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Relationship between the compressive strength of silica fume mortar applied to the substratum and the one obtained in standardized cylindrical test specimens

Relação entre a resistência à compressão da argamassa com adição de sílica ativa aplicada ao substrato e àquela obtida em corpos-de-prova cilíndricos normatizados

N. R. VASKE [a]
nei.vaske@ufrgs.br

J. L. CAMPAGNOLO [b]
campagnolo@ppgec.ufrgs.br

D. C. C. DAL MOLIN [c]
dalmolin@ppgec.ufrgs.br

Abstract

Compressive strength values obtained from standardized tests are adopted in the use of silica fume mortar as a reinforcement material, however, they usually do not represent the compressive strength of mortar applied to the substratum. In a reinforcement procedure, each portion of mortar applied to the substratum undergoes densification according to the energy with which it collides with the substratum, resulting in different compressive strength values along the reinforcement; this affects the overall strength of the reinforcement as a whole, which, in turn, defines the new loading capacity of the reinforced structural element. In order to verify the actual behavior of a reinforcement mortar, a silica fume mortar plate dimensionally similar to a reinforced column face was executed, and prismatic samples extracted from the mortar plate were submitted to compression tests. The average compressive strength obtained was compared with the average compressive strength observed in cylindrical test specimens, molded from the same material used in the mortar plate. The prismatic samples' average compressive strength presented a reduction of 35% in this particular case.

Keywords: mortar, silica fume, reinforcement.

Resumo

No uso de argamassa com adição de sílica ativa como material de reforço adotam-se valores de resistência à compressão provenientes de ensaios normatizados, que tendem a não representar a resistência à compressão da argamassa após lançada ao substrato. Na execução de um reforço, cada porção de argamassa que é lançada sofre um adensamento que varia em função da energia com que colide com o substrato, gerando, desta forma, pontos de diferentes resistências à compressão por toda a extensão do reforço, refletindo diretamente sobre a resistência do reforço como um todo, que por sua vez define a nova capacidade de carga do elemento estrutural que esta sendo reforçado. Procurando verificar o comportamento real da argamassa de reforço, executou-se uma placa de argamassa com adição de sílica ativa com dimensões iguais a um reforço de uma das faces de um pilar, sendo extraídas amostras prismáticas desta placa e ensaiadas à compressão. Deste ensaio foi determinada uma resistência à compressão média que, comparada com a resistência à compressão média obtida de corpos-de-prova cilíndricos, moldados com a mesma argamassa com que foi executada a placa, demonstrou que a resistência à compressão média das amostras prismáticas extraídas da placa apresenta, particularmente neste estudo, uma redução em relação à resistência à compressão média resultante dos corpos-de-prova cilíndricos da ordem de 35%.

Palavras-chave: argamassa, sílica ativa, reforço.

[a] *Engenheiro Civil, Espec., M. Sc., Doutorando do Programa de Pós-graduação em Engenharia Civil (PPGEC), Universidade Federal do Rio Grande do Sul (UFRGS), Av. Osvaldo Aranha, 99, 3º andar, 90.035-190, Porto Alegre – RS, nei.vaske@ufrgs.br.*

[b] *Engenheiro Civil, M. Sc., Programa de Pós-graduação em Engenharia Civil (PPGEC), Universidade Federal do Rio Grande do Sul (UFRGS), Av. Osvaldo Aranha, 99, 3º andar, 90.035-190, Porto Alegre – RS, campagnolo@ppgec.ufrgs.br.*

[c] *Engenheira Civil, M. Sc., Drª, Programa de Pós-graduação em Engenharia Civil (PPGEC), Universidade Federal do Rio Grande do Sul (UFRGS), Av. Osvaldo Aranha, 99, 3º andar, 90.035-190, Porto Alegre - RS, dalmolin@ppgec.ufrgs.br.*

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1. Introduction

Reinforcement procedures, either to modify the structural function of elements when the service load increases or to correct structural damages that demand recuperation, require preliminary structural calculations that take into account the characteristics of the material to be employed.

Whether to reinforce or recuperate, knowing the compressive strength of the chosen material is essential in order to reliably design the reinforced structural element.

In the structural reinforcement technique using reinforced concrete and mortar (with or without the addition of products to improve its quality), the compressive strength is determined based on standardized procedures. However, the results obtained usually do not represent the compressive strength of mortar applied to the substratum.

The need for more realistic data concerning reinforcement procedures has become significant because they allow the design to be made according to different requirements, avoiding structural under-dimensioning, which may lead to unintended results.

This study aims at establishing the relationship between the average compressive strength of mortar applied to the substratum in reinforcement procedures and the average compressive strength related to the failure of test specimens using the same material, in this case, with the addition of silica fume.

2. Reinforcement Silica Fume Mortar

Silica fume is a by-product of silicon metal or ferrosilicon alloys industries, derived from the production of highly pure quartz and coil in electric arc furnaces. When the raw material used to produce these materials is heated, chemical reactions leading to the production of vaporized SiO_2, which looks like silica "smoke," occur. Under low temperatures, the "smoke" oxidizes and condenses into very small cylindrical particles consisting of amorphous silica. To remove these particles, the exhausting gases are filtered in funnel-filters, whose average diameter is about 0.1 μm, and the specific surface, 20,000 to 25,000 m²/kg (Neville [1]; Sellevold & Nilsen [2]; Malhotra & Mehta [3]).

Regarding the average diameters of the particles as well as the specific surface of silica fume, Kulakowski [4] performed analyses on silica fume samples from two sources in three different laboratories, using the laser granulometry method. The first results indicated that the average size of the particles widely exceeded the value of 0.3 μm; in the fourth analysis, performed with granulometric distribution by sedimentation, the average size was 0.3 and 0.25 μm for samples 1 and 2, respectively, with a specific surface of about 13,000 to 30,000 m²/kg.

The effects of silica fume added to concrete and mortar are observed through its physical and chemical properties.

The physical effect is due to the spherical shape of the particles and their extreme fineness, with an average diameter around one thousand times smaller in relation to cement. They act as microfillers, that is, fill the void spaces originated from cement hydration and lead to the decrease of capillarity, which provides greater densification and continuity to the cement paste and, consequently, to concrete or mortar.

The chemical effect is due to the high amorphous silica content and pozzolanic activity index with Portland cement of around 210% (Wolsiefer [5]). Mehta [6] refers to silica fume as a super pozzolan because of its high reactivity. The Portland cement hydration process generates mixes of calcium silicate hydrate and calcium hydroxide. The calcium hydroxide reacts in the presence of silica fume, forming calcium silicate hydrate in a very similar manner to the primary reaction, which responds for the main part of the paste strength.

The combined action of the physical and chemical effects results in changes in the microstructure and the macroscopic properties of mortars, both in the fresh and hardened states. Several researches on silica fume materials have reached the same conclusion.

Mailvaganam and Deans [7] state that silica fume addition is extremely important for mortars that will be used to repair/reinforce reinforced concrete structures, especially when high strength, low porosity, and permeability are required.

Buil et al. [8] analyzed the addition of silica fume in mortars with silica fume/cement ratio of 0.40 and superplasticizer/cement ratio of 2.4%, and observed a ***compressive strength*** 2 to 2.7 times higher in relation to the reference mortar, which was 28 days old.

Dal Molin and Schuler [9] studied the compressive strength of silica fume mortar and observed an increase of around 15% whenever the silica fume content grows from 0 to 10%.

Shannag [10] analyzed combinations of natural pozzolan and silica fume and verified that certain combinations can improve the compressive strength of mortars more effectively than silica fume or pozzolan acting alone. A strength of about 110 MPa was obtained using 15% silica fume and 15% natural pozzolan in relation to the cement mass at 28 days old.

Investigating the mechanic strength of mortars with silica fume contents from 0 to 30% of the cement mass and water/binder ratios of 0.35, 0.40, 0.45, and 0.50, Rao [11] concluded that, during the first ages (3 and 7 days), the compressive strength and the strength development rate for silica fume mortars was significantly greater, in general terms, considering any water/binder ratio. For water/binder ratios of 0.35, 0.40, and 0.45, the optimum silica fume content to obtain the highest compressive strength varied from 17.5 to 22.5%. For the water/binder ratio of 0.50, the mortar's compressive strength increased regardless of the silica fume content. The compressive strength improvement after 28 days was more moderate for water/binder ratios of 0.35 and 0.40 and relatively superior for 0.45. The best and most solid improvement in the compressive strength for any age and regardless of the silica fume content was observed in water/binder ratio of 0.50.

Mirza [12] analyzed several types of mortars as repairing material and, through slant shear tests with mortars with silica fume addition of 6%, observed a bonding strength of 12.7 MPa, which is approximately 2.5 times greater than the strength of the reference mortar (4.9 MPa).

Dal Molin and Schuler [9] considered the adhesion of mortars to the substratum employing mortars without silica fume, with 10% silica fume and water/binder ratio of 0.55. After conducting pull-out tests on wall claddings, they obtained strength values of 0.38, 0.33, and 0.37 MPa for mortars with silica fume addition at 3, 7 and 21 days old, and strength values of 0.17, 0.18, and 0.38 MPa for mortars without silica fume addition, which demonstrates a significant increase in the strength values with addition of silica fume, particularly in the first ages.

Referring to the adhesion between ribbed steel bars and silica fume mortar, Schuler [13] could not confirm significant differences

between mortars with and without silica fume addition but, on the other hand, pointed out the importance of activities such as the preparation and execution of a repair or reinforcement, since they determine the adhesion efficiency of steel bars aggregated to the hardened concrete surface and the covering material (in this case, mortar with and without silica fume addition).

Mattos et al. [14] studied the physical and mechanical properties of industrial cement- and polymer-based mortars and cement and sand mortars in a 1:3 mix, based on mass proportions, silica fume addition of 10% and water/binder ratio of 0.4. In slant shear tests with silica fume mortar, they observed a bonding strength of around 9.62 MPa, overcoming the industrial mortar strength (8.68 MPa) as well as the tensile strength minimum level (1.0 MPa) proposed by Silva [15] for repair mortars.

Mirza [12] observed that the ***elasticity modulus*** of a mortar with silica fume addition of 6% is similar to that of a common cement and sand mortar. The elasticity modulus of a silica fume mortar was about $1.12x10^4$ MPa, and the corresponding value for the mortar without addition was about $1.07x10^4$ MPa.

Paillere et al. [16] analyzed aspects related to mortar ***durability*** and highlighted the presence of silica fume in mortars, mainly in order to reduce their porosity. However, these mortars need to be carefully cured to efficiently reach their capacity. Wet cured, silica fume mortars obtained a total porosity reduction of 25% to 45% regarding the reference mortar.

Kulakowski [17] reports that both the water/binder ratio reduction and the silica fume content increase are statistically significant in relation to the chloride ion penetration, resulting in increases of up to 6 times in the chloride ions penetration resistance with silica fume addition of 15%.

Torii and Kawamura [18] report changes in the pore structure of mortars with 10 to 15% silica fume content, with an increase of pores smaller than 0.04 μm and a reduction of pores bigger than 0.1 μm. The silica fume mortar showed lower chloride ion permeability in relation to common mortars in the first and subsequent ages.

Schuler [13] studied the evolution of carbonation depth for silica fume mortars and recommends the use of mortars with addition of up to 10% as reinforcement passivation material. Vieira et al. [19] have recently confirmed this observation by studying the effects of silica fume addition in concrete in the event of reinforcement corrosion caused by carbonation.

Aköz et al. [20] studied the behavior of silica fume mortar under the action of sodium sulfate and magnesium sulfate solutions and temperatures of 20°C and 40ºC during a period of 300 days, observing that mortar deterioration was not accelerated due to the increase of the sulfate solutions temperature; in fact, some mortar qualities were significantly improved.

Zain et al. [21] studied the water permeability of mortars with and without silica fume addition under different curing temperatures and observed that the latter presented a water permeability increase under temperatures above 75ºC. In turn, silica fume mortars presented a water permeability decrease due to the increase of temperature, which suggests that the silica fume high pozzolanic reaction and microfiller effect under medium temperatures modify the open channels near the transition zone, making it denser and stronger with a thin and discontinuous porous structure.

Gao et al. [22] studied the qualities of silica fume mortars and the polyacrylic ester emulsion, and observed a decrease in porosity and diffusion of chloride ions as well as density increase. They also verified an increase in the mortars' compressive and bending strength.

After studying the carbonation process of silica fume concretes and mortars with water/binder ratios of 0.30 to 0.80 and silica fume content from 0 to 20%, Kulakowski [4] reported the existence of a threshold interval for the water/binder ratio, varying from 0.45 to 0.50. Below the water/binder ratio threshold interval, the carbonation process is mainly governed by the cement matrix porosity resulting from water content, pH, and $Ca(OH)_2$ content, hardly affecting the carbonation depth. Above the threshold interval, the chemical characteristics begin to significantly affect the carbonation depth. In this case, the $Ca(OH)_2$ consumption in pozzolanic reactions generated by silica fume becomes unfavorable for carbonation.

Regarding the presence of silica fume in mortars to be used to ***reinforce structural elements with reinforced concrete***, Campagnolo and Dal Molin [23] pointed out increases in durability, facility, and execution speed for this kind of reinforcement, as well as the elimination of formworks and the non-need of skilled labor, leading to costs reduction.

Campagnolo et al. [24] highlighted that the execution of reinforcements using silica fume mortars facilitates the execution and acquisition of the required materials and improves the adherence between the mortar and the old concrete, giving the reinforced element a monolithic aspect and financial advantages if compared to other techniques.

Schuler [13] analyzed the use of mortars with and without silica fume addition in relation to the above mentioned qualities and recommends a silica fume addition of 10% and water/binder ratio of 0.55, stating that this mix has the most favorable aspects regarding its application on the repair of reinforced concrete structures.

Campagnolo et al. [25] conducted a comparative study of techniques that improve the loading capacity of concrete beams using steel plates glued with epoxy resin, carbon fiber tissue glued with epoxy resin, and reinforcements incorporated through the use of Portland cement and silica fume addition mortar. From an economical point of view, the reinforcement technique using silica fume mortar obtained the lowest unit cost per loading capacity increase (cost/kN), being about 11 times lower in relation to the reinforcement technique using glued plates and 48 times lower regarding the carbon fiber reinforcement technique.

These references suggest that mortars with silica fume addition present the necessary requirements for reinforcing concrete structures, mainly due to the beneficial effects of silica fume on several qualities searched for in a reinforcement material.

3. Experimental Program

This item describes tests with the silica fume mortar. The mortar average compressive strength was determined based on the failure of prismatic test specimens extracted from the substratum and the mortar average compressive strength based on the failure of standardized cylindrical test specimens. The ratio between these values was determined in order to establish a coefficient able to express said relation, indicating the mortar compressive strength behavior when applied to the substratum in relation to the compressive strength verified in standardized cylindrical test specimens.

3.1 Conducted Tests

Due to the lack of a Brazilian standard indicating the use of prismatic samples to determine the compressive strength of mortars, we used the American standard ASTM C 109/C 109M [26], which determines the compressive strength of cement mortars using cubic samples with 50 mm long edges. Recommendations referring to load application speed during the experiment were taken from the American standard, as well as other recommendations concerning the cross-sectional area to be used to calculate the compressive strength, and the shape of the sample, since the cubic samples utilized in the present study have 25 mm long edges, delimited by the thickness of the plate acting as reinforcement.
Rectangular prismatic samples 50 mm high and with a square section of 25 mm were adopted in order to compare the compressive strength of the samples considering height/side ratios of 1 and 2.
Regarding the cylindrical test specimens, the compressive strength determination was based on recommendations indicated by Brazilian standard NBR 13279 [27].

3.2 Used Materials

3.2.1 Cement

Most reinforcements are executed on damaged structures that may collapse, and this intervention usually disturbs the users; therefore, the use of materials whose mechanical properties manifest right after the execution is highly recommended. High Early Strength Portland Cement (CPV-ARI) was utilized as hydraulic binder because, having a specific mass of 3.13 kg/dm³, it becomes highly resistant in the first days. The Portland cement CPV-ARI was also chosen because its composition has the least addition, being silica fume the only pozzolanic addition to the mortar (NBR 5733 [28]).

3.2.2 Silica Fume

Silica fume collected in a silicon metal factory and commercialized as a non-dense pure powder with a specific mass of 2.22 g/cm³ was used.

3.2.3 Fine Aggregate

Quartz sand with a specific mass of 2.63 g/cm³, determined according to Brazilian standard NBR NM 52 [29], presenting maximum characteristic dimension of 4.8 mm and fineness module of 2.50, according to Brazilian standard NBR NM 248 [30], was utilized as fine aggregate

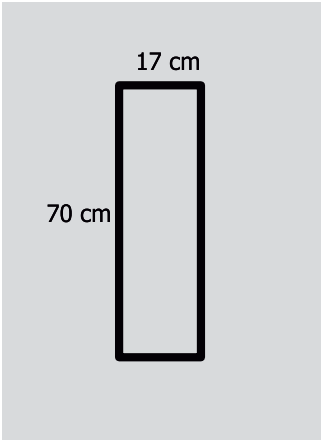
3.2.4 Water

Potable water made available by the water supply network of the City of Porto Alegre, State of Rio Grande do Sul, Brazil, was employed.

3.3 Methodology

Two wooden lathes with a cross section of 2.5 x 2.5 cm and 70 cm long were nailed, 17 cm apart, to a plywood plate 14 mm thick. Perpendicularly to them, two other lathes with the same cross section were also nailed, one of them near one edge and the other, near the opposite edge, forming a rectangular frame 70 cm high, 17 cm wide, and 2.5 cm thick, aiming at simulating a reinforcement 2.5 cm thick applied on a column face with cross section of 12 x 12 cm, and 70 cm high (Fig. 1). The plywood plate was firmly and vertically attached to a rigid structure so as not to suffer any vibration due to the mortar impact, representing a very similar situation to the one actually observed in the reinforcement of columns.

Figure 1 – Device used to make the plate



The mix chosen for the mortar mass was 1(cement): 3(sand), with 10% silica fume addition on the cement mass and water/binder ratio of 0.50, based on recommendations by Schuler [13], according to item 2.
A 4.0 dm³ mixture was made in a vertical axis, laboratory concrete mixer, which is enough to mold the plate, the cylindrical tests specimens, and eventual losses during the execution of the plate.
A laboratory technician used a trowel (Fig. 2) to apply the mortar, previously wetting the application surface. After straightening out, the plate was molded from the base towards the top and the edges towards the center.
The mortar was submitted to one form of densification only, induced by the impact of each mortar portion applied to the plywood plate, the pressure exerted by the laboratory technician during the straightening out, and the weight of the superposing mortar layers.
After the straightening out, the plate was wrapped in plastic paper in order to prevent the mixing water from evaporating until the mortar setting was finished; subsequently, the plastic was removed and replaced for a wetted burlap sack, which was once again covered with plastic to minimize the wet-curing water evaporation. This assembly was wetted 3 times during a 7 days period. The relative humidity beneath the burlap sack was measured before the new wetting procedure and a 97% rate was verified, confirming the efficiency of the curing method adopted.
After the cure, the plate was removed from the formwork and divided into 3 parts according to height, each part presenting 1/3 of the plate height, and into 6 parts according to width, each part presenting 1/6 of the plate width. The test specimens were labeled according to their position in the plate, so that, when submitted to

Figure 2 – Mortar applied to the plate

compression, in the case of the cubic test specimens, the loads were not applied perpendicularly to the reinforcement effective direction; the indications were made by numbers (Fig. 3); the tests specimens were extracted by shearing using a diamond disc, its top and bottom surfaces being polished afterwards. Subsequently, a paquimeter was used in order to verify their real dimensions, given the inaccuracy of the test specimens shearing process, which may lead to differences in the samples dimensions.

The prismatic test specimens were analyzed after 28 days through the placement of a leather plate 40 mm high, 40 mm wide, and 3 mm thick between the press plates and their top and bottom in order to prevent friction and stress concentration due to irregularities on the contact surface. The load speed required for the samples to fail was 1,000 N per second.

The cylindrical test specimens were molded and tested according to Brazilian standard NBR 13279 [26], except for the curing process, in which a similar procedure to the one utilized in the plate curing process was adopted. After molding, the test specimens were wrapped in plastic until the setting process ended, then removed from the formworks and wrapped in a wet burlap sack, on top of which was placed a plastic paper to prevent the water from evaporating. The assembly was wetted similarly to the plate and during the same period. The failure happened after 28 days.

3.4 Results Obtained

Table 1 presents the compressive strengths observed in the cylindrical test specimens using the reference reinforcement mortar.

Tables 2 and 3 indicate dimensions, failure loads, and strengths observed in the prismatic test specimens with height/side ratio of 1 (1 to 36) and height/side ratio of 2 (37 to 72), respectively.

Figures 4 and 5 show graphics comparing the failure strengths observed in samples with height/side ratio of 1 and 2, as well as the average strengths of the prismatic and cylindrical samples, respectively.

3.5 Analysis of the Results

The variation coefficient of the prismatic and cylindrical samples is satisfactory. In general, a variation coeffcient of 25% is considered as a limit to define a sample as being acceptable (NANNI and RIBEIRO, [31]).

The results related to the prismatic samples compressive stength were statistically analyzed by means of variance analysis (ANOVA), which allows the comparison of value groups considering the variability of averages among the groups and the variability of observations made within the groups. The analysis was based on the Fischer's distribution, in which F represented a significance level of 5% and F(ni,ne), in which ni equals the degrees of freedom for the effect and ne, the degrees of freedom for the error.

Figure 3 – Localization of samples on the plate

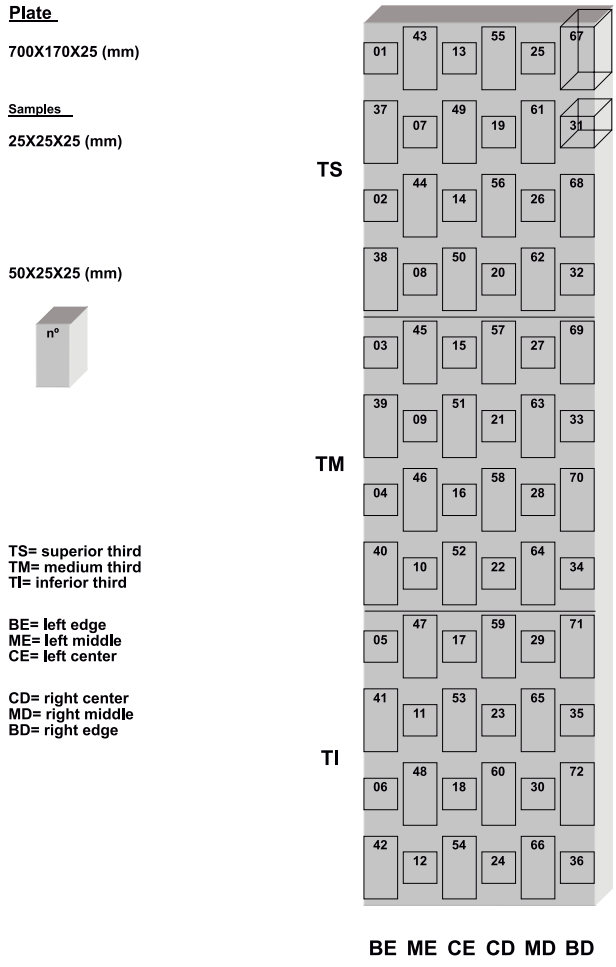


Table 1 – Results from compression tests using the reference mortar cylindrical test specimens

Sample (n°)	Load (kN)	Area (mm²)	Strength (MPa)
1	76,00	1963,50	38,7
2	86,50	1963,50	44,1
3	95,00	1963,50	48,4
Average strength (MPa)			43,7
Standard deviation (MPa)			4,85
Coefficient of variation (%)			11,1

Table 2 – Samples with height/side ratio of 1

Sample (n°)	Heigth (mm)	Cross section (mm)			Load (kN)	Strength (MPa)
		a	b	Area (mm²)		
1	24,95	24,83	24,87	617,52	20,5	33,2
2	24,56	24,86	24,85	617,77	18,5	29,9
3	24,79	24,80	24,90	617,52	16,0	25,9
4	24,75	24,89	24,88	619,26	22,5	36,3
5	24,68	24,78	24,85	615,78	20,0	32,5
6	24,70	24,78	24,83	615,29	20,5	33,3
7	24,68	24,80	24,93	618,26	23,0	37,2
8	24,86	24,89	24,82	617,77	19,0	30,8
9	24,77	24,83	24,80	615,78	22,5	36,5
10	24,84	24,78	24,75	613,31	17,0	27,7
11	24,71	24,84	24,89	618,27	20,0	32,3
12	24,69	24,83	24,88	617,77	22,0	35,6
13	24,72	24,90	24,85	618,77	20,0	32,3
14	24,75	24,86	24,80	616,53	24,0	38,9
15	24,98	24,85	24,75	615,04	21,0	34,1
16	24,71	24,79	24,85	616,03	24,5	39,8
17	24,88	24,82	24,84	616,53	19,0	30,8
18	24,89	24,78	24,79	614,30	18,5	30,1
19	24,87	24,85	24,80	616,28	20,5	33,3
20	24,87	24,86	24,76	615,53	20,0	32,5
21	24,82	24,87	24,80	616,78	20,0	32,4
22	24,81	24,78	24,83	615,29	19,5	31,7
23	24,78	24,82	24,75	614,30	20,5	33,4
24	24,92	24,90	24,84	618,52	17,5	28,3
25	24,69	24,84	24,80	616,03	19,0	30,8
26	24,87	24,76	24,80	614,05	19,5	31,8
27	24,92	24,83	24,85	617,03	15,5	25,1
28	24,84	24,77	24,78	613,80	18,0	29,3
29	24,77	24,78	24,80	614,54	21,5	35,0
30	24,88	24,82	24,79	615,29	21,5	34,9
31	24,80	24,78	24,76	613,55	25,5	41,6
32	24,73	24,80	24,78	614,54	20,5	33,4
33	24,81	24,80	24,76	614,05	16,5	26,9
34	24,90	24,84	24,75	614,79	14,0	22,8
35	24,94	24,90	24,87	619,26	22,0	35,5
36	24,82	24,83	24,88	617,77	21,5	34,8
Average strength (MPa)						32,5
Standard deviation (MPa)						4,0
Coefficient of variation (%)						12,4

The variance analysis model assumes that all observations are independent and normally distributed, and that each treatment has the same variance. Such assumptions were validated by means of residual analysis.

The variables, that is, factors that may influence the analyzed propriety, include the width of the plate divided into six strips, the corresponding height divided into three identical parts, and the height ratios among the samples, as well as the interactions among said variables.

Observing the ANOVA results (Table 4), one can verify that the samples height/side ratio significantly affects the compressive strength. On the other hand, the remaining factors, as well as the interactions among them, have only a minor influence on the compressive strength.

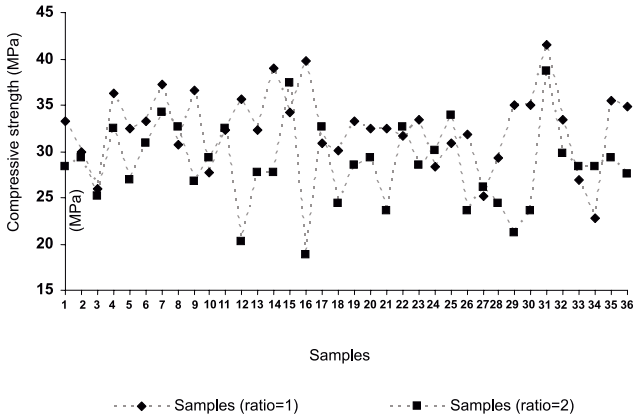
Regarding cylindrical test specimens, Neville [1] recommends a height/side ratio of 2, not only due to the elimination of top effects and the existence of a uniaxial compressive region inside the test specimen, but also because the obtained strength value is not significantly affected by small deviations in relation to said ratio. As to the prismatic test specimens, the influence of height relation on the smaller transversal dimension is also valid.

Mehta and Monteiro [32] inform that, compared to the standard test specimen, whose height/diameter ratio equals 2, test specimens with height/diameter ratio of 1 have strengths 15% higher, approximately.

Table 3 – Samples with height/side ratio of 2

Sample (n°)	Heigth (mm)	Cross section (mm)			Load (kN)	Strength (MPa)
			b	Area (mm²)		
37	50,08	24,87	24,86	618,27	17,5	28,3
38	50,19	24,75	24,85	615,04	18,0	29,3
39	50,01	24,78	24,83	615,29	15,5	25,2
40	50,23	24,84	24,84	617,03	20,0	32,4
41	50,20	24,79	24,76	613,80	16,5	26,9
42	50,15	24,82	24,78	615,04	19,0	30,9
43	50,29	24,77	24,77	613,55	21,0	34,2
44	50,16	24,80	24,78	614,54	20,0	32,5
45	50,01	24,78	24,85	615,78	16,5	26,8
46	50,18	24,79	24,77	614,05	18,0	29,3
47	50,38	24,82	24,88	617,52	20,0	32,4
48	50,42	24,77	24,84	615,29	12,5	20,3
49	50,10	24,84	24,77	615,29	17,0	27,6
50	50,00	24,75	24,76	612,81	17,0	27,7
51	50,17	24,82	24,77	614,79	23,0	37,4
52	50,36	24,77	24,75	613,06	11,5	18,8
53	50,02	24,79	24,77	614,05	20,0	32,6
54	50,05	24,78	24,83	615,29	15,0	24,4
55	50,04	24,79	24,80	614,79	17,5	28,5
56	50,10	24,81	24,79	615,04	18,0	29,3
57	50,00	24,85	24,77	615,53	14,5	23,6
58	50,08	24,84	24,74	614,54	20,0	32,5
59	50,03	24,79	24,78	614,30	17,5	28,5
60	50,05	24,85	24,80	616,28	18,5	30,0
61	50,04	24,80	24,98	619,50	21,0	33,9
62	50,11	24,85	24,75	615,04	14,5	23,6
63	50,03	24,78	24,79	614,30	16,0	26,0
64	50,14	24,83	24,78	615,29	15,0	24,4
65	50,17	24,77	24,76	613,31	13,0	21,2
66	50,16	24,85	24,80	616,28	14,5	23,5
67	50,01	24,94	24,90	621,01	24,0	38,6
68	50,19	24,93	24,88	620,26	18,5	29,8
69	50,28	24,78	24,90	617,02	17,5	28,4
70	50,04	24,82	24,88	617,52	17,5	28,3
71	50,58	24,80	24,79	614,79	18,0	29,3
72	50,21	24,88	24,88	619,01	17,0	27,5
Average strength (MPa)						28,4
Standard deviation (MPa)						4,4
Coefficient of variation (%)						15,5

Figure 4 – Strengths of samples with height/side ratios of 1 and 2



Considering that both cylindrical and prismatic test specimens behave similarly in relation to changes in geometry, height/diameter, and height/side ratios, it is possible to compare the average strength observed in test specimens with height/side ratio of 1 and 2, concluding that test specimens with height/side ratio of 1 have an average strength about 14% higher compared to test specimens with height/side ratio of 2. The behavior was as expected.

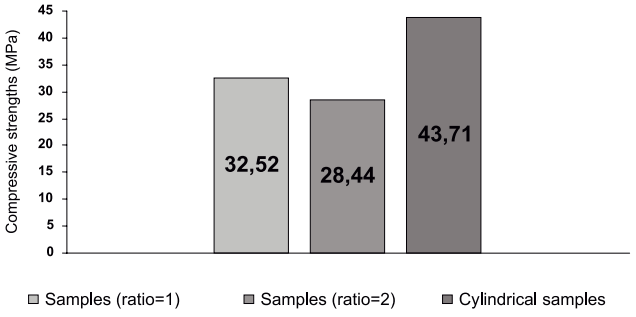
Considering the resulting factor from the ratio between the averages, 32.52/28.44, and correcting the test specimens' strengths with height/side ratio of 1 according to it, a new strength distribution is obtained for said samples, whose average strength is now equal to the average strength of test specimens with height/side ratio of 2.

The plate's average strength may be considered equivalent to the average of the studied samples' average strengths, that is, an average value of 28.44 MPa and standard deviation of 3.97 MPa.

Figures 6 and 7 present graphics comparing the corrected failure strengths from samples with heigth/side ratio of 1, heigth/side ratio of 2, and the average strength of the plate, as well as the average strengths from prismatic samples, plate, and cylindrical samples, respectively.

Table 5 shows the results from the new total sample variance analysis.

Figure 5 – Average strengths



Variables such as height, width, and the interaction between them, have no significant effects on the results; after correcting the samples with height/side ratio of 1, the ratio variable no longer affected the results, as expected.

Figures 8, 9, and 10 are transversal, longitudinal, and surface distribution graphics that allow a better understanding of the plate's strength behavior, considering the corrected strength of samples with height/side ratio of 1. Terms such as BE, ME, CE, CD, MD, and BD are the same as in Fig. 3, "Localization of samples on the plate."

Observing the prismatic samples extracted from the mortar plate that simulates a reinforcement, and considering the average strength of 28.44 MPa as its representative value, it is possible to establish a correlation with the cylindrical samples' average strength.

The average strength of the cylindrical test specimens molded with the same mortar as the plate was 43.71 MPa. Compared with the average compressive strength of the prismatic samples extracted from the plate (that is, 28.44 MPa), there is a reduction of about 35% in relation to the cylindrical test specimens' average compressive strength.

This reduction is probably due to a less effective densification, which leads to larger amounts of air trapped in the mortar during its application to the substratum in comparison with the stan-

Table 4 – Variance analysis of prismatic samples' compressive strengths

Source	SQ	GL	MQ	F_{calc}	F_{tab}	p-value	Effect
A (heigth)	97,90	2,00	48,95	2,56	3,26	9,10%	not significant
B (width)	82,55	5,00	16,51	0,86	2,48	51,41%	not significant
C (ratio)	299,96	1,00	299,96	15,71	4,11	0,03%	*significant*
AB (axl)	161,32	10,00	16,13	0,85	2,11	59,00%	not significant
AC (axr)	26,51	2,00	13,26	0,69	3,26	50,60%	not significant
BC (lxr)	39,09	5,00	7,82	0,41	2,48	83,90%	not significant
ABC (axlxr)	157,63	10,00	15,76	0,83	2,11	60,69%	not significant
Error	687,24	36,00	19,09				
Total	1552,19	71,00					

Obs: If $F_{calc} > F_{tab}$ consider that the treatment averages are different at level of significance $\alpha = 5\%$

dard densification occurred during the cylindrical test specimens' molding process.

When the reinforcement is being executed, each portion of the applied mortar undergoes densification according to the energy with which it collides with the substratum, which results in different strength values throughout the reinforcement, reflecting directly on its strength as a whole and defining the structural element's new load-bearing capacity.

The energy with which a given mortar portion is applied and which is transferred in the form of densification varies according to the mass of the mortar portion, the application speed, and the collision angle with the substratum. These factors, along with other factors that determine the strength of mortars and concretes, justify the stress variations observed.

Figure 6 – Strengths of samples with height/side ratio of 1 (corrected value), height/side ratio of 2, and the plate's average strength

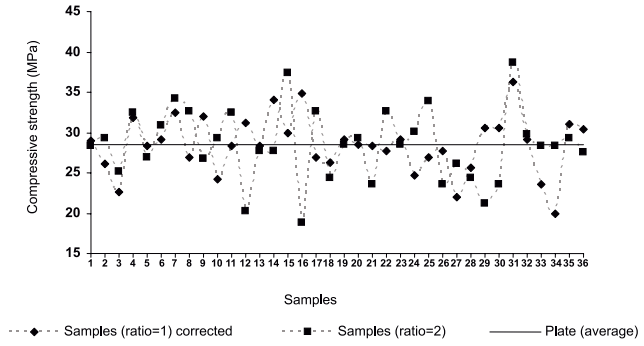
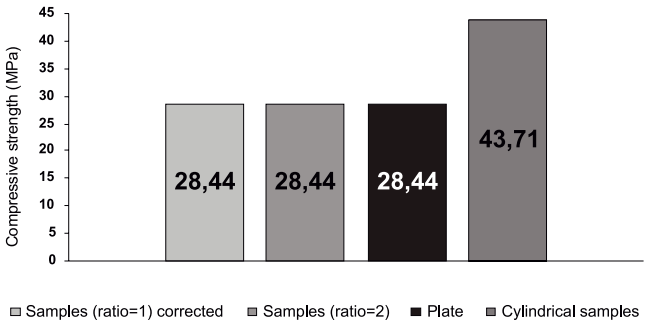


Figure 7 – Average strengths



4. Conclusions

- Considering the reinforcement technique for reinforced concrete structures, which was manually executed including all intrinsic variables involved in such a procedure, as well as the use of common materials, we have observed, in spite of the plate's strength loss compared to cylindrical test specimens, an average strength superior to most strengths present in currently used concretes.
- One possible way to reduce the variability of these results is making the plate by means of a mechanized process in which the mortar is more uniformly applied.
- We have noticed that the use of prismatic samples with height/side ratio of 2 is completely viable considering the ratio analysis regarding the used samples' heights, which facilitates the extraction, handling, and testing of the samples and does not demand the correction of the results. Therefore, we suggest such ratio for future works.
- Being the samples' compressive strength a continuous random variable which obeys normal distribution, and considering that the central tendency parameter is the arithmetic mean of the samples' strength and that the dispersion parameter is the standard deviation, it is possible to determine the typical strength for the mortar "$F_{a,}$" that is, a particular distribution value whose probability to be exceeded is 95%, and of not being exceeded, is naturally only 5%.
- Considering the 35% reduction observed in the plate-extracted prismatic samples' average compressive strength compared to the cylindrical test specimens' average compressive strength, as well as the mean and the standard deviation of the cylindrical

Table 5 – Variance analysis of prismatic samples' compressive strengths (with height/side ratio of 1, corrected values)

Source	SQ	GL	MQ	F_{calc}	F_{tab}	p-value	Effect
A (heigth)	86,12	2,00	43,06	2,45	3,26	9,39%	not significant
B (width)	75,10	5,00	15,02	0,85	2,48	51,68%	not significant
C (ratio)	0,00	1,00	0,00	0,00	4,11	100,00%	*not significant*
AB (axl)	133,03	10,00	13,30	0,76	2,11	67,00%	not significant
AC (axr)	23,69	2,00	11,85	0,67	3,26	51,34%	not significant
BC (lxr)	37,09	5,00	7,42	0,42	2,48	83,23%	not significant
ABC (axlxr)	129,81	10,00	12,98	0,74	2,11	68,69%	not significant
Error	633,63	36,00	17,60				
Total	1118,47	71,00					

Obs: If $F_{calc} > F_{tab}$ consider that the treatment averages are different at level of significance $\alpha = 5\%$

test specimens, and being the typical strength value "F_{ak}" correspondent to the distribution's 5% quartile, one can calculate "F_{ak}" using the table of normal distribution values and based on the average strength and the standard deviation, in which F_{ak} = (43.71 x (1-0,35)) – 1.65 x 4.85 = 20.41 MPa. This would be the most suitable strength value for dimensioning purposes.

- It is too soon to consider the reinforcement average strength as being equivalent to 65% of the reference cylindrical samples' average strength; therefore, more plates should be analyzed in order to effectively prove the relation that has been determined in this study.

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Figure 8 – "Cross-sections" of the plate

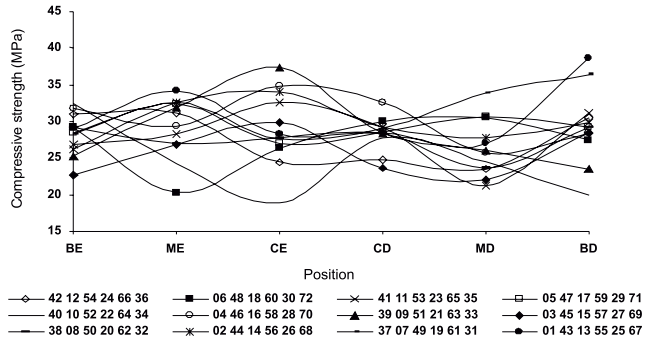


Figure 9 – "Longitudinal profiles" of the plate

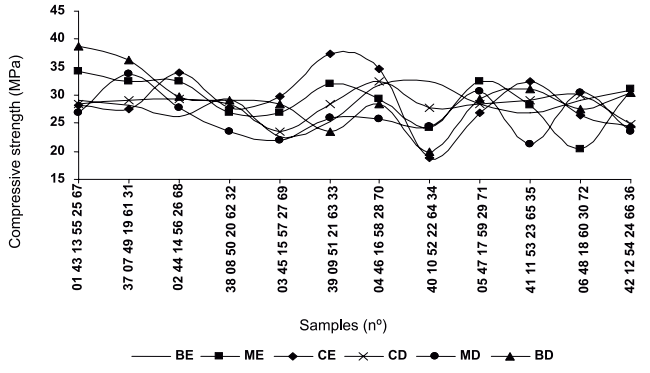
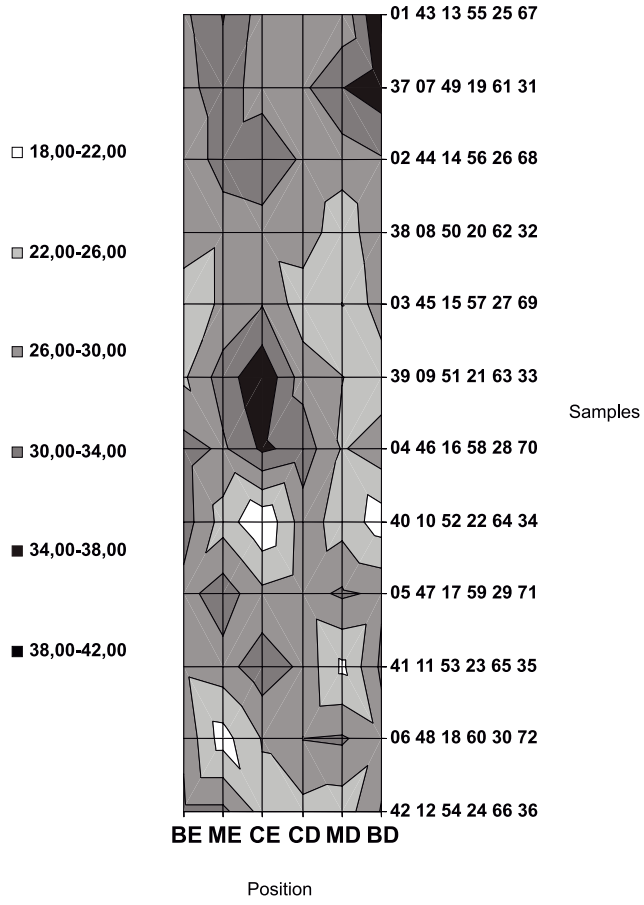


Figure 10 – Strength distribution on the plate (MPa)



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