Poisson Behaviour of Bedding Mortar Under Multiaxial Stress State

by

G MOHAMAD[1], P B LOURENCO[2] and H R ROMAN[3]
[1] PhD Student of Civil Engineering department of Minho University, CAPES-MEC-UNIVALI-UNESC,
Azurém- Postal Code: 4800-058, Guimarães-Portugal
[2] Associate Professor- Civil Engineering department of Minho University –
Azurém- Postal Code: 4800-058, Guimarães-Portugal
[3] Professor- Civil Engineering department of Federal University of Santa Catarina,
Postal Code: 88049-900, Florianópolis-Brazil

ABSTRACT

The main goal of this work is to understand the tri-axial compression capacity of joint mortar through the Poisson behaviour. The conclusions drawn from the present study are the following: the behaviour of stress-strain diagram is strongly non-linear and depends on the increase of lateral stress. In all studies present here, the ultimate strength envelope can be represented by a linear function in the p-q plane and the angular coefficient is quite similar. The initial elasticity modulus of confined mortar decreases with the increase in the confining stress for mortar type 1:1:6 in studies of KHOO [1] and MOHAMAD [3], in opposition with the results from ATKINSON and NOLAND [2]. All authors observed a significant reduction in Poisson ratio of mortar when the confined stress increases. Apparently this decrease shows to be exponential for mortars types 1:1:6 and 1:2:9 and linear for mortars type 1:1/4:3 and 1:1/2:4.5. A simple model is proposed to represent the modification of Poisson ratio throughout the normalized stress range.

NOTATION

f_m^* = ultimate confinement compressive strength.
f_m = uniaxial compressive strength of mortar.
σ_3 = confinement stress.
σ_1 = vertical stress.
K = relation between σ_3 and σ_1.
β = non-linearity ratio.
ν^a = Poisson ratio.
ν_i^a = initial Poisson ratio.
ν_f^a = final Poisson ratio.

1. INTRODUCTION

When masonry is submitted to a vertical load, a number of joint phenomena arise between the unit and the mortar which induce lateral tension and compression as shown in Figure 1. Few analyses for the modification of mechanical properties of mortar associated to failure mode for masonry have been found in the literature. Previous numerical simulations used the elasticity modulus and the Poisson ratio obtained from uni-axial tests and the material non-linearity is taken into account by using secant module obtained for a stress level of 60% of strength.

The mortar behaviour is important to understand the failure criterion of the assembly (if it occurs by tensile stress or by crushing of bedded mortar). The main goal of this work is to discuss mechanical properties under confined stress obtained from experimental tests such as elasticity module, Poisson ratio and the compressive strength. This becomes the first step towards a future model to represent the behaviour of masonry.

2. STUDIES DEVELOPED BY KHOO [1]

KHOO [1] was the first author to verify the behaviour of mortar under tri-axial stress. Two types of mortar were studied, which were designed by volume ratio for each material. The types of mortar were 1:1/4:3 and 1:1:6, the water/cement ratio was 0.64 and 1.29 respectively. Specimens, 38mm diameter x 102mm high, were cast in steel moulds. Table 1 presents the envelope failure of tri-axial tests in mortar from different confinement pressure.

A line equation was the best fit that represented the failure envelope of the confined mortar. Tests carried out by KHOO [1] point out that it is difficult to maintain lateral stress because there are changes in the volume of the specimens. The cube strength was much greater than the corresponding cylinder strength, and was about 1.4 times higher for both mixes. The magnitude of the initial tangent modulus was constant for the 1:1/4:3 mortars and decreased with increased lateral stress for the 1:1:6 mortars. The initial value of Poisson ratio decrease with increase of lateral stress for the 1:1/4:3 and 1:1:6 mortars. Poisson ratio decrease quite slowly for the 1:1/4:3 mortar and dropped quickly for the 1:1:6 mortar as show in Figure 2.

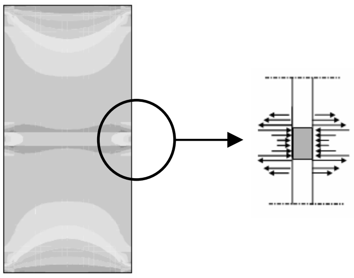

Figure 1 Horizontal stress level developed in block/mortar assemblies

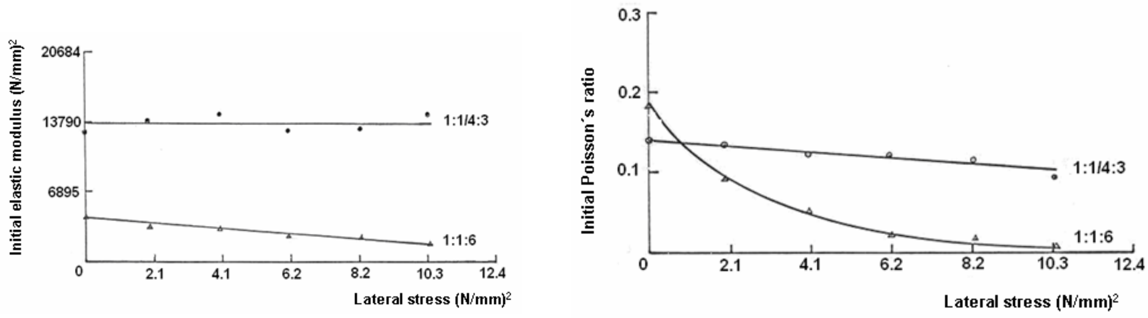

Figure 2 Initial elastic modulus and Poisson ratio under lateral stress

Table 1
Envelope failure of mortar

Mortar type	Envelope of failure
1:1/4:3	$f_m^*=f_m + 3.4\sigma_3$
1:1:6	$f_m^*=f_m + 2.3\sigma_3$

Table 2
Physical and mechanical characteristics of mortar studied by ATKINSON and NOLAND [2]

Type	Uniaxial comp. strength (N/mm^2)	a/c	Lateral stress (N/mm^2)
1:1/4:3	32.6	0.55	0.21; 0.69; 1.72; 3.44; 6.88; 10.31
1:1/2:4.5	26.4	0.85	“
1:1:6	13.7	1.19	“
1:2:9	3.4	1.96	“

Table 3
Envelope failure of mortar

Mortar type	Envelope of failure
1:1/4:3	$f_m^*=f_m + 5\sigma_3$
1:1/2:4.5	$f_m^*=f_m + 3\sigma_3$
1:1:6	$f_m^*=f_m + 2\sigma_3$
1:2:9	$f_m^*=f_m + 2\sigma_3$

3. STUDIES DEVELOPED BY ATKINSON E NOLAND [2]

ATKINSON and NOLAND [2] have done tri-axial tests on four types of mortar with six different levels of confined pressure. Physical and mechanical characteristics of different types of mortar are shown in Tables 2 and 3 which show the failure envelope of mortar under tri-axial compression.

There is a straight linear relationship between the confined strength and the confined stress as show in Figure 3. The stress-strain behaviour of each mortar was nonlinear at all the confining pressures used and clearly shows that there is a transition between brittle type behaviour to ductile type behaviour for different level of confinement stress as shown in Figure 3. The stress-strain diagram of 1:1/2:4.5 mortar shows a fragile behaviour for stress levels of 0.2, 0.7 and 1.7N/mm^2, while ductile behaviour is shown for stress levels of 3.45, 6.9 and 10.9N/mm^2. The stress-strain diagram of 1:1:6 mortar shows a fragile behaviour for stress levels of 0.2 and 0.7N/mm^2, ductile behaviour is show for a stress level of 1.7N/mm^2, while for the other stress levels a bilinear behaviour is shown.

Lateral stress has influenced the stress-strain diagrams and marked differences in behaviour were detected. There are three behaviour types for stress-strain diagrams: brittle, ductile and bilinear. Bilinear behaviour was characterized by a continuous increase of stress and strain. Authors affirm that 1:1:6 and 1:2:9 mortars exhibited bilinear behaviour at high confining pressures. This may indicated that the behaviour changes are caused by the collapse of the internal structure of the mortar and this rearrangement of the grains modifies the stable configuration of the materials, although the bearing capacity of the mortar was sometimes unaffected. Figure 4 shows the elastic modulus and Poisson ratio of mortar under tri-axial compression for 1:1/2:4.5 mortar types.

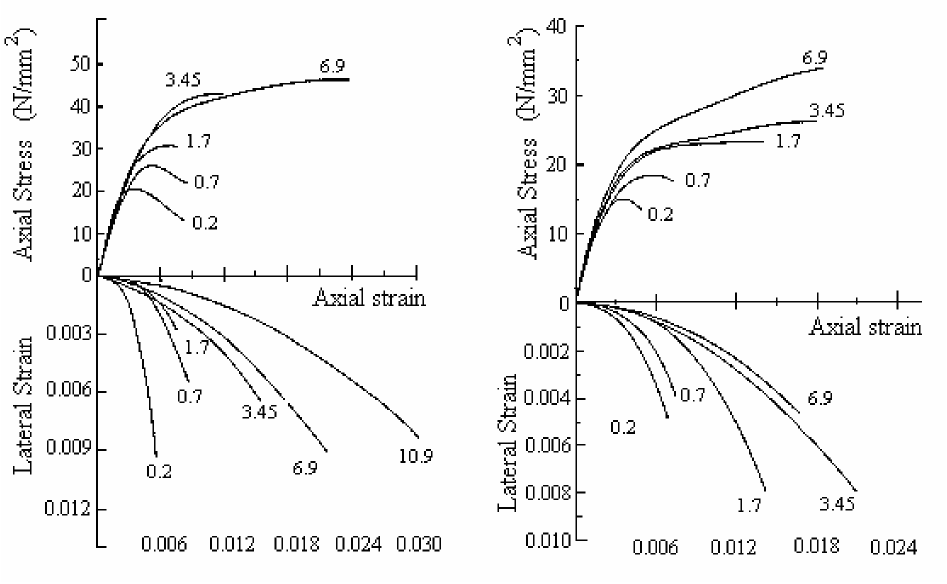

Figure 3 Axial stress and lateral strain diagram for 1:½:4.5 and 1:1:6 mortars

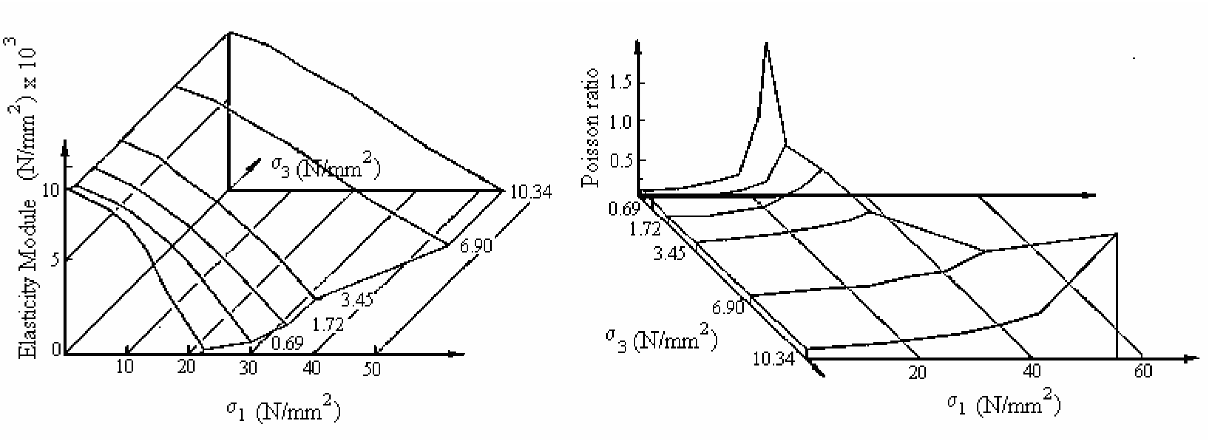

Figure 4 Elastic moduluse and Poisson ratio of mortar under tri-axial compression for 1:½:4½ mortar

4. STUDIES DEVELOPED BY MOHAMAD [3]

MOHAMAD [3] carried out a series of tests on mortar samples in a state of tri-axial compression and obtained the envelope of failure for 1:1/4:3, 1:1/2:4.5, 1:1:6 mortars as show in Table 4.

Increasing lateral stress led to an increase in the mortar strength, the failure envelope of which was similar to a Mohr-Coulomb envelope. The correlation coefficient of the relationship between confined stress and compressive strength was 0.99. Figure 5 shows the change of the elastic modulus with increase of confined stress. For 1:1/4:3 and 1:1/2:4.5 mortars, it is observed that with increase of confined stress the initial tangent modulus increases also, and for 1:1:6 mortar there is a decrease of the initial elastic modulus. Table 5 shows the experimental results for Poisson ratio.

5. POISSON VARIATION OF MORTAR UNDER CONFINING STRESS

The failure mechanisms of masonry are caused by the difference in stiffness of the mortar and the masonry units. The mortar, being softer than the units, is confined laterally, giving rise to lateral tension in the units and lateral compression in the mortar. Describing the Poisson ratio behaviour during the loading process is a rather difficult task due the variability of results; but it is required in numerical simulations. Nowadays, the use of a constant value for the Poisson ratio during the load cycle which does not represent the change in volume due the confined stress is conservative. As shown by KHOO [1], ATKINSON and NOLAND [2] and MOHAMAD [3], the failure of assemblies are caused in compression by the initiation and propagation of cracks, which sometimes start in mortar due the high porosity and different sizes of voids. Probably there is a decrease in volume caused by closing of flaws and voids, after this the Poisson ratio increases significantly until failure. The crack initiation occurs when material cohesion reaches a stress level enough to break the intermolecular bond.

The cohesive strength of masonry should be analysed by two modes: the loss of adherence between the interfaces of the materials and the pore-collapse of internal structure caused by crushing of the mortar. Knowledge of the configuration and distribution of internal structures is limited. Thus, to prove and comprehend this microstructure phenomenon, and in consequence the internal architecture of the materials, tests are needed using scanning electron microscopy.

Table 4
Envelope failure of mortar

Mortar type	Envelope of failure
1:1/4:3	$f_m^*=f_m+4\sigma_3$
1:1/2:4.5	$f_m^*=f_m+3.6\sigma_3$
1:1:6	$f_m^*=f_m+2.6\sigma_3$
1:2:9	$f_m^*=f_m+2.5\sigma_3$

Table 5
Poisson ratio of confined mortar

Type	**Lateral stress (N/mm^2)**	**Poisson ratio**	
		Initial stress level	**Final stress level**
1:1/4:3	0, 0.5, 1	0.20	0.20
	2.5	0.10	0.10
1:1/2:4.5	0	0.10	0.14
	1	0.13	0.17
	2.5	0.09	0.24
1:1:6	0	0.10	0.37
	0.5	0.07	0.11
	2.5	0.05	0.09
	4	0.02	0.09
1:1:6	0	0.17	0.14
	0.5	0.04	0.17
	1	0.05	0.07

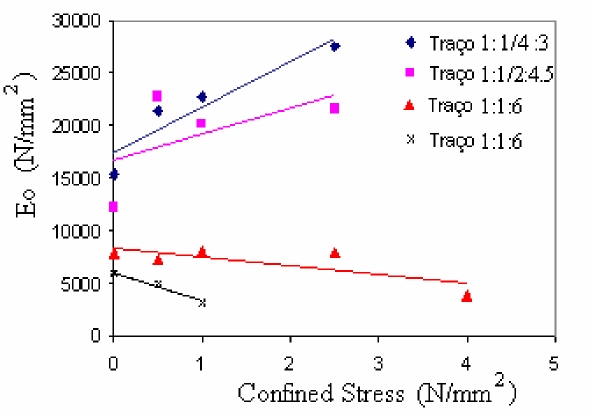

Figure 5 Relation between initial tangent modulus and confined stress

The pore-collapse is a phenomenon that could only be identified by scanning electron microscopy, where the material surface is scanning by electron beam. DIAMOND [4] presented an investigation using scanning electron microscopy carried out on 28 day old mortars with sand contents in excess of 48% by volume. It is possible to verify the uniform grey sand grains, the extensive areas of bright, dense, hardened cement paste and the smaller areas of porous, darker hardened cement paste. It is noted that pore size is up to 15μm in length. Most of large pores appear to be interconnected.

Concerning the investigation of DIAMOND [4], it is possible to conclude that the high porosity of mortar and the state of stress could modify some mechanical properties such as the elastic modulus and Poisson ratio. The porosity of mortar depends of its composition, water/cement ratio, maximum diameter and the grain size distribution of the sand. Specifics studies would have to be done to evaluate the influence of cement and lime percentages in porosity and in the range of grains of mortar. These considerations allow an understanding of the pore-collapse phenomenon and explain the decrease of Poisson ratio when there is an increase lateral stress for the 1:1:6 and 1:2:9 mortars.

Tri-axial tests have been carried out by HAYEN et al. [5] on historical mortars including putty lime mortar, hydraulic lime mortar, lime-cement mortar the compressive strength of which was 1.85N/mm^2. The relationship between horizontal stress and vertical stress (k) change throughout the test in which the k ratio was 0, 0.05, 0.10, 0.15, 0.25, 0.5, 0.75 and 1. The authors assess the influence of the test conditions on the pore structures of mortar by total pore volume through vacuum submersion and the analyses of the pore structure by means of mercury intrusion and scanning electron microscopy.

The multi-axial stress analyses by HAYEN et al. [5] lead to the following conclusion: volumetric strains under tri-axial loads show for $k < 0.25$ shear failure mechanisms, whereby a decrease in volume of the specimens occurs at the beginning, probably due to the internal closing of existing cracks and flaws. After this, an increase in volume was observed when shear bands develop. The collapse of the mortar sample occurred along diagonal shears bands: for $k \geq 0.25$, the failure mechanisms in mortar samples are rather distinct and were characterized by a straight decrease in the volume of the samples. Thus, with this evidence it is easy to conclude that pore-collapse occurs at $k \geq 0.25$.

A constitutive model to represent the non-linear elasticity of high strength concrete was proposed by OTTOSEN [6]. The model consists in establishing steps for the Poisson ratio as a function of the non-linearity rate, β (stress versus strength ratio). When β reach the value of β_1, the Poisson ratio starts to increase significantly. The initial Poisson ratio was constant until it reached β_1 after which there is a significant increase in Poisson ratio until failure occurs, as shown in Figure 6. In high strength concrete (60 to 120N/mm^2), the lateral stresses do not have a great influencing on the Poisson ratio until failure occurs because the lateral stress reaches only 10 to 20% of ultimate strength and this is not sufficient to modify the Poisson ratio. The range of strengths of mortars used for bedding masonry is lower than that of concrete and depends on the type of masonry unit. The strength of mortar ranges from 2 to 10N/mm^2. For this, the lateral stress increases to reach a proportion of between 50 and 100% of the ultimate strength of the specimen.

Equations that represent the Poisson behaviour proposed by OTTOSEN [6] are shown in Equations (1) and (2).

$$\nu^a = \nu_i^a \qquad \text{if, } \beta \le \beta_1, \qquad (1)$$

$$\nu^a = \nu_f^a - (\nu_f^a - \nu_i^a).\sqrt{1 - \left(\frac{\beta - \beta_1}{1 - \beta_1}\right)} \qquad \text{if, } \beta > \beta_1 \qquad (2)$$

In the meantime, through experimental tests done by KHOO [1], ATKINSON and NOLAND [2], MOHAMAD [3] and HAYEN et. al. [5] it is possible to verify the modification of Poisson ratio under an increase of lateral stress. Thus, a generalized model of OTTOSEN [6] is proposed to represent the modification of Poisson ratio as shown in Figure 7. For case "*a*" the Poisson behaviour decreases until it reaches β_1 and than gently increases until collapse, in which shear failure mechanism develops. For case "*b*", the Poisson behaviour decreases until it reaches β_1 and then increases quite suddenly due the pore collapse, the lost of cohesive grain and the closing of cracks. The dotted line is an Ottosen model modification and depends of the physical characteristics such as porosity and cement content.

Equations (3) and (4) represent the change in Poisson behaviour of mortar under tri-axial compression for case *a*, as shown in Figure 7.

$$\nu^a = (\nu_i^a).e^{-\beta} \qquad \text{if, } \beta \le \beta_1, \qquad (3)$$

$$\nu^a = \nu_f^a - (\nu_f^a - \nu_i^a).\sqrt{1 - \left(\frac{\beta - \beta_1}{1 - \beta_1}\right)} \qquad \text{if, } \beta > \beta_1 \qquad (4)$$

Equations (5) and (6) represent the change in Poisson behaviour of mortar under tri-axial compression for case *b*, as shown in Figure 7.

$$\nu^a = (\nu_i^a).e^{-\beta} \qquad \text{if, } \beta \le \beta_1, \qquad (5)$$

$$\nu^a = (\nu_i^a).e^{\beta} \qquad \text{if, } \beta > \beta_1 \qquad (6)$$

Figure 8 shows an example of the changes in Poisson ratio as a function of β, whose value was obtained from Equations (5) and (6). When β = 0.8, there is an abrupt increase in the Poisson ratio and this causes a volume change (branch 1). The cohesive loss of mortar arises suddenly and increases the tensile stress in the unit. The branch 1 is characterized by a straight reduction of the value of Poisson ratio.

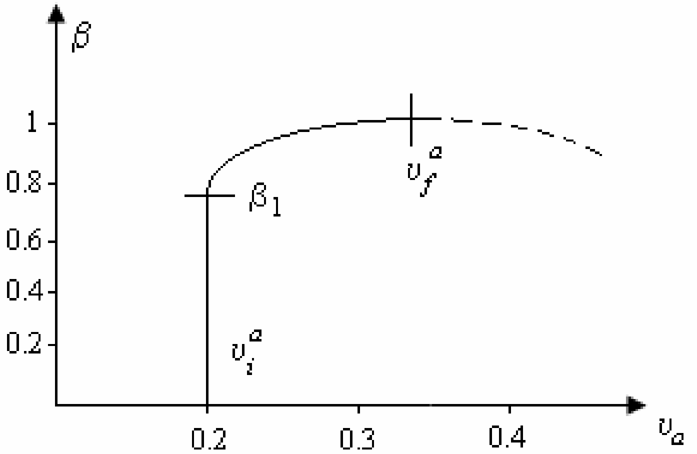

Figure 6 Poisson behaviour proposed by OTTOSEN [6]

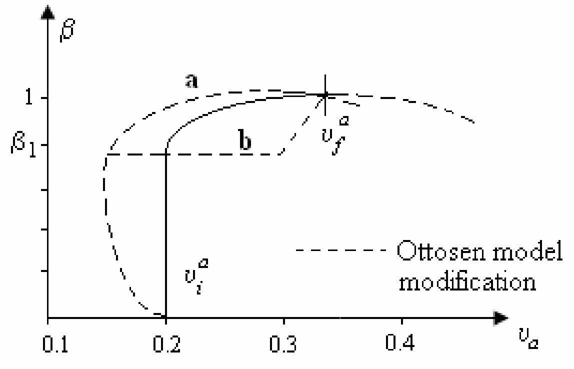

Figure 7 **Model proposed by OTTOSEN [6] and hypothetical model to represent the behaviour of mortar**

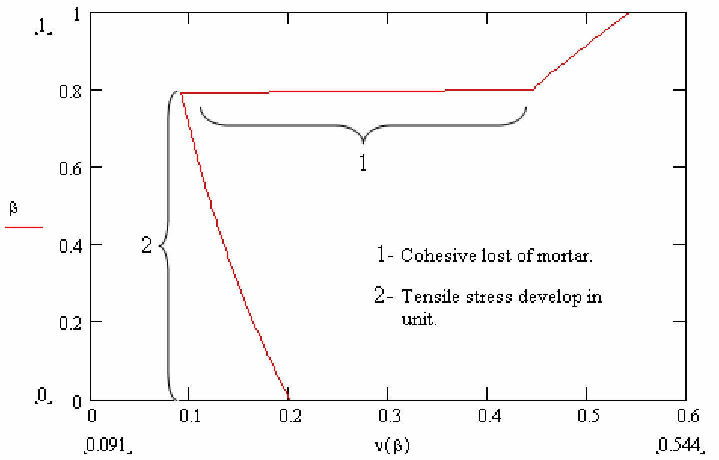

Figure 8 **The Poisson ratio versusβ**

6. CONCLUSION

The main conclusions of the present study are:

- The failure envelope of confined mortar strength with lateral stress increase is shown to be linear and can be expressed by a Coulomb linear relationship with an angular coefficient quite similar to the studies done by KHOO [1], ATKINSON and NOLAND [2] and MOHAMAD [3].
- The initial tangent elastic modulus decreases with an increase of confined stress for 1:1:6 mortar according to KHOO [1] and MOHAMAD [3]. For ATKINSON and NOLAND [2], the elastic modulus increases with confining stress for 1:¼:3 and 1:½:4.5 mortars. For 1:1:6 and 1:2:9 mortars, the elastic modulus keeps constant with a lateral stress increase. The confining pressure has a strong influence in elasticity module. More studies will have to be done to assess the cohesive loss and internal pore distribution.
- There seems to be a decrease in Poisson ratio of mortar under tri-axial compression. Apparently this reduction is exponential for 1:1:6 and 1:2:9 mortars and linear for 1:¼:3 and 1:½:4.5 mortars. An assessment of the Poisson behaviour and the elastic modulus of mortar may lead to the conclusion that a different failure mode occurs for weak mortar (1:1:6 and 1:2:9) than for strong mortar (1:1/4:3 and 1:1/2:4.5).

The Poisson behaviour model presented here is the first step towards a knowledge of the failure mechanism of stack bonded prisms under compression.

REFERENCES

1. KHOO, C L. A Failure criterion for brickwork in axial compression, Thesis submitted for the degree of Doctor of philosophy, University of Edinburgh, February, 1972.
2. ATKINSON, R H, NOLAND, J L, ABRAMS, D P and McNARY, S. A deformation failure theory for stack-bond brick masonry prisms in compression, Proc. 3rd NAMC, Arlington, Texas 1985.
3. MOHAMAD, G. Comportamento mecânico na ruptura de prismas de blocos de Concreto, dissertação (Mestrado em Engenharia Civil)-UFSC, Florianópolis, 1998-178p.
4. DIAMOND, S. The microstructure of cement paste and concrete-a visual primer, Cement & Concrete Composites- www.sciencedirect.com, Fev 2004, Vol. 26:919-933.
5. HAYEN, R, VAN BALEN, K and VAN GEMERT, D. The mechanical behaviour of mortars in tri-axial compression, Proceedings of Arch Bridge IV- Advances in Assessment, Structural Design and Construction- Barcelona, 2004; 395-404.
6. OTTOSEN, N S. Constitutive model for short-time loading of concrete, J. Eng. Mech. Div., ASCE, 1979, Vol. 105(n° 2):127-141.