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THE RESPONSE OF CALCIUM SILICATE ELEMENT WALLETTES TO 2D COMPRESSION LOADING

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ABSTRACT

This paper describes and presents results of an experimental programme investigating the structural response of 630 mm long by 630 mm wide by 100 mm thick, wallettes made of calcium silicate elements laid in thin layer mortar. This material is increasingly employed in wall construction in Europe.

Wallettes were built, using thin layer mortar, from one large and two small triangular pieces cut from 600 mm by 900 mm by 100 mm elements. The wallettes had one long diagonal joint (900 mm) and one short diagonal joint (450 mm). The four, 630 mm by 100 mm side surfaces were loaded.

Calcium silicate prisms cut from elements were tested separately in uni-axial compression. Each of thirteen wallettes was subjected to an in-plane combined vertical and horizontal load, the ratio of which was varied. Deformations measured in both directions allowed for the establishment of the modulus of elasticity and Poisson's ratio.

A small horizontal/vertical loading ratio caused shear over the long diagonal joint. With higher ratios the wallettes behaved isotropically. Load-deformation curves show linear behaviour to almost peak load. However, in some cases deviations were found. In some cases the edges failed while in other cases fracture occurred in the bed joint. The responses, together with the stress strain relationships and failure behaviour provide a data base that can be used to calibrate a finite element model of larger walls.

KEYWORDS: bi-axial compression, Poisson's ratio, CASIELs, thin layer mortar, stiffness

INTRODUCTION

In the Netherlands, load bearing walls are usually built with CASIELs: Calcium Silicate Elements, [1]. Ongoing studies show that CASIEL-walls can be used as an infill in steel or concrete frames [2] and for shear walls to give stability to low and medium-high rise buildings. In these situations, the material is bi-axially loaded. To simulate wall behaviour numerically, mechanical properties such as strength, Young's modulus and Poisson's ratio are required. The research described in this paper was aimed at establishing these parameters and to study the failure behaviour under (bi-axial) compressive loading. A positive effect on the strength was expected under bi-axial loading as is the case with comparable materials such as concrete, [3].

A number of series of tests as indicated in Table 1 were performed. An L-series and an E-series of tests were performed with varying vertical/horizontal loading ratios. Besides that, the influence of the thin bed joints used was studied.

The so called 2D-specimens were bi-axially loaded in a compression test rig. For comparison Uni-axial tests were performed on prisms made of the same materials as the 2D-specimens. An extra C-series was uni-axially tested. The uni-axial tests were performed in a standard Schenk hydraulic test machine. Mortar-joint shear tests, designated N-series were performed on 51 specimens. Table 1 shows an overview of the number and types of tests used.

Table 1 - Overview of material compressive strengths and number and types of tests.

	Strength (N/mm^2)		**Number of compression tests**		**Number of shear**
series	**CASIEL**	**mortar**	**uni-axial**	**bi-axial (2D)**	**tests**
E	10.45	20.37	3	5	
L	12.94	12.80	5	8	
C	12.34	--	5		
N	14.40	14.51			51

DESCRIPTION OF TESTS

Materials

One large and two small triangular pieces, cut from one 600 by 900 mm^2, 100 mm thick element, were used to build one specimen of 630 by 630 mm^2 as shown in Figures 1 and 2. The prisms used for uni-axial testing were also cut from elements.

The 2D-Specimens were built in the laboratory by positioning the largest triangular piece between two steel beams with the longest edge surface horizontal. Then the two smaller pieces were laid on top of this element, using thin layer mortar. In this way, the joints were made similar to real practice.

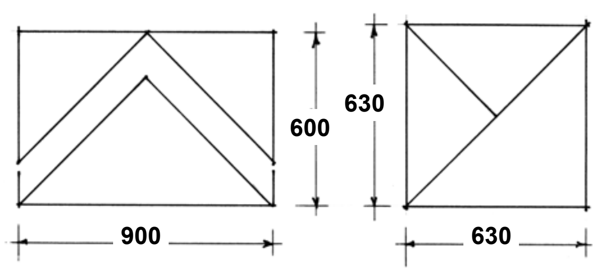


Figure 1 - Cutting scheme

Figure 2 - 2D-Specimens in building and storage position

All specimens were made from three deliveries of CASIELs, with the same nominal strength. The mortars used to build the 2D-specimens were provided by Ankerplast BV. The cube compressive strengths (40 mm cubes according NEN 3835) were 12.40 N/mm^2 (C.o.V of 8.6%) and 20.37 N/mm^2 (C.o.V of 4.1%) for the L and E-series respectively.

For the infilled frame investigation of Ng'andu [2], shear tests on joints, made with a type of mortar, similar to the one used in the L-series, were performed according to prEN 1052-3:2001 [4]. Specimens of 150 x 200 x 800 mm^3 were used. In total 51 specimens - 3 per mortar batch - were tested under prestresses of 0.2, 0.6 and 1.0 N/mm^2. The relationship between shear strength, ($f\tau$) and prestress, ($\sigma\perp$) gave the following best fit Equation 1, based on the Mohr Coulomb criterion:

$$f_v = \mu\,\sigma + f_{v0} = 0.563\,\sigma_{\perp} + 0.578 \qquad (R^2 = 0.70) \qquad \text{Equation 1}$$

with: μ = coefficient of friction and f_{v0} = initial shear strength. It was considered necessary that the specimen had at least one crossing between a head-joint and a bed-joint to be representative of a wall. The size should be large enough to produce a uniform stress distribution in the centre of the specimen. Thus a specimen as large as possible is most suitable. Two layers of Teflon were used to reduce the friction between the specimen and the load platen to make the stress distribution more uniform. For reasons of symmetry the height and length were taken as 630 mm, the maximum length that could be cut from a 900 mm long element.

Test equipment

The specimens were tested in a specially designed and built test frame. The design was based on ideas from Page [5] and a 3D-test rig originally built to test concrete cubes [3]. More details of the test frame are given in [6]. The columns and beams of this frame were double European HE300B steel profiles, with bolted connections.

Four 0.5 MN jacks were mounted in the frame, Figure 3. Their loading was transferred into the specimen using 'ball bearings' and steel profiles with a cross section of 100 x 100 x 630 mm^3. To vary the σ_2/σ_1 ratio, one pair of 0.5 MN jacks was replaced by jacks with a smaller cylinder area, i.e. a capacity of 0.2 MN or 0.045 MN. These jacks produced a smaller load under the same hydraulic pressure as the remaining other two 0.5 MN jacks.

The applied ratios between the smaller (σ_2) and the larger (σ_1) stresses were 0 (4 tests), 0.009 (1test), 0.2 (3 tests), 0.4 (3 tests) and 1.0 (2 tests).

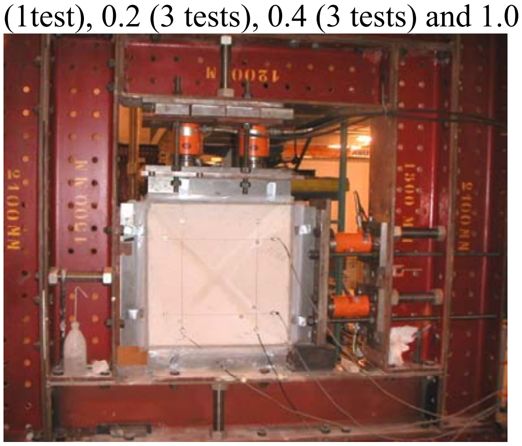


Figure 3 - Test rig and hydraulic system

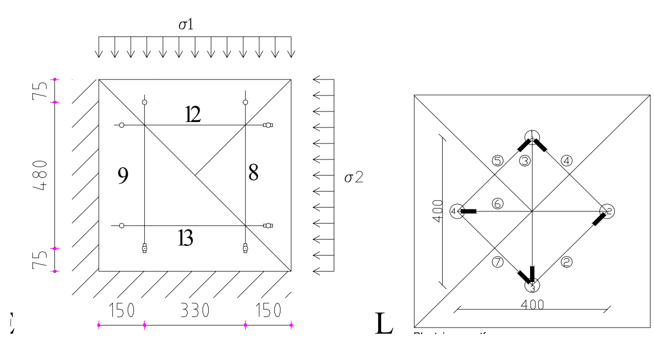


Figure 4 - Loading scheme and LVDT positions

The opening between the load platens and the specimen was filled with a high strength pointing mortar after the specimens were positioned in the test set-up. The compressive strength of the pointing mortar, after 24 hours was at least 20 N/mm^2. Between the pointing mortar and the steel of the test machine, two layers of 0.05 mm thick Teflon sheeting and one layer of PVC sheeting were placed. The PVC sheeting protected the Teflon from damage.

Two configurations for the LVDTs were used on the 2D-specimens, see Figure 4. In the grid configuration used in the L-series (Figure 4), three LVDTs - gauge length 280 mm - measured deformations across a joint while one LVDT measured deformations parallel to the longest diagonal joint. One LVDT - gauge length 400 mm - measured vertical deformations and another horizontal. The results showed no significant strain difference for each individual reading. Because the grid was only mounted at one face of the specimen, it was decided to change the LVDT configuration for the E-series and to use LVDTs both at the front and back face.

UNI-AXIAL TEST RESULTS

Figure 5 - Prism after testing

Prisms, cut from elements, were uni-axially tested in a 2.5 MN Schenck testing machine. Deformations were measured with LVDTs on the front and at the back, both lengthwise and laterally. The loading platens were displacement controlled at 0.1 mm/min by means of an in-built LVDT.

In the L- and C-series Teflon sheets were used to minimize confinement by the load platens. The surfaces were capped with a 2 mm thick layer of gypsum to smoothen cutting traces. In the E-series, three layers of 3 mm thick card board were used to minimize the effect of the cutting traces in the loaded surfaces.

Prism test results are presented in Table 2.

The modulus of elasticity was established using least squares best fit techniques over the linear part of the σ-ε diagram. To establish Poisson's ratio, lateral strains (ε_2) were plotted against axial strains (ε_1). Figure 6 is an example of the ε_2-$\varepsilon_1$diagrams of the three specimens of the E-series.
A second degree best fit was constructed, which showed that the ε_2-ε_1 relationships can be described with Equation 2.

$$\varepsilon_2 \times 1000 = A\varepsilon_1^2 + B\varepsilon_1 - C \qquad \text{Equation 2}$$

The values for the parameters A, B and C were: 51.0, 85.5, and 12.5 for specimen 1; 54.7, 162.3, and 1.40 for specimen 2; and 82.6, 117.0 and 1.80 for specimen 3. The value for R^2 was more than 0.95 in all three cases.

The first crack was clearly detected by the LVDTs; the σ-ε diagrams showed a discontinuity. Cracking was recognized by a loud noise. Some vibrations occurred that caused the LVDT-shafts to shift in their housing, particularly in the C-series. When the graphs are corrected by translating the top part of the graph, relatively smooth graphs were obtained.

Table 2 - Prism test results of series L, E and C

	strength N/mm^2			**E-values N/mm^2**		**Poisson's ratio *)**	
#	L-series	E-series	C-series	E-series	C-series	E-series	C-series
1	12.6	10.14	12.00	3760	5188	0.086	0.16
2	12.8	11.30	12.47	4590	5259	0.16	0.16
3	13.3	9.92	12.14	3660	5057	0.12	0.14
4	13.0	--	12.55	--	5525	--	0.16
5	13.0	--	12.52	--	5414	--	0.15
avg	12.94	10.45	12.34	4000	5290	0.12	0.15
CoV	2.0%	7.1%	2.0%	12.7%	3.5%	30.4%	5.8%

L-series: 100 x 100 x 400 mm^3 prisms and 2 layers teflon, no correction for size nor
E-series: 100 x 100 x 500 mm^3 prisms and 3 layers cardboard, slenderness made
C-series: 150 x 200 x 500 mm^3 prisms and 2 layers Teflon. *) Poisson's ratio in the origin.

It is remarkable that after this cracking - splitting in vertical direction - the specimen still was able to carry higher loads. After this first splitting crack, some inclined cracks appeared near the specimen's ends, which induced shear failure. The failure pattern was similar for all specimens. The ε_2-ε_1 graphs in the C-series showed a more linear relationship than the ε_2-ε_1 graphs in the E-series.

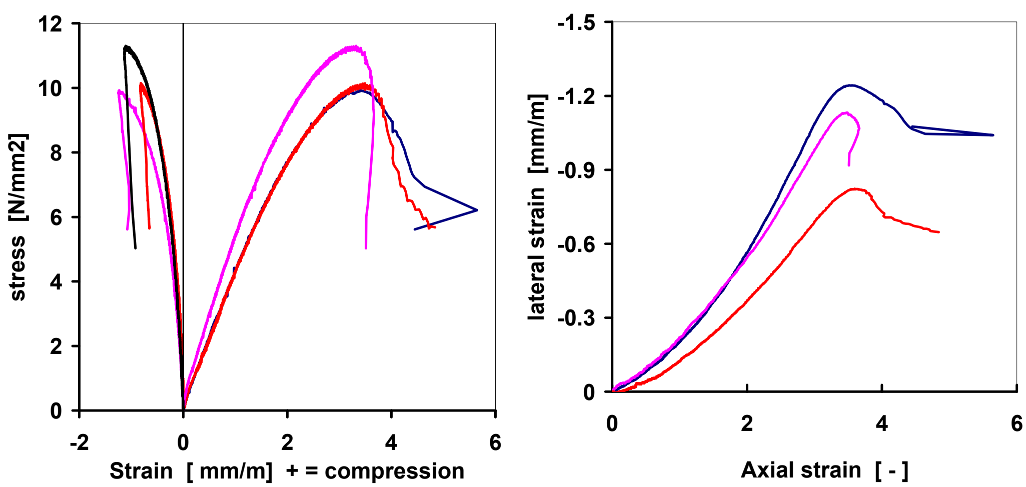


Figure 6 - Example of stress strain results of the specimens of the E-series

BIAXIAL TEST RESULTS

The results of the biaxial tests are presented in Table 3. The difference in strength of the specimens of the E-series and the L-series was obvious.

Failure of wallettes tested in the 2D-test set-up with vertical loading only ($\sigma_2 = 0$).

The tests L1 and L2 with $\sigma_2 = 0$ failed by shear over the largest diagonal joint at axial stresses of 5.1 and 4.9 N/mm^2 respectively, which is approximately 40 % of the uni-axial strength. The uni-axial strengths in the L-series were 12.94 N/mm^2 for CASIEL and 12.80 N/mm^2 for the mortar.

Table 3 - Results 2D-tests

	σ_2/σ_1	$F_{c,bi}$	$E_{1,dir}$	$E_{1,est}$
L1	0	5.1 *)	5350	5350
L2	0	4.9 *)	6300	6300
L4	0.4	14.5	8700	9460
L5	1	10.2	8050	10060
L6	1	12.6	7900	9875
L7	0.2	11.8	9200	9600
L8	0.2	12.9	10400	10830
L9	0.4	13.1	7900	8590
E1	0.4	8.98	5720	6217
E2	0.2	12.14	---	--
E3	0.09	7.98	7470	7600
E4	0	10.45	5220	5220
E5	0	9.29	6070	6070

$F_{c,bi}$ = largest load divided by loaded area, i.e. maximum value observed for σ1.
$E_{seriesL}$ = 9736 N/mm^2 (CoV = 7.6 %)
$E_{seriesE}$ = 6280 N/mm^2 (CoV = 15.7 %)
$E_{1,dir}$ = modulus of elasticity obtained from strains measured in the σ1 direction.
$E_{1,est} = E_{1,dir}/(1-\nu\sigma_2/\sigma_1)$ and $\nu = 0.2$

*) shear in diagonal bed joint

L3 failed prematurely

Similar specimens from the E-series, (E4 and E5), failed outside the joints, at 10.5 and 9.3 N/mm^2, as if the wallettes were made of one homogenous material. The uni-axial strengths in the E-series were 10.45 N/mm^2 for CASIEL and 20.37 N/mm^2 for the mortar. This indicates that the shear strengths of the two E-specimens were much higher, probably due to the differences in the material – mainly mortar - properties. The specimens failed as a monolithic volume. The E-series CASIELs were less strong, but the mortar was two times stronger than in the L-series.

A joint under 45° of the principal loading direction, experiences shear and normal stresses of

$$\sigma_\perp = \tau = \tfrac{1}{2}(\sigma_1 + \sigma_2) \qquad \text{Equation 3}$$

Using equation 1 as an indication, the shear strength (fv) of the specimens would be approximately equal to 1.32 N/mm^2 (or σ_1,ult equal to 2.64 N/mm^2). The experimental value for σ_1, ult was approximately 5 N/mm^2 for specimen L1 and L2. The strength of specimens E4 and E5 however was (much) higher, indicating a shear strength (fv) equal to 5 N/mm^2 (σ_1, ult equal to 10 N/mm^2). The stronger mortar may be an explanation for this higher shear strength, although the Equation 1 parameters were established for pre loads smaller than 1.0 N/mm^2.

Failure under 2D compression (σ_2 > 0 N/mm^2)

The capping of specimen E1 failed in the corner between the two load platens that were rigidly connected to the frame. The specimen itself was not cracked except near the failed capping. The strength of the specimen however was similar to the other results.

A crack became visible at a load of 450 kN. The E1-specimen failed at 510 kN and cracked into two pieces of approximately half the element thickness over its full 630 x 630 mm^2 surface, see Figure 7. This became only visible after removal of the wallette from the test rig. All other specimens had similar splitting fracture patterns, see Figures 7 and 13.

Figure 7 - Specimens split over its thickness

In test E2, the load dropped suddenly from 720 kN to 500 kN. During further loading, the original deformation load path was resumed and at 760 kN the E2-specimen failed. It is assumed that the specimen's deformation was (partly) prevented until the first load drop - indicated by the LVDT results - because of problems with test-control.

Multiple regression analyses into the effects of bi-axial stress

The results are 'normalized' by dividing them by the value of the uni-axial material strength ($f_{c,uni}$) of 12.94 N/mm^2 for the L series and 10.45 N/mm^2 for the E series respectively. The maximum recorded values for $\sigma_1/f_{c,uni}$ and $\sigma_2/f_{c,uni}$ are plotted against each other in Figure 8. The following multiple regression model was proposed:

$f_{c,bi} = \beta_0 + \beta_1.h+\beta_2.\sigma_2/\sigma_1 + \beta_3.f_{c,uni}$ Equation 4

Using Statgraphics [5] for the analysis of the results of the 2D-tests, the following equations were found:

$f_{c,bi} = -4.156 - 1.583*\sigma_2 + 1.353*f_{c,uni}$ Equation 5

$f_{c,bi} = -1.76757 + 1.10388 * f_{c,uni}$ Equation 6

In Equation 6, the effect of the (smaller) lateral load is left out. The probability (P) values were: $P_{\sigma 2} = 0.3857$ and $P_{fc,1} = 0.0185$ for Equation 5 and $P_{fc,1} = 0.0147$ for Equation 6.

A parameter with a P-value larger than 0.05 is statistically not significant and can be omitted from the model (compare Equations 5 and 6). The values calculated with the Equations 5 and 6 were plotted against the experimental results in Figure 9. The results show that a) confinement stress (σ_2) has only a minor effect on strength while b) the uni-axial material strength (fc,uni) has a significant effect, indicated by the ◊ markers at 9.8 N/mm^2 and 12.5 N/mm^2 in Figure 9.

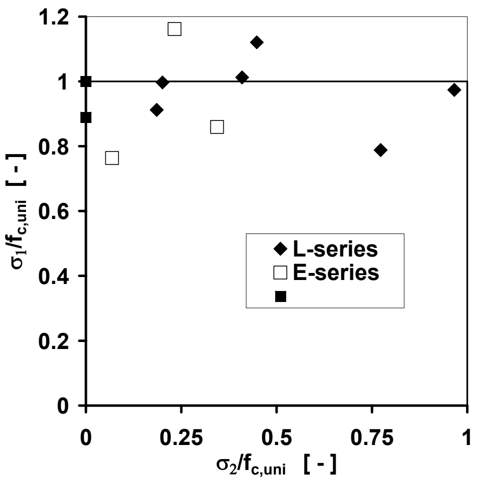


Figure 8 - $\sigma_1/f_{c,uni}$ versus $\sigma_2/f_{c,uni}$

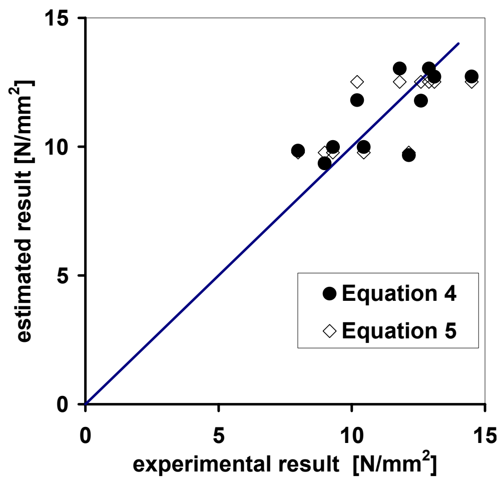


Figure 9 - Estimated versus experimental strength for 2D tests specimens

Deformation measurements in 2D-tests

The grid with LVDTs was chosen to provide information about the effects of the thin layer joint, and to indicate when shear failure occurred. In the grid one measurement was redundant. This allowed for an estimation of measuring errors, using 'plane truss' techniques as explained in [8]. This showed that the errors were smaller than 4% of the measured values.

The four LVDTs at the sides of the square grid in the L-series, - gauge length 280 mm- measured approximately equal deformations, showing that the TL-joint had no significant effect on E-values. The averaged values, measured under 45°, are plotted against the applied stress (σ_1) in Figure 10. The two specimens (L5 + L6) with a σ_2/σ_1 ratio of 10:10 had the largest deformation.

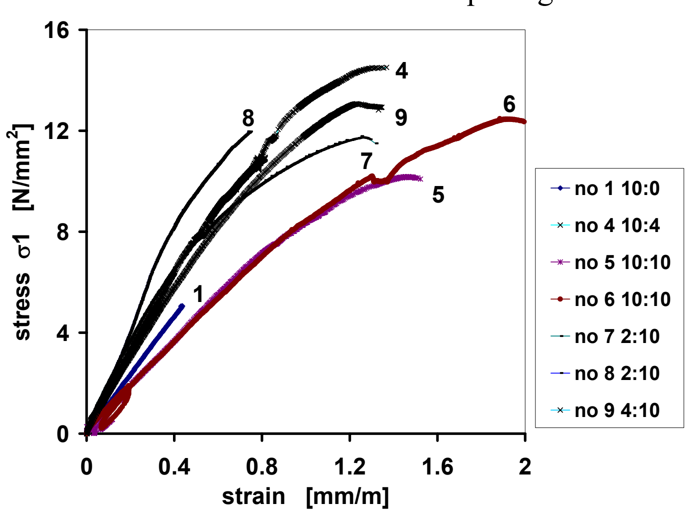


Figure 10 - $\sigma 1$-$\varepsilon_{45°}$ diagram.

The behaviour of the specimens L4 and L9 with a σ_2/σ_1 ratio of 10:4 was similar, with a smaller deformation than specimens L5 and L6. The effect of σ_2 on the deformation was self evident.

Poisson's effects in 2D-tests

In Figure 11 the measured axial strains (ε_1) were plotted against the lateral strains (ε_2). For σ_2/σ_1 ratios equal to one, strains were almost equal in both directions. For smaller values of σ_2/σ_1 the strain in the second direction (ε_2) became negative. For σ_2/σ_1 equal to zero, the result was similar to the uni-axial test results. Figure 11 shows the obvious effect of the σ_2/σ_1 ratio, indicating the effects of Poisson's ratio (ν) on deformations. The following equation was used to express this effect:

$$\varepsilon_2/\varepsilon_1 = (-\nu + \sigma_2/\sigma_1) / (1 - \nu\, \sigma_2/\sigma_1) \qquad \text{Equation 7}$$

In Figure 12, Equation 7 is plotted for various values of Poisson's ratio (ν). The experimental $\varepsilon_2/\varepsilon_1$ values are plotted against the σ_2/σ_1 ratio as well. It was assumed that the material was isotropic. The $\varepsilon_2/\varepsilon_1$ ratio for each σ_2/σ_1 ratio (average of 2 specimens) obtained from the results shown in Figure 11 are presented in Table 4. From Figure 12 it can be concluded that the $\varepsilon_2/\varepsilon_1$ ratios are on the line for $\nu = 0.2$ for smaller σ_2/σ_1 ratios. For σ_2/σ_1values of less than 0.4 the effect of the smallest stress (σ_2) on the E-modulus is relatively small, ($\nu.\sigma_2/\sigma_1 \leq 0.08$). The measuring accuracy is of the same order of magnitude.

For a σ_2/σ_1 of one, the experimental value for $\varepsilon_2/\varepsilon_1$ is approximately 0.85 or 1.15, depending on the choice for the direction of the stresses. Considering the symmetry in the specimen, the strains in both perpendicular directions can be averaged. This would mean that the modulus of elasticity found for this situation could be increased by a factor 1.25%, i.e. the ratio $1/(1-\nu\, \sigma_2/\sigma_1)$.

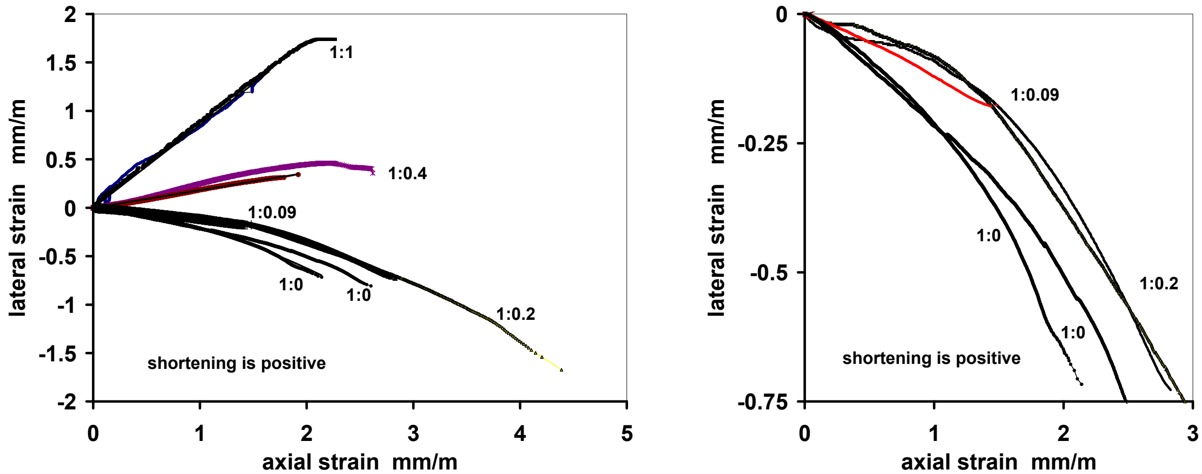
For most results a linear $\varepsilon_2/\varepsilon_1$ relationship was assumed. However, for the specimens with a σ_2/σ_1 ratio of 0.2 this resulted in extreme values. Therefore, for these specimens a parabolic fit was made and the tangent to this fit used, resulting in: $\varepsilon_2 = -0,0527\varepsilon_1^2 - 0.159\varepsilon_1$.

The results of Table 4 plotted in Figure 12 indicate that a Poisson's ratio of 0.2 is a reasonable estimation for the 2D-specimens. This value corresponds well with the values obtained from the uni-axial tests.

Table 4 - The $\varepsilon_2/\varepsilon_1$ ratios (L-series)

σ_2/σ_1	**1**	**1**	**0.4**	**0.4**	**0.2**	**0.2**	**0.2**	**0.09**	**0**
ε_1	1.51	1.41	1.51	1.55	$\varepsilon_2 = -0,0527\varepsilon 1^2 - 0.159\varepsilon_1$			1.44	1.07
ε_2	1.32	1.19	0.37	0.29	$R^2 =$	0.988		-0.18	-0.23
$\varepsilon_2/\varepsilon_1$	0.874	0.844	0.246	0.185	0.097	-0.016	0.007	-0.124	-0.216
$\varepsilon_2/\varepsilon_1$*)	1.00		0.217			0.000		-0.112	-0.200

*) Calculated value using a Poisson's ratio of 0.2 in Equation 7.



a) all σ_2/σ_1 ratios **b) small σ_2/σ_1 ratios**

Figure 11 - Lateral (ε_2) versus axial (ε_1) strain, various σ_2/σ_1 ratios

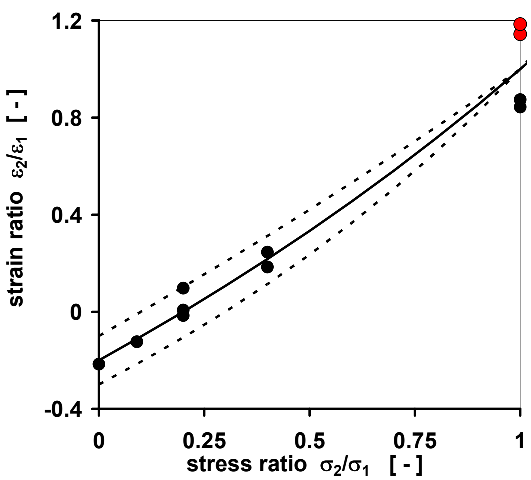


Figure 12 - Strain ratio ($\varepsilon_2/\varepsilon_1$) versus stress ratio ($\sigma_2/\sigma_1$)

Figure 13 - Specimen split diagonally

CONCLUSIONS

From the tests described, the following conclusions are drawn.

- The lateral confining stress (σ_2) had only a minor effect on strength.
- The fact that the effect of the lateral load (σ_2) was minor on strength and significant on deformation may indicate that failure was affected by lateral tensile stresses in the third direction, and perhaps to some extent, by the boundary conditions of the tests.
- In 2D-tests the effect of the lateral stress (σ_2) on the $\varepsilon_2/\varepsilon_1$-ratio was clear.
- Poisson's ratio ($\varepsilon_2/\varepsilon_1$) increases with higher loads.
- The ε_2-ε_1 relationship can be accurately described by a second degree parabola, Figure 6.

First, vertical splitting cracks appear, followed at higher loads by inclined shear surfaces at about 45° from the loaded edges. The 2D-specimens split over the full 630 mm by 630 mm section in half the thickness, similar to the uni-axially tested specimens.

- The thin layer mortar joints had no effect on strength and on E-values for σ_2/σ_1ratios smaller than 0.15. When the σ_2/σ_1 ratio was smaller than 0.15 shear failure occurred in two instances, which was explained by the lower mortar strength.
- Calcium silicate elements are not fully isotropic. Some effect of pressing during fabrication is observed in the failure pattern. The strength is not uniform over the height.

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