field optical set-up. The results from these measurements are still being analysed and will not be discussed here.

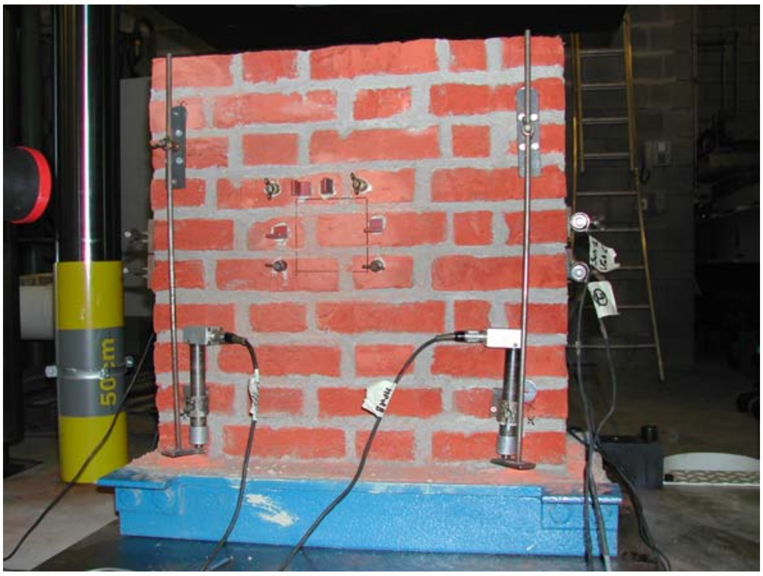

Figure 6 View on the front surface of a masonry sample

4. Test results

The resulting strain and stresses are represented in Figure 7.

Table 6 summarises the main numerical data describing the mechanical behaviour of the brickwork masonry structure: i) the compressive strength of the masonry panels, ii) the Young's modulus, iii) the vertical strain at failure of the masonry panel and iv) the remaining plastic strains at the end of each loading/unloading cycle (one at 250 kN in the case of the putty lime mortar and two at 250 kN and 500 kN, respectively, in the case of both the natural hydraulic lime and the cement mortar samples). The Young's modulus has been determined by means of a linear regression on the data in between about 250 kN and 500 kN.

Table 6 Numerical data on the mechanical behaviour of the masonry structure

	f_c [MPa]	E_v [MPa]	$\varepsilon_{failure}$ [mS]	$\varepsilon_{visco\text{-}plastic}$ [mS]
Putty Lime				
	4.17	671.9	5.66	1.23 / -
	4.20	635.5	6.10	1.25 / -
Hydraulic lime				
	5.49	1195.1	5.02	0.69 / 1.25
	6.36	1552.7	4.50	0.47 / 0.85
Cement				
	8.53	3428.1	3.09	0.14 / 0.25
	8.18	4029.5	2.23	0.13 / 0.23

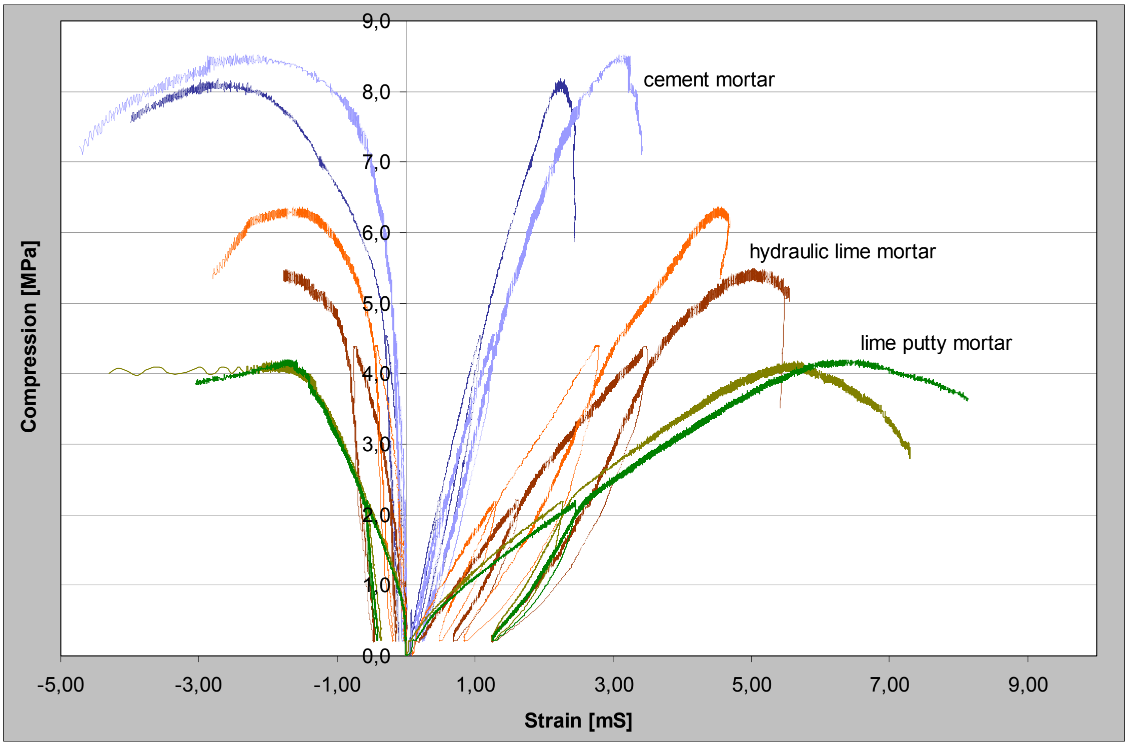

Figure 7 Development of the vertical stress and strains
(-) horizontal strains on the left and (+) vertical strains on the right

5. Conclusions

Several conclusions can be drawn from the presented data on the mechanical behaviour of the masonry composite i) the limited influence of the compressive strength of the mortar on the strength of the masonry composite structure, ii) the increased deformability of the masonry structure for lower strength lime mortars and iii) an increase in plastic deformability with lower strength lime mortars as well.

While on average the cement mortar is about 4.5 and 25 times stronger in compression compared to a natural hydraulic lime mortar and a putty lime mortar, respectively, this increase in strength is only partially reflected on the strength of the composite structure; the increase in compressive strength is restricted to only 40% and 100%, respectively. Although the decrease in strength of the masonry structure is relatively important, the remaining compressive strength of the masonry composite for low strength mortars, even in the case of the 'weak' putty lime mortar, is still high enough to be acceptable for most structures. In addition, the decrease in strength of the brickwork goes together with an important increase in deformability of the masonry composite, giving the structure more possibilities to adapt to settlements and movements of the structure. To conclude, the measurements evidence that the increase in deformability is due to an increase in plastic deformation of the composite structure as can be derived from the remaining plastic strains at the end of each loading/unloading cycle in the case of the natural hydraulic lime and putty lime based masonry.

6. Acknowledgements

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