COMPARISON OF STANDARD TEST RESULTS AND IN-PLACE MECHANICAL PROPERTIES OF EMBEDDING MORTARS AND CONCRETE BLOCKS

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SUMMARY

Numerical analyses of masonry structures are supplied by a number of mechanical parameters such as compressive strength, tensile strength and modulus of elasticity of the blocks and the embedding mortar. These mechanical properties are mostly obtained from standard tests of blocks and mortar samples. However, the standard block test represents the structural behavior of the unit under mechanical conditions that are not the same in all tests. Moreover, the block test cannot directly provide the material's properties, in this case concrete. Mortar samples are moulded and cured under different conditions of the in-place embedding mortar layer. Water is absorbed by the blocks reducing the mortar w/c ratio and thus increasing its strength. Also confinement effect may occur and the mortar is subjected to a triaxial stress state. This paper presents a discussion about these topics, based on test results and bibliographic references. Hollow core concrete blocks were moulded in three different strength levels. Plastic consistency concrete was applied to assure the application of the same material and the same compacting method. Embedding mortar samples were moulded in cylindrical, cubic and prismatic shapes and under different curing conditions. A comparison of the results showed sharp differences in the values of compression strength and deformability of concrete blocks and samples, depending on the nature of the test and the samples' geometry. Correlation factors were found to exemplify the magnitude of these differences. Distinct mechanical properties of embedding mortar were found when considering different water loss and confinement effect conditions. It is emphasized that the complete characterization of the constituent materials of masonry will only be achieved by numerical simulations.

INTRODUCTION

Despite the scientific development of masonry technology in the last years, many factors that influence the masonry behavior are not completely understood. The mechanical properties of the constituent materials of blocks are not known and the embedding mortar is subject to water loss, during the cure, and to confinement effect under compression. These phenomena change its mechanical properties in comparison to the ones obtained in axial compression standard tests with samples.

Thus, in a numerical micro-modeling (which represents the units and mortar layers) the mechanical properties obtained from a block test and from standard mortar samples tests are utilized. Sometimes, adjusted properties are also used. Marzahn 2003 relates that a much accurate analysis of masonry structural behavior is necessary especially because the mechanical properties are not adequate to represent the condition in a numerical micro-modeling for masonry computational simulation or failure conditions. In accordance with Pina-Henriques 2005, in a numerical micro-modeling it is adequate to realize a closer evaluation of the mechanical properties of masonry constituent materials, e.g., concrete and embedding mortar. The mechanical properties differ in their real values and can induce to a completely opposing behavior of the structure. It is necessary to isolate and have a better knowledge of each parameter that influences the structural behaviour at service and ultimate stages. However, there is a number of challenges to be succeeded, especially because many of these parameters are derived from tests and the test conditions are not unique. Block geometry is different from case to case, confinement effects in block and prism tests are variable, steel plate stiffness affects the stress distribution in the tests, etc.

This paper aims to present the attempts of several researches to measure the machanical properties of the materials that constitute the block and the changes in mechanical properties of mortar when subjected to the effect of loss water and confinement. The research under development at the Laboratory of Structures in Sao Carlos is also emphasized. The further steps of the ongoing research are the performance of new test series, calibration of theoretical models for direct and reverse analyses and performed numerical analysis.

MECHANICAL PROPERTIES OF MATERIAL THAT CONSTITUTE THE MASONRY UNITS

Some researchers approach the correlation between material strength and unit strength, however most of them do not treat this subject in full detail and only establish direct correlations. For all presented analyses, the area of units used in calculations is the average cross sectional area.

Becica and Harris 1983 carried out experimental analysis with concrete blocks, prisms and samples extracted from the units. The stress-strain diagram of samples was obtained, besides the direct correlation between compressive strength samples and units. The sizes of hollow concrete blocks are 200 x 200 x 390 mm. The samples dimensions correspond to height/length ratio from 1:1 to 2:1 with constant thickness. The average compressive strength is 18.4 N/mm², 21% higher

than the blocks' compressive strength. Table 1 shows the mechanical properties obtained from blocks, prism and samples extracted from masonry units and Figure 1 depicts a comparison between the stress-strain curves of the elements tested.

Table 1. Strength of blocks, prisms and samples.

Element	Compressive Strength (N/mm²)		Ultimate Strain (μ)
	Gross Area	Net Area	
Sample	-	18.4	2094
Block	9.8	15.1	1805
Prism	5.2	8.0	1652

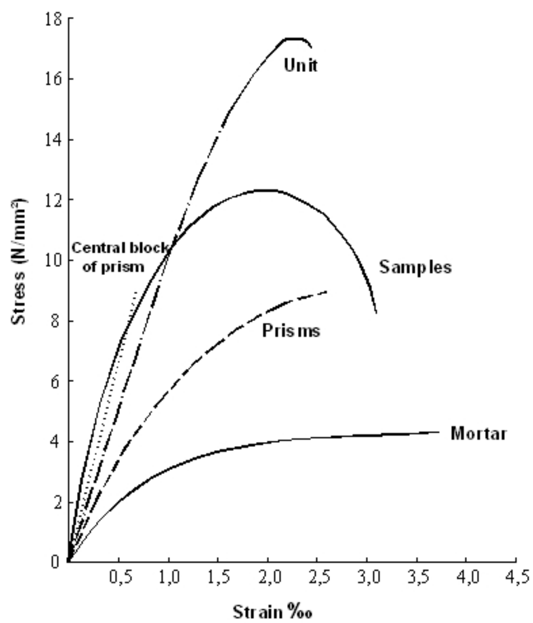


Figure 1. Stress-strain curves obtained from concrete, mortar, block and prism tests, adjusted from Becica and Harris 1983.

Similar tests were realized by Ganzerli et al. 2003 utilizing non-standard units in accordance with the American Code. The research also presents a background of other researchers that compare the compressive strength of samples to the concrete blocks. The authors evaluated the best thickness/height ratio to compare to the units' results. The tests used concrete blocks with dimensions that correspond to 200 x 200 x 400 mm and extracted samples with 35x70x140 mm, thickness: height:length (Table 2).

The differences found are justified by the authors because the samples are solid and have sizes smaller than blocks while blocks have cores and slender face-shells. Besides, due to the smaller sizes of samples, there is also less probability of failure in the bulk. The compressive strengths of the samples are almost 26% higher than the ones of the blocks and the differences between top and bottom compressive strengths are induced due to the compactness rate in the layers of the blocks.

Table 2. Test results obtained by Ganzerli et al. 2003.

Element	Average compression strength in the net area (N/mm²)	Standard deviation (N/mm²)	Coefficient of variation (%)
Block 200 x 200 x 400	34.8	1.31	3.8
Sample (Top)	49.1	0.14	0.3
Sample (Bottom)	39.0	3.65	9.4

Hawk et al. 1997 tested a non-standard unit with 250 mm of thickness and its extract samples. The values of average compressive strength are 21.9 N/mm² and 24.2 N/mm² in relation to the net area for the sample and the block, respectively.

Tests with limestone silic (A, B), autoclaved blocks (C, D) and samples extracted from the units were performed by Marzahn 2003. The results obtained from the compression tests (f_b), indirect tensile test ($f_{bt,sp}$) and flexional tensile test ($f_{bt,f}$) are presented in Tables 3 and 4. A correction was applied to the compression test values by the block shape factor.

Cylindrical samples were extracted from blocks and tested in axial compression. The author proposes that the elastic modulus (at 33% of maximum strength, E_b) should be calculated by Equation 1. The Poisson ratio values were 0.10 and 0.20 for the limestone silica and concrete blocks, respectively. Direct tensile tests were carried out with cylindrical samples ($f_{bt,ax}$) and Equation 2 was obtained.

$$E_b = 450\, f_{b,cil} \qquad (1)$$

$f_{b,cil}$: compressive strength of samples.

$$f_{bt,ax} = 0.26\, f_{b,cil} \qquad (2)$$

The cylindrical samples were chosen as they are widely utilized in researches to obtain the mechanical properties of the concrete.

Table 3. Compressive strength of blocks and samples obtained by Marzahn 2003.

Block	Sizes (mm)	Specific mass (kgf/cm³)	f_b (N/mm²)	$f_{b,cil}$ (N/mm²)	E_b (N/mm²)	$\frac{f_{b,cil}}{f_b}$
A	238 x 240 x 500	1857	25.9	17.1	10088	0.66
B		1864	20.9	12.8	9908	0.61
C	200 x 240 x 500	544	4.1	3.9	1938	0.95
D		450	3.2	2.8	1516	0.86

Table 4. Tensile strength of blocks and samples obtained by Marzahn 2003.

Block	$f_{bt,f}$ (N/mm²)	$f_{bt,sp}$ (N/mm²)	$f_{bt,ax}$ (N/mm²)	$\frac{f_{sp}}{f_{fb}}$
A	2.21	1.19	1.42	0.04
B	1.99	0.95	1.56	0.04
C	0.93	0.33	0.95	0.08
D	0.57	0.27	0.46	0.08

Frasson Junior 2000 tested cylindrical samples (50 x 100 mm) constituted by no slump concrete used to manufacture hollow concrete blocks. The compressive strength of the moulded sample was lower than the one of the blocks, referring to the net area. Nevertheless, the main goal of this research was to develop a methodology for mixture design and production control in concrete block production plants. Three series of hollow concrete blocks (140 x 190 x 390 mm) were moulded varying their thickness of face-shells. Three levels of strength, took as reference, were obtained in relation to the gross area of the blocks: 6 N/mm², 9N/mm² and 12N/mm². The values summarized in Table 5 are related to the net area.

In all groups it can be noted that the compressive strength of the samples are close to 20% of the blocks.

Table 5. Correlation between compressive strength of blocks and samples obtained by Frasson Junior 2000.

Level of strength (N/mm²)	Thin face-shell			Thick face-shell		
	Block	Sample	Relation (%)	Block	Sample	Relation (%)
6.0	18.5	14.5	78.4	16.4	13.0	79.3
9.0	27.0	21.0	77.8	21.4	17.4	81.3
12.0	32.4	26.0	80.2	32.8	25.3	77.1

In this way, Barbosa (2004) moulded hollow concrete blocks and samples with plastic concrete in different levels of compressive strength. After casting, the densities of both elements are similar. The size of the block was 140 x 190 x 390 mm and cylindrical samples (50 x 100 mm, 100 x 200 mm and 150 x 300 mm), cube samples with 100 mm of edge length and prismatic sample (30x30x60 mm) were moulded. Compression and indirect tensile tests (with cylindrical 100x200 mm) were carried out and the results are presented in Tables 6 and 7, related to the net area. Additional tests were realized with 100 x 200 mm cylindrical samples and blocks and a correlation given by Equation 3 was identified between their compressive and tensile strengths.

$$f_b = 0{,}72\ f_c + 3{,}34 \qquad (3)$$

Different geometries of samples induced to distinct correlations between samples' and blocks' strengths. The values obtained from the 100 x 200 mm and 150 x 300 mm cylindrical samples provided the best approximation to ones of the hollow concrete blocks. The variance of concrete strength induced to a changing in relation to the mechanical properties of samples and blocks. This behavior was identified by the curves plotted in Figure 2.

Each case has its particularities and prismatic and cylindrical samples with different bottom dimensions and manufacturing process (moulded or extracted) were tested. For this case a better standardization is necessary due the distinct relationships obtained. Becica and Harris 1983 and Ganzerli et al. 2003 found the compressive strength of the samples was around 24% higher than the blocks, while Frasson Junior (2000) found it was 20%. On the other hand, the values found by Marzahn 2003 are between 60% and 95% of the block strength. It is clear that all the tests have their particularities and they utilize the geometry of distinct samples (in which the confinement effect performs differently), different thickness/ height ratio and some methods to manufacture the samples.

Table 6. Correlation between compressive strength of blocks and different size samples.

Sample	G1		G2		G3	
	f_{comp} (N/mm²)	Relation	f_{comp} (N/mm²)	Relation	f_{comp} (N/mm²)	Relation
Hollow block	16.8	-	19.8	-	35.7	-
150 x 300 mm	15.4	0.92	18.6	0.94	36.6	1.03
100 x 200 mm	17.3	1.03	20.4	1.03	41.5	1.16
50 x 100 mm	19.9	1.18	22.3	1.13	46.6	1.31
100 x 100 x 100 mm	21.1	1.26	26.6	1.34	52	1.46
30 x 30 x 60 mm	22.1	1.32	24.6	1.24	54.4	1.52

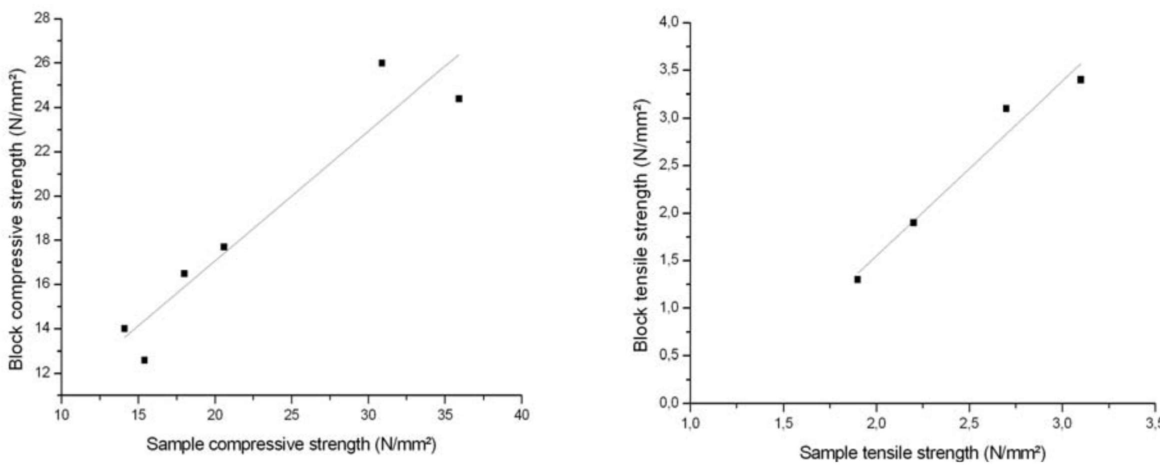
[1] Relation between block and sample.

Table 7. Correlation between tensile strength of blocks and samples.

$f_{ct,sp}$ (N/mm²)	$f_{bt,sp}$ (N/mm²)	$\frac{f_{ct,sp}}{f_{bt,sp}}$
1.9	1.3	1.46
2.2	1.9	1.16
2.7	3.1	0.87
3.1	3.4	0.91

$f_{ct,sp}$: Indirect tensile strength in samples.

$f_{bt,sp}$: Indirect tensile strength in blocks.



(a) (b)

Figure 2. Evolution of compressive (a) and tensile strength (b) of block due to the variation of concrete strength.

CONSIDERATIONS ABOUT MECHANICAL PROPERTIES OF EMBEDDING MORTAR

To measure the influence of the absorption of the blocks, Barbosa, Hanai and Barbo 2005 utilized 1:1:3 (cement:lime:sand) mortar. Special shape moulds were manufactured utilizing a material with high absorption rate, like gypsum, to produce cylindrical (50 x 100 mm) and cube samples (edge = 100 mm).

It can be observed that during the cure of the mortar, the suction of modified shapes reduces the w/c of mortar and changes its mechanical properties if it is compared to standard tests. The compressive strength increases twice in modified test, as the tensile strength has an increase of

approximately 26%. A large increase can be also observed in the elastic modulus value in the same proportion to the compressive strength. The values are summarized in Table 8.

Table 8. Mechanical properties of mortar in standard and modified tests.

Test	f_{cm} (N/mm²)	$f_{t,sp}$ (N/mm²)	E (N/mm²)
Standard tests	19.3	2.3	12800
Modified tests	39.5	2.9	26700

f_{cm} : average of compressive strength of mortar.

$f_{t,sp}$: average of indirect tensile strength of mortar.

E: elastic modulus of mortar.

The authors also performed additional tests to evaluate the physical properties in both types of mortars, after the water loss phenomena. The results are summarized in Table 9.

Table 9**.** Physical properties of mortar in standard and modified tests.

Test	Absorption	Specific mass	Void ratio
Standard tests	12.3%	1.92	0.24
Modified tests	8.7%	2.07	0.18

From previous results it can be concluded that the lowest strength values are due to excessive water for the cement and lime hydration (supposed to occur in modifies test). This excessive water causes an increase of the void ratio in samples. Thus, the mortar that contains the smallest void ratio will present the highest specific mass value and a smallest absorption capacity.

Barbo, Hanai and Barbosa 2004 also moulded cubes in shapes constructed utilizing concrete blocks besides modified gypsum and standard shapes. The concrete shape was idealized to compare the absorption rate of gypsum to concrete. The relations obtained in all tests are presented in Table 10.

Table 10. Correlations between compressive strength of mortar subjected to distinct cure process.

$f_{cy,g} / f_{cy,s}$	3.90
$f_{cb,g} / f_{cb,s}$	2.06
$f_{cb,c} / f_{cb,s}$	2.00
$f_{cb,g} / f_{cb,c}$	1.03

$f_{cy,s}$: compressive strength, cylindrical sample, standard mould

$f_{cy,g}$: compressive strength, cylindrical sample, gypsum mould

$f_{cb,s}$: compressive strength, cube sample, standard mould

$f_{cb,g}$: compressive strength, cube sample, gypsum mould

$f_{cb,c}$: compressive strength, cube sample, concrete mould

Once again the suction effect is clearly present in tests. It can be emphasized that the compressive strength of cube samples presents the same value when they are moulded in gypsum or concrete shapes. Proximity between the absorption rate of the concrete and the gypsum is identified.

Cylindrical and cube samples do not have the same strength increase and justified due by different contact areas with mould of the two distinct geometries. The higher the relationship between the area subjected to absorption and volume of sample, the larger the increase of compressive strength in comparison with standard tests.

Figure 3 presents the moulds utilized in the manufacture of cylindrical (gypsum) and cube (gypsum and concrete) samples.

Figure 3. Moulds utilized in mortar samples production.

Casali, Weidmann and Prudencio Junior 2005 evaluated the compressive strength of embedding mortar utilizing a penetration directly into the embedding mortar. The results were compared to the ones obtained in 40 x 40 x160 mm prismatic samples and 50 x 100 mm cylindrical samples. 12 types of mortars were mixed and it was found that the compressive strength values in mortar samples were similar. Distinct behaviours were observed between the penetration test and the mortar samples, probably, due to the differences of water retention rate. In premixed mortar, the compressive strength value obtained for the penetration test was lower than the one obtained in samples contrarily to the values found to other mortars. Differences in compressive strength close to 60% were found in penetration and standard tests.

Studies of the confinement effect on mortars were conducted by Khoo 1972. Two types of mortar were studied and a line equation was the best fit to determine the failure envelope of the confined mortar. Mohamad 1998 relates that Atkinson and Noland 1985 found a linear relationship between the compressive strength of the confined mortar and the transversal confinement stresses. The results obtained by Atkinson and Noland (1985) are summarized in Table 11.

Table 11. Strength of mortars under triaxial compression obtained by Atkinson and Noland 1985.

Confinement Stress (N/mm^2)	Compressive Strength (N/mm^2) Mortar type	
	1:0.25:3	1:2:9
0	32.6	3.4
0.21	31.1	6.9
0.69	32.4	8.2
1.72	39.3	11.7
3.44	44.2	15.2
6.88	69	22.1

The envelope failure obtained by Mohamad 1998 also presented linear behaviour in the four types of mortars analyzed. The values of compressive strength are presented in Table 12.

Guimaraes, Barbosa and Hanai 2006 carried out compression tests in triaxial cells to evaluate the confinement effect. Two strain gages were disposed in cylindrical mortar samples to obtain the longitudinal strains. Two types of mortar were mixed, 1:0.25:3 and 1:0.5:4.5. The results are presented in Table 13. A linear fit of envelope failure was obtained, too.

Table 12. Strength of mortars under triaxial compression obtained by Mohamad 1998.

Confinement Stress (N/mm²)	Compressive Strength (N/mm²) Mortar type			
	1:0.25:3	1:0.5:4.5	1:1:6	1:1:6
0	34.6	24.1	11.4	5.1
0.5	36.7	19.4	13.7	6.6
1	39.7	25.7	14.3	7.6
2.5	44.6	31.0	17.8	-
4	-	-	22.4	-

Table 13. Strength of mortars and elastic modulus under triaxial compression.

1:0.25 :3		1:0.5:4.5		
Confinement Stress (N/mm²)	f_a (N/mm²)	Confinement Stress (N/mm²)	f_a (N/mm²)	E (N/mm²)
0	15.8	0	10.3	4104
2.0	19.0	1.5	15.0	5456
4.5	22.0	3.0	22.2	7140
7.5	28.0	4.5	24.1	7360

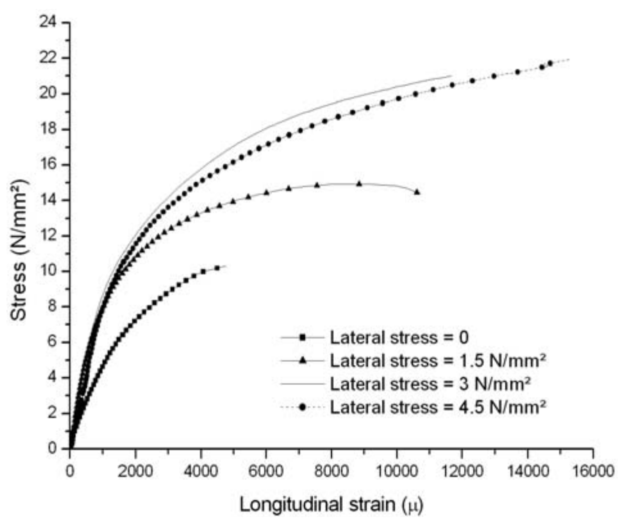


Figure 4. Stress-strain diagrams of cylindrical samples in triaxial tests.

The increase of lateral stress causes an increase of compressive strength of mortars. Although the uniaxial compressive strength of the 1:0.25:3 mortar is 50% higher than 1:0.5:4.5 mortar, the difference does not remain during the increase of lateral stresses. In Figure 4 is presented the

stress-strain diagram of 1:0.5:4.5 mortar for the four level of transversal stresses. Like in the absorption test, the mortar in triaxial tests presents higher elastic modulus.

Both the confinement effect and the water loss of the units explain the fact that mortars with different compressive strengths, obtained in standard tests, do not reflect the same changes in the compressive strength of walls. The changes in mortar behavior under the two distinct phenomena can be clearly noted but their real influence on the mechanical properties of mortar and, consequently, on the behavior of the walls will be completely understood after numerical simulations that consider these phenomena.

CONCLUSIONS

Many difficulties will be found in researches that aim to carachterize the mechanical properties of constituent materials of masonry units, mainly due to the fact that the concrete blocks have a distinct mould process in comparison with the standard plastic consistency process conventionally adopted. As a consequence, some researches utilize samples extracted from units, assuring the equality of the materials´ mechanical properties. However, the extraction process is a difficult method, which demands care, cost and time and may damage the extracted samples. A coherent requirement relative to samples of units is necessary to standardize this procedure, mainly in the compressive tests subjected to factors that induce different behaviours, such as the steel platen restraint and the element geometry.

The highest values of compressive strength and elastic modulus were found in mortar samples obtained from absorptive moulds and higher confinement pressures. The gypsum or concrete mould induces the water loss of mortar, changing its w/c water and, consequently, its mechanical and physical properties.

In triaxial tests, a little increase in the transversal stress causes significant increases in the values of compressive strength and elastic modulus. The subsequent increases in the transversal stresses affect less the compressive values. Similarly, the complex phenomena that occur in the embedding mortar can be noted. To improve the characterization of mortars’ mechanical properties it is necessary carry out simultaneously experimental and numerical analyses to compare the values obtained from samples tests to the ones from embedding mortar. Further tests on masonry walls are necessary to quantify the real effect of the mortar’s mechanical properties.

ACKNOWLEDGEMENTS

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

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