

## **TRIAXIAL COMPRESSION TESTS ON BEDDING MORTAR SAMPLES LOOKING AT CONFINEMENT EFFECT ANALYSIS**

C.S. Barbosa<sup>1</sup>; P.B. Lourenço<sup>2</sup>; G. Mohamad<sup>3</sup>; J.B. Hanai<sup>4</sup>

### **Abstract**

This paper presents an analysis of the mechanical behavior of bedding mortar samples under triaxial compression tests. When masonry is subjected to vertical loads, mechanical interactions between blocks and bedding mortar at the joints induce lateral tension and compression stresses. Thus, the mortar layer is submitted to a triaxial stress state that modifies its mechanical properties and behavior under confinement effects. This phenomenon may affect the failure mode of masonry and almost no information about this subject is found in literature. Here, test procedures are detailed and results are discussed. In addition to the compressive strength test results, also elastic modulus and Poisson ratio values are addressed. Significant differences were observed among triaxial and uniaxial standard test results. The obtained mortar behavior under different levels of lateral pressure is compared with test results done by other researchers in order to produce relevant conclusions for different mortar compositions.

Keywords: bedding mortar, mechanical properties, triaxial test.

### **Introduction**

The compressive strength of masonry elements and their failure mode depends of mechanical properties of units and mortars mainly. These mechanical properties are obtained from standard tests even if, some times, the tests do not represent the real value found in components, e.g. compressive test of the bed mortar joint and the masonry unit.

---

<sup>1</sup> Ph.D. Student in Structural Engineering, University of Sao Paulo – Sao Carlos, SP, Brazil

<sup>2</sup> Associate Professor of Civil Engineering, University of Minho – Guimaraes, Portugal

<sup>3</sup> Ph.D. Student of Civil Engineering Department, University of Minho – Guimaraes, Portugal

<sup>4</sup> Professor of Structural Engineering, University of Sao Paulo – Sao Carlos, SP, Brazil

To improve the knowledge of structural analysis of masonry structures it is necessary to gain more knowledge about the factors that influence the material properties, and the structural behavior at service and ultimate stages.

With respect to mortar technology, it is known that the compressive strength, elastic modulus and Poisson ratio are obtained from cylindrical and cubes standard tests. But the bedding mortar in a masonry structure under compression is submitted to two relevant phenomena: mortar loses water to the units and to the environment during the curing process and mortar is submitted to a triaxial state. The triaxial state of bedding mortar leads to a change of the material behavior, whereas masonry can also change from mortar crushing to tensile cracking in the units.

The aim of this paper is to present new experimental values obtained from triaxial tests with mortar samples and to compare them with results from other researchers, improving the knowledge about the failure of masonry under compression.

## **Behavior of mortar under triaxial compression**

The bedding mortar joint under compression is submitted to a triaxial compression state with different levels of lateral stresses that arise due the distinct values of lateral strains between the block and mortar. The prediction of the compressive strength of masonry and of the associated failure mode ideally requires that this effect is taken into account.

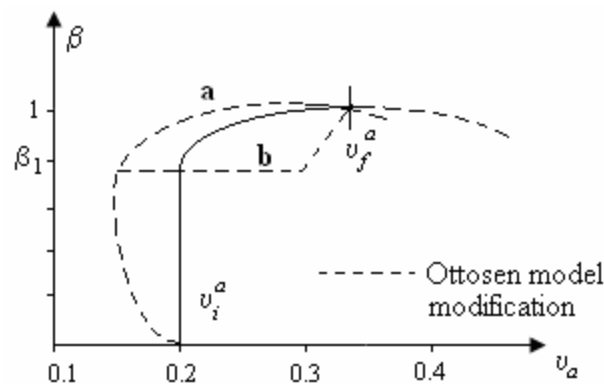
Khoo 1972 and McNary 1984 were the first researchers to evaluate the behavior of mortar under triaxial compression, claiming that the behavior of masonry depends considerably on the non-linear behavior of mortar. Near failure, this effect governs the behavior of masonry. The change of mechanical properties of mortar due to the multiaxial stress state is considered by both authors in their proposed analytical methods to predict the compressive strength and the failure mode of masonry. The failure mode of masonry is defined by Khoo 1972 as the vertical load associated with a lateral strain of mortar (under triaxial state) equal to the limit lateral tensile strain of the unit – obtained from experimental tests. McNary 1984 considers the changes in mechanical properties of mortar due the dilatancy in his analytical model. The author demonstrates that the non-linear behavior of mortar modifies the failure mode of masonry in the following: the failure might not occur by mortar crushing, as expected using linear elastic mechanical properties; mortar dilatancy in the failure process leads to an increase of tensile lateral stresses and a reduction of vertical compressive stress.

Hayen et al. 2004 identified two types of failure in mortars under triaxial compression, subjected to vertical stress  $\sigma_v$  and radial stress  $\sigma_h$ . With  $\sigma_h / \sigma_v < 0.25$  the failure is due to shear mechanisms, with decreasing volume followed by increasing volume. For  $\sigma_h / \sigma_v > 0.25$  the mechanisms of pore-collapse leads the material to failure under a constant decrease of volume.

Mohamad, Lourenço and Roman 2006 stressed that the use of a constant value for the Poisson ratio does not represent the volume change of the material due the confining

stresses, stating that the failure of their tests occurred in compression by initiation and propagation of the cracks, which can start in the 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 the material cohesion reaches a stress level enough to break intermolecular bond. The authors propose a simple model to represent the modification of Poisson ratio through the normalized stress range based in poro-collapse phenomena.

The model proposed by the authors is presented in Figure 1 and it is constituted for two cases. A decrease of the Poisson ratio can be observed until  $\beta_1$  (relationship between vertical stress  $\beta$  and compressive strength value) is reached, followed by smooth increase until collapse for case "a". In case "a", the failure mechanism is developed by shear. The change in case "b" occurs after the Poisson ratio value reaches  $\beta_1$  and it can be observed a quite sudden increase of the value due the pore-collapse and cohesive loss of grain. The authors emphasize that model depends on the physics characteristics, such as porosity and cement contents.  $v_i^a$  and  $v_f^a$  are the initial and final values for the Poisson ratio.



**Figure 1.** Tentative model to represent the behavior of the Poisson ratio of the mortar, Mohamad, Lourenço and Roman 2006.

## Results from experimental analysis

The pioneer tests with mortars under triaxial compression were carried out by Khoo 1972 utilizing two mortar mixes 1:1/4:3 ( $w/c=0.64$ ) and 1:1:6 ( $w/c= 1.29$ ), denoted parts by volume. The authors used cast cylindrical specimens with 38 x 102 mm. Specimens were demoulded and immersed in water for the subsequent 13 days and dried in an oven at 110 degrees Centigrade for one day. The longitudinal and transversal strains were obtained with strain gages placed in two perpendicular directions.

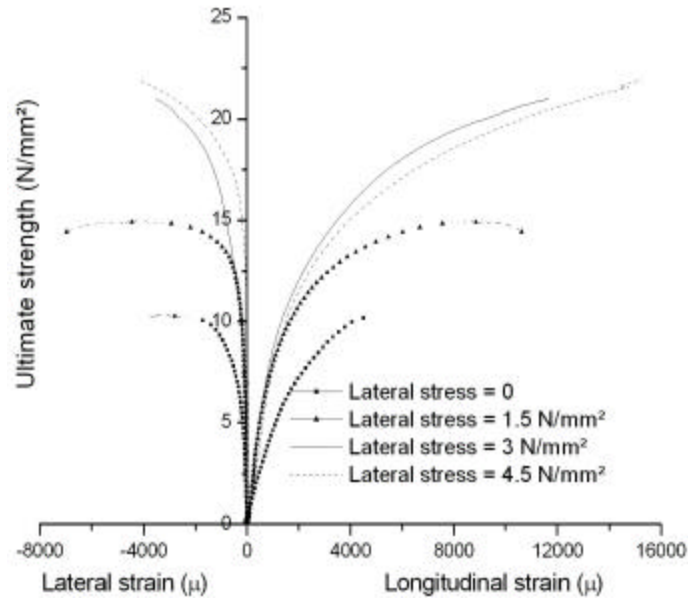
The increase of lateral stress produces an increase of the ultimate strength and an increase in longitudinal ultimate strains. Until 40%-60% of the ultimate strength the curve is reasonable straight; beyond this point, due to the bond failures at the aggregate-paste interfaces, there is

an initiation of major microcracking leading to increased strains corresponding to the flattening of the stress-strain curve. Due to the nonlinear mortar behavior in triaxial state the value of elastic modulus and Poisson ratio depend on the level of triaxial stress.

McNary 1984 cast four mortar mixes 1:1/4:3, 1:1/2:4.5, 1:1:6 and 1:2:9 with water/cement ratio of 1.83, 1.18, 0.84 and 0.51, respectively, corresponding to a flow of 110%. The dimensions of the cylindrical specimens were 54 x 108 mm. The specimens are demoulded after 24 hours and remained in a saturation chamber for 13 more days. After curing, the specimens were dried in air until the test on 28<sup>th</sup> day. For all tests the lateral strain decreased with increased confining pressure. The ultimate strength envelopes can be represented with a straight line for each mortar type. In spite of the fact that all curves presented nonlinear behavior, marked differences were observed, which the authors grouped in three types: brittle type behavior, ductile type behavior and bilinear type behavior. The two stronger mortar mixes exhibited ductile behavior and the two weaker mortar mixes exhibited bilinear behavior under high confining pressures. The confining pressure has a strong influence on the magnitude and variation of the elastic modulus and Poisson ratio, and the weaker mortar mixes have their mechanical properties hardly changed with the confining pressure. The mechanical properties were strongly influenced by the cement content.

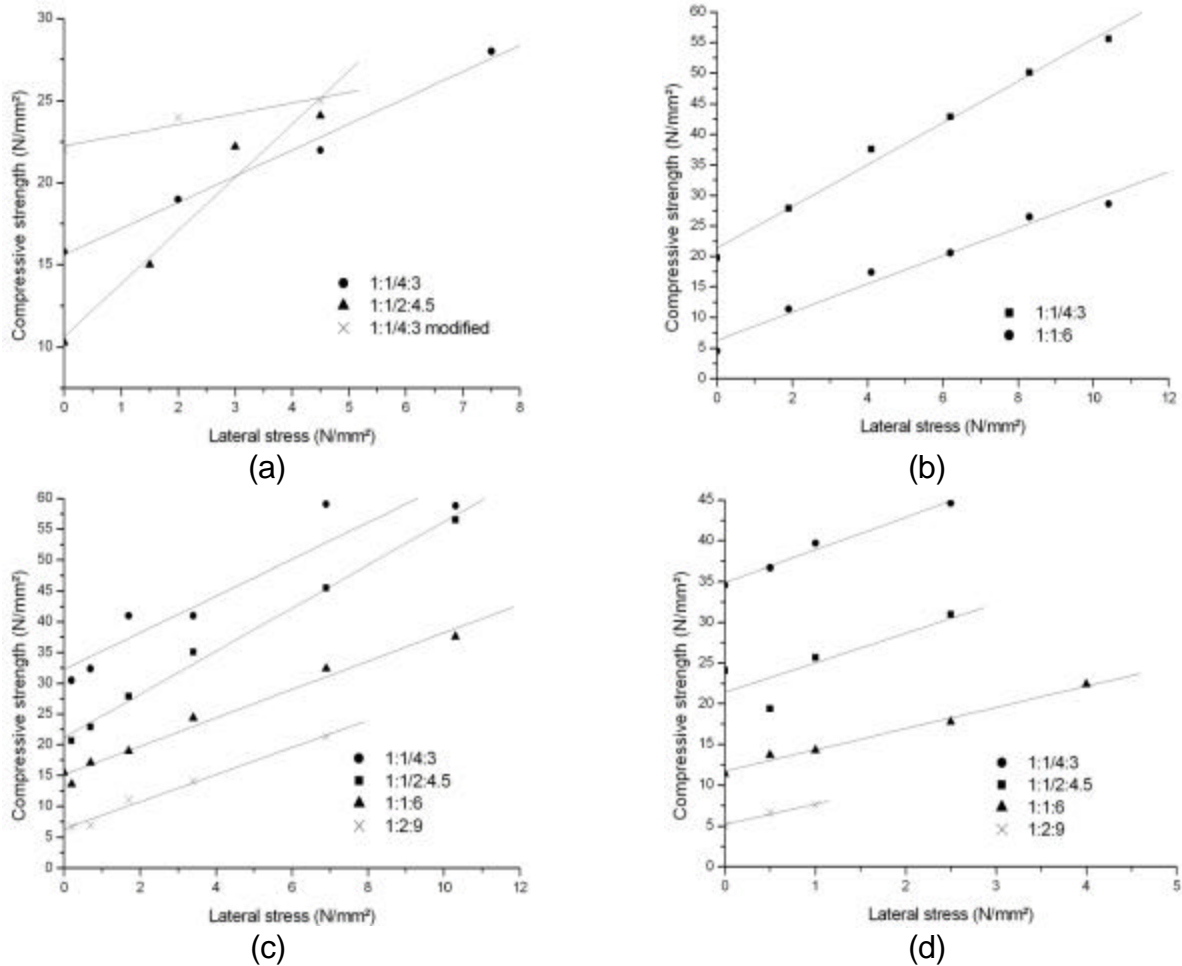
The same mortar mixes types were utilized by Mohamad 1998 to carry out his tests. For all mortar types, a failure envelope in a triaxial state was found. This was a Mohr-Coulomb envelope with linear slope. It was observed that the longitudinal and transversal strains were higher for the weaker mixes as the lateral stress increased, presenting less linearity. Brittle behavior was obtained for the stronger mixes, while the weaker mix presented higher ductile.

Additional mortar samples were moulded, constituted by two mix types 1:1/4:3 and 1:1/2:4.5. In the day after casting the specimens were demoulded and put in laboratory conditions until testing, after seven days. For the 1:1/4:3 mortar type, some specimens were cast in gypsum moulds to evaluate the influence of the water loss process that occurs in the bedding joints. More details about the modified tests can be found in Guimaraes, Barbosa and Hanai 2006. Figure 2 presents the stress-strain diagram of mortar under distinct lateral stresses. The behavior is strongly nonlinear for all cases but it is possible to observe three distinct types of changes. Brittle type behavior occurs for zero confinement stress; at the first increment the behavior is ductile and towards the higher confinement stress it changes to bilinear. The increase of lateral stress increases the ultimate longitudinal strain and decreases the ultimate lateral strain. An anomalous behavior is observed in the longitudinal stress for a 4.5 N/mm<sup>2</sup> confining stress, which presents higher values of strain for the same level of stress, when compared with the 3 N/mm<sup>2</sup> confining stress-strain curve.



**Figure 2.** Stress-strain (longitudinal and lateral) of mortar in triaxial tests of the current experimental analysis.

Figure 3 depicts the failure envelopes of the selected triaxial tests with mortars. For most cases the failure envelopes presents a good linear fit with similar slope. The lower normal compressive strength values obtained in Figure 3a is due the earlier age of specimens in the date of the tests. In this case, the large differences between the inclination of the curves, in comparison with the others cases, is attributed to the characteristic differences of materials and the age of testing, that probably modified the microstructure of the bulk. As stated above, the behavior under confinement depends strongly on porosity and voids size. The mix 1:1/4:3 modified, due the water loss to gypsum mould, has also its porosity modified and its behavior changed with respect to the original mix.



**Figure 3.** Several envelopes obtained from mortar triaxial tests. Present research (a), Khoo 1972 (b), McNary 1984 (c) and Mohamad 1998 (d).

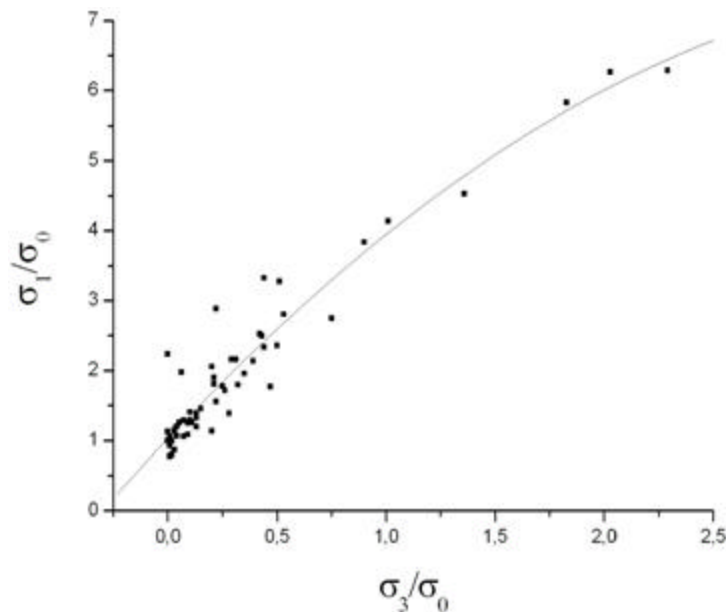
Table 1 summarizes the linear failure envelopes and the lateral pressure for all mortar types in the four experimental analyses presented.

It is emphasized that the curves do not consider the relations  $\sigma_1/\sigma_0$  and  $\sigma_3/\sigma_0$ , being  $\sigma_0$  the normal compressive strength,  $\sigma_1$  the triaxial compressive strength and  $\sigma_3$  the confinement stress. The diagram of Figure 4 considers simultaneously these stresses for 63 tests with variable mortar mixes and lateral pressures. The relationship can be well approximated by a 2<sup>nd</sup> order polynomial fit.

**Table 1.** Linear failure envelope for distinct mortar types and its confinement conditions. Present research<sup>1</sup>, Khoo 1972<sup>2</sup>, McNary 1984<sup>3</sup> and Mohamad 1998<sup>4</sup>.

	Lateral pressure $\sigma_3$ (N/mm <sup>2</sup> )	Mortar type	Failure envelope
1	2; 4.5; 7.5	1:1/4:3	$\sigma_1 = \sigma_0 + 1.6\sigma_3$
	1.5; 3; 4.5	1:1/2:4.5	$\sigma_1 = \sigma_0 + 3.2\sigma_3$
	2; 4.5; 7.5	1:1/4:3*	$\sigma_1 = \sigma_0 + 0.7\sigma_3$
2	1.9; 4.1; 6.2; 8.3; 10.4	1:1/4:3	$\sigma_1 = \sigma_0 + 3.4\sigma_3$
		1:1:6	$\sigma_1 = \sigma_0 + 2.3\sigma_3$
3	0.02; 0.05; 0.13; 0.25; 0.5; 0.75	1:1/4:3	$\sigma_1 = \sigma_0 + 3\sigma_3$
		1:1/2:4.5	$\sigma_1 = \sigma_0 + 3.5\sigma_3$
		1:1:6	$\sigma_1 = \sigma_0 + 2.3\sigma_3$
		1:2:9	$\sigma_1 = \sigma_0 + 2.2\sigma_3$
4	0.5; 1; 2.5; 4	1:1/4:3	$\sigma_1 = \sigma_0 + 4\sigma_3$
		1:1/2:4.5	$\sigma_1 = \sigma_0 + 3.6\sigma_3$
		1:1:6	$\sigma_1 = \sigma_0 + 2.6\sigma_3$
		1:2:9	$\sigma_1 = \sigma_0 + 2.5\sigma_3$

\* Modified cure process.

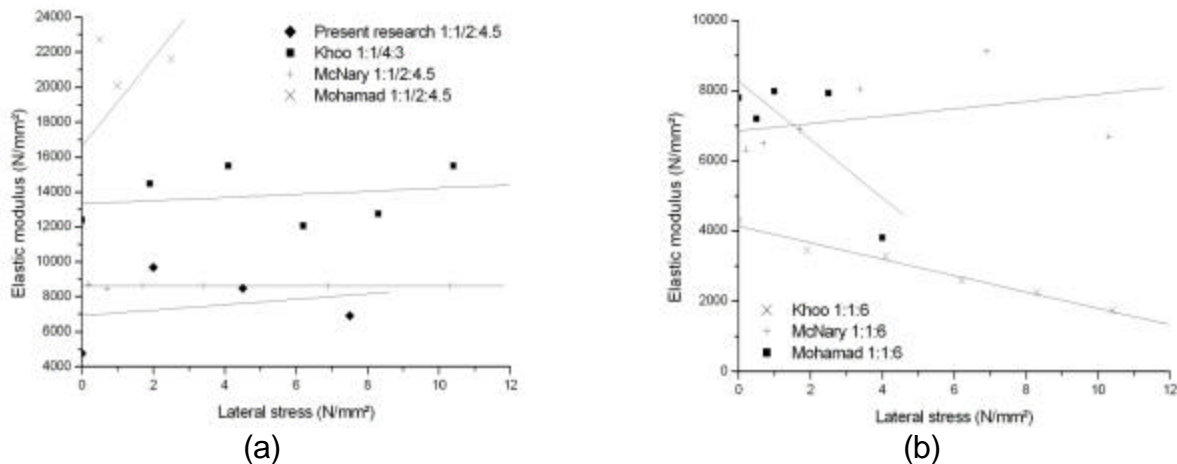


**Figure 4.** Principal stress relationships for triaxial tests with mortars.

In general, it is not possible to define the trend for the variation of elastic modulus with the increase of lateral stress.

Figure 5a, related to stronger mixes, shows the same absence of any tendency, in the present research and in Mohamad 1998, with an increase of elastic modulus due to a first increase of lateral stress, followed by a decrease with a second increase of lateral stress. Random values were also found by Khoo 1972. McNary 1984 did not find any variation in the elastic modulus with the increase of lateral stresses. The decrease found for the elastic modulus values with the increase of lateral stress can probably be attributed to micro-cracking in the specimen during the test and the data acquisition system, where the membrane surrounds the specimen with strain gauges causing some friction.

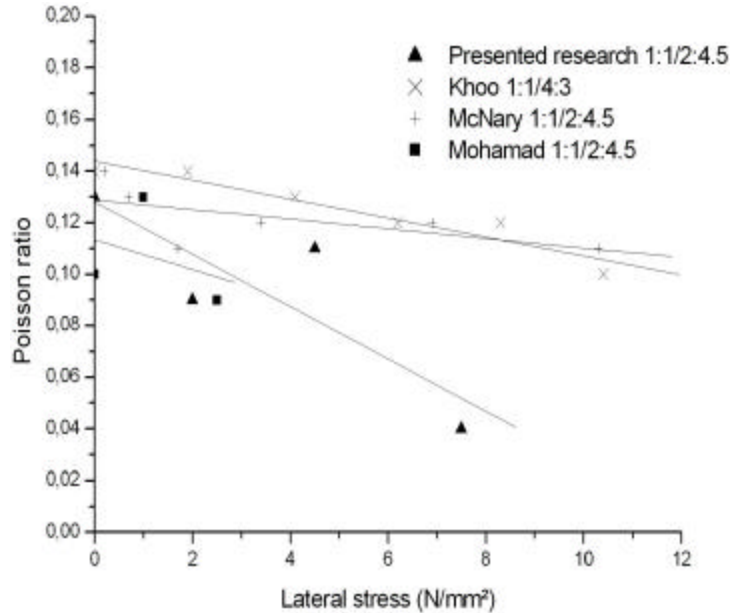
For the weaker mixes, see Figure 5b, Khoo 1972 and Mohamad 1998 found a decrease in the elastic modulus values with an increase of lateral stress, in opposition to the tendency observed in McNary 1984 values. Due the porosity of weaker mortar, cracks can arise with the application of the lateral stresses, reducing the stiffness of the bulk.



**Figure 5.** Variation of elastic modulus with increase of lateral stress.

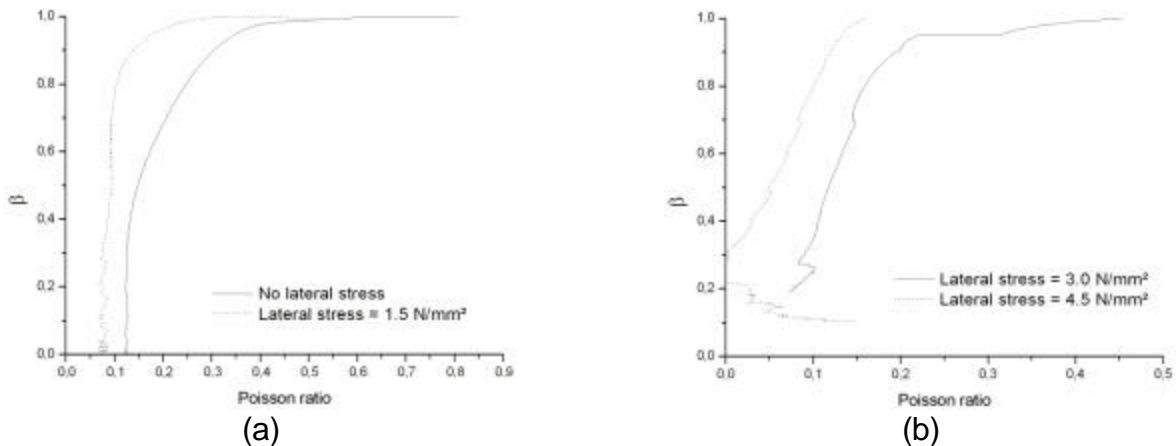
For all mortar mixes of the experiments analyses, a decreasing linear tendency of Poisson ratio with the increase of lateral stress was found. Exceptions were again found: a mortar mix from McNary 1984 presented an increase tendency and the weakest mix of Khoo 1972 presented an exponentially decreasing tendency. Figure 6 depicts the variation of Poisson ratio for stronger mixes, in all testing programs.





**Figure 6.** Variation of Poisson ratio with increase of lateral stress.

Figure 7 presents the behavior of Poisson ratio for the four levels of confinement stress. For the two higher confining levels the configuration of the curve was affected for the deficient measurement of strains, as it can be seen in Figure 7b. In Figure 7a, for no confinement and 1.5 N/mm<sup>2</sup> lateral stresses, an initial constant value of Poisson ratio was found. Later when the test reached a given level of  $\beta$  – named  $\beta_1$ , an increase of the Poisson ratio if found until failure of the specimen. The change in the diagram behavior seems to depend on the level of lateral stress: for the no confinement test,  $\beta_1$  is around 0.5 and for the test with lateral stress of 1.5 N/mm<sup>2</sup>,  $\beta_1$  is higher (about to 0.9).



**Figure 7.** Behavior of Poisson ratio under increasing confining stress.

## Conclusion

It was possible to present solid results about the behavior of mortar specimens under triaxial effect, carried out by distinct researches, including different mortar mixes and different confining levels.

With the increase of lateral stress there is an increase of the ultimate longitudinal strain and a decrease of the ultimate lateral strain. For all cases, the failure envelope can be defined by linear functions that depend on the lateral stress level and the normal compressive strength of the mortar specimen. The relationship between the ultimate compressive strength and lateral stress (normalized by the normal compressive strength) can be well approximated by a polynomial expression of the 2<sup>nd</sup> order.

The elastic modulus seems to depend on the mortar mix. For a weak mix, a tendency of decrease is found with the increase of lateral stress. For a strong mix, the opposite occurs. In relation to the Poisson ratio, a decrease tendency with the lateral stress was found in most experimental results. It is noted that the test conditions are likely to strongly affect the measurements of strains in specimen due the friction between the external membrane of the specimen and the strain gauges. Due the small sizes of the specimens, there is also a considerable probability that the crack or crushing areas affect the strain measurements.

## Acknowledgement

The authors would like to acknowledge FAPESP – Sao Paulo State Research Support Foundation – and CAPES – Brazilian Research Support Foundation – for the financial support given to this research.

## References

- Guimarães 2006: Guimaraes, T.A.C.; C. S. Barbosa, J. B. Hanai, “Water loss and confinement effect in embedding mortars of concrete blocks for structural masonry”, Proceedings of 48<sup>o</sup> Brazilian Conference of Concrete. Rio de Janeiro, IBRACON, 2006.
- Hayen 2004: Hayen, R., K. Van Balen, D. Van Gemert “The mechanical behavior of mortars in triaxial compression”, Proceedings of Arch Bridge IV- Advances in Assessment, Structural Design and Construction-Barcelona, 2004; 395-404.
- Khoo 1972: Khoo, C.L., “A failure criterion for brickwork in axial compression”. Thesis (Ph.D. Degree). University of Endinburgh. February, 1972.
- McNary 1984: McNary, W.S., “Basic properties of clay-unit masonry in compression”. Thesis (M.Sc. Degree). University of Colorado. 1984.

- Mohamad 1998: Mohamad, G., "Mechanical behavior in failure of concrete block prisms". Thesis (M.Sc. Degree). Federal University of Santa Catarina, Florianopolis, 1998. (in Portuguese).
- Mohamad 2006: Mohamad, G.; P. B. Lourenço, H. R. Roman, "Poisson behavior of bedding mortar under multiaxial stress state". Proceedings of the Seventh International Masonry Conference, London, England, 2006.