

Analysis of Main Parameters that Affect Contact Area Between Mortar Rendering and Substrate: Use of 3D Laser Scanning Technique

Carina Mariane Stolz and Angela Borges Masuero

Abstract The objective of this research is to analyze the influence of granulometric composition of sand, application energy, and substrates superficial tension on the contact area of rendering mortars. Three different substrates were selected with distinct wetting behaviors: polyethylene, acrylic, and glass. The contact angle of drop water was measured by goniometer. Mortars were prepared with cement:lime:sand ratios of 1:0:3, 1:1:6, and 1:2:9, by content converted in mass, with sand composition of 25 % of each 0.15, 0.3, 0.6, and 1.2 mm grain sizes. Characterization tests in fresh and hardened mortars were performed to provide the technological control of mortars and concretes, as well as the characterization of the different rheological behaviors of the mortars by squeeze-flow and rotational rheometer methods. Mortars were applied to substrates with two different energies, and after curing time were parted from substrates and submitted to scanner 3D digitalization of interfacial area. Results showed that both mortar proportion and substrate superficial tension exercise influence on interfacial contact area development. Additionally, interaction between application energy and substrates superficial tension was significantly influent on contact area. Finally, 3D scanning is a promising new method that shows good performance to measure contact area to improve the understanding of bond strength.

Keywords Contact area · Mortar rendering · Laser 3D scanner · Application energy

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1 Introduction

In several countries, as Brazil, most building constructions use mortar rendering. However, poor technological control and the lack of technical expertise in the production of mortars rendering often produce pathological manifestations that may compromise the functions of renderings like protection, waterproofing, and aesthetic appearance of constructions.

In order to mitigate the onset of pathological manifestations, many researchers (Hall 1977; Hall and Yau 1987; Yates et al. 1994; Sugo et al. 2001; Ramos et al. 2012) have focused attention on the adhesion of rendering mortars.

Texture characteristics of substrates, the physical/chemical characteristics may influence the development of the contact area at the interface between mortar and substrate, exerting direct influence on adhesion. In this way of thinking, some researches focused on parameters related to substrates characteristics, as porosity (Pagnussat 2013) and rugosity (Hola et al. 2015; Santos et al. 2007; Pretto 2007; Stolz 2011), both the study of the interface between mortar and substrates, as in the study of the interface between layers of concrete structures. However, it is rare to find studies researching the influence of surface tension of cementitious materials on adherence at the interface between materials (Stolz and Masuero 2015).

In addition, researchers (Pretto 2007; Stolz 2011; Carasek 1996) have published images that indicate that increasing the surface texture of a substrate is not enough to increase adhesion if the mortar applied to the surface cannot penetrate the texture and wet the substrate. In this context, the rheological characteristics of mortar flows (Banfill 2003; Bauer et al. 2007; Senff et al. 2009) have been investigated in order to understand their influence on the phenomenon of adhesion and effective interfacial contact area.

Analogously, the adequate energy of mortars application that is fundamental to improve the flow and wet property of mortars on substrates has been investigated by many researchers.

The techniques of adhesion measurement are, generally, destructive. The most common technique is to apply a tensile strength on a mortar coating sample, measuring their tensile bond strength with a pull-off tester. However, some researchers look to correlate the bond strength behavior with the parameters measured in nondestructive testing.

Some nondestructive techniques found in technical researches consist of measure faults on interfacial contact area with ultrasound, correlating bigger times of wave's passage with failures presence (Tan et al. 1996; Davis and Brough 1972). Nevertheless, values measured by this technique are only comparative, and have influence of the heterogeneous characteristics of cementitious materials and substrate and rendering voids.

Other researches investigate interfacial failures by using thermographic cameras (Kylili et al. 2014; Freitas et al. 2014). This technique is effective to identify zones

with coating detachment, because of voids' difference in temperature; however, this does not demonstrate the quantitative values of adhesion in interface.

Thus, the path to find nondestructive techniques to estimate adhesion at the interface between systems, appears to thoroughly investigate the properties that affect this property and develop mathematical models for predicting the behavior of building systems.

In this line, the use of 3D laser scanning for characterizing surfaces appears as an accurate and easy to use tool. Some authors (Hola et al. 2015; Santos et al. 2007; Pretto 2007; Stolz 2011; Logins and Torims 2015; Deltombe et al. 2014) have used it to characterize surface roughness, using parameters provided by this device. The measurement of failures present at the mortar/substrate interface in order to quantify the real interfacial contact area is innovatory.

Considering all the variables that can influence the interface contact between surfaces, this study aims to analyze the influence of mortar proportioning and application energy of rendering mortar on interfacial contact area, when applied to substrates with different superficial tensions.

2 Methodology

The experimental program consists of producing three different mortars, with the same binder: aggregate ratio of 1:3, ranging lime hydrated percentage. So, mortars were produced in the proportions of 1:0:3, 1:1:6, and 1:2:9 (cement:hydrated lime:sand, in volume, dry materials, converted in mass in laboratory). These mortars were applied with two application energies in three different no porous and no rough (smooth) substrates, with distinct characteristics of wettability.

Experimental matrix is shown in Fig. 1.

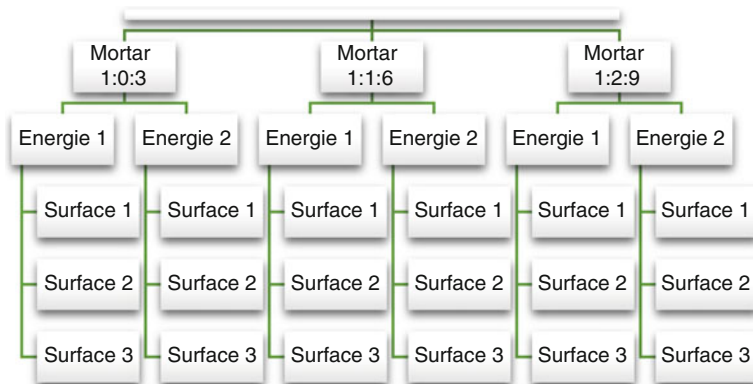


Fig. 1 Experimental matrix

2.1 *Mortars Production*

Three mortars prepared with compositions of 1:0:3, 1:1:6, and 1:2:9 (cement:hydrated lime:dry sand) were produced according to the Brazilian Standard NBR 13276/2005, for a 240 mm consistence index. The quartz sand used (specific mass: 2.50 g/cm^3) consist of the composition of sand with grains retained in sieves #1.2, 0.6, 0.3, and 0.15 mm, with equal fractions of each sieve, 25 % each (Unitary mass: 1.51 g/cm^3).

The cement used was Portland cement type IV (equivalent to the American IP (MS) grade), and the calcitic lime (specific mass 2.37 g/cm^3 , mean particle size $22.4 \text{ }\mu\text{m}$) complied by Brazilian standards limits.

2.2 *Mortars Characterization*

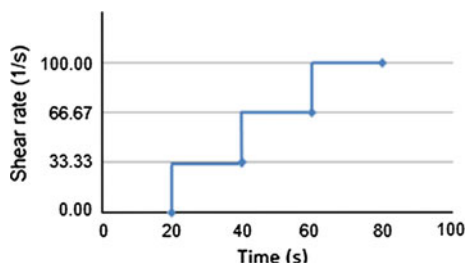
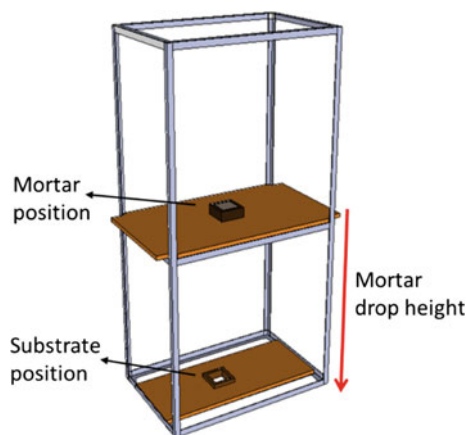
Characterization tests of fresh and hardened mortars were performed to provide the technological control of the materials, in addition to the characterization of the different rheological behaviors. In fresh state, bulk density, water retentivity, and air content characterization were performed, all of them according to Brazilian standards. In hard state, 28 days before mortars production, were performed flexural strength, compressive strength, dynamic elasticity modulus, density and capillary water absorption characterization tests, all according to Brazilian standards.

A Brookfield Rotational Rheometer R/S plus was used for the rheological characterization. The vane type V 30×15 was used, with a height of 30 mm and a diameter of 15 mm, in a standard container for all mortars. This type of vane is the most suitable for rheological tests on mortar coating suspensions and high-viscosity materials. The size of the vane was determined in preliminary tests. The rotational rheometer data was then treated with the Rheo3000 Software.

The routine chosen for mortar analysis consists of four lectures levels, each 20 s, reaching a maximum of 100 1/s shear rate (Fig. 2). The objective of this characterization was to take an apparent viscosity in a fixed point to compare different mortars.

2.3 *Mortars Application*

Mortars were applied to the substrates by means of a device called “drop box,” illustrated in Fig. 3, from two fixed fall heights of 30 cm and 1 m. A “drop box” is a simple device, used by some researchers (Pagnussat 2013; Stolz 2011; Stolz and Masuero 2015; Carasek 1996; Antunes 2005; Paes 2004), which allows users to

Fig. 2 Rheometer routine**Fig. 3** Schematic figure of “drop box” device

adjust the height from which the mortar will be dropped into the substrate, therefore controlling the applied energy.

2.4 Substrates Selection

Through preliminary analysis, three nonabsorbent substrates with different wettability ratings were chosen: glass, acrylic, and polyethylene. These substrates were characterized by measuring the contact angle of a drop of water projected on their surface, through a goniometer. Table 1 presents the chosen surface with their respective contact angles. The glass surface can be considered hydrophilic, with a contact angle of 27° , the acrylic surface is an intermediary surface, with 52° of contact angle, and the polyethylene surface is hydrophobic, with 96° of contact angle.

Using the Young–Laplace equation, the superficial tension of the surfaces was evaluated, which are presented in Table 2.

Table 1 Contact angle of a water drop with selected surfaces

Glass	Acrylic	Polyethylene
		
		
$\theta_m= 27^\circ$	$\theta_m= 52^\circ$	$\theta_m= 96^\circ$

Table 2 Superficial tension calculated by Young-Laplace equation

Surface	Superficial tension (dynes/cm)
Water (20 °C)/air (liquid/steam)	$\gamma_{LS} = 72.8$
Glass (solid/steam)	$\gamma_{SS} = 1000$
Acrylic (solid/steam)	$\gamma_{SS} = 41$
Polyethylene (solid/steam)	$\gamma_{SS} = 31$
Glass (solid/liquid)	$\gamma_{SL} = 935.13$
Acrylic (solid/liquid)	$\gamma_{SL} = -3.82$
Polyethylene (solid/liquid)	$\gamma_{SL} = -38$

3 Results

The results of mortar characterization and contact area quantification are presented in this section.

3.1 Mortar Characterization

Mortars proportioning are presented in Table 3.

Tables 4 and 5 present fresh and hardened (28 days) states characterization of mortars, respectively.

Table 3 Mortars proportioning

Mortar	Water (g)	Consistency (mm)	Water/cement ratio	Water/binder ratio
1:0:3	214	245	0.95	0.95
1:1:6	222	244	1.91	1.19
1:2:9	250	250	3.21	1.44

Table 4 Characterization tests of fresh rendering mortars

Mortar	Bulk density of fresh mortar NBR 13278/05 (kg/m ³)	Water retentivity NBR 13277/05 (%)	Air content NBR NM 47/02 (%)
1:0:3	2064	97	2.57
1:1:6	2062	98	2.20
1:2:9	2039	95	2.00

Table 5 Characterization tests of hardened rendering mortars

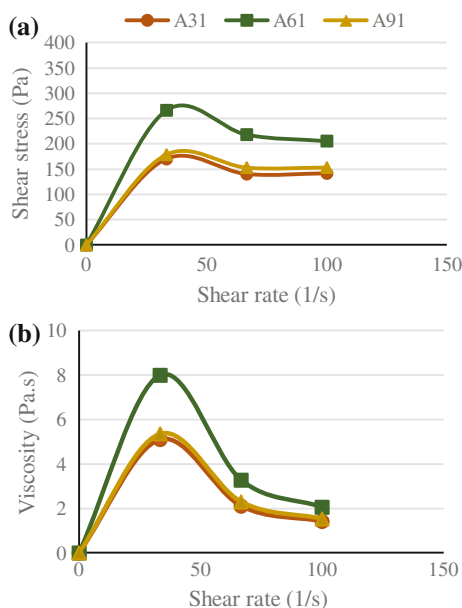
Mortar	Compressive strength NBR 3279/05 (MPa)	Flexural strength NBR 13279/05 (MPa)	Dynamic elasticity modulus NBR 15630/08 (GPa)	Density of hardened mortar NBR 13280/05 (kg/m ³)	Capillary water absorption NBR 15259/05 (g/dm ² min ^{1/2})
1:0:3	7.63	2.34	14.66	1908	8.89
1:1:6	2.27	0.25	7.31	1880	15.67
1:2:9	0.73	0.35	3.45	1810	24.43

In fresh state, it was possible to observe that the hydrated lime presence on mortars proportioning exerted influence on air content and bulk density. The more the content of lime, the smaller the bulk density, as the density of lime density is less. The greater presence of lime decreases the air content. It can result in small grains of mortar fill of voids in admixture. Water retentivities of all mortars were similar, and it does not seem to be influenced by these mortar proportionings.

The hardening state characterization shows that hydrated lime's presence significantly reduced the mechanic strength of mortars, reducing also the dynamic elasticity modulus and density, as expected. On the other hand, capillary water absorption was increased by lime presence on mortars proportioning.

Rheological characterization with rotational rheometer is presented in Fig. 4. The 1:1:6 mortar showed a viscosity and yield stress increase fairly sizeable. It is believed that a set of phenomena may have caused this behavior, the most evident was interaction between the proportioning associated with a uniform particle size of sand, generating a worst packaging.

Fig. 4 Curves resulting of rotational rheometry of mortars: **a** Shear stress (Pa s) versus Shear rate (1/s); **b** Viscosity (Pa s) versus Shear rate (1/s). Where: A31 = 1:0:3; A61 = 1:1:6; A91 = 1:2:9



This fact reaffirms that the understanding of how the flow occurs in heterogeneous suspensions, such as coating mortars, is quite complex. So that, apparently, it should be considered not only the packaging and the particle size distribution of the aggregates, but its interaction with the paste of all the dispersion and how the particles react when subjected to tension, flowing in a homogeneous or heterogeneous way (with particles segregation).

Calculating void volume (Vv) of all mortars it was observed that mortar 1:1:6 presented bigger Vv percentage (41.87 %), followed by 1:2:9 mortar with Vv = 41.66 % and 1:0:3 with Vv = 40.56 %. So, it can be concluded that bigger Vv mortar has also bigger viscosity values.

The grains friction of heterogeneous suspensions and their influence on mortars rheology was subject of Mendes' (2008) study. The author states that particle size distribution of aggregates has influence on suspension rheological behavior. However, for the variables evaluated by the author, it was not possible to establish direct correlation between the coefficient of friction of the aggregates and the suspensions viscosity. Olhero and Ferreira (2004) corroborate with this statement, emphasizing that the rheological behavior can not only be based on the suspension particles' size, but also on the distribution of particle sizes, which plays a more important role in this behavior.

Another phenomenon that may be occurring on the 1:1:6 mortar, which has lime in its composition, however, showed high viscosity and flow resistance, which can be related to the content of fines having reached a "critical value." This theory has

been reported by some authors (Zahia et al. 2005; Benabed et al. 2012; Zhang and Han 2000), who observed that, for the same cement content (constant w/b ratio), the adding of fine particles reduces the viscosity of the paste before increasing this property. It happens, when the fines content exceeds a certain critical value, which is the water/cement ratio dependence.

Lee et al. (2003) and Kashani et al. (2014) complement that, when a mineral admixture with a large particle dispersion is added to the cement paste, the smaller particles fill the pores, enhancing packing, while increasing the free water of cement pastes fluidity. In smaller dispersion particle size distributions case, pores among particles are greater, thus reducing fluidity.

In the 1:0:3 mortar case, the lack of fine aggregates on composition could result in more easier exit of water present in porous mortar that is accumulated on vane surrounding, generating a small viscosity.

3.2 *Three-Dimensional Laser Scanning*

After curing time, mortars were separated from the substrates and digitized with a tridimensional laser scanner. The results were treated with the Geomagic Studio 10 Software to generate a tridimensional image. This image was saved in the PNG (Portable Network Graphics) format and opened with the Photoshop CS5 Software, where contact and noncontact areas were quantified. It is important to emphasize that the images were not altered, but only treated to connect 3D scanned points and highlight the noncontact areas.

One example of the results of these treatments is presented in Fig. 5, where dark blue and black points represent the noncontact areas.

The results for the contact area measurement of mortars are presented in Table 6, for mortars 1:0:3, 1:1:6, and 1:2:9, respectively. The technique of 3D laser scanning proved to be adequate for interface contact area measurement, considering that variation coefficients resultant of the method were lower than 10 %.

In order to verify the statistical significance of the obtained values, an analysis of variance (ANOVA) was performed with the Software Statistica 7 (Table 7). It is possible to observe that mortar proportioning and fall heights are significant factors on contact area development, with 95 % of reliability. In addition, the interaction between surface $\times$ fall heights is significant on interface contact area development.

The graphs of significant interactions, i.e., mortar, fall heights, and the interaction between mortar/surface/fall heights, are presented in Figs. 6, 7 and 8. Figure 6 shows that mortar 1:1:6 presented worst behavior in relation to contact area. This fact can be related with the viscosity of this mortar, which was higher than the others, as presented on rheological results.

Fig. 5 Images resulting from the 3D scan. The noncontact area points are shown in *dark blue* and *black*: **a** 3D image resulting from treatment in Geomagic Studio 10 Software, **b** 2D image treated in Geomagic Studio 10 Software, **c** 2D image treated in Photoshop CS5 Software

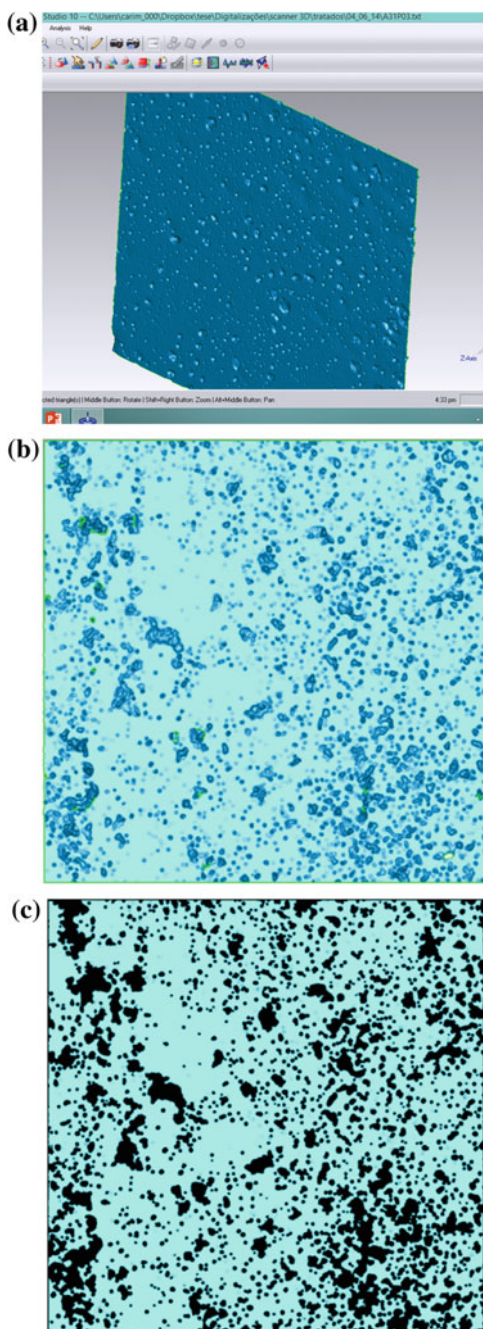


Table 6 Measurement of contact areas of mortars 1:0:3, 1:1:6, and 1:2:9, applied to the polyethylene, acrylic, and glass substrates with fall heights of 30 and 100 cm

Mortar	Surface	Fall heights (cm)	Mean contact area (%)	SD (%)	VC (%)
1:0:3	Polyethylene	100	79.32	2.89	4
1:0:3	Acrylic	100	90.53	3.07	3
1:0:3	Glass	100	89.53	3.72	4
1:0:3	Polyethylene	30	83.34	6.67	8
1:0:3	Acrylic	30	78.33	5.23	7
1:0:3	Glass	30	78.89	7.89	10
1:1:6	Polyethylene	100	75.92	3.14	4
1:1:6	Acrylic	100	87.11	2.17	2
1:1:6	Glass	100	81.98	5.24	6
1:1:6	Polyethylene	30	71.77	1.56	2
1:1:6	Acrylic	30	73.29	2.44	3
1:1:6	Glass	30	74.37	3.57	5
1:2:9	Polyethylene	100	84.66	4.66	6
1:2:9	Acrylic	100	81.71	3.36	4
1:2:9	Glass	100	92.19	1.42	2
1:2:9	Polyethylene	30	87.77	4.63	5
1:2:9	Acrylic	30	82.12	6.22	8
1:2:9	Glass	30	79.57	7.13	9

SD Standard deviation; VC Variation coefficient

Table 7 Controlled factors and contact area data factorial analysis of variance (ANOVA)

Factor	SS	DOF	MS	Calc.F	P factor
Mortar	984.7	2	492.4	12.46	0.000028
Surface	4.0	2	2.0	0.05	0.950539
Fall heights (cm)	504.0	1	504.0	12.75	0.000688
Mortar*surface	169.5	4	42.4	1.07	0.377863
Mortar*fall heights (cm)	42.5	2	21.3	0.54	0.586510
Surface*fall heights (cm)	424.8	2	212.4	5.37	0.006997
Mortar*surface*fall heights (cm)	258.5	4	64.6	1.64	0.176483
Error	2490.0	63	39.5		

SS Sum of square, DOF Degree of freedom, MS Mean square

Figure 7 shows that greater energy application of rendering mortar results in greater percentage of contact area, i.e., less contact failures.

Analogously, as can be seen in Fig. 8, it is possible to conclude that, for the lower application energy, the surface hydrophobicity was not a significant influent

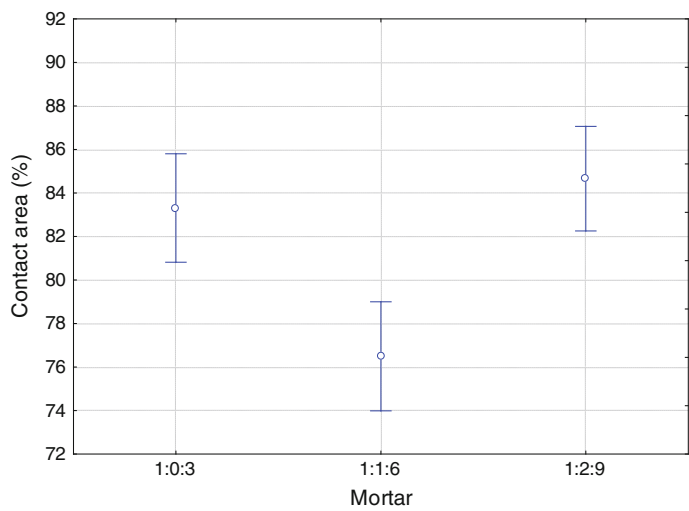


Fig. 6 ANOVA of mortars proportioning influence on interfacial contact area

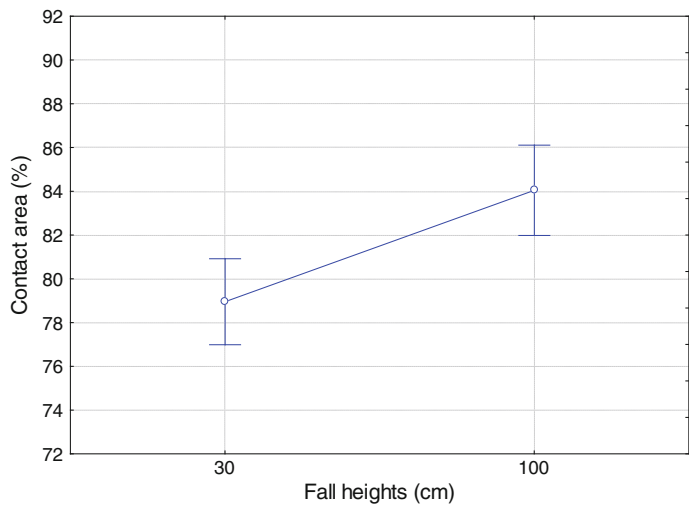


Fig. 7 ANOVA of fall heights (energy of application) influence on interfacial contact area

in contact area development. On the other hand, the greater fall height evidences how bigger is the contact angle of the drop water on surface, i.e., the greater the degree of hydrophobicity, the lower the contact area percentage.

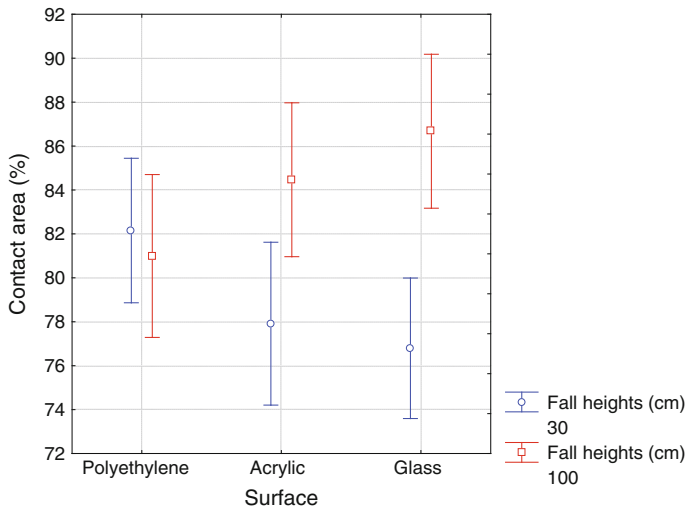


Fig. 8 ANOVA of fall heights (energy of application) and surface angle of contact interaction on interfacial contact area

4 Conclusions

Based on the results of this experimental program, it is possible to establish the following conclusions, for variables studied:

- the mortar proportioning is the most influent variable on substrate/mortar interface contact area, presenting lower p factor on statistical analysis;
- application energy of mortars have to be controlled and measured looking for a bigger interfacial contact area. In practice, it is important to standardize as much as possible this variable, using mechanized application instead of manual (which is frequent in most Brazilian works);
- superficial tension of substrates is a property that deserves more attention from researchers studying adhesion. This property can be affected by the substrate composition or mold release agents used in concrete, for example, and its interaction with application energy of mortar has a significant influence on interfacial contact area;
- packing of all grains present in mortar composition have to be measured, not only for sand or aggregates, since there is an interaction between aggregates and binders grains that can modify flow;
- 3D laser scanning is an important and innovative technique to quantify interfacial contact area, showing a good potential for further improvements.

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