POISSON OF BEDDING MORTAR UNDER MULTI-AXIAL STRESS CONDITIONS

Mohamad, Gihad[1]; Lourenço, Paulo Brandão[2]; Roman, Humberto Ramos[3]; Rizzatti, Eduardo[1]; Sartori, Tatiane[4]

[1] Dr., Professor, Federal University of Santa Maria, Civil Engineering Department, gihad.civil@gmail.com; edu_rizzatti@yahoo.com.br;

[2] PhD, Professor, University of Minho, Civil Engineering Department, pbl@civil.uminho.pt

[3] PhD, Professor, Federal University of Santa Catarina, Civil Engineering Department, humberto@ecv.ufsc.br

[4] Federal University of Santa Maria, Master Science Student on Production Engineering Department, tatianesartori@yahoo.com.br

The main goal of this work is the understanding of triaxial compression capacity of bedding mortar. It was observed by the experimental tests that the behavior of the stress and strain response is highly nonlinear and depends on the increase of lateral stress. In all studies presented here, the ultimate strength envelope of triaxial mortar can be represented by a linear function with similar angular coefficients. It was observed a significant reduction in the Poisson ratio of mortar with increasing confined stress. This decrease is apparently exponential for mortars types 1:1:6 and 1:2:9 (proportion on volume of cement:lime:sand) and linear for mortars type 1:0.25:3 and 1:0.5:4.5. A simple model is proposed to represent modification of the Poisson ratio throughout the normalized stress range.

Keywords: *Poisson behavior, Bedding mortar and Multi-axial stress state;*

INTRODUCTION

When masonry is submitted to a vertical load, a number of joint phenomena occur between the unit and the mortar that induce lateral tension and compression, as shown in Figure 1. The stress and strain behavior of block under compression are essentially linear, however mortar under the same conditions of stress and strain is nonlinear. Such behavior must be taken into account in any numerical simulation to predict the capacity of the masonry. This is important for understanding the failure criterion of the assembly caused by crushing of the bedding mortar and is essential for accurate constitutive modelling of masonry.

The main goal of this work is to verify the mechanical properties of mortar under multiaxial stress conditions. Experimental tests had been done by Khoo (1972), Atkinson et al. (1985) and Hayen et al. (2004) to obtain the confined elasticity modulus, Poisson ratio and compressive strength of mortar, which allowed us to conclude that a few analyses of the mechanical properties modification of mortar under multiaxial stress conditions associated with failure mode have been found in the literature. The greatest challenge to develop a constitutive modelling of masonry is to understand the influence of the mechanical parameters using expressions that reproduce the state stress of block and mortar. This is the first step toward a development of future model to predict the ultimate compressive capacity of masonry.

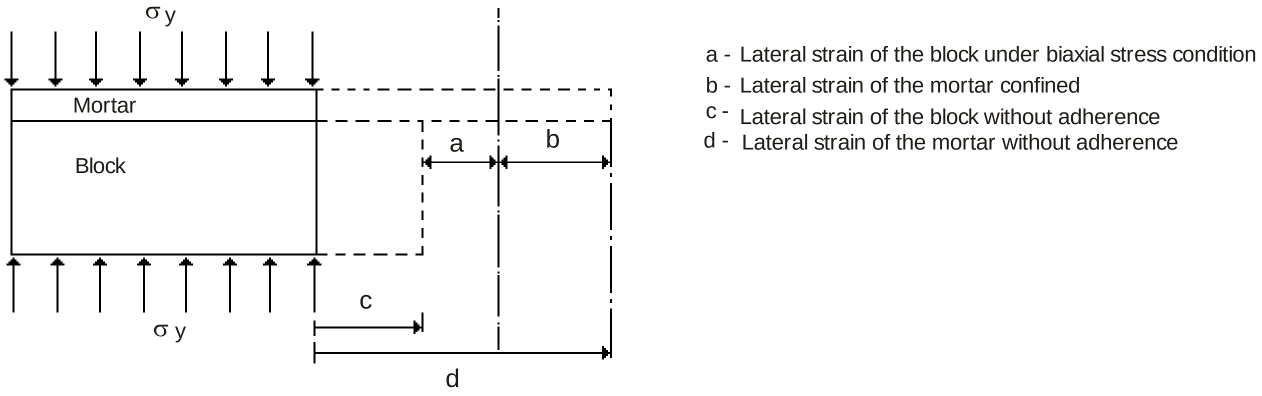

Figure 1: Horizontal strain capacity in block/mortar assembles under compression.

STUDIES DEVELOPED BY KHOO (1972)

A failure criterion for brickwork in axial compression was studied by Khoo (1972). Biaxial compression-tension tests using clay specimens and triaxial compression tests to describe the failure mode of masonry were carried out. Khoo (1972) cast two types of mortar mixes 1:0.25:3 and 1:1:6 with water/cement ratio of 0.64 and 1.29, respectively. The proportion of materials was designated by the volume ratio of the materials. The dimension of the specimens was 3.8 cm in diameter and 10.2 cm in height. Table 1 presents the failure envelope of triaxially loaded mortars under different confinement pressures.

Table 1: Envelope failure of mortar obtained by Khoo (1972).

Mortar –Ty	Envelope of failure
1:0.25:3	$f_m^* = f_m + 3.4\sigma_3$
1:1:6	$f_m^* = f_m + 2.3\sigma_3$

A simple linear regression provided the best fit to represent the failure envelope of the confined mortar under triaxial compression. Tests carried out by Khoo (1972) point out the difficulties in supporting lateral stress due to changes in the volume of the specimens due to entry of the loading ram into the cell, expansion of the system with the pressure and unavoidable leakage as around the loading ram. Cube strength was much greater than the corresponding cylinder strength, about 1.4 times greater for both mixes. The magnitude of the initial elasticity modulus was constant for the 1:0.25:3 mortars and decreased with increased lateral stress for the 1:1:6 mortars. The initial value of the Poisson ratio decreased with an increase of lateral stress for the 1:0.25:3 and 1:1:6 mortars. The Poisson ratio decreased quite slowly for the 1:0.25:3 mortar and dropped quickly for the 1:1:6 mortar, as shown in Figure 2.

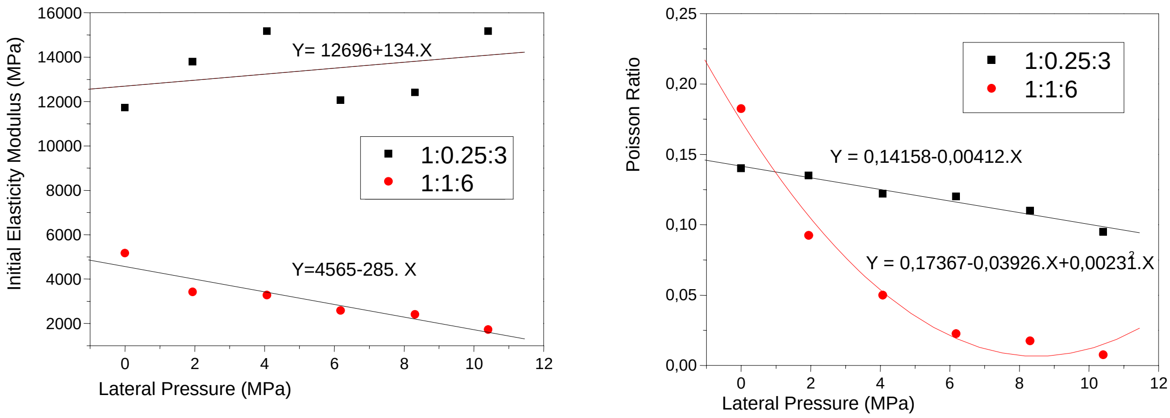

Figure 2: Initial elasticity modulus and Poisson ratio under lateral stress – Khoo(1972).

STUDIES DEVELOPED BY ATKINSON AND NOLAND (1985)

Atkinson and Noland (1985) conducted triaxial tests in four types of mortar with six different levels of confined pressure. The physical and mechanical characteristics of the different types of mortar and the failure envelope of the samples under triaxial compression are presented in Table 2. There is a linear relationship between confined strength and lateral stress, as shown in Figure 3. The stress and strain behavior of each mortar sample was nonlinear at every confining pressure used and clearly shows that there is a transition between brittle to ductile type behavior for different levels of confinement applied, as presented in Figure 3. The stress and strain diagram of the 1:0.5:4.5 mortar shows fragile behavior for stress levels of 0.2, 0.7 and 1.7 N/mm^2, and ductile behavior is shown for stress level of 3.45, 6.90 and 10.90 N/mm^2. The stress and strain diagram of the 1:1:6 mortar shows fragile behavior for stress levels of 0.2 and 0.7 N/mm^2, while ductile behaviors are shown for stress levels of 1.7 N/mm^2 and a bilinear behavior is shown for the remaining stress levels.

Table 2: Mechanical characteristics of mortar studied by Atkinson e Noland (1985).

Type	Uniaxial Compression strength (N/mm^2)	Water / cement	Lateral stress (N/mm^2)	Envelope of failure
1:1/4:3	32.6	0.55	0.21; 0.69; 1.72; 3.44; 6.88; 10.31	$f_m^*=f_m + 5.\sigma_3$
1:1/2:4.5	26.4	0.85	“	$f_m^*=f_m + 3.\sigma_3$
1:1:6	13.7	1.19	“	$f_m^*=f_m + 2.\sigma_3$
1:2:9	3.4	1.96	“	$f_m^*=f_m + 2.\sigma_3$

Lateral stress has a critical influence on the stress and strain diagrams, and marked differences in behavior were detected. There are three general behavior types for stress-strain diagrams: brittle, ductile and bilinear behavior. Bilinear behavior was characterized by a continuous increase of stress and strain. The authors in experimental tests established that 1:1:6 and 1:2:9 mortar types exhibited bilinear behavior at high confining pressures. This may indicate that the behavior changes are caused by the collapse of the internal structure of the mortar and that this rearrangement of the grains modifies the stable configuration of materials, although the load-bearing capacity of the mortar was sometimes unaffected. Figure 4 presents the modulus of elasticity and the Poisson ratio of mortar under tri-axial compression for 1:0.5:4.5 mortar types.

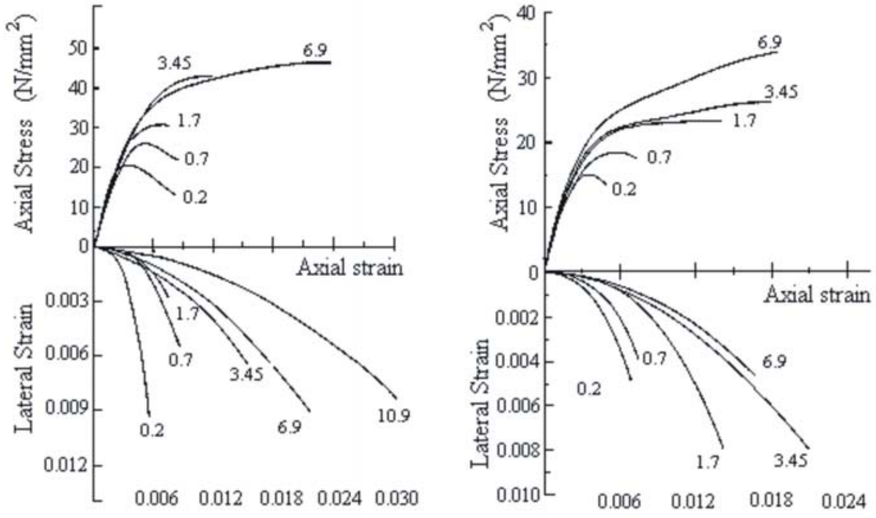

Figure 3: Stress and axial and lateral strain diagram (1:0.5:4.5 and 1:1:6 mortar types) - Atkinson e Noland (1985).

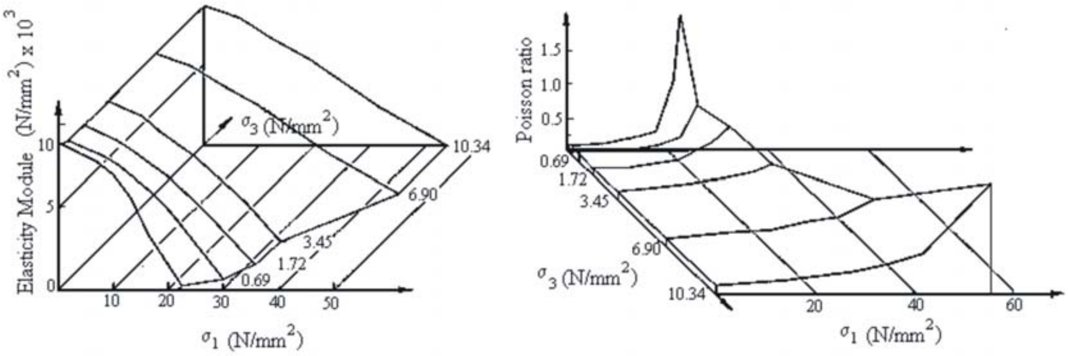

Figure 4: Elasticity modulus and Poisson ratio of mortar under triaxial compression for 1:0.5:4.5 mortar types - Atkinson e Noland (1985).

STUDIES DEVELOPED BY MOHAMAD (1998)

Mohamad (1998) carried out a series of tests on mortar samples in a state of triaxial compression and obtained failure envelopes for 1:0.25:3, 1:0.5:4.5, 1:1:6 and 1:2:9 mortar types, as shown in Table 3.

Table 3: Envelope failure of mortar.

Mortar –Type	Envelope of failure
1:0.25:3	$f_m^{*}=f_m + 4\sigma_3$
1:0.5:4.5	$f_m^{*}=f_m + 3.6\sigma_3$
1:1:6	$f_m^{*}=f_m + 2.6\sigma_3$
1:2:9	$f_m^{*}=f_m + 2.5\sigma_3$

The effects of a confining pressure on mortar specimens produce a higher ultimate strength and an increased of ultimate strain. The envelope of mortar under triaxial compression describes a linear relationship between normal and shear stresses (maximum and minimum principal stresses) similar to the Mohr-Coulomb envelope. The correlation coefficient between confined stress and compressive strength was 0.99. Figure 5 presents the results of elasticity modulus in relation with lateral pressure. For mortar type 1:0.25:3 and 1:0.5:4.5, it was observed that the initial elasticity modulus increased with increasing of confined stress and for the mortars types 1:1:6 and 1:2:9 there was a decrease in the initial elasticity modulus. Table 4 shows the experimental results for the Poisson ratio measured at stress level of 30% of the compressive strength of the specimens (initial stress level) and near to failure (ultimate stress level).

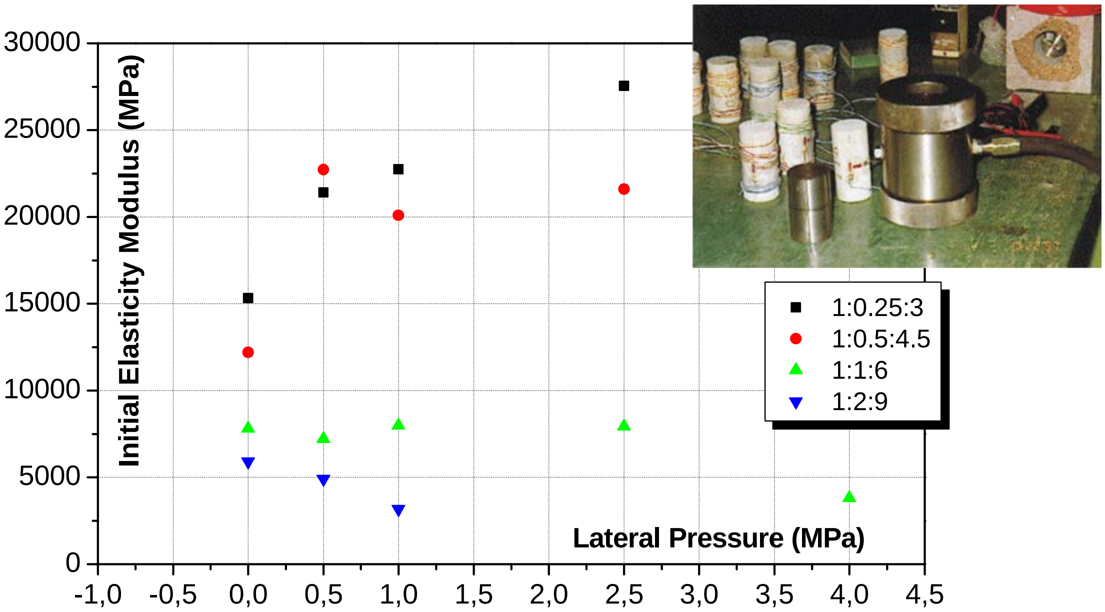

Figure 5: Relation between initial elasticity modulus and confined stress.

Table 4: Poisson ratio of confined mortar.

Type	Lateral Stress (N/mm^2)	Poisson ratio	
		Initial stress level	Ultimate stress level
1:0.25:3	0, 0.5, 1	0.20	0.20
	2.5	0.10	0.10
1:0.5:4.5	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
1:2:9	0	0.17	0.14
	0.5	0.04	0.17
	1	0.05	0.07

POISSON RATIO OF MORTAR UNDER CONFINED STRESS

The failure mechanisms of masonry under compression are caused by the difference in stiffness of mortar and block, because, the bedding mortar is softer than the blocks. To describe a model for preview the changes of Poisson ratio under loading is a rather difficult task due to the variability of results. Currently in most contemporary masonry codes, the use of a constant values for the Poisson ratio during the load cycle is common, although it does not represent the change in volume due to confined stress, as showed in the mechanical properties reported by Khoo (1972), Atkinson and Noland (1985) and Mohamad (1998). The failure mechanisms of masonry under compression are caused by the initiation and propagation of cracks that sometimes starts in mortar due to the high porosity and different void sizes. There is, probably a decrease in volume caused by the collapse of defects and voids, after which the Poisson ratio increases significantly until failure. Pore collapse is a phenomenon that can be identified by scanning electron microscopy (SEM), where the surface of a material is imaged at high magnification using an electron beam probe. Diamond (2004) presented an investigation using scanning electron microscopy on 28 day old mortars with sand content in excess of 48% by volume. In the resulting images, it is possible to verify the uniform gray sand grains, the extensive areas of bright, dense hardened cement paste, and the smaller areas of porous, darker hardened cement paste. Pore sizes of up to 15 μm in diameter can be seen and most of the large pores appear to be interconnected. Concerning the investigation of Diamond (2004), it is possible to conclude that combinations of the high porosity of mortar and certain stress states could modify mechanical properties such as elasticity modulus and the Poisson ratio. The porosity of mortar depends on its composition, water/cement ratio, maximum diameter and the granulometry distribution of the sand. These considerations allow us for greater understanding of the pore-collapse phenomenon and provide a potential explanation for the decrease on Poisson ratio with increasing lateral stress for 1:1:6 and 1:2:9 mortar types.

Triaxial tests have been carried out by Hayen et al. (2004) in historical mortar constituted of putty lime mortar, hydraulic lime mortar, and lime and cement mortar, whose compressive strength was 1.85 N/mm^2. The relationship between horizontal stress and vertical stress (k) changed throughout the test with k ratio values of 0; 0.05; 0.10; 0.15; 0.25; 0.5; 0.75 and 1. The authors assess the influence of the tests conditions on the pore structures of mortar by measuring total pore volume using vacuum submersion and analyzing the pore structure by means of mercury intrusion and scanning electron microscopy.

The multiaxial stress analyses of Hayen et al. (2004) led to the following conclusion: volumetric strain under triaxial loads show shear failure mechanisms for $k < 0.25$, where an initial decrease in the volume of specimens (probably due to the internal collapse of existing cracks and defect) is followed by an increase in volume where shear bands develop. The collapse of mortar samples occurs along diagonal shear bands. For $k \geq 0.25$, the failure mechanisms in mortar samples are rather distinct and were characterized by a linear decrease in the volume of the samples. Thus, with this evidence, it is easy to conclude that pore collapse occurs at $k \geq 0.25$. The pore collapse phenomenon is a microstructural observation that indicates microcraking dominates the deformation in the periphery of the pore, without changing the volume of the sample.

For mortars under triaxial stress condition, a constutive model to represent the Poisson ratio changing and the failure mode was presented using a modification of the model proposed by Ottosen (1979) for high strength concrete. The model consists of established steps for the Poisson ratio as a function of a non-linearity rate, β (stress versus strength ratio). When β reaches the value of β_1, the Poisson ratio starts to increase significantly. The initial Poisson ratio remains constant until reaching β_1, which leads to a significant increase in Poisson ratio until failure occurs, as shown in Figure 6. In high strength concrete (60 to 120 N/mm^2), lateral stress does not have a strong influence on the Poisson ratio until failure occurs because the lateral stress reaches only 10 to 20% of the ultimate strength, and this is not significant to modify the Poisson ratio.

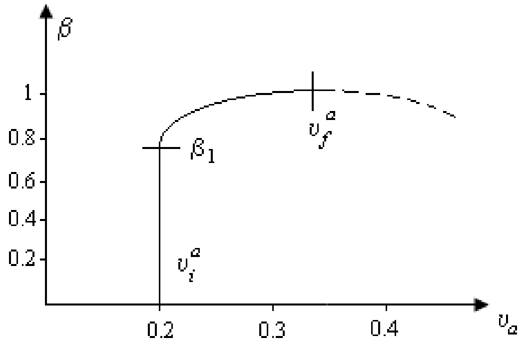

Figure 6: Model of Ottosen (1979) for representing the Poisson modification with increasing stress/strength ratio – Ottosen (1979).

Equations representing the Poisson behavior proposed by Ottosen (1979) are:

$$\nu^a = \nu_i^a \qquad \text{if, } \beta \leq \beta_1, \tag{1}$$

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

Meanwhile, through experimental tests done by Khoo (1972), Atkinson and Noland (1985), Mohamad (1998) and Hayen et. al. (2004), it is possible to verify the modification of the Poisson ratio under increases in lateral stress. Thus, a generalization of the model of Ottosen (1979) is proposed to represent the modification of Poisson ratio, as shown in Figure 7. For case "*a*", the Poisson ratio behavior decreases until reaching β_1 and then gently increases until collapse when the shear failure mechanism develops. For case "*b*", the Poisson ratio behavior decreases until reaching β_1 and then increases quite suddenly due to pore collapse, cohesive loss between the grains and the closing of cracks. The dotted line represents an Ottosen model modification and depends on physical characteristics such as porosity and cement proportion. Equations (3) and (4) represent the change in Poisson behavior of mortar under triaxial compression for case "*a*", as shown in Figure 7.

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

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

Equations (5) and (6) represent the change in Poisson ratio behavior of mortar under triaxial compression for case "*b*", as shown in Figure 7.

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

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

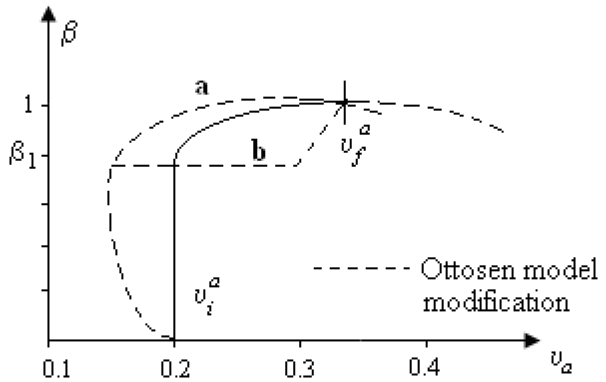

Figure 7: Model proposed by Ottosen (1979) and hypothetic model to represent the behavior of mortar.

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, causing a volume change (Branch 1). The cohesive loss of mortar arises suddenly and increases tensile stress in the masonry unit. Branch 1 is characterized by linear reduction in the value of the Poisson ratio.

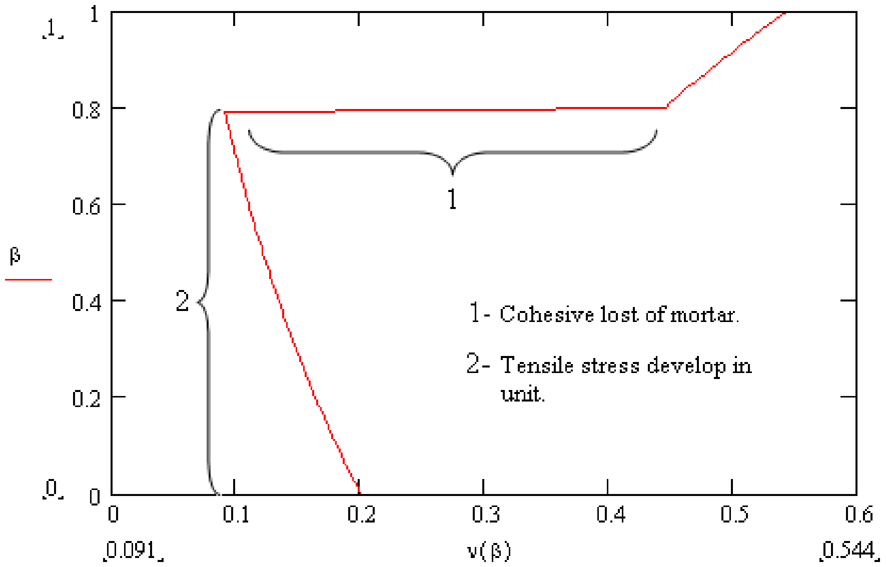

Figure 8: The Poisson ratio versus *β*.

CONCLUSIONS

The main conclusions of this review are:

- The failure envelope of confined mortar strength with increases in lateral stress has been shown to be linear and should be expressed by the Coulomb linear relation. The studies conducted by Khoo (1972), Atkinson and Noland (1985) and Mohamad (1998) resulted in very consistent values for the angular coefficient.
- The initial tangent elasticity modulus decreases with an increase in confined stress for 1:1:6 mortar type according to the Khoo (1972) and Mohamad (1998) studies. Atkinson and Noland

(1985) showed that the modulus of elasticity increases with confining stress for 1:0.25:3 and 1:0.5:4.5 mortars types. For 1:1:6 and 1:2:9 mortar types, the elasticity modulus remains constant with lateral stress increases. The confining pressure has a strong influence on the elasticity modulus. More studies will have to be done to assess the cohesive loss and internal pore distribution.

- There seems to be a decrease in the Poisson ratio of mortar under triaxial compression. This reduction is apparently exponential for 1:1:6 and 1:2:9 mortar types and linear for 1:0.25:3 and 1:0.5:4.5 mortar types. Assessment of the Poisson ratio behavior and elasticity modulus of mortar may lead to the conclusion that different failure modes occur for weak mortars (1:1:6 and 1:2:9) and strong mortars (1:0.25:3 and 1:0.5:4.5).
- The Poisson behavior model to represent the failure mode of mortar presented here is the first step toward acknowledgement of the failure mechanism of stack bonded prisms under compression.

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