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MECHANICAL COMPRESSIVE PROPERTIES OF SMALL SIZED MORTAR CYLINDERS

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1. ABSTRACT

Test pieces made form mortar that hardened between bricks are more representative for mortar behaviour in masonry than specimens made in steel moulds. Cylinders and square prisms were cut out of slices of mortar hardened between bricks, having a thickness of at most 15 mm because this is the largest bed joint thickness commonly used. To test these small sized mortar specimens a press was modified in two different ways and the behaviour of the modifications was investigated.

The effects of capping materials and of teflon layers between cylinder and platens, the position of the cylinder in the mortar slab before drilling and the effect of moisture conditions of the bricks on the mortar were studied. Tendencies of these various experimental details on strength and stiffness were found. However, subsequent research into the large variation of the properties using ESPI is required. Results can be used in numerical simulations.

2. INTRODUCTION

Analytical and numerical models for masonry mostly assume uniform properties for mortar across the joint. However, Groot [1], Kjær [2] and Isbener [3] showed that mortar properties vary over the height and width of the joint due to moisture exchange. Mortar properties also can vary because of the brick laying process [4] and the weather changes during erection [1].

Main goal of this project was to investigate the variation of mortar properties over the joint and to establish strength, modulus of Elasticity and Poisson's ratio. For that, small sized specimens hardened under the proper conditions are required. Mortar prisms made in steel moulds are only meant for qualification and they are not appropriate to establish properties to be used for numerical simulation. The following experimental details, based on [5] were studied:

load introduction : brass bar or tube and springs
specimen preparation : hardening conditions: moisture condition unit; position in joint; slab of origin traceable ?
fabrication : cylinder or square prism
was paper used or were specimens taken from a wall ?
interface : interface material: teflon
capping : gypsum; X60 glue or Bolidt
thickness and application of the capping
non parallelism of prism : spherical adjuster or bullet adjuster

3. EXPERIMENTAL DETAILS

3.1 Test machine modifications

Mortar specimens taken from masonry will be small. The joints are thin and the width is limited by wall thickness. To test these small samples small equipment is needed. To simulate the situation in masonry where a mortar slab is compressed between two units were strong (stiff) and weak (soft) parts are deformed similarly, a specimen should be loaded with a uniform deformation field. From a certain position, the load surfaces of the machine should not rotate but only translate. To obtain this, a test machine was modified in two ways: a brass bar and a tube and spring system.

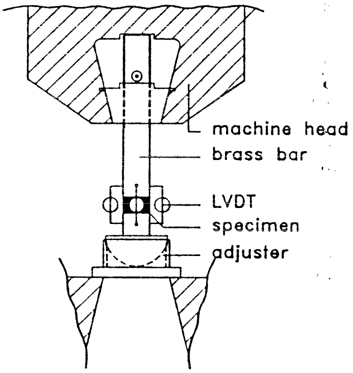

Figure 1 Brass bar in the head of a testing machine

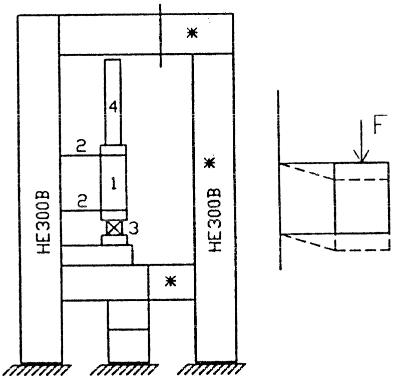

Figure 2 Tube and spring system forming a parallelogram

3.1.1 Brass bar

A brass bar was mounted in the head of a testing machine, Figure 1. The bottom of the machine was adjusted, see par. 3.3, to allow for the positioning of the mortar specimen. It was expected that the machine head would move play less over a vertical axes. The end of the brass bar, perpendicular to the length of the bar, would consequently move horizontally.

3.1.2 Tube and spring system.

A load platen was bolted to a steel tube (1) which was mounted in a frame by means of two springs (2), Figure 2. These springs were made of steel strips 5 x 100 mm^2 with recessed ends. To load the specimen (3) the tube can easily be moved vertically with a hydraulic jack (4). The axes of the tube and the vertical edge of the frame form two opposite sides of a parallelogram, the two springs the other two sides. The horizontal displacement of the tube is negligible in comparison with the vertical displacement ($\leq$ 2mm) due to the length of 200 mm of the rectangular sides. The vertical stiffness of the combination of tube, springs and frame equalled 200 N/mm for which the measured force was compensated when evaluating tests.

3.2 Specimen - test machine interaction

The load will always have some eccentricity due to imperfections in the material and in the preparation of specimens and due to errors in the positioning. To prevent eccentricity effects the system should be much stiffer than the specimen.
The specimen and the brass bar can be schematised as shown in Figure 3

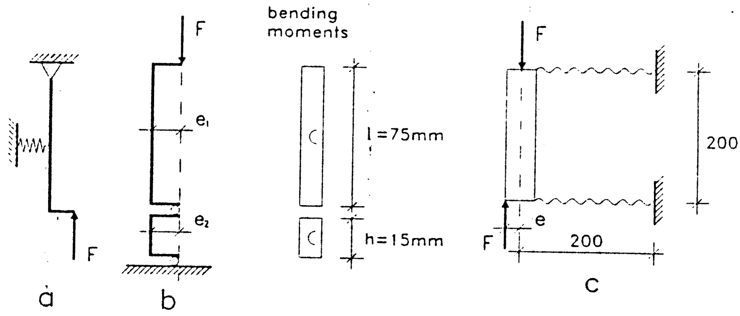

Figure 3 Mechanical scheme of specimen and test machine

The deformation of the rest of the machine and the play in the head (scheme Figure 3a) are neglected. With E_{brass}= 80 kN/mm^2 and an estimated E_{mortar} = 2 kN/mm^2 a stiffness ratio for bar and specimen of $\varphi_{bar} : \varphi_{specimen} = 1 : 8$ is found, based on the scheme in Figure 3a.
The tube and spring system is much stiffer. The tube can be assumed to be supported by springs formed by the steel strips with different stiffnesses in two directions, Figure 3c. Measurements with an eccentric positioned steel block showed that the tube and springs, together with the rest of the system act as a linear spring system. The contribution of the system to the deformations reduced the stiffness ratios to $\varphi_{tube} : \varphi_{specimen} = 1 : 1000$ and 1: 200 respectively.

3.3 Control of parallelism and locking of the spherical hinge

A specimen with its ends made smooth and parallel is loaded by moving the load platens towards each other. One edge of the specimen is touched first and consequently force transfer starts at that edge, Figure 4a. Assume the thickness of the prism is 15 mm and the difference in thickness is 0.005 mm. Then a strain difference of 0.3 ‰ will occur when the load plate makes contact over the whole area, Figure 4b, which is about 1/3 of the ultimate strain. A thickness difference of 0.005 mm is a perhaps optimistic, estimated average, see par. 3.4. Consequently larger stress-strain differences can be expected.

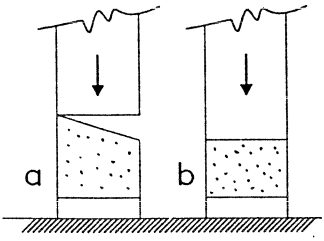

Figure 4 Forces transmitted trough the specimen.

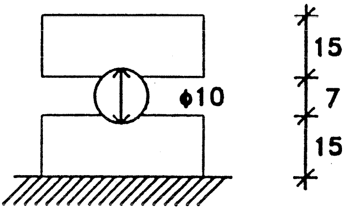

Figure 5 Bullet hinge: two steel plates with a bullet of 10 mm between..

When a separate piece of steel is placed on top of the mortar prism and loaded via a small bullet, Figure 5, the force is concentrated in the centre of the prism. The piece of steel does not have to be exactly parallel to the surface of the loading plate, it can rotate easily. Using the bullet hinge, the stiffness of the machine (par. 3.2) is not that important anymore. However, because one side of a prism is always weaker than the other side, the prism will fail suddenly while the load platen can rotate. Then, the deformation field conditions mentioned in par. 3.1 are not valid. Therefore, a larger sphere, cut in two, was placed in a steel ring, Figure 6a.

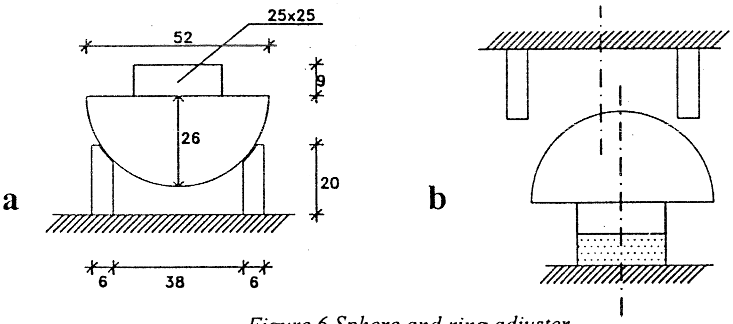

Figure 6 Sphere and ring adjuster

Before the test starts, the sphere can be rotated manually. During closing of the space between the prism and the load platen the sphere can be adjusted to allow for thickness variation of the prism. The dead weight of the sphere causes friction in the connection between the ring and the sphere. Therefore, the sphere has to be positioned manually. When the vertical load increases, the friction force increases too, and the position of the sphere is locked.

The sphere could also be placed on top of the specimen, Figure 6b, where it would position itself. In that case, the centre of the sphere does not always coincide with the centre of the test machine, and as a consequence, horizontal movements will occur.

In this research the sphere was placed beneath the specimen.

The idea behind a spherical hinge is that the loading area can rotate allowing for non parallelism of the specimen, and that after a small load is applied the system is rotation free [7].

3.4 Specimen preparation and capping

To obtain representative values for the behaviour of mortar in real masonry walls, specimens have to be cut from these walls or the real conditions have to be simulated in the production process of the prisms. To produce specimens for this project the following method was used. Bricks, ground smooth and level, were covered with a special kind of paper to prevent mortar from bonding with the brick. Then, the quantity of mortar needed for one joint was placed and covered with paper. With the top brick the mortar was squeezed to the proper joint thickness. Therefore, wooden laths were placed at the end of the units, Figure 7.

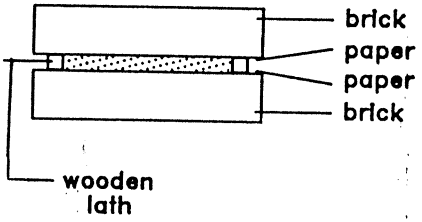

Figure 7. Mortar placed between two units, with paper to prevent bonding of the mortar. Wooden laths to allow for the required joint thickness.

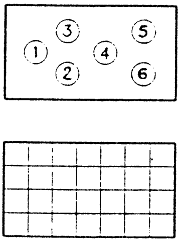

Figure 8 Position where cylinders were drilled from a slab, possible sawing lines for square specimens.

This method was adopted from [6]and [8], however the use of a teflon grid to obtain square prisms was omitted because the bricklaying process is not simulated properly and the teflon grid prevents moisture exchange from the edges to the middle.

From mortar slabs, cylinders or square prisms can be cut. With square prisms more slab material can be used, also close to the edges of the slab, Figure 8.

To obtain an equal distribution of the applied force, specimens have to be made smooth by grinding or capping. Capping is the easiest. Grinding is not appropriate for soft mortar, grains of sand come loose from the surface. Variation in capping thickness can also contribute to eccentricities (par. 3.1) Another way to overcome the problems with prisms being not smooth, level nor parallel is gluing them in. Then they fit perfectly. However, this is time consuming. The glue has to harden and sticks to the load platens which have to be cleaned every test. Gluing of the specimens also influences test results while they are horizontally confined then. However this can be prevented by teflon layers. In combination with glue it is difficult to apply thin layers of teflon and to become a smooth surface. After a few attempts it was decided not to use the 'glue in' method in this research.

Capping material

To make specimens smooth and level, the following capping materials were used in this project: Bolidt and X60 glue, both two component materials and gypsum. These capping materials were applied in the following way. A small amount of capping material was put on a glass sheet. The prism was squeezed and turned into the material, and left to dry and harden. After that, the prism was taken from the glass sheet and the surplus of capping material was removed from the edges of the specimen. The same procedure was followed for the opposite side. The use of the glass sheet resulted in a very smooth surface. A little oil was sometimes used to prevent the capping material from sticking to the glass. The thickness of the capping depended mainly on the capping material used. The cappings were made with an equal thickness and thickness differences of the specimen were not compensated.

4. TEST RESULTS

4.1 Test series P

Main goal of this test series P was to investigate the effects of the type of capping material (par. 3.4) and the effects of ring or bullet hinge (par. 3.3).
The results obtained with calcium silicate cylinders and three types of capping may be summarised as follows in Table 1.

Table 1 Capping material thickness

Capping material		Average Thickness [mm]	C.V. [%]
X-60	:	0.24	1.14
Bolidt	:	0.31	2.45
gypsum	:	1.4	13.90

The functioning of the ring and sphere hinge, used for adjusting for non parallelism of the prisms was tested, using calcium silicate specimens 26 mm in diameter and capped with X60. From the results given in Table 2 the unit type can be recognised, the effect of ring or sphere hinge could not. In another project [9] an averaged strength of 18.8 N/mm^2 and E=8800 N/mm^2. were found with prisms made of 7 half units of the soft type units bonded with Bolidt (size: 100 x 100 x 380 mm^3) see [10].

Table 2 Effects of adjuster type and unit type on strength and E modulus

Adjuster type			strength	CV	E-modulus	
	unit type	##	N/mm^2	%	N/mm^2	CV
ring hinge	hard	5	32.5	4	13800	17
ring hinge	soft	4	18.0	5	9600	16
sphere hinge	hard	5	29.8	5	11600	30
sphere hinge	soft	3	17.2	10	8000	11

4.2 Test series N [11]

Main goal of this series N was to investigate the effect of the moisture condition of the unit on the properties of the mortar. Two types of mortar were used. Slabs were made of mortar 1:½:4½ (c:l:s) and 1:2:9. The slabs hardened between units having three moisture conditions: dry, medium (absorption rate 1.5 $kg/m^2/min$), and saturated. Cylinders with a diameter of 26 mm for the 1:½:4½ mortar and 35 mm for mortar 1:2:9 were drilled from the slabs and capped with gypsum. The averaged results of 108 compressive test on mortar cylinders are presented in Table 3.

Table 3 Strength and E-modulus of strong and weak mortar cylinders hardened under various moisture conditions

mortar type	moisture condition	Number	f'c N/mm^2	C.V. %	E-modulus N/mm^2	C.V. %	E/f'c	C.V. %
1: ½:4½	dry	18	10.20	28	1037	50	99	27
S	medium	18	10.80	24	1059	28	77	28
	saturated	18	8.87	23	815	50	67	32
1:2:9	dry	18	4.33	25	630	77	139	75
W	medium	18	5.56	22	700	62	128	70
	saturated	18	3.25	21	283	55	92	77

The compressive strength according to NEN3835 with prisms 40x40x160 mm^3 of the 1:½:4½ mortar was 12.2 N/mm^2, and 3.3 N/mm^2 for the 1:2:9 mortar.

As an example, the top graph in Figure 9 shows the measured σ-ε diagrams of the 1:½:4½ prisms (SD), the bottom graph those of the 1:2:9 prisms (WD). Both the SD and the WD prisms hardened between dry bricks. A large deviation of the slopes (E moduli) can be observed.

Whether there is a relationship with the position in the slab and the mechanical properties of a specimen is not clear due to the large deviations.

In Table 3 also the averaged ratio between strength and E modulus is given. These ratios follow the same tendency as E moduli. In a few cases the C.V. of E/f'_c is considerably less than for E.

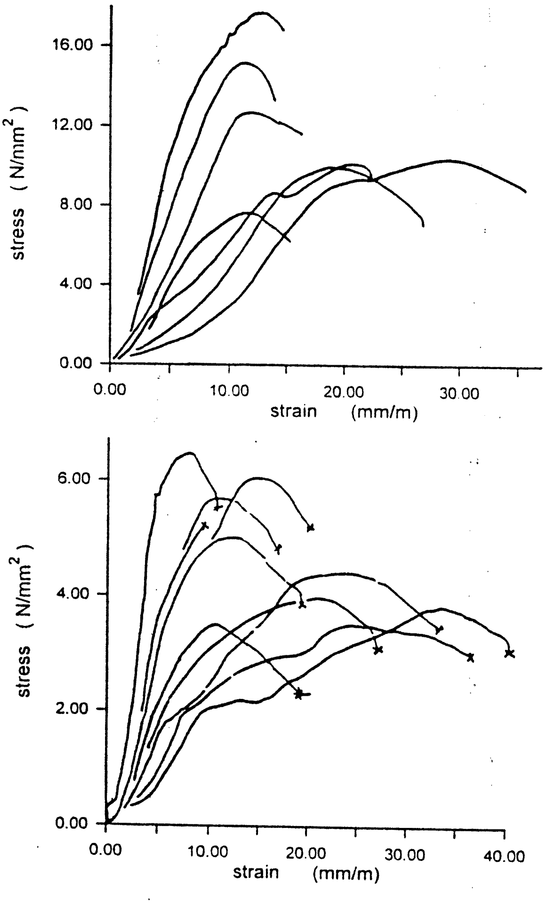

Figure 9 Examples of stress strain diagrams measured with a clip on gauge [11]at two sides

4.2.1 Masonry prisms

Together with the already mentioned strong and weak mortar slabs masonry prisms five bricks high were made with the same mortar. The averaged results of compressive tests on these masonry prisms are given in Table 4. Moisture effects on strength and stiffness were clear as also found in [2]. Mortar E-moduli were calculated by subtracting brick deformations from masonry deformations using E brick = 6000 N/mm^2 and 50 and 15 mm for brick and joint thickness respectively. For the 1:2:9 mortar the E moduli derived from masonry deformation are roughly the same as the values found with cylinders drilled from slabs. The 1:½:4½ mortar results gave a difference of almost a factor two.

Table 4 Strength and E-modulus of masonry prisms that hardened under various moisture conditions and mortar E modulus derived from it. In the utmost right column the E-moduli from cylinders (Table 3) are given.

Specimen type (3 specimens tested per type)		compressive strength N/mm^2	E-modulus masonry N/mm^2	E-modulus mortar N/mm^2	E-mortar from cylinders N/mm^2
1:½:4½	dry	12.5	3020	1260	1037
S	medium	13.3	3660	1530	1059
	saturated	11.1	3310	1340	815
1:2:9	dry	8.0	1830	617	630
W	medium	9.0	2130	770	700
	saturated	6.2	1390	440	283

4.3 Test results series G

Test series G consisted of 29 tests on cylinders Ø 26 mm drilled out of mortar slabs which hardened between calcium silicate units. They were capped with gypsum and tested with the brass bar and the spherical hinge using teflon.

The averaged compressive strength was 7.9 N/mm^2 and C.V. = 24 %. Averaged per slab the difference between the strongest and weakest cylinder was 2.1 N/mm^2. Cylinders drilled from the middle of the slabs were in average 1.2 times as strong as the cylinders drilled at the sides. The largest and the smallest E modulus differed a factor ten and even the largest E modulus of 2,000 N/mm^2 was only one quarter of the expected value on the basis of masonry tests [9]. These small E -moduli were due to the fact that interface deformations (teflon)were included in the measurements.

During testing, no cracks became visible. Afterwards, mainly vertical cracks were visible in the loaded surfaces, Figure 10. Few cylinder segments remained in the shape of columns. The rest of the specimen crumbled after the load platens were separated. Tests were stopped after the load was back under 80% of the observed maximum load. From the mainly vertical running cracks it can be concluded that friction between platens and specimen is considerably reduced by the teflon layers.

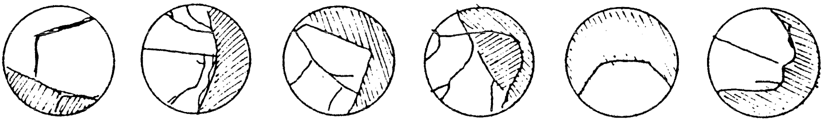

Figure 10 Top view of cracking patterns of prisms of series G.

Table 5 Averaged compressive strength and E modulus of cylinders drilled from five similar slabs, grouped for slab of origin (top of table) and for position in the slab.

Series G		n	strength N/ mm²	C.V. %	E N/ mm²	C.V. %
Slab	1	6	7.8	20	750	58
	2	4	6.7	21	360	44
	3	6	8.5	4	600	50
	4	5	9.1	30	830	75
	5	6	7.8	34	840	100
Position	1	5	7.6	7	760	52
		4	8.3	21	720	70
	2-3	5	7.1	13	440	34
	4	5	9.3	27	790	87
	5-6	3	7.7	16	550	34
		5	8.2	40	860	107
smallest			4.6		175	
average		27	7.9	24	700	77
largest			13.3		2330	

E modulus established with measurements that included teflon interface layers.

4.4 Test series O

In series O the mortar was taken from a damage case. Due to dry and warm conditions during erection of masonry in the summer of 1992 poor bond was obtained. Slabs were picked up easily from the walls. Prisms were cut from three different slabs in order to get an impression of compressive strength and of variation of mortar quality over the walls. The results are given in Table 6.

With the same types of mortar and unit, bond wrench and cross couplet test were recently performed in the laboratory. Square mortar prisms were sawn from the rest pieces. Three hardening conditions were used: warm and dry, warm and moisture, normal and moisture. Strength results are given in Table 7. The effect of hardening conditions on strength was obvious. The effect of the position of the prisms in the slabs could not be recognised.

Table 6 Compressive strength and E modulus of mortar prisms 25 x 25 mm² cut from different slabs taken from a damage case (1992).

Series O1	n for f'	f' N/mm²	vc %	n for E	E N/mm²	vc %
slab 1	16	14.7	22	3	17300	28
slab 2	15	13.2	34	4	21500	12
slab 3	15	16.3	21	4	14700	61
averaged	46	14.7	26	11	17900	36

n: number of tests

Table 7 Strength of mortar prisms 25 x 25 mm^2 cut from laboratory made slabs, slabs were taken from rest pieces of bond wrench tests.

Series Og			n	strength N/mm^2	V.C. %
slab 1	90 % R.H.	30 °C	6	19.7	6
slab 2	90 % R.H.	20 °C	5	19.9	7
slab 3	30 % R.H.	30° C	5	4.9	17
averaged for slab 1 and 2			11	19.8	6

4.5 ESPI results

Main goal of the ESPI tests was to investigate deformation behaviour in more detail. Four mortar prisms as used in series Og were tested using the ESPI system to measure deformations [4]. The strength of these specimens was approximately 1.5 times as big as the prisms tested earlier see Table 7, probably because of age or loading speed differences. Figure 11 shows the strain distribution over the observed surface for a specimen. The vertical strains at a height of 4 and 7 mm respectively were divided by the applied stress ($\varepsilon/\sigma = 1/E$) and their average was plotted versus the position in the width direction of the prisms. See Figure 12.

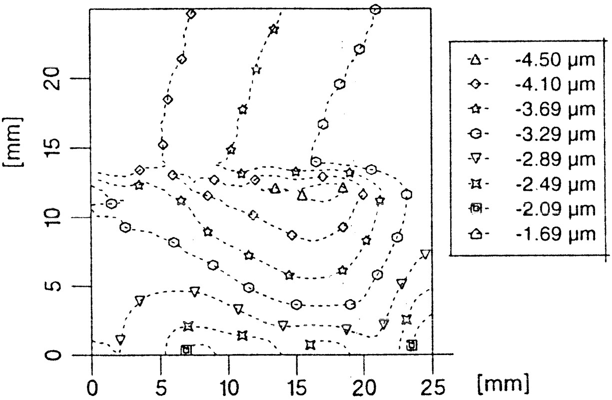

Figure 11 Displacements in vertical direction measured with ESPI. Contour plot. Teflon between mortar and brass bar at 13 mm height.

These figures show some rotation at the contact surface between brass bar and specimen. The large strain variations over the specimen surface indicate that when measuring deformations with a clip on gauge at one or two positions the results depend enormously on the position where the measurement is taken. Normally, the large deformation differences in Figure 11 are invisible and E modulus is calculated as the ratio between 'averaged' stress and 'averaged' strain. The general trend is that strains at the edges are smaller than strains in the middle surface of the specimen.

The averaged strains and E moduli are presented in Table 8. The ESPI measurements confirm the large deviation in E moduli found with the clip on gauge measurements (par.4.2 and Figure 9).

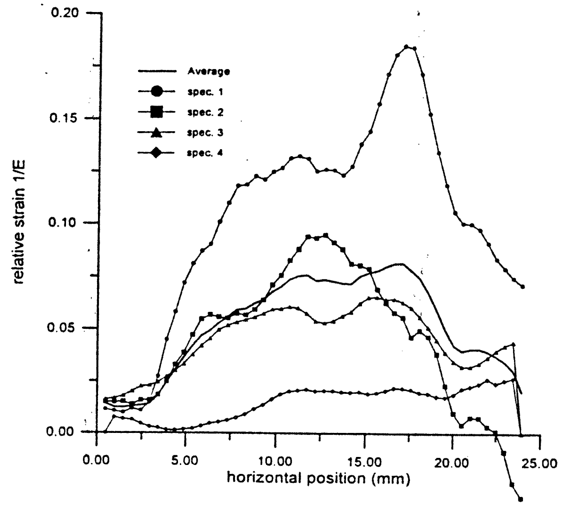

Figure 12. ESPI results. Strain distribution over observed surface

Table 8 Strain/stress ratio's obtained with ESPI [4] at 4 and 7 mm from the bottom

	strength N/mm^2	σ_0 N/mm^2	$\Delta\sigma$ N/mm^2	averaged ε/σ 4mm	averaged ε/σ 7mm	$E = \sigma/\varepsilon$ N/mm^2
1	--	2.4	1.1	0.094	0.111	10,300
2	32.2	4.1	3.6	0.062	0.026	27,500
3	29.6	5.4	3.0	0.042	0.049	22,200
4	32.4	5.8	5.0	0.022	0.008	--
avg	31.4					20,000

σ_0: applied stress applied when taking first ESPI-picture
$\Delta\sigma$: stress difference between first and second ESPI picture

5. CONCLUSIONS.

In this project several problems with the testing of small mortar prisms were investigated. A considerable number of tests on prisms made of calcium silicate units and different types of mortar that hardened under various conditions were performed.

1. Due to large variation, differences between test methods were not significant.
2. The bar mounted in the head of a tensile test machine worked satisfactory. However, for stronger (stiffer) specimens the stiffness of the bar itself and its connection in the head should be improved.
3. Gypsum is a relatively soft capping material, giving thicknesses of 1 to 1.4 mm, which is large compared to the height of the specimen. The strength of the two component materials used is much larger than mortar strength in general, however the thickness is approximately 0.3 mm. Effects of the strength of capping layers on mortar strength could not be recognised.
4. When capping layers are made with constant thickness, the load surfaces of a specimen are not parallel. An adjuster made of half a sphere in a steel ring can be

used and adjusted manually before the load is applied. After that, a uniform displacement field is imposed on the prism.

5. From fracture patterns, showing mainly vertical cracks, it was concluded that teflon interface layers between specimen and load platens reduce friction and that the confining effect on strength becomes small.
6. Measurements that included teflon in the measure length can not be used to establish E modulus. The deformation of the teflon layers is supposed to be different in each test. Consequently, it is not accurate to subtract the (estimated) teflon deformation from the measured total deformation.
7. Deformation measurements on mortar specimens itself showed large variations. This is confirmed by four tests where deformations were observed by ESPI.
8. Due to variation of strength and stiffness it was not possible to clearly recognise effects of the position in the slab.
9. The relationship between the stiffness of mortar cylinders and of mortar in masonry prisms will be studied further, using ESPI.

6. ACKNOWLEDGEMENTS

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