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Hourglass-shaped specimen: compressive strength of concrete and mortar (numerical and experimental analyses)

Corpo de prova na forma de ampulheta: resistência à compressão de concretos e argamassas (análises numérica e experimental)

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Abstract

Cylindrical specimens whose diameter is equal to half its height have been used worldwide. The statistical scattering in experimental testing of cementitious materials is a phenomenon known in literature and one reason is linked to the geometry of the specimens, which implies the possibility of different failure modes. This paper shows the evaluation of an hourglass-shaped sample , in which the highest stress occurs at the centre of the specimen, with negligible influence of stress distribuition from its ends. An amount of 260 cylindrical and hourglass samples were tested, with varying water/cement ratio and age. FEM analyses showed that stress in the central part of the hourglass specimens is 2.25 higher than that present at its ends. Modes of failure occured in differente ways in cylindrical specimens, whereas only one mode of failure was verified in hourglass specimens. The cylindrical samples showed bimodal frequency distribution, demonstrating the influence of the central part (material properties) and of its ends (boundary conditions), while the hourglass displayed a Gaussian distribution.

Keywords: hourglass, specimen geometry, compressive strength, cementitious material, FEM.

Resumo

Corpos de prova cilíndricos com diâmetros iguais à medtade da altura tem sido empregados em todo o mundo. A dispersão estatística de resultados em experimentos com materiais cimentícios é um fenômeno conhecido da literatura e uma das razões deste fenômeno corresponde à geometria dos corpos de prova, o que pode explicar a ocorrência de diferentes modos de ruptura. Este trabalho mostra a avaliação de corpos de prova na forma de ampulheta, com a imposição de que tensões de ruptura ocorram em sua parte central, tornando desprezível a influência das condições de contorno de suas extremidades (pratos da máquina universal de ensaios). Um total de 260 corpos de prova cilíndricos e na forma de ampulheta foram testados, variando-se o fator água/cimento, empregando concreto e argamassa além da variação das dimensões dos corpos de prova. O método dos elementos finitos foi emprgado para analisar as tensões despertadas nos modelos. As análises mostraram que as tensões máximas ocorrem na parte central das amostras de ampulheta com valor 2,25 maior do que as tensões despertadas em suas extremidades. Os ensaios mostraram que ocorreram diferentes modos de ruptura nas amostras cilíndricas, enquanto que nas amostras na forma de ampulheta um único modo de ruptura foi observado. Além disso, enquanto as amostras cilíndricas mostraram distribuições de Gauss bimodais para as frequências dos resultados, o que parece demonstrar a influência da propriedade do material (parte central) e a influência dos pratos da máquina de ensaiso (condições de contorno), as amostras na forma de ampulheta apresentaram sempre distribuições de Gauss unimodais para os resultados.

Palavras-chave: ampulheta, geometria de corpo de prova, resistência à compressão, material cementício, método dos elementos finitos.

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1. Introduction

"One naturally wonders who or what people first discovered that lime, when burnt and slaked with water, together with sand as an additive, can be used as a mortar. The answer has to be: we will never know - it just happened". This inquiry, spoken by Hamelau [1], may very well be paraphrased as the problem of this paper and be rewritten as: "one naturally wonders who or what engineer or institution first established that the geometry of the specimens of cementitious material should be a cube or a cylinder? The answer has to be: we will never know - it just happened". Of course there are some names, institutions and curiosities in this story; after all, it is not as old as the invention of mortar. In 1836, in Germany, the first tests to evaluate mechanical properties of cementitious materials began. So, that country has shown itself as a great center of research in mechanical properties of cementitious materials from the mid-nineteenth century [2].

From the historic and pleasant testimony of Professor Antonio Carlos Reis Laranjeiras [3], who personally experienced some of the historical moments of the engineering in Europe, this paper was able to approach something of what happened during the definition of the geometry of specimens for cementitious materials.

The adoption of specimens for mechanical tests with different geometries occurred at the beginning of last century. The cubic form was adopted initially in Germany, where there is an extensive tradition regarding early studies on concrete technology. The initial idea was to obtain a specimen with surfaces perfectly parallel for being submitted to compressive testing. Turns out that a 15-cm-sided cube had an excellent parallelism of its faces. For concretes and machines of that period, these dimensions appeared to be adequate, because larger dimensions was not able to be used, due to the machines' capacity.

The United States school, however, followed another pattern. They adopted the cylindrical form, with larger ease of confection, once it does not run the risk of developing heterogeneous density as it is typical at edges of a cubic form. However, for this form, it still appeared the problem of top surface finishing, that generally becomes irregular, and it is frequently necessary to correct it by adding molten sulfur or cement paste on such surface.

Early in the 20th century, the cylinder with height/diameter ratio equal to one proved to be inadequate, because the failure modes were strongly influenced by the friction of the machine plates on the surfaces of the specimens. Then, the German engineer Hubert Rüsch conducted studies about slenderness and determined that the value of 2 was the most appropriate relationship between the height and diameter of the specimen. The idea of Rüsch was that the planes of rupture did not pass by the machine plates. Even though it was a reasonable approach, many specimens had (and still have) a tendency to break through their extremities, making it difficult to determine the actual value of the material strength. The other problem concerning cylindrical samples preparation, related to the surface finishing, was recently solved by simply putting a lid on the top of the form (Figure 1 (a)) and positioning it horizontally (Figure 1 (b)). With this, a slight edge over the height of the specimen is produced, but this does not compromise its cross section, because the reduction produced is insignificant.

In the course of time, several researchers have studied new geometries that could alter some of the peculiarities in concrete compressive strength tests as well as others aspects of materials.

Figure 1 – Specimens with lid in vertical (a) and horizontal (b) positions

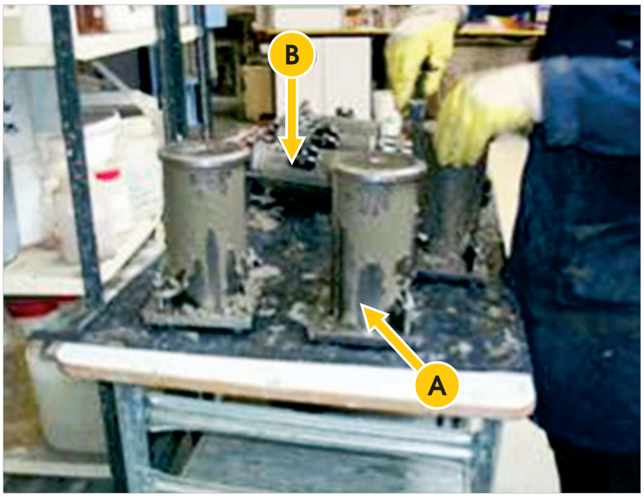


Figure 2 – Cross sections to predict the failure mode of concrete (from (5))

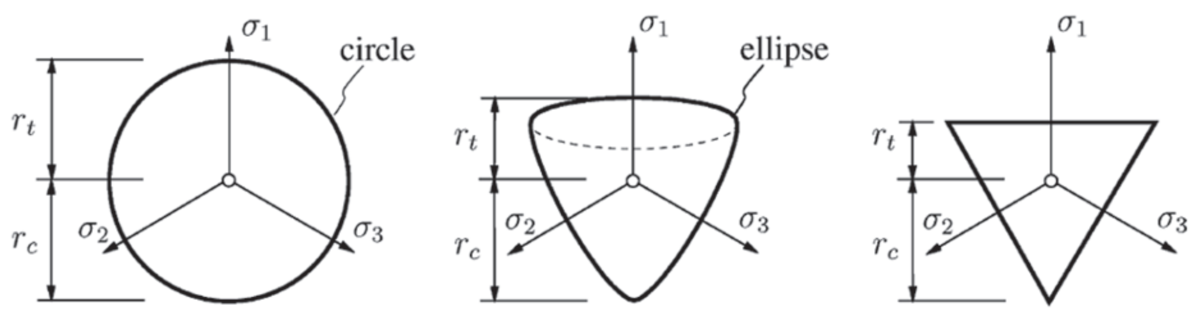
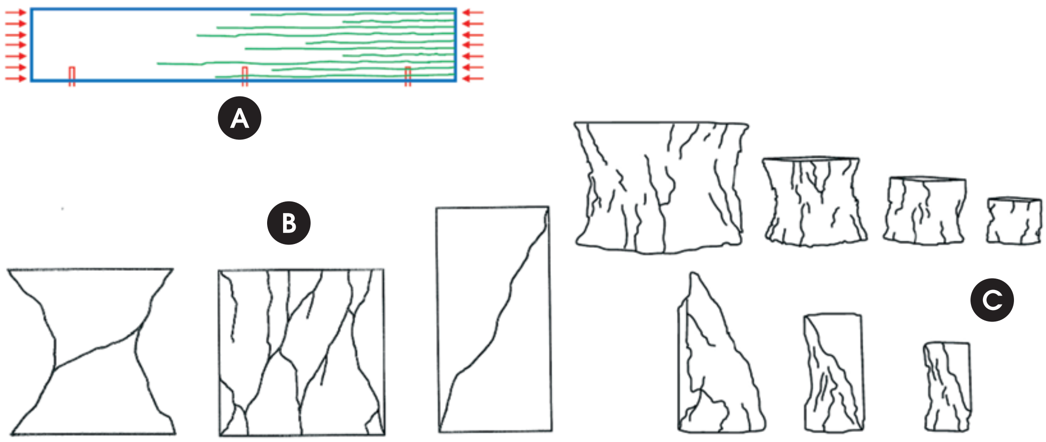


Figure 3 – Failure modes of concrete specimens (from (9) (a), (10) (b) and (11) (c))



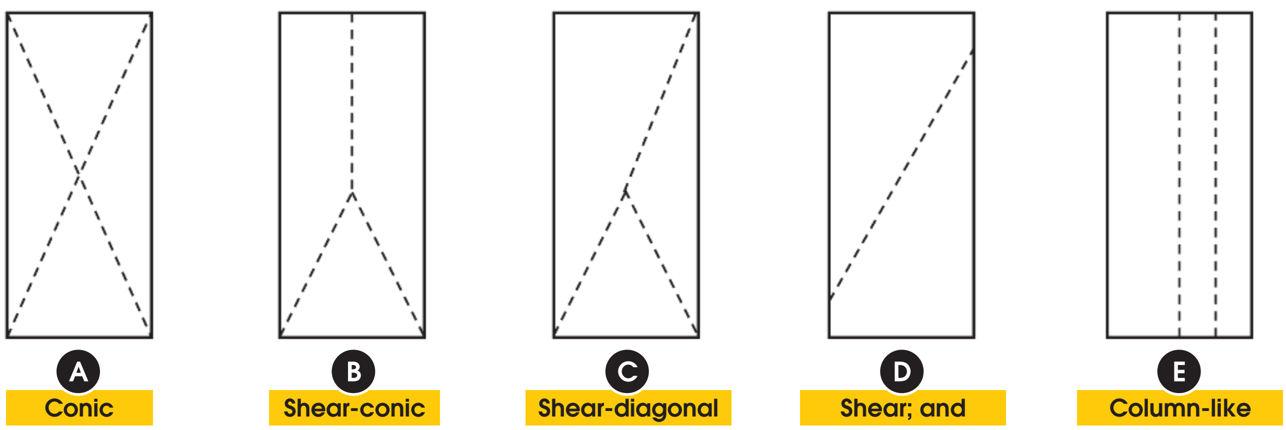
Hampel *et al*. [4] and Pivonka *et al.* [5] performed studies on prediction of failure mode in concrete samples (Figure 2). However, they neglected to account for the friction between the loading platens and the specimen (a procedure that significantly simplifies the structural analysis, but does not solve the problem of the influence from the extremities). Because the Poisson effect [6], in the contact platen-specimen friction, stresses necessarily arise due to the difference of freedom to deformation of the central part of the specimen and the restriction of its ends. These stresses are negligible in the case of samples of high slenderness, which was considered at the time of the choice of height/diameter ratio of 2 (cylindrical form). However, for this relationship, another problem comes out, which is the beginning of the effects of buckling, studied by Leonard Euler in the 18th century [7]. So, it is not easy to find a geometry that does not present limitations (i.e., engineering should be content with a geometry that has fewer problems, instead of an ideal geometry).

Another question, addressed by Bažant and Becq-Giraudon [8], refers to the evaluation of cross sections subjected to compressive stress by the fracture mechanics of Griffith. From the analysis of some accidents involving concrete structures, these researchers have proposed a way to predict the fracture energy of concrete from the compressive strength, size of aggregates, etc.

Specifically focused on failure modes of high strength concrete, several researchers evaluated both cubic and cylindrical samples, like Tue and Tung [9], Vonk [10] and Viso *et al.* [11], observing that the first break with a format similar to an hourglass, and the latter tends to a plan that breaks across the ends (Figure 3).

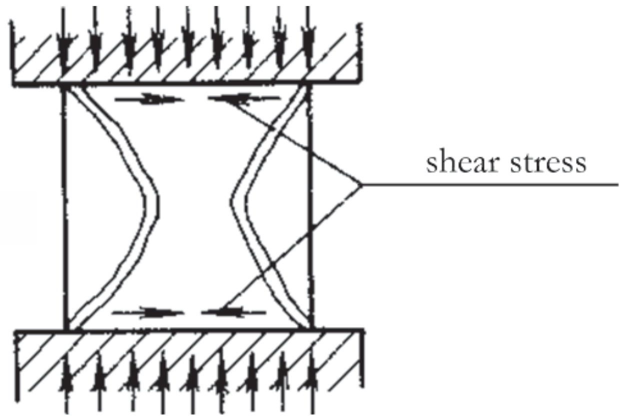
In research conducted on the fatigue behavior of metals (through alternating cycles of compression and tension), Miwa *et al.* [12]

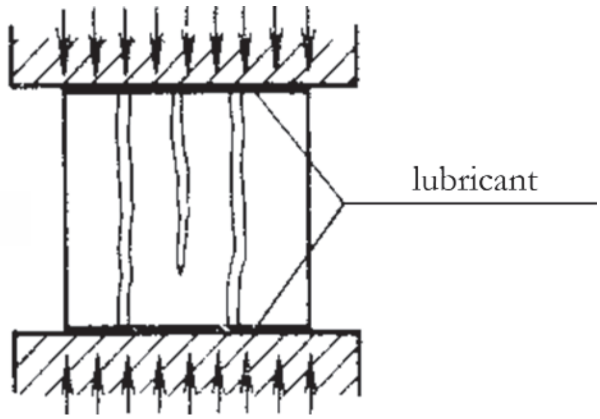
Figure 4 – Cylindrical failure modes according to Brazilian standard (14))



1 http://www.mathworks.com - Student version.
2 Licensed Software to Santa Catarina Federal University. Mix System is a system developed by Engineer Ricardo Sergio Pinheiro Medeiros and marketed by TQS Informática Ltda.

Figure 5 – Failure modes of cubic specimens (from (15))





analyzed modified cylindrical specimens of small dimensions. The novelty of such work is that the specimen geometry is the hourglass shape.

There are several important factors that affect the assessment of such strength, namely: (i) stress rate; (ii) height-to-base ratio; (iii) surface-related defects of the specimens such as planarity, parallelism and horizontality of the contact faces and also (iv) contact-related defects such as frictions and roughness between specimens and machine surfaces. Geometry of testing specimens also affects the assessment of the actual strength of the material. For instance, compressive strength determined by cubic specimens is almost 15 % higher than that obtained in cylindrical ones [13]. Under compressive loads, it has been shown that most failure patterns in cylindrical samples follow an hourglass shape due to shear stress, which direct cracking propagation orientated 45º in relation to the load direction [6]. However, there are several instances when crack profiles do not necessary follow such trend, which is evidently due to geometric features rather than intrinsic properties of the materials. Indeed, as pointed out by the Brazilian standard NBR 5739 – 1994 [14], it is expected that cylindrical specimens might fail in at least five possible ways, as shown in Figure 4. In these modes, it is possible to see the cracks generally pass through the contact faces in all modes with just one exception. This might corroborate the view that the strength distribution can be greatly affected by contact factors as pointed out earlier.

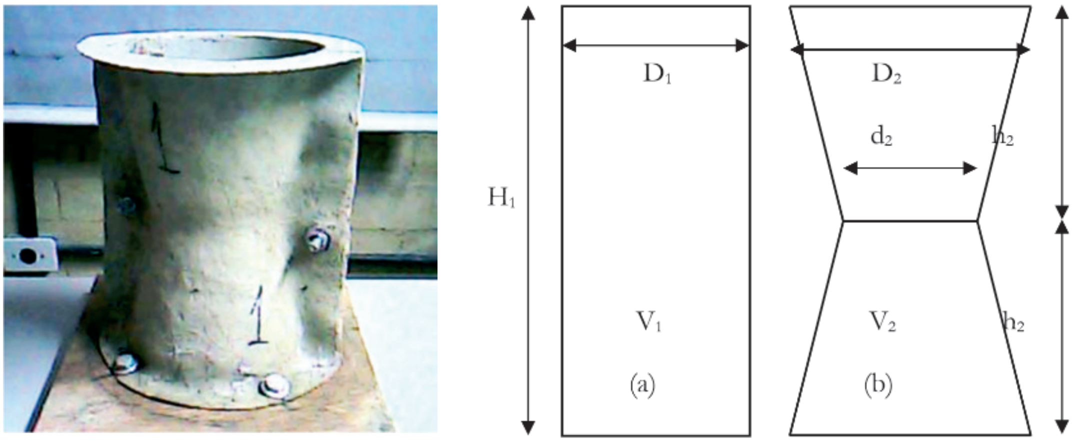
In the book *Estructuras de Hormigon Armado* (Spanish for Reinforced Concrete Structures), the Russian authors Sigalov and Baykov [15] analysed an interesting illustration (Figure 5) which deals with how specimens are subjected to compressive stress break.

Table 1 – Variations of geometry

Geometry	Dimension (cm)	Area (cm^2)	Material	Problem	Origin
Cube	15 x 15	225.0	Concrete	Densification*	Germany/Europe
Cube	5 x 5	25.0	Mortar	Densification*	Europe/USA
Cylinder	30 x 15	176.7	Concrete	Coating**	Usa
Cylinder	20 x 10	78.5	Mortar	Coating**	Usa
Cylinder	10 x 5	19.6	Paste/mortar	Coating**	Usa
Hourglass	30 x 18 x 12	113.1	Concrete	Unknown	Brazil
Hourglass	20 x 12 x 8***	50.3	Concrete/mortar	Unknown	Brazil
Hourglass	10 x 6 x 4***	12.6	Mortar/paste	Unknown	Brazil

* The density of corner is different of the center; ** the bottom coating is different of top coating, and the friction of plates change the results; *** this geometries were adopted here.

Figure 6 – Hourglass mold made by fiberglass and polyester. Cylinder (a) and hourglass (b)



In this figure, it is possible to see the characteristic bi-cone of rupture in the case (a). Thus, from observation of natural rupture in cubic and cylindrical specimens, and with the literature references, this work deals with the modeling of concrete specimens in an hourglass shape to evaluate the compressive strength.
So, even with the elimination and/or reduction of some problems presented by the geometry and form of preparation of specimens over the 20th century (and also in the beginning of this one), an unsolved problem still remains: what to do for the boundary conditions (edges) have no influence in the measures of the compressive strength of cementitious materials? Or else: how to make the platens of the machines do not interfere in the magnitude of the compressive strength of cementitious materials?
This study proposes a new geometry for the molds to cast specimens of cementitious materials, incorporating the solutions obtained during the 20th century, and significantly reducing the problems from the influence of boundary conditions.

2. Materials and experimental program

Variations in geometry experienced in the last century are summarized in Table 1. It can be seen that the cubes predominate in Europe, while the cylinders are mostly present in the Americas.
In the last lines of the Table 1 (in bold typing), three new geometries of specimens that are proposed in this paper, for testing cementitious materials, are included.

2.1 Materials

Concrete and mortar with Portland cement CP II (equivalent to Pozzolan-Modified Portland Cement type I (MP) of the ASTM classification) were prepared (quartz sand, granitic coarse aggregate and potable water were used). The mold releasing was made 24 hours after casting the samples, followed by water curing until 7 and 28 days (after tests) at room temperature. The strength was determined by dividing the force by the area (half height) of the samples. The data was analyzed by Gaussian curve [16] fitted with least square method.

2.2 Experimental approach

Two shapes were used: (i) cylinder and (ii) hourglass shape (details in Figure 6 and Table 2).
For higher dimension specimens, adopted for concrete, a variation of water/cement ratio was used to analyze the difficulty in

Table 2 – Characteristics of geometries tested

Geometry	Material	Mold	H_1 (cm)	h_2 (cm)	D_1 (cm)	D_2 (cm)	d_2 (cm)	$A_{extreme}$ (cm^2)	A_{centre} (cm^2)	V_1 (cm^3)	$2V_2$ (cm^3)
Cylinder	Mortar	Steel	10.00	–	5.00	–	–	19.63	–	196.35	–
Hourglass	Mortar	Acrylic	10.00	5.00	–	3.00	2.00	28.27	12.57	–	198.97
Cylinder	Concrete	Styren	20.00	–	10.00	–	–	78.54	–	1570.80	–
Hourglass	Concrete	Fiberglass	20.00	10.00	–	6.00	4.00	113.10	50.26	–	1591.74

Table 3 – Geometries – mix proportion of tested samples

Material Mort./Concr.	Geometry Cyli./Hour.	Specimens (Unit)	Mix proportion				Age of curing (day)
			Cement	Sand	Coarse aggregate	W/C	
Mortar	Cylinder	20	1.00	3.00	–	0.50	7
Mortar	Cylinder	20	1.00	3.00	–	0.50	7
Mortar	Hourglass	20	1.00	3.00	–	0.50	28
Mortar	Hourglass	20	1.00	3.00	–	0.50	28
Concrete	Cylinder	30	1.00	2.20	2.50	0.45	28
Concrete	Cylinder	30	1.00	2.20	2.50	0.55	28
Concrete	Cylinder	30	1.00	2.20	2.50	0.65	28
Concrete	Hourglass	30	1.00	2.20	2.50	0.45	28
Concrete	Hourglass	30	1.00	2.20	2.50	0.55	28
Concrete	Hourglass	30	1.00	2.20	2.50	0.65	28

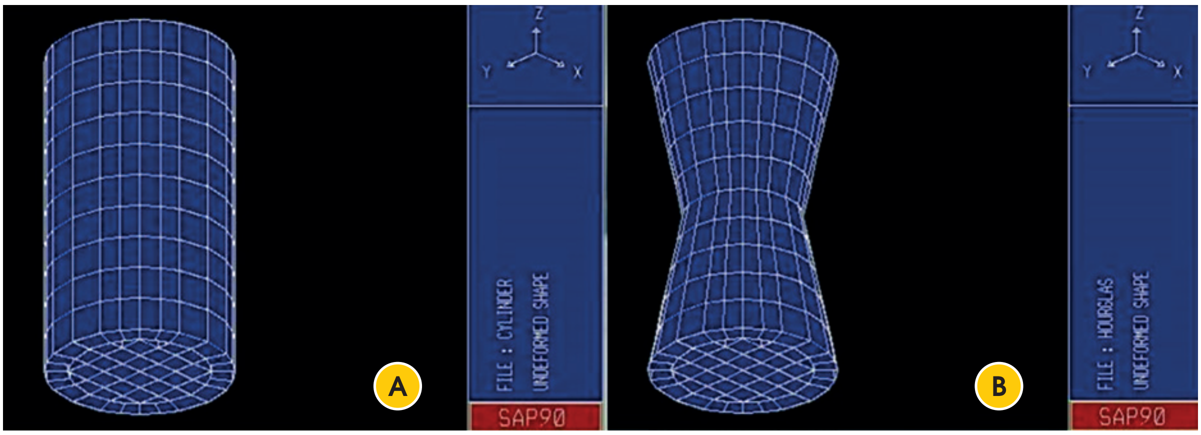
Note: no additives, admixtures and/or superplasticizers were used.

accomplishing densification of concrete in the hourglass mold type, due to necking of the central section.
For the mortars, 20 specimens for each age (7 days and 28 days) were casted. For concrete, due to its natural heterogeneity, 30 specimens of each condition were prepared. Czarnecki *et al.* [17] conducted statistical studies on concrete specimens, and adopted the quantity of 36 as an adequate number of tests, considering distribution of T-test (significance level of 95%).
The mixes used for the preparation of the specimens are listed in Table 3.
Concerning the difficulty of casting, the traditional procedure, specified in the Brazilian Standard (12 strokes per layer for a total of 2 layers), fits satisfactorily in the hourglass shape specimens, for those prepared with both high and low water/cement ratio (0.65 and 0.45).

2.3 Numerical approach

Numerical simulation was carried out by means of Finite Element Method (FEM), using the Structural Analysis Program (SAP) software and Ritz method (brick Wilson formulation) [18, 19]. The material was assumed to be perfectly elastic, with modulus of elasticity of 30 GPa, and Poisson's ratio of 0.2.
The discrete FEM models for both geometries can be seen in Figure 7.
On the top and bottom of the samples, the joint horizontal displacements were restricted. On the bottom, even vertical displacements were restricted. In all the other nodes, all 6 degrees of freedom were released. This procedure allows the Poisson's effect, which is compatible with the actual testing of compressive strength, practiced in laboratories.

Figure 7 – Cylindrical (a) and Hourglass-like (b) FEM mesh



3. Results and discussion

3.1 Mortar analysis

3.1.1 Experimental analysis

Table 4 shows the compressive strength results for both shapes at the ages of 7 and 28 days.
A first look shows that the average of both shapes was very similar at both ages despite the reduced section at the middle of the hourglass specimens. Hence, there should be no significant effect of the specimens shape on the assessment of the compressive strength of the mortar.
Nevertheless, the standard deviation was slightly higher for cylinder-shaped specimens, which was greater at later age. Nonetheless, a closer look at the stress distribution reveals that the effect of specimens shape were rather different at both ages as can be seen in Figure 8.
For cylindrical shapes, a Gaussian fitting could only be performed with certain significance when two peaks were considered, suggesting two groups of effects dominating the strength of such specimens. This trend was not observed for the hourglass shape in which a single Gaussian peak was able to fit the data with better correlation coefficients at both ages. This might indicate that the different failure modes, as suggested by the aforementioned standard ([14], Figure 4), might have influenced such a trend. It is interesting to note that the velocity of the rupture was much slower for hourglass shapes, because of its smooth section reduction variation. This might represent an interesting alternative in the case of high strength concrete in which rupture is very abrupt.
Figures 9 and 10, respectively, show typical failure modes in cylindrical and hourglass-like specimens. Indeed, whereas most failure modes in cylinders were shear (Figure 9(a)) and column-like (Figure 9(b)), shear mode of failure was the only mode observed in all hourglass shape specimens ((Figure 10(a) and (b)). The fact that cracks propagated through contact faces in cylinders, but not in hourglass shape, seems to corroborate the view that the reduction of section, as in hourglass shapes, helps to concentrate stresses in sections. Hence, there is evidence to suggest that the latter seems less affected by contact-surface-related problems than the former shape. In fact, the normal stress on the top of the cylinder sample is twice as high as that of hourglass shape sample. Therefore,

Table 4 – Compressive strength of mortars

7 days curing			28 days curing		
Sample	Strength (MPa)		Sample	Strength (MPa)	
	Cylinder	Hourglass		Cylinder	Hourglass
1	17.57	20.46	1	36.92	41.60
2	21.77	19.05	2	36.16	38.64
3	17.19	17.63	3	37.56	39.13
4	18.33	24.97	4	42.65	39.79
5	18.97	20.81	5	42.02	37.65
6	21.65	23.98	6	35.65	42.42
7	21.77	21.73	7	43.42	36.17
8	19.23	19.05	8	35.78	43.57
9	17.19	20.46	9	45.96	40.78
10	22.15	22.57	10	36.29	39.79
11	19.10	20.46	11	41.89	39.30
12	18.46	22.57	12	42.40	36.34
13	22.03	18.34	13	37.18	38.97
14	21.65	19.05	14	35.91	32.72
15	23.55	19.75	15	42.02	40.28
16	22.28	21.87	16	37.94	37.82
17	17.44	21.87	17	37.31	44.39
–	–	–	18	41.38	41.43
–	–	–	19	43.04	42.25
–	–	–	20	44.44	40.45
Average	20.02	20.86	Average	39.80	39.67
St. deviation	2.15	1.99	St. deviation	3.39	2.73

the horizontal stresses due to friction are twice lower for hourglass shape samples.

3.1.2 Numerical analysis

Numerical analyses show stress distribution of both shapes (Z-axis, vertical stress) as can be seen in Figure 11 and Figure 12, respectively. Although it is not possible to determine the ultimate compressive strength by using linear elastic analysis, the strength distribution is important to assess possible failure patterns that are more likely to occur at greater strength concentration. Stress distribution in cylinders is more concentrated at the top of the specimens, where the load is applied. Also, failure can occur at any position in this geometry given that strength is somewhat uniform throughout the section. Interestingly, natural hourglass shape for the stress distribution appears in the middle of cylindrical specimen.
Nonetheless, the central part of the hourglass shape experiences greater stress concentration, hence, greater chances of failure will be concentrated at the middle height of specimens.

3.2 Concrete analysis

3.2.1 Experimental analysis

After one day, the specimens were uncased. Just one hourglass specimen (W/C ratio = 0.45) presented excessive voids. Due to the quantity of imperfect specimens being small (just one sample), the geometry in the form of hourglass does not affect the density, significantly.

3.2.1.1 Compressive strength results

The results of compressive strength are expressed in Table 5.
The results clearly indicate that the specimens prepared in the hourglass shape have compressive strength greater than the

Figure 8 – Compressive strength distribution of cylinder (top) and hourglass (bottom) shapes at 7 (left) and 28 days (right)

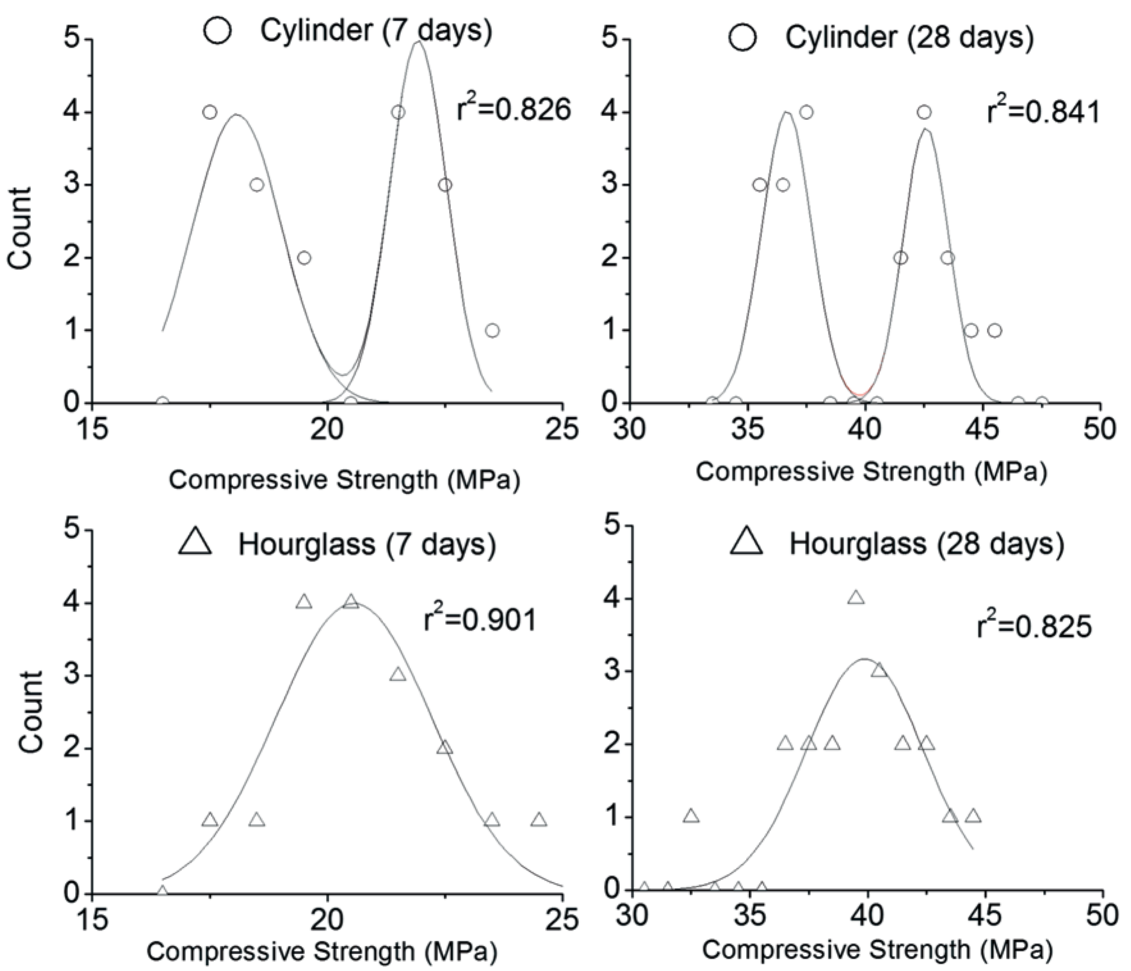


Figure 9 – Cylinder: shear plane mode of failure and column-like mode of failure

A Shear plane mode of failure

B Column-like mode of failure

Figure 10 – Hourglass: shear plane mode of failure

cylindrical (48.01%, 44.07% and 36.83%, respectively). This means that the effects related to the ends of the specimens (present in the cylindrical ones) have influenced the results, while results for the specimens in the hourglass shape represent only the determination of the resistance of the material. Thus, the measurement of the characteristic 'strength of concrete' from cylindrical specimens leads to lower values than the actual ones.

What is the explanation for the difference between the compressive strength of concrete and mortar prepared in the hourglass? Consider the following figures (Figures 13 and 14).

The type grading and distribution of the aggregates have an

Figure 11 – Stress distribution for cylinder shape

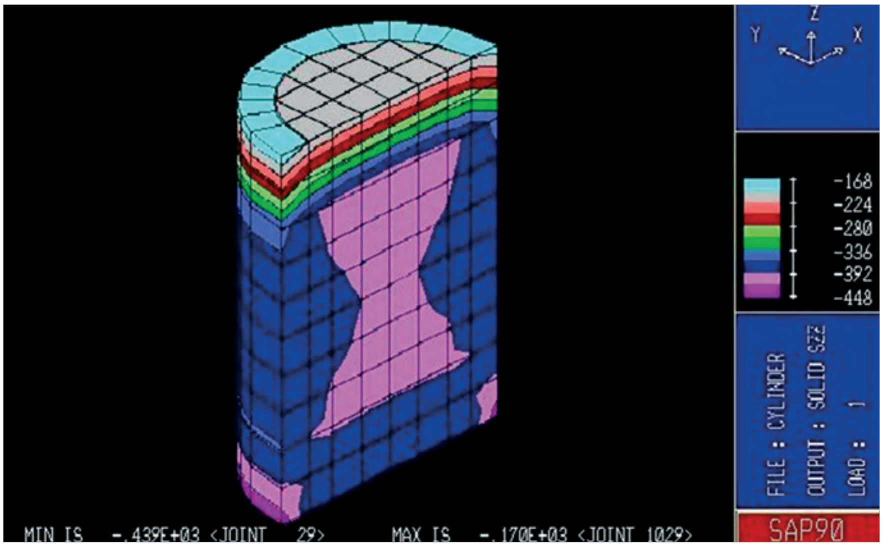
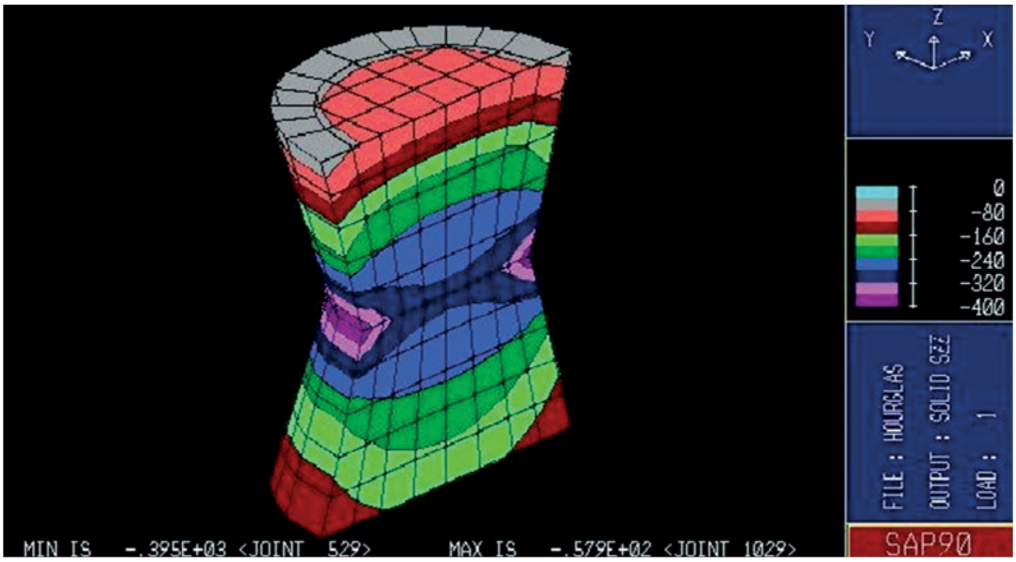


Figure 12 – Stress distribution for hourglass shape



effect on the failure mechanism. However, for hourglass, the failure mode is always a single shear plane (≈ 46º).
So, the hourglass is able to assess concrete and mortar, whereas the cylinder which is only able to evaluate resistance of mortars. Therefore, the hourglass is recommended for any type of cementitious material, whether it is composed only of small grains of sand or large gravel grains, such as concrete. Note that the hourglass shape forces the concrete to break at a certain angle (≈ 46º) at which the shear occurs in gravel (unlike the cylinder, which tends to break due to the effect of separation of parts of the tensile specimen).
This is an interesting result because it shows that concrete evaluated in cylinders has the compressive strength lower than the

Table 5 – Results of compressive strength of cylinders and hourglass specimens (MPa)

W/C ratio					
0.45		0.55		0.65	
Hourglass	Cylinder	Hourglass	Cylinder	Hourglass	Cylinder
31.89	48.34	28.27	39.79	19.61	27.95
31.19	47.75	28.65	39.19	22.15	28.45
31.32	48.14	26.48	40.58	22.66	31.04
32.59	49.74	29.54	40.39	20.75	29.05
34.38	53.12	30.43	38.99	21.39	30.44
33.74	50.13	26.67	39.89	20.50	29.05
32.09	49.74	25.21	38.60	21.52	29.44
34.38	49.74	29.54	36.80	21.45	30.64
35.27	49.14	30.05	40.19	19.35	30.44
32.59	47.55	30.30	40.98	21.20	31.23
34.25	46.75	25.46	35.81	19.61	23.87
31.70	48.34	22.66	36.21	18.33	25.96
31.58	48.94	23.94	31.43	16.30	24.27
31.77	47.85	26.23	31.83	19.74	24.47
28.78	44.76	21.90	36.61	19.61	26.66
34.32	46.15	25.72	37.00	19.35	26.26
34.76	43.77	24.45	37.00	17.19	25.66
34.31	42.97	26.48	30.24	18.59	25.86
33.10	48.94	25.21	38.99	19.86	23.87
30.62	52.52	22.92	33.42	19.61	25.66
33.68	50.53	24.19	35.61	19.48	23.28
32.59	49.54	23.94	32.43	18.08	23.87
33.87	51.53	24.45	36.01	19.74	27.26
35.90	49.34	21.39	33.02	20.12	26.06
34.38	50.53	20.63	37.80	16.93	27.06
35.14	50.73	24.19	34.22	20.12	25.46
35.40	50.13	20.88	35.01	19.61	27.06
31.07	51.63	23.68	35.81	19.86	24.77
34.63	52.92	23.17	33.82	19.74	27.45
36.03	54.61	21.77	34.82	19.74	27.65
Average					
33.24	49.20	25.28	36.42	19.74	27.01
Standard deviation					
1.74	2.60	2.85	2.93	1.41	2.32

Figure 13 – Case of mortar

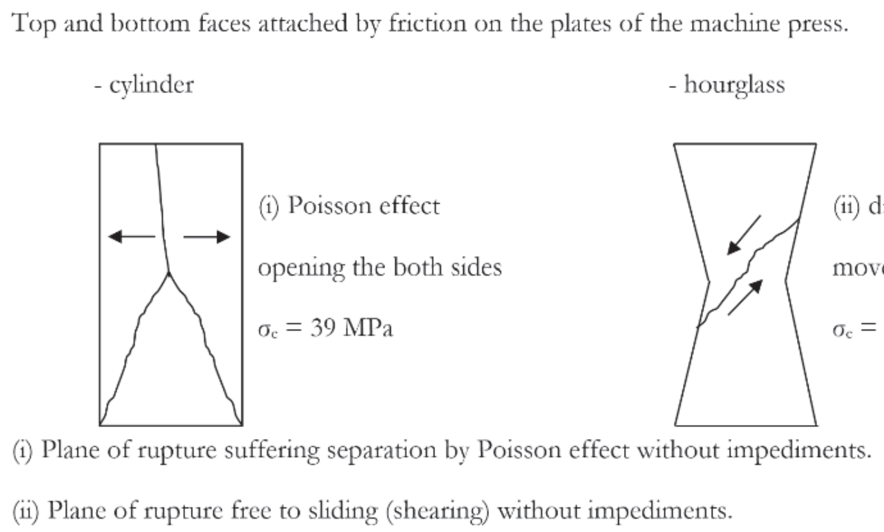


Figure 14 – Influence of course aggregate in cracking of concrete

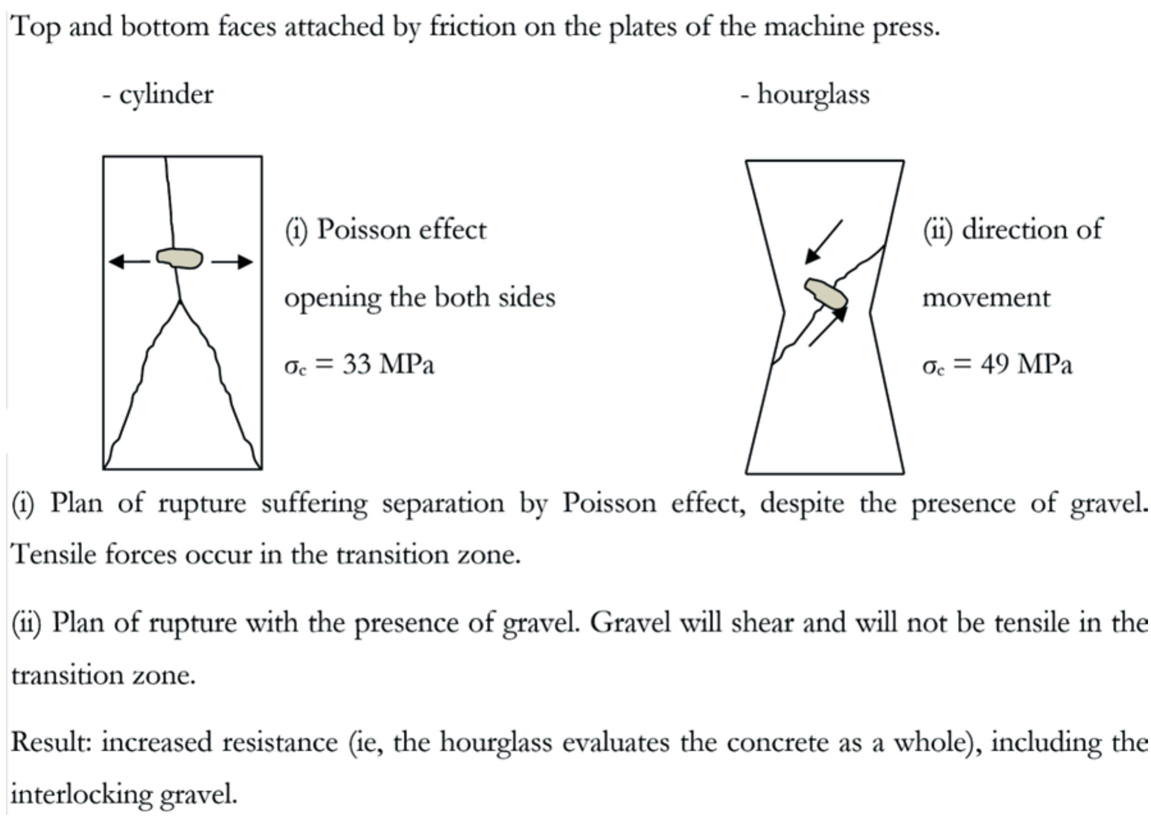
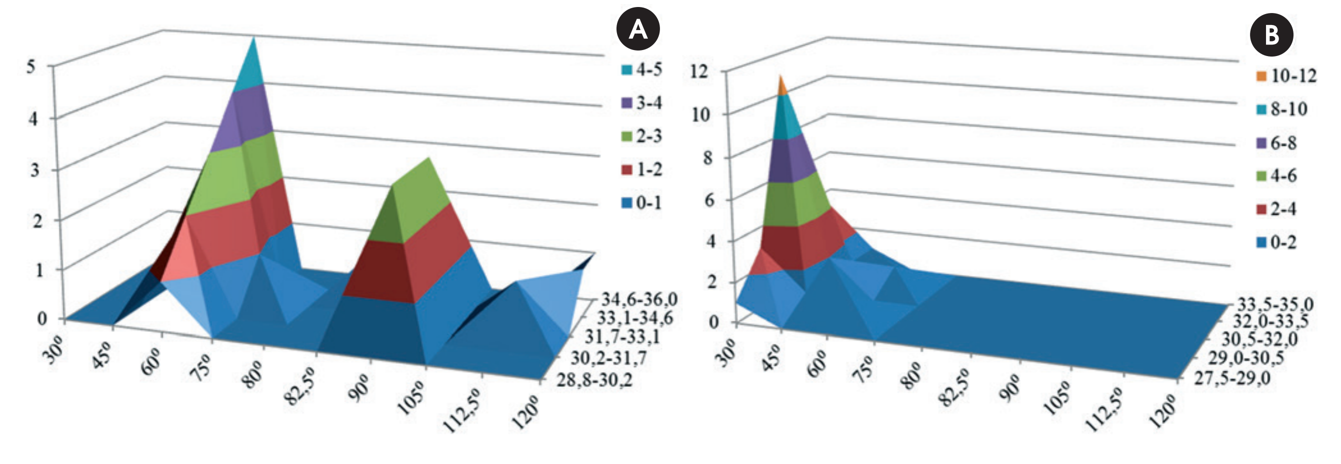


Figure 15 – WCR = 0.45. Count (vertical axis) x angle of rupture (o) x compressive strength (MPa): cylinder (a) and hourglass (b)



actual value (i.e., concrete structures safety is greater than what is considered). This result does not cease to be good because it points to lower values, which implies an additional security to concrete structures.
However, this fact should not be interpreted as a way to reduce the safety coefficients of the structures, because several other factors interfere in their calculation, and researches on this subject are still preliminary for deciding on something of this nature.
The organization of Table 5 in form of frequency distributions can be seen in Figure 15, Figure 16, and Figure 17.
The distributions clearly show the trend of the hourglass specimens ruptured at low angles in the central region. This result is interesting because it shows that the hourglass induces the rupture in the material without the interference of shear developed in contact with the mechanical press. In the cylindrical shape the distributions have been more open with the presence of several angles of failure, many of them passing through its ends. The work initial expectation was to assess, with a certain approximation, the compressive strength according to the angle of rupture. However, even the tests with hourglass distribution do not allow this inference yet. Certainly, a larger number of samples may suggest a better behavior. In any case, the hourglass shape significantly reduces the problems that arise from the plates of the machine.
Working with mortar specimens (10 cm high and 5 cm in diameter), Bezerra *et al.* [20, 21] found Gaussian distribution curves with correlation coefficients roughly equal to 0,900. The curves presented above do not reach this level of correlation, and indicate a new factor in the shape of an hourglass for concrete: probably

Figure 16 – WCR = 0.50. Count (vertical axis) x angle of rupture (o) x compressive strength (MPa): cylinder (a) and hourglass (b)

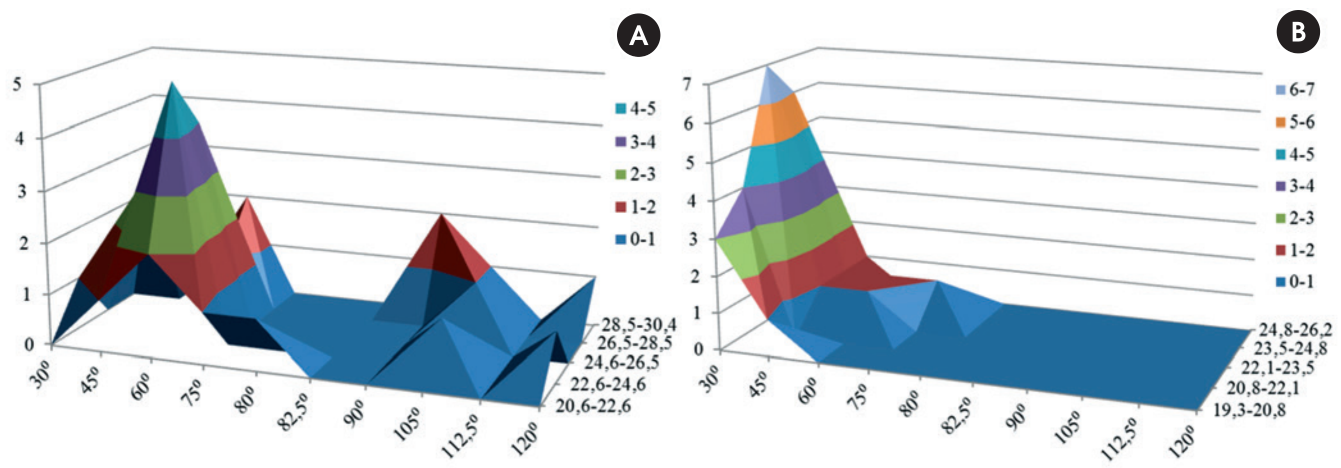
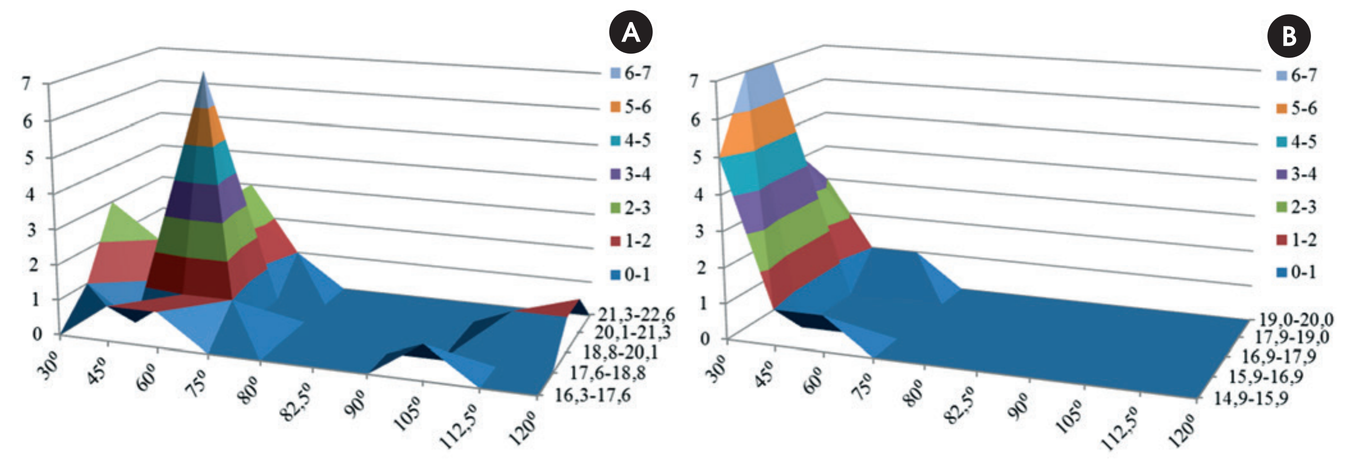


Figure 17 – WCR = 0.55. Count (vertical axis) x angle of rupture (o) x compressive strength (MPa): cylinder (a) and hourglass (b)



the presence of coarse aggregate in the area of disruption influences the type of breakdown, reducing the occurrence of rupture of the sheared type (see Figure 14), because of the friction developed between the broken halves and the coarse aggregates, which should hinder the sliding plane of rupture. Then, the results suggest that an hourglass shape with 20 cm high should be used for concrete with coarse aggregate of a maximum diameter of 19 mm. Of course, for larger sizes of coarse aggregate, it is necessary to prepare larger molds.

3.2.2.2 Another curiosity: Duff Abrams adjustment

The correlation between the compressive strength and the water/cement ratio has been a concern in civil engineering since the work carried out by Duff Abrams in 1908 [22]. For the Abrams curve, which obeys an equation of the type $Cs = A/B^{W/C}$, the following results were obtained (Figure 18).

As one can observe, the correlation between the two models was satisfactory, indicating the adaptation of the hourglass shape to the Abrams curve.

3.2.2.3 Numerical analysis

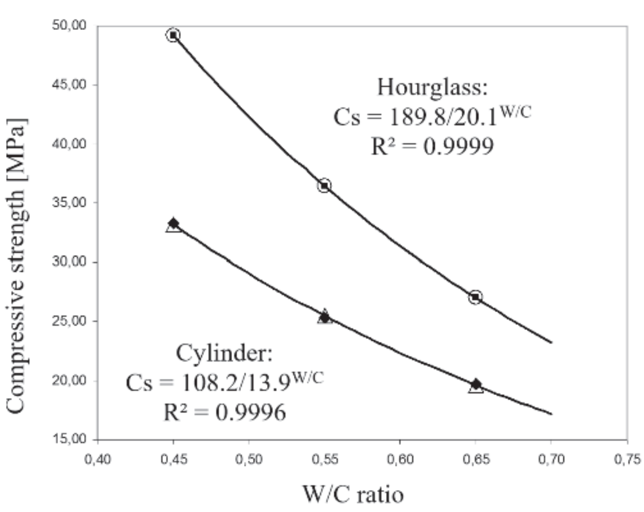
As with the specimens of mortar, the specimens prepared with concrete were also evaluated numerically by the FEM. It employed the software Structural Analysis Program (SAP) with the formulation of brick by Wilson and Habibullah [19] and Hirth Jr. [18]. The considered modulus of elasticity of the concrete was assumed to equal 30 GPa, and a Poisson ratio of 0.2. Figures 11 and 12 show aspects of the two models in the deformed condition of vertical stress.

A quick observation of the cylindrical model (Figure 11) reveals a unique figure of interest in the center, it is similar to an hourglass with a constant tension level (pink area). With the sample, you also see that the contour of the cylinder has tension levels of the same order of magnitude (blue area), suggesting the possibility of rupture at any point along the samples sides, and even the nearby parts of the support (edges). Thus, the cylinder is a shape that can break in both middle and ends, which is found in the tests, whose planes pass through several regions.

In the case of the hourglass shape, there is a stress concentration in the central part. It was also noted that, as you move away from this part, the tensions are reduced and the probability of failure in these regions is diminished.

Here you get to the main point of this work: it is unlikely that the hourglass breaks at the ends, because the tensions are small at such region (about 8 MPa). In the middle, there is a concentration of stress due to the reduction of the cross section. This fact is very interesting from the standpoint of casting and assessment of concrete strength, because two problems no longer exist in this

Figure 18 – Abrams adjustment curves



situation: (i) the first refers to the elimination of accuracy, concerning how to cap the specimens, i.e., the hourglass capping stops interfering in the results; (ii) the other refers to the certainty in determining the compressive strength of concrete without the interference of the particular characteristics of the machines.
An interesting feature is also the fact that specimens in the hourglass do not break abruptly, because only the central part is under a high level of tension. Hence the specimen will gradually break through an irradiation of cracks, unlike the cylindrical specimens that can break anywhere and ruptures, being more likely to brake brusquely. Thus, the hourglass specimens become particularly interesting in case of high-strength concrete, which often release sharp debris in compressive strength tests.

4. Conclusions

The hourglass shape is an interesting alternative for compressive strength assessment of normal strength mortars and concretes. Obviously, specifics studies have to be developed for high strength concretes.
However, the present study allows the following conclusions:
Hourglass specimens appears to present less contact-related effect than cylinders ones;
It (hourglass) does not seem to have a significant effect on the average value of compressive strength;
it does not appear to promote different modes of failure but, preferably, shear mode around the middle section. Hence, hourglass specimens tests result in statistical distribution (i.e. a satisfactory statistical correlation coefficient);
finite element model helped to assess strength distribution, which confirmed the advantages of the hourglass over the cylinder shapes as far as strength concentration at middle height is concerned;
the hourglass specimens have excellent correlation with the Abrams curve;
cylindrical specimens have a compressive strength lower than the real value; which means that concrete structures are a more safer than expected in the tests;
the adoption of the hourglass shape for evaluating the compressive strength of specimens is a feasible way to eliminate problems arising from the cap and particular characteristics of presses; and
the hourglass shape does not cause sudden rupture, as seen in the cylinders (which may be a good characteristic for compressive tests in high strength concretes).
In short, the hourglass shape is an interesting specimen geometry to assess the compressive strength of cementitious materials because it eliminates the interference of machines.

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