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SUSCEPTIBILITY FOR CRACKING OF MASONRY MORTAR JOINTS WHEN SUBJECTED TO COMPRESSION

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ABSTRACT

Cracking occurs frequently in masonry walls of buildings. Cracks are usually located in the joints between the blocks or bricks because joints generally represent planes of weakness. Cracking has negative implications for building performance, due to the possibility of rain penetration through the cracks and due to negative aesthetic aspects. So, the objective of this paper is essentially to achieve a better knowledge of the compression behaviour of masonry walls (common block/block joint), for the particular cases of a) solid lightweight concrete blocks (blocks of aerated autoclaved concrete and blocks of lightweight concrete with expanded clay aggregates) and b) solid bricks.

In this paper, the principal results and conclusions of an experimental study are presented. The experiments were mainly concerned with the study of the deformation behaviour and the susceptibility for cracking of mortar joints together with the surrounding blocks as well as the blocks alone when subjected to a triaxial state of compression stress. From the results of the experimental tests it can be concluded that the level of biaxial compression applied to specimens with joints, significantly influences the deformation behaviour and the failure modes of the joints.

KEYWORDS: masonry walls, buildings, shear, AAC, lightweight concrete

INTRODUCTION

Cracking occurs frequently in masonry walls of buildings. Cracks are usually located in the joints between the blocks or bricks because joints generally represent planes of weakness. Compression of masonry walls can generate high stress concentrations in restricted areas of those walls, which results in cracks, especially in their mortar joints. This is frequently due to a local biaxial state of compression stress (example: wall lower corner zone of a wall/beam element). Cracking has negative implications in building performance, due to the possibility of rain penetration through the cracks and due to negative aesthetic aspects. So, the objective of this paper is essentially to achieve better knowledge of the biaxial compression behaviour of masonry wall joints (common unit/unit joint), for the particular cases of solid lightweight concrete blocks (blocks of aerated autoclaved concrete – material X, with dry mass of around 560 kg/m^3; blocks of lightweight concrete with expanded clay aggregates – material Y, with dry mass of around 1040 kg/m^3) and solid clay bricks (material Z with dry mass of around 2110 kg/m^3).

In this paper, the principal results and conclusions of an experimental study, carried out at LNEC, are presented. The experiments were mainly concerned with the study, for the types of blocks and bricks above, of the deformation behaviour and the susceptibility for cracking of mortar joints together with the surrounding blocks or bricks as well as the blocks and bricks alone when subjected to a triaxial state of compression stress.

GENERAL DESCRIPTION OF TRIAXIAL COMPRESSION TESTS

Initial considerations

Masonry is often subjected to axial compression, which leads to local stress concentrations in mortar joints. In such cases the state of stress within the joint is complex due to the influence of the surrounding blocks. To investigate such phenomena it is important to access the mortar joint properties, which cannot be defined from simple uniaxial tests performed on the mortar alone. So the mortar properties must be estimated taking into account not only the results of uniaxial compression tests, and flexural tension tests but also those of triaxial compression tests on mortar samples (mortars for material X and Y), and on specimens made of blocks alone and of blockwork couplets with mortar joint.

Triaxial compression tests were developed as part of an experimental study on masonry walls and their supporting beams [3, 4]. In that study, material properties of the units used for the masonry specimens as well as the mortar used in their joints were estimated taking into account the results of uniaxial compression tests and flexural tension tests (Table 1). The resistances of the lightweight concrete blocks were estimated from uniaxial compression tests (see Table 1).

The blocks of aerated autoclaved concrete (material X) and the blocks of lightweight concrete with expanded clay aggregates (material Y) had nominal compressive strengths respectively of 3.9 MPa and 10.1 MPa; the estimated values of modulus of elasticity, $E_{b,}$ were respectively of 930 MPa and 8500 MPa. A thin mortar layer was used for material X, while a medium strength mortar, of a 1:1:6 mix by volume of cement, lime and sand, was used for materials Y and Z. The strength of the joint under tension was estimated from a series of flexural strength tests on solid blockwork couplets (with a vertical joint in the middle of the specimen). The estimated tensile strengths were 0.6 MPa and 0.2 MPa, respectively for couplets made of material X and Y (no tests of this type were made on material Z - see Table 1), which illustrates the low value of masonry tensile bond strength, a value that is well bellow the tensile strengths of the respective mortars (respectively 2.9 and 2.5 MPa - Table 1).

The triaxial compression tests mentioned above were carried out on mortar specimens (thin mortar specimens associated with material X and cement mortar with material Y and Z – see size in Table 3) and on specimens made from the material of the three types (X,Y,Z) of units used (see description in Table 2). From the triaxial compression tests on unit and mortar materials, average stress-strain curves were derived and relevant mechanical properties were estimated.

In the triaxial compression machine, axial load was applied by means of a hydraulic jack. The lateral pressure load could be transferred to the specimen fixed inside the triaxial cell, while the vertical displacements could be monitored with a digital transducer, and so vertical pressure load-vertical displacements curves could be obtained. The triaxial compression tests were performed on cylindrical specimens with a diameter of approximately 52.5 mm, made from: a) blocks of aerated autoclaved concrete (material X - Dx and Ex series) including a thin mortar joint (thickness of approximately 3 mm); b) blocks of lightweight concrete with expanded clay aggregates (material Y- Dy and Ey series) including a cement mortar joint (thickness of approximately 5 mm); c) solid bricks (material Z- Dz and Ez series) including a cement mortar joint similar to that used for Dy and Ey (thickness of approximately 5 mm). The main difference between Dx, and Ex consisted in the inclusion, in Ex specimens, of an additional joint to simulate vertical joints in a real masonry wall, normal to the other joint (this last to simulate bed joints) present in the specimens of Dx series (Table 2). The same considerations could be made about the differences between Dy and Ey or Dz and Ez. Mortar thin layer (adhesive type - Ak series) and cement mortar (Aw series) specimens were also subjected to triaxial compression tests.

Table 1 - Material properties of masonry constituents: units of material X, Y, Z and associated mortar (compressive and tensile strength)

Type of masonry material	f_c (MPa)			f_t (MPa)	
(units and mortar joints)	*Block*	*Mortar**	*Masonry*	*Block*	*Mortar**
MATERIAL X ***Blocks***: aerated autoclaved concrete (used in Cx, Dx and Ex series) ***Mortar***: thin layer mortar (adhesive type – used in Ak, Dx, and Ex series)	3.9	5.2 (Ak) 7.0 (Dx, Ex)	2.0	1.3	2.9(Ak) 3.2 (Dx, Ex)
MATERIAL Y ***Blocks***: lightweight concrete with expanded clay aggregates (used in Cy, Dy and Ey series) ***Mortar***: cement, sand (mix proportions - 1 :5 – used in Aw, Dy, and Ey series)	10.1	2.7 (Ak) 2.6 (Dx, Ex)	4.5	2.7	1.4 (Ak) 2.5 (Dx, Ex)
MATERIAL Z ***Bricks***: solid clay bricks (used in Cz, Dz and Ez series) ***Mortar***: cement, sand (mix proportions - 1:5– used in Dz, and Ez series; same type of mortar used in Aw series)	27.1	2.7 (Dz, Ez)	-	5.5	1.4 (Dz, Ez)

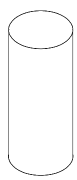
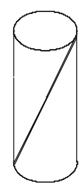
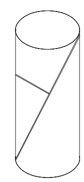
* mortar properties values are presented in this table together with indication of triaxial compression test series which used the same batch of mortar material (MPa = N/mm^2)

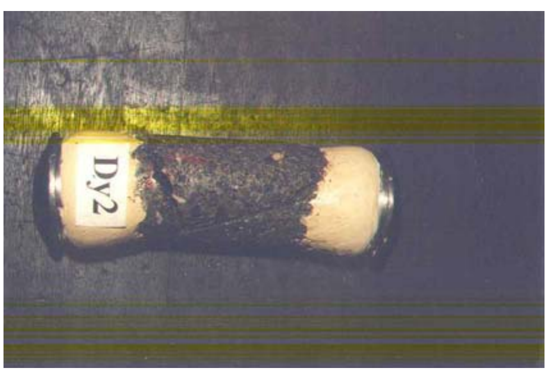
The methodology of the triaxial compression tests consisted in the application, on each specimen (Fig. 1), of a constant ratio of lateral compressive and vertical compressive load (level of ratio σ_L/σ_V different from specimen to specimen – Table 2). The ratio of lateral stress/vertical stress, (σ_L/σ_V), of the specimens on each series could vary, generally, between 0.05 and 0.30. In additional specimens Dxi, Exi, Dyi, Eyi, Dzi and Ezi, a strain gauge installed in the face of the specimens allowed the lateral displacements to be monitored and a vertical or lateral pressure load-lateral displacement curves could also be obtained. In the test, stresses across the inclined joint of the specimens used in this study, were expected to be approximately uniform with exception of the extreme zones of that joint.

Generally, an initial axial load of 0.50 MPa and a lateral pressure load, dependent on the value of the ratio σ_L/σ_V previously chosen, were applied to the specimens and, after that, both lateral and axial loads were increased, while σ_L/σ_V was maintained approximately constant, until failure was reached. During the test the vertical displacements measurements were recorded, generally, by step increments of 0.5 MPa of applied axial load.

The relative peak vertical pressure load corresponding to the last load step before reaching the maximum shear load was recorded. This last value was difficult to record, unless it was coincident with the load at the end of the corresponding step.

Table 2– General description of triaxial compression tests of specimens

Type of block	Mortar specimens	Block specimens	Block/simple joint	Block/double joint
Blocks of aerated autoclaved concrete	Ak1, Ak2, Ak3, Ak4 **$0,05 \leq \sigma_L/\sigma_V \leq 0,30$**	Cx1, Cx2, Cx3, Cx4 **$0,05 \leq \sigma_L/\sigma_V \leq 0,30$**	Dx1, Dx2, Dx3, Dx4 **$0,025 \leq \sigma_L/\sigma_V \leq 0,20$**	Ex1, Ex2, Ex3 **$0,025 \leq \sigma_L/\sigma_V \leq 0,10$**
Blocks of lightweight concrete with expanded clay aggregates	Aw1, Aw2, Aw3 **$0,05 \leq \sigma_L/ \sigma_V \leq 0,30$**	Cy1, Cy2, Cy3 **$0,05 \leq \sigma_L/ \sigma_V \leq 0,30$**	Dy1, Dy2 **$0,05 \leq \sigma_L/ \sigma_V \leq 0,10$**	Ey1, Ey2, Ey3 **$0,05 \leq \sigma_L/ \sigma_V \leq 0,20$**
Solid bricks		Cz1, Cz2, Cz3 **$0,05 \leq \sigma_L/\sigma_V \leq 0,30$**	Dz1, Dz2, Dz3 **$0,05 \leq \sigma_L/\sigma_V \leq 0,30$**	Ez1, Ez2 **$0,05 \leq \sigma_L/\sigma_V \leq 0,10$**
Graphic scheme of the specimen (see size of specimens in Table 3)				



a) **b)**

Figure 1– a) Example of specimen for the triaxial compression test (Dy2 specimen); b) Final aspect of triaxial test specimens Ex1, C´yi, Dxi and Exi

Taking in account the results of the tests, Poisson coefficient, μ, and shear modulus, G, were evaluated (see Table 3). In the case of specimens with joints, the normal and tangential stresses in the joint plane were evaluated considering a constant angle (angle related with the slope of the joint specimen – see graphic scheme in Table 2, Figure 1a), which provided the base for calculating the friction angle of the joint, tan φ. Although the thickness of the joint was not similar in the different series, a simplified procedure was adopted in the calculations, which assumed a zero thickness for all specimens.

The values of relative peak vertical load for all specimens are presented in Table 3, which corresponds to the last registered value (last increment of load) where the ratio of lateral stress/vertical stress, (σ_L/σ_V), during the test, could be kept constant, before the discharge of the specimen occurred with a variable and unknown ratio of σ_L/σ_V, and the residual value was achieved. The values of cohesion and friction angle are based on the values obtained from the failure envelope (based on Mohr circles), which were evaluated from the relative peak vertical load values (see example of peak values on the graphs of Figures 3, 5 and 7).

RESULTS OF TRIAXIAL COMPRESSION TESTS

Mortar specimens (Ak and Aw series)

In the triaxial compression test of Ak series specimens, Ak0, Ak1, Ak2, Ak3, Ak4, and Aki, as well as Aw series specimens, Aw0, Aw1, Aw2, Aw3, Aw4 and Awi, the applied constant ratio σ_L/σ_V were respectively, 0.025, 0.05, 0.10, 0.20, 0.30 and 0.075 (Table 3). That ratio was usually in correspondence with an initial vertical pressure load of respectively 0.50 MPa, and with an initial lateral pressure load dependent on the ratio (σ_L/σ_V) chosen for each specimen. In specimens Ak0, Ak1, Ak2, Ak3, Ak4 and Aki, failure occurred for vertical pressure loads of respectively 8.0 MPa, 8.0 MPa, 13.9 MPa, 14.5 MPa, 11.8 MPa and 11.7 MPa; and for specimens Aw0, Aw1, Aw2, Aw3, Aw4, and Awi the pressures were respectively, 8.0 MPa, 8.5 MPa, 13.0 MPa, 15.5 MPa and 8.0 MPa. In specimens Aki and Awi failure occurred at peak vertical deformations of 11.1 mm/m and 10.9 mm/m respectively. The transverse deformation of Aki was 0.9 mm/m, while the residual vertical deformations were, for Aki and Awi, 18.8 mm/m and 19.3 mm/m respectively. The failure of the majority of the specimens for both the Ak and Aw series occurred along a shear plane with a slight fragmentation of the material. From the results of these tests it can be inferred that confining mortar specimens (Ak and Aw series) throughout triaxial compression can increase the ultimate strain and produce a higher ultimate strength compared with uniaxial compression of the materials.

Specimens of blocks

As described before triaxial tests were made on blocks of aerated autoclaved concrete, blocks of lightweight concrete with expanded clay aggregates, and solid clay bricks (specimens with and without joints).

a) specimens of blocks of aerated autoclaved concrete with and without joints (Cx, Dx, Ex series and additional specimens Cxi, Dxi, Exi)

In the triaxial compression tests on specimens Cx1, Cx2, Cx3, Cx4 and Cxi, the applied constant ratio σ_L/σ_V values were respectively, 0.05, 0.10, 0.20, 0.30 and 0.075; for specimens Dx1, Dx2, Dx3, Dx4, and Dxi respectively, 0.025, 0.05, 0.10, 0.20 and 0.075; and for specimens Ex1, Ex2, Ex3, and Exi respectively, 0.025, 0.05, 0.10, and 0.075 (Table 3). That ratio was in correspondence with an initial vertical pressure load of 0.5 MPa.

After an initial approximately linear phase the relation between vertical deformations and the applied vertical load, with the increased load the slope of the curve decreased especially near the peak value (Fig.2 – see results of Dx series).

In Cx1, Cx2, Cx3, Cx4 and Cxi failure of the specimens occurred for vertical pressure loads of 5.0 MPa, 6.0 MPa, 6.5 MPa, 7.0 MPa and 6.0 MPa respectively; for specimens Dx1, Dx2, Dx3, Dx4, and Dxi 5.3 MPa, 6.0 MPa, 6.7 MPa, 6.3 MPa and 6.0 MPa respectively; and for specimens Ex1, Ex2, Ex3, Ex4, and Exi, 5.5 MPa, 5.5 MPa, 6.0 MPa, 6.1 MPa and 6.0 MPa respectively (Table 3, Figures 2 and 3). In specimen Dxi, failure occurred for peak vertical and transverse deformations of 5.8 mm/m and 2.7 mm/m respectively, and the residual vertical deformation was 6.5 mm/m.

The results of the tests on the Cx series show values of the resistance of the block material to triaxial compression to be lower than those obtained from the mortar specimens series (Ak), as can be confirmed through the respective curves of the failure envelopes (based on extrapolation of the curves illustrated in Figure 3).

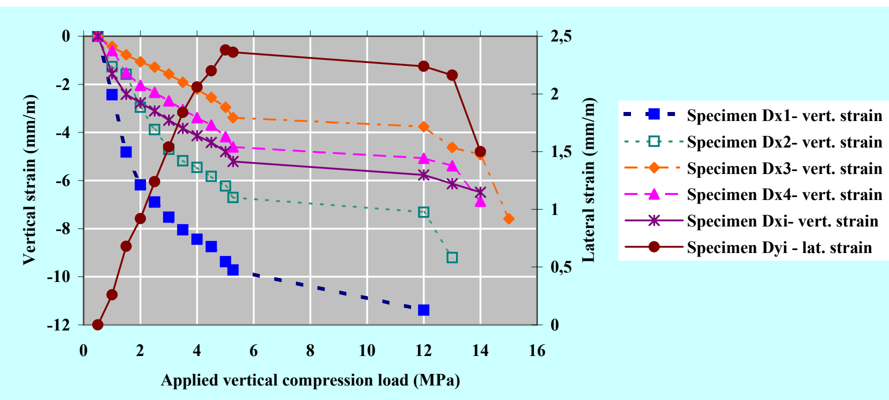


Figure 2 - Vertical and lateral displacements of specimens of Dx series during the triaxial tests, until peak values were obtained (cellular autoclaved concrete specimen with simple joint – Dx series)

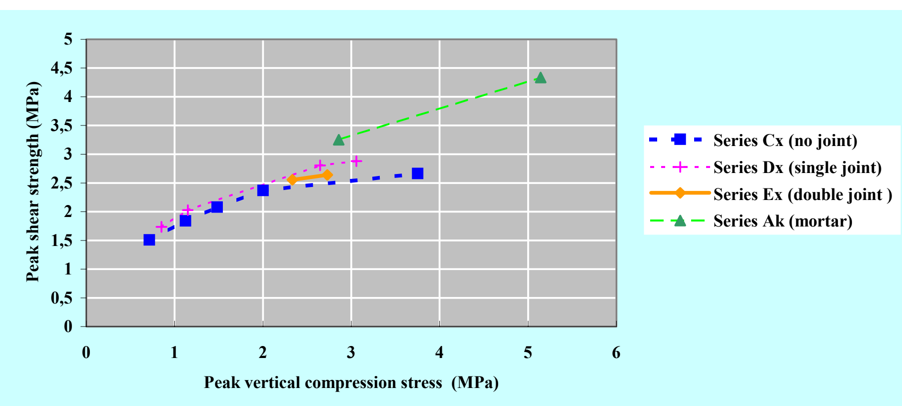


Figure 3 – Failure envelopes of Cx, Dx Ex and Ak series (cellular autoclaved concrete specimens, Cx series, simple joint – Dx series, double joint- Ex series; mortar specimens – Ak series)

The type of failure found for the specimens with lower σ_L/σ_V ratios in the Cx series, was typical of shear failure along approximately a slope plane. For higher values of that ratio, the failure of the specimens was predominantly by crushing. The values of vertical peak pressure load in the Cx series were, generally, slightly larger than those obtained in the Dx and Ex series, due to some extent, to the presence of the mortar joint that presumably may confer more resistance to the specimen (Dx-type and Ey type) than that of the block material alone (Cx-type specimen). This indication was also revealed when comparing the Cx and Ak series results. Failure in the Dx and Ex series resulted in the majority of the cases from local failure of the block material of specimens (in some cases due to shear), and not along the joint plane as would usually be expected from the situation where the mortar joints act as planes of weakness. Comparing the failure envelopes of the Dx and Ex series, it was not possible to detect major differences that could be an expression of the direct influence of two different existing situations - one consisting of the presence of a double orthogonal joint (Ex) and the other of the presence of a single joint (Dx). Comparing the vertical pressure load-vertical deformation curve of the Cxi specimen with those of the Dxi and Exi specimens, a similar trend of progression was detected although with increased values of vertical pressure load in the Dxi and Exi series, some appreciable differences on that progression become evident.

a) Specimens of blocks of lightweight concrete with expanded clay aggregates with and without joints (Cy, Dy, Ey series and additional specimens Cyi, Dyi, Eyi)

In the triaxial compression test on the specimens Cy0, Cy1, Cy2, Cy3, Cy4, Cyi and C´yi (this last specimen was extracted from the block in a perpendicular direction to that of the Cyi) the applied constant σ_L/σ_V ratios were 0.025, 0.05, 0.10, 0.20, 0.30, 0.075, and 0.075 respectively; for specimens Dy1, Dy2, and Dyi, 0.05, 0.10 and 0.075 respectively; for specimens Ey1, Ey2, Ey3 and Eyi, 0.05, 0.10, 0.20, 0.075 respectively (Table 3). After an initial approximately linear phase, the relationship between the vertical deformations and the applied vertical load showed a decreasing slope of the curve with increasing load, especially near the peak value. Failure of Dy-type and Ey-type specimens generally occurred by slipping along the joint, sometimes with local grinding of joint material. In specimens Cy0, Cy1, Cy2, Cy3, Cy4, Cyi and C´yi, failure occurred at vertical pressure loads of 11.5, 5.0 MPa, 6.00 MPa, 6.50 MPa, and 7.00 MPa respectively; for specimens Dy1, Dy2, and Dyi, 2.50 MPa, 5.50 MPa, and 1.50 MPa respectively; for Ey1, Ey2, Ey3, and Eyi 2.50 MPa, 5.00 MPa, 5.00 MPa, and 2.25 MPa respectively (Table 3, Figures 4, 5).

In specimen Dyi failure occurred at peak vertical and transverse deformations of 4.1 mm/m and 0.1 mm/m respectively, and the residual vertical deformation was 22.4 mm/m.

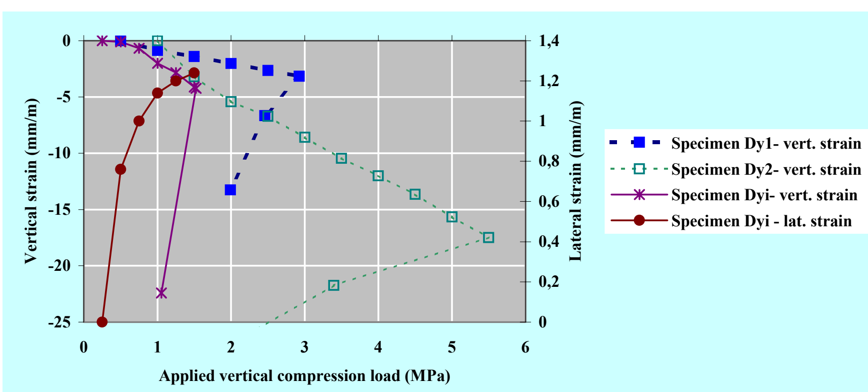


Figure 4 - Vertical and lateral displacements of specimens of Dy series during the triaxial test, until peak values were obtained (lightweight concrete with expanded clay aggregates specimen, simple joint – Dy series)

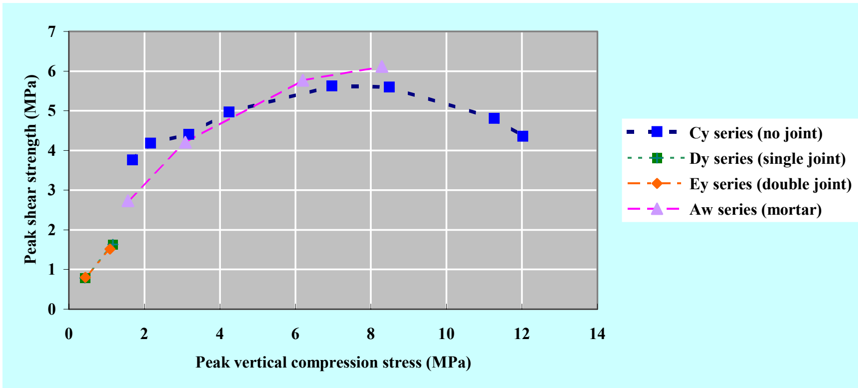


Figure 5– Failure envelopes of Cy, Dy, Ey and Aw series (light-weight concrete with expanded clay aggregates specimens, Cy series, simple joint – Dy series, and double joint – Ey series; mortar specimens – Aw series)

Contrary to what was observed in the Cx, Dx and Ex series, the results of the tests on the Cy, Dy and Ey series showed values of the resistance to triaxial compression of the block material to be higher than those obtained from the mortar specimen series (Aw) or from specimens with joints, as can be confirmed through the respective failure envelope curves (Fig. 5). The failure along the joints by slipping and local grinding in these series confirmed the individual results of the Cy and Aw series, where the higher values of the block resistance, when compared with those of the mortar, were evident.

c)specimens of solid clay bricks with and without joints (Cz, Dz, Ez series and additional specimens Czi, Dzi, Ezi)

In the triaxial compression tests on specimens Cz1, Cz2, Cz3, Cz4, Czi and C´zi, the applied constant ratio σ_L/σ_V values were 0.05, 0.10, 0.20, 0.30 and 0.075 respectively; for specimens Dz1, Dz2, Dz3, and Dzi, 0.05, 0.10, 0.20, and 0.075; and for specimens Ez1, Ez2, and Ezi, 0.05, 0.10 and 0.075 (Table 3). C´zi differs from Czi in the direction of extraction of the cylindrical specimen being parallel to bed joint direction of the brick, and normal to that of Czi.

In specimens Cz1, Cz2, Cz3, Czi and C´zi, failure occurred for vertical pressure loads of 27.50 MPa, 32.50 MPa, 42.50 MPa, 62.50 MPa, 52.50 MPa, 57.50 MPa respectively (values much higher than those of Cx and Cy series); for specimens Dz1, Dz2, Dz3, and Dzi, 2.75 MPa, 2.75 MPa, 13.50 MPa and 3.00 MPa respectively; and for specimens Ez1, Ez2, and Ezi, 4.00 MPa, 6.00 MPa and 6.25 MPa respectively (Table 3, Figures 6 and 7).

Failure of Dz-type and Ez-type specimens generally occurred by slipping along the joint, occasionally with local grinding of joint material (similar to Dy-type and Ey-type specimens). In specimen Dzi failure occurred at a peak vertical deformation of 11.3 mm/m and a residual vertical deformation of 15.4 mm/m.

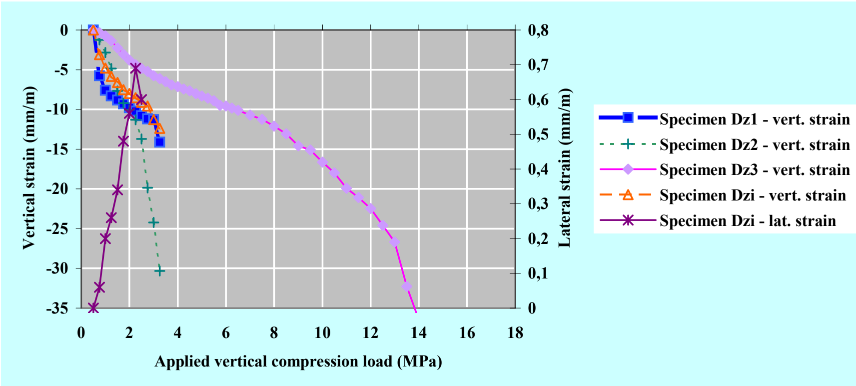


Figure 6 - Vertical and lateral displacements of specimens of Dz series during the triaxial test, until peak values were obtained (solid clay bricks specimens, simple joint – Dz series)

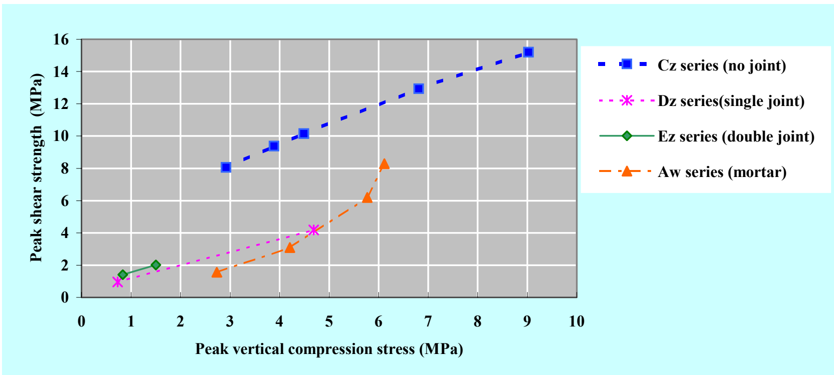


Figure 7 – Failure envelope of Cz, Dz, Ez and Aw series (solid clay bricks specimens, Cz series, simple joint – Dz series, and double joint- Ez series, mortar specimen – Aw series)

Here, a similar pattern to that of Cy, Dy and Ey was observed for the relation between the resistance to triaxial compression of the block material and the mortar joints (these last clearly less resistant than the former ones). In the Dz and Ez series, early failure and low values of peak vertical deformation were detected, when compared to those of the Cz series, which indicates that failure was more or less ruled by the relative weak character of the mortar material.

Shear strength and shear modulus

From the tests results, average stress-strain curves were derived and a Coulomb type failure criterion for the block and mortar materials and the mortar joints was approximately obtained (estimated values of initial shear strength (cohesion), f_{bvko}, and of friction coefficient tan φ, maximum and residual value from regression analysis of tests - Table 3). The relationship between the shear strength and the applied constant normal load in the the triaxial tests (Cx, Dx, Ex, Cy, Cz, Dx, Dy, Dz, Ez series) as well as the corresponding linear best fit was computed, and a tentative interpretation of the results with the relation of Mohr-Coulomb was made:

$\tau_u = f_{vko} + \sigma_d \tan(\varphi)$; where f_{vko} – initial shear strength; σ_d – normal stress in the bed joints; tan (φ) – tangent of internal friction angle.

The initial shear strength (cohesion), f_{bvko}, obtained from linear regression of the triaxial test results of Dx, Ex, Dy, Ey, Dz, Ez were, respectively, around 0.89 MPa, 1.90 MPa, 0.30 MPa, 0.32 MPa, 0.36 MPa, 0.67 MPa. These values can not be considered totally reliable due to uncertainties related to the influence of local effects near the ends of the mortar joint specimens during the triaxial tests, and the limited number of specimens tested in each series, particularly regarding the need to obtain low values of peak vertical loads (for extrapolation to zero). Considering carefully these limitations, it seems possible from the calculated results (Figs. 3, 5 and 7), to observe that the values of peak shear strength (and the associated failure envelope, for the range of normal stress applied in each series) show some dependence on the type of units (material X, Y or Z), and the mortar used in the joints. Shear modulus ($G=0,5.[\sigma_V - \sigma_L]/[\varepsilon_V - \varepsilon_L]$), was calculated for the specimens where lateral displacements were recorded, Cxi, Cyi, Czi, Aki, and Awi.

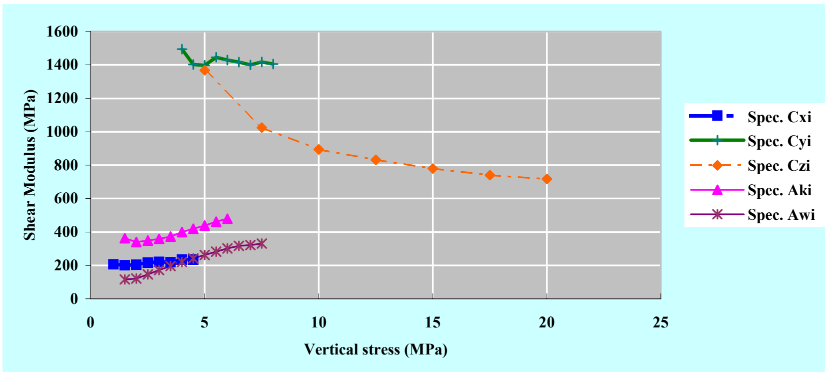


Figure 8 – Shear modulus, G, versus vertical pplied stress for specimens Cxi, Cyi, Czi, Aki and Awi

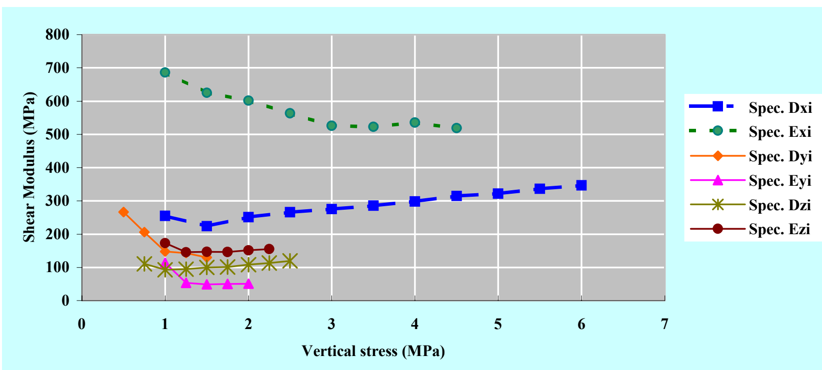


Figure 9– Shear modulus, G, versus vertical applied stress for Dxi, Dyi, Dzi, Exi, Eyi, Ezi, (specimens with joints)

Analyzing the results (Figures 8 and 9), the shear modulus apparently shows some dependence on the type of specimen material and a tendency, in certain series, to increase with axial applied stress.

Table 3 – Summary of triaxial test results series Cx, Dx, Ex, Ak, Cy, Dy, Ey, Aw, Cz, Dz, Ez

Série	Dimensions of Specimens (Cylindrical)			Test initial parameters					Maximum & residual strain				Maximum & residual axial stress			Maximum & residual lateral stress		Poisson Coefic., Shear modulus, Cohesion, and friction angle			
	Diameter, height (mm)		Vert. S (cm^2)	Rel. ó$_R$/ó$_V$	Initial pressure applied (zero of deformations readings) Vertical		Lateral		Vertical mm/m (10^{-3})		Lateral * mm/m (10^{-3})		σ_V (rel. max, resid.) (MPa)**		Mode/ descr. of failure	σ_L (MPa)		Poisson Coef. Shear modulus G (MPa)		Cohesion C_s (MPa) friction angle φ_s (degree)	
	Diam.	Heig.			σ_V (bar)	σ_V (MPa)	σ_L (bar)	σ_L (MPa)	ε_V max	ε_V resid.	ε_L max	ε_L resid.	σ_V max	σ_V res.		σ_L max.	σ_L res.	μ	G	C_s	φ_s
Cx1	52.5	100	21.65	0.05	4.27	0.50	0.25	0.025	3.52	7.87	-	-	5.00	2.46	s (3c)	0.25	-	-	-	0.92	39
Cx2	52.5	100	21.65	0.10	17.1	2.00	0.49	0.05	10.80	22.68	-	-	6.00	-	s (3a)	0.60	-	-	-		
Cx3	52.5	100	21.65	0.20	4.27	0.50	0.98	0.10	6.03	6.93	-	-	6.50	4.57	c (1d)	1.30	1.52	-	-		
Cx4	52.5	100	21.65	0.30	4.27	0.50	2.96	0.15	8.40	11.54	-	-	7.00	6.21	-	2.10	1.42	-	-		

	Dimensions of Specimens (Cylindrical)			**Test initial parameters**					**Maximum & residual strain**				**Maximum & residual axial stress**			**Maximum & residual lateral stress**		**Poisson Coefic., Shear modulus, Cohesion, and friction angle**			
					Initial pressure applied (zero of deformations readings)																
Cxi	52.5	100	21.65	0.075	4.27	0.50	0.37	0.038	9.07	14.75	4.74	-	6.00	3.75	-	0.45	0.49	0.14	832		
Dx1	52.5	100	21.65	0.025	4.27	0.50	0.12	0.013	9.37	11.38	-	-	5.00	1.99	s-r (4b)	0.13	0.14	-	-	0.89	44
Dx2	52.5	100	21.65	0.05	4.27	0.50	0.25	0.025	7.31	9.21	-	-	6.00	2.58	s (3d)	0.30	0.24	-	-		
Dx3	52.5	100	21.65	0.10	4.27	0.50	0.49	0.05	4.62	7.59	-	-	6.50	3.63	c (1d)	0.65	0.66	-	-		
Dx4	52.5	100	21.65	0.20	4.27	0.50	0.98	0.10	5.08	6.86	-	-	6.00	4.68	c (1d)	1.20	0.58	-	-		
Dxi	52.5	100	21.65	0.075	4.27	0.50	0.37	0.038	5.77	6.49	2.74	1.50	6.00		-	0.45	0.49	0.12	869		
Ex1	52.5	100	21.65	0.025	4.27	0.50	0.12	0.013	8.02	10.06			5.50	2.81	s-r (3d)	0.14	0.16	-	-	1.90	25
Ex2	52.5	100	21.65	0.05	4.27	0.50	0.25	0.025	6.96	10.05			5.50	2.11	-	0.28	0.29	-	-		
Ex3	52.5	100	21.65	0.10	12.81	1.50	0.49	0.15	4.91	18.59			6.00	5.97	c (1d)	0.60	0.70	-	-		
Exi	52.5	100	21.65	0.075		0.50	0.37	0.038	4.72	6.84	2.56	15.5	6.00	3.04	s-r (4a)	0.45	0.47	0.11	925		
Ak1	52.5	100	21.65	0.05	4.27	0.50	0.25	0.025	7.04	11.00	-	-	8.00	7.61	s (3a)	0.40	0.40	-	-	-	-
Ak2	52.5	100	21.65	0.10	4.27	0.50	0.49	0.05	6.00	12.43	-	-	8.00	7.61	c (1c)	0.80	0.86	-	-		
Ak3	52.5	100	21.65	0.20	4.27	0.50	0.98	0.10	10.29	27.6	-	-	12.00	13.93	c (1c)	2.40	2.76	-	-		
Ak4	52.5	100	21.65	0.30	12.81	0.50	1.47	0.15	6.90	17.97	-	-	12.00	14.52	c (1c)	3.60	3.84	-	-		
Aki	52.5	100	21.65	0.075	8.54	0.50	0.37	0.038	11.13	18.79	0.86	1.95	11.00	11.47	s (3b)	0.83	1.00	0.10	1410		
Ak0	52.5	100	21.65	0.025	4.27	0.50	0.12	0.013	4.05	7.03			11.50	10.89	s-r (4b)	0.29	0.34				
Cy1	52.5	120	21.65	0.05	4.27	0.50	0.25	0.025	10.25	11.54	-	-	10.50	4.80	s-r (4a)	0.53	0.58	-	-	2.26	42
Cy2	52.5	120	21.65	0.10	4.27	0.50	0.49	0.05	2.76	3.58	-	-	12.50	4.45	s (3c)	1.25	1.28	-	-		
Cy3	52.5	120	21.65	0.20	4.27	0.50	0.98	0.10	6.33	11.10	-	-	14.00	3.86	s (3c)	2.80	2.89	-	-		
Cy4	52.5	120	21.65	0.30	4.27	0.50	2.96	0.30	5.74	7.83	-	-	14.50	10.65	c (1a)	4.35	4.42	-	-		
Cyi	52.5	120	21.65	0.075	4.27	0.50	0.37	0.038	2.57	3.40	0.64	0.85	12.00	5.50	s-r (4d)	0.90	0.82	0.13	4920		
C'yi	52.5	120	21.65	0.075	4.27	0.50	0.37	0.038	5.60	6.41			12.50	4.80	-	0.94	0.56	-	-		
Cy0	52.5	120	21.65	0.025	4.27	0.50	0.13	0.013	5.71	7.43			11.50	3.28	-	0.28	0.04	-	-		
Dy1	52.5	120	21.65	0.05	4.27	0.50	0.25	0.025	3.15	13.25	-	-	2.50	2.47	s (2b)	0.13	0.17	-	-	0.30	49
Dy2	52.5	120	21.65	0.10	8.54	1.00	0.49	0.10	17.49	21.75	-	-	5.50	3.40	s-r (2c)	0.55	0.70	-	-		
Dyi	52.5	120	21.65	0.075	2.14	0.25	0.19	0.018	4.12	22.42	0.12	0.12	1.50	1.05	s-r (2e)	0.11	0.15				
Ey1	52.5	120	21.65	0.05	8.54	1.00	0.25	0.05	5.19	10.53	-	-	2.50	2.58	s (2d)	0.13	0.17	-	-	0.32	48
Ey2	52.5	120	21.65	0.10	4.23	0.50	0.49	0.05	6.80	10.56	-	-	5.00	3.51	s (2d)	0.50	0.65	-	-		
Ey3	52.5	120	21.65	0.20	8.54	0.50	0.98	0.10	10.30	12.56	-	-	5.00	3.51	s (2d)	1.00	0.32	-	-		
Eyi	52.5	120	21.65	0.075	4.23	0.50	0.37	0.038	17.13	21.26	1.65	-	2.25	2.22	s (2d)	0.17	0.21				
Aw1	52.5	100	21.65	0.05	4.27	0.50	0.25	0.025	7.86	8.18	-	-	10.00	9.50	s-r (4c)	0.50		-	-	1.23	44
Aw2	52.5	100	21.65	0.10	4.27	0.50	0.49	0.05	6.50	10.13	-	-	8.50	7.70	s-r (4c)	0.85		-	-		
Aw3	52.5	100	21.65	0.20	4.27	0.50	0.98	0.10	10.12	13.42	-	-	13.00	12.60	s-r (4d)	2.60		-	-		
Aw4	52.5	100	21.65	0.30	4.27	0.50	1.47	0.15	16.03	26.70	-	-	15.50	13.00	c (1b)	4.65		-	-		
Awi	52.5	100	21.65	0.075	4.27	0.50	0.37	0.038	10.89	19.26	-	-	8.00	7.7	s (3a)	0.60		-	-		

	Dimensions of Specimens (Cylindrical)			**Test initial parameters**					**Maximum & residual strain**				**Maximum & residual axial stress**			**Maximum & residual lateral stress**		**Poisson Coefic., Shear modulus, Cohesion, and friction angle**			
					Initial pressure applied (zero of deformations readings)																
Aw0	52.5	100	21.65	0.025	4.27	0.50	0.13	0.013	10.89	14.35	-	-	8.00	7.6	s (3a)	0.20		-	-		
Cz1	52.5	105	21.65	0.01	21.4	2.50	0.25	0.025	13.35	18.99	-	-	27.50	11.71	c (1a)	0.28	0.27	-	-	4.09	54
Cz2	52.5	105	21.65	0.025	21.4	2.50	0.62	0.063	18.94	27.06	-	-	32.50	21.43	c (1a)	0.81	1.17	-	-		
Cz3	52.5	105	21.65	0.05	21.4	2.50	1.24	0.125	25.34	27.06	-	-	42.50	35.71	c (1c)	2.13	2.01	-	-		
Cz4	52.5	105	21.65	0.10	21.4	2.50	2.47	0.250	36.19	36.73	-	-	62.50	57.60	c (1c)	6.25	5.23	-	-		
Czi	52.5	105	21.65	0.075	21.4	2.50	1.85	0.188	40.05	40.74	4.34		52.50	28.10	c (1c)	3.94	2.99	0.17	457		
C'zi	52.5	105	21.65	0.075	21.4	2.50	1.85	0.188	17.40	23.38	-	-	57.50	43.55	-	4.31	3.77				
Dz1	52.5	105	21.65	0.05	4.27	0.50	0.25	0.025	11.26	14.10	-	-	2.75	1.29	s (2b)	0.14	0.16	-	-	0.36	39
Dz2	52.5	105	21.65	0.10	4.27	0.50	0.49	0.05	19.88	30.33	-	-	2.75	2.46	s (2e)	0.28	0.35	-	-		
Dz3	52.5	105	21.65	0.20	4.27	0.50	0.98	0.10	32.29	52.22	-	-	13.5	13.82	s (2b)	2.70	2.60	-	-		
Dzi	52.5	105	21.65	0.075	4.27	0.50	0.37	0.038	11.28	15.37	-0.06		3.00	2.46	s (-)	0.23	0.28				
Ez1	52.5	100	21.65	0.05	4.27	0.50	0.25	0.025	13.25	16.70	-	-	4.00	2.70	s (2d)	0.20	0.13	-	-	0.67	42
Ez2	52.5	100	21.65	0.10	4.27	0.50	0.49	0.05	9.16	11.33	-	-	6.00	4.80	s (2d)	0.60	0.24	-	-		
Ezi	52.5	100	21.65	0.075	4.27	0.50	0.25	0.038	13.04	19.92	-0.07		6.25	7.14	s (2d)	0.47	0.53				

* The test of specimens Cxi, Cyi, Czi, Aki, Awi, Dxi, Dyi, Dzi , Exi, Eyi, Ezi included the recording of vertical deformations (common for all specimens) and lateral deformations (Cx,y,z e Ak – horizontal direction; Dx,y,z e Ex,y,z series– normal to the principal diagonal joint);
**Readings of residuals deformations are generally in correspondence with residuals values of vertical and lateral pressure load ;
*** symbols: c – crushing; s – splitting; s- r – splitting and cracking in tension

Description of the type of failure

Type of failure 1 (crushing)	1a - Slight crushing without clear desegregation
	1b – Crushing near the base of the specimen with material desegregation
	1c – Crushing of the specimen with formation of a central internal wedge and slashed aspect
	1d – Crushing of the specimen with formation of a internal wedge near the base of the specimen
Type of failure 2 (slipping)	2a - Slight slipping along the diagonal joint, associated with significant deformation, but without a clear separation between the mortar and the block material
	2b - Slipping along the diagonal joint with a clear separation between the mortar and the block material
	2c - Slipping along the diagonal joint with cracking and fracture of the specimen near the base
	2d - Slipping along the double joints with a clear separation between the mortar and the block material
	2e - Slight slipping along the diagonal joint, but without a clear separation between the mortar and the block material, and fracture of the specimen near the base
Type of failure 3 (slipping)	3a - Slipping along a shear plane all the way through the base of the specimen
	3b - Slipping along a shear plane all the way through the base of the specimen, with crushing of the material
	3c - Slipping along a slightly inclined shear plane centrally located in the specimen
	3d - Slipping and cracking along an irregular surface far from the joint
Type of failure 4 (cracking)	4a - Cracking or fracture approximately in a horizontal plane near the two bases of the specimen
	4b - Cracking or fracture approximately in a horizontal plane near the one base of the specimen
	4b - Cracking or fracture approximately in a horizontal plane near the one base of the specimen with formation of a internal wedge
	4a – Slight cracking of the specimen

FINAL CONSIDERATIONS

From the results of the experimental study on materials X, Y and Z it can be concluded that the level of the biaxial compression ratio (σ_L/σ_V) applied to the specimens with joints, in the triaxial compression tests significantly influences the deformation behaviour and the failure modes of the joints. The results of these tests suggests that if the compressive stress is high, the residual shear stiffness can be estimated from the final slope of the shear stress-shear strain curve obtained in triaxial compression tests on blockwork couplets that incorporate a mortar joint. An increase in the joint peak shear strength was generally detected with increasing σ_L/σ_V ratio for series with joints. For the series of specimens with joints, an approximate linear relationship (Coulomb law) could be established between normal applied stress and joint peak shear strength for low levels of normal applied force in the specimens, but the limited number of specimens in each series does not allow representative and definite conclusions to be drawn.

These results indicate that the joint elements have relatively high compression capacity, and a shear capacity which is a function of the imposed compression and the bond strength. Finally, from the results of the experimental tests it can be inferred that the behaviour of the joints, when subjected to biaxial compression, are significant for the overall wall behaviour.

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