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Determination of rheological parameters of mortar and concrete by alternative techniques

Determinação de parâmetros reológicos de argamassas e concreto através de técnicas alternativas

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Abstract

Pastes, mortar and concrete are reactive suspensions whose consistency is modified over time, especially by cement performance. They present a non-Newtonian fluid behavior and exhibit viscosity that varies with the applied stress. Based on alternative techniques, the behavior and rheological properties of mortars and concretes were determined, analyzed and compared from the experimental measurements of slump, yield stress calculation, with and without addition of admixtures, and viscosity values. The alternative techniques used were the cylinder of Pashias and the modified slump test for mortars and concretes, respectively. The rheometric parameter values obtained by the alternative techniques for mortars and concretes were compared with the results from tests performed with a rheometer, indicating the alternative techniques' good acceptance and lower costs to determine the rheological parameters of cementitious materials. It could even be inferred that the Bingham rheological model, with two rheological parameters (yield stress and viscosity), proved to be a necessary and sufficient condition to represent the behavior of the mixtures tested in this paper.

Keywords: mortar; concrete; rheology; slump test; yield stress.

Resumo

As pastas, juntamente com as argamassas e os concretos, são suspensões reativas, cuja consistência é modificada ao longo do tempo, sobretudo pela atuação do cimento. Eles apresentam um comportamento de fluido não-newtoniano e exibem uma viscosidade que varia com a tensão aplicada. Com base em técnicas alternativas, foram determinados, analisados e comparados o comportamento e as propriedades reológicas de argamassas e de concretos a partir de medidas experimentais de abatimento, cálculo da tensão crítica ou de escoamento, com e sem adição de aditivos, assim como valores de viscosidade. As técnicas alternativas utilizadas foram o cilindro de Pashias e o ensaio de abatimento de tronco de cone modificado para as argamassas e os concretos, respectivamente. Os valores de parâmetros reométricos obtidos a partir das técnicas alternativas para as argamassas e concretos testados foram comparados com resultados de ensaios realizados em reômetro, apontando boa aceitação das técnicas alternativas e menos onerosas na determinação de parâmetros reológicos de materiais à base cimentícia. Pôde-se inferir ainda que o modelo reológico binghamiano, com dois parâmetros reológicos (tensão crítica ou de escoamento e viscosidade), mostrou-se como condição necessária e suficiente para representar o comportamento das misturas estudadas neste trabalho.

Palavras-chave: argamassa, concreto; reologia; ensaio de abatimento; tensão crítica.

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1. Introduction

Rheology, as a science, studies the correlations between requests and responses of the material in its solid, liquid, gas, and also intermediate states. The requests can be called stress and the responses strain rates.
Associated with rheology (originated from the Greek words rhein: “drain”, logos: “study”), defined by E.C. Bingham in 1929, there is the rheometry that deals with the techniques, procedures and equipment use for verifying and assessing the above correlations under permanent and non permanent conditions. According to HU et al. [1], de LARRARD et al. [2] and ANTUNES [3], mortars in the fluid (fresh) state are reactive suspensions, whose consistency is modified over time, especially by the performance of cement. Pastes and mortars present a non-Newtonian fluid behavior (shear thinning) and display a viscosity that varies with the applied stress and only show significant strain from a yield stress. The cement pastes exhibit rheological properties that are very adjustable to the Herschel-Bulkley rheological model, provided they comply with some limits of water/cement ratio. For the experimental tests with mortar in this research, the yield stress values were fitted by the Herschel-Bulkley rheological model for a limited time between the preparation and the initial setting time.
Concrete can be considered as a concentrated suspension of solid particles (aggregates) in a viscous liquid (cement and/or binder paste), making its workability dependent on the characteristics of aggregates and paste matrix. On a macroscopic scale, the fresh concrete flows like a liquid [4]. Thus, concrete can be considered a liquid and to study its behavior under strain in the fresh state, nothing is more appropriate than applying the rheology concepts that are suitable for “complex” materials that do not fit a simple classification of solid, liquid or gas [5]. The rheological behavior of concrete, under certain conditions and compositions, as well as those presented in this paper, can be well fitted by Bingham rheological model.
The rheology of cement based materials is therefore important for several reasons. The quality control for the production of these materials can be simultaneously performed with its utilization, rather than waiting for the results of tests performed in the hardened state: a correct definition of its rheological properties means that simple control test methods, perfectly justified and informative, can be suggested and implemented. A rheological consideration of the utilization conditions can provide useful information to those involved in the concrete mix design. In practice, the rheology of a mixture must be precise for its application, otherwise the worker will perform the job incorrectly: the material may be changed by adding more or less water, thus possibly changing its performance [6]. It is well known that the economical success of a concrete construction is determined, above all, by streamlining and automating the steps involved in the process of mixing, transport and casting of fresh concrete [7].
If on the one hand the determination of rheological/rheometric parameters is of unique interest to the determination and proper application of the final product, it is also known that their accurate determination requires attention that goes beyond that of having precision equipment. This type of experimental research especially depends on carefully handling and operating the materials. This paper discusses these cautious procedures, in addition to proposing the use of alternative techniques for the determination of these parameters. For example, to obtain the yield stress value of a fluid, it should be associated with the idea that it effectively presents a real yield stress below which “it does not deform”, being considered a solid, and that above it, it deforms like a liquid. This proposition has been the subject of much discussion in the work of BARNES; WALTERS [8], ASTARITA [9], among others. In fact, the discussion may even be based on a particular property of a viscoplastic fluid that simply displays a high viscosity when subjected to low strain rates. Viscoplastic mixtures have a property that changes suddenly in the boundary of yield stress: if $\tau < \tau_c$, the mixture has a high viscosity or, somehow, it “deforms elastically”; while if $\tau > \tau_c$, the mixture flows as a liquid. However, it should be noted that the yield stress is related to the minimum stress required to break the interaction of the particle network within the mixture.

Considerations about rheology/rheometry

2.1 Rheological models

Many materials can be modeled as non-Newtonian fluids, especially the cement based ones. Although their rheological behavior is regarded as complex, many pastes, mortars and concretes may present a Bingham rheology behavior. Some studies [10] have also indicated more complex and complete behaviors for these materials from the Herschel-Bulkley rheological model, under permanent conditions. Most of these materials have a nonlinear relationship between shear stress and shear rate, which directly impacts the viscosity.
The most common constitutive equations are represented by the generalized Newtonian model, according to equation (1):

$$\boldsymbol{\tau} = \tau_c \dot{\boldsymbol{\gamma}} \left(-\dot{\gamma}_{II}\right)^{-1/2} + f\left(\dot{\gamma}_{II}\right)\dot{\boldsymbol{\gamma}} \quad (1)$$

where $\dot{\gamma}$ represents the strain rate tensor; τ the shear stress tensor; $\dot{\gamma}_{II}$ the second invariant of strain rate tensor; τ_c the yield stress and $f(\dot{\gamma}_{II})$ a positive continuous function that defines the most appropriate rheological model for the system. This paper addresses fluids or materials of a non-Newtonian nature and, as already substantiated in the literature [5], it has a more simplified and validated behavior for pastes, mortars and concretes based on the Bingham rheological model, where $f(\dot{\gamma}_{II}) = 2\mu$, which under simple shear conditions, it reduces to Equation (2):

$$\tau = \tau_c + \mu\dot{\gamma} \quad (2)$$

where μ is the viscosity.

2.2 Rheology of mortars and concretes

According to PILEGGI et al. [11] mortars can be considered concentrated suspensions predominantly composed of fine aggregates (60% to 80% by weight of quartz sand, crushed limestone, fine crushing)

Figure 1 – (a) Modified slump test proposed by PASHIAS et al. (19) (Source (21)); (b) equipment available at UNESP/Ilha Solteira/SP

mixed with reactive fine materials (Portland cement, hydrated lime) and sufficient water content to place them in a fluid state.
It is known that the deviations usually seen on the rheological behavior of suspensions result from physicochemical interactions dictated by the proportion and nature of the liquid phase with the individual characteristics and content of particles and other constituents that compose the solid phase [12]. With regards to the addition of chemical admixtures, one can add to these deviations the change in the fluid/particle interaction, in addition to the modifications introduced by the presence of entrained air [11].
Thus, the subjective concept of workability is one of the most important properties of mortar and also of fresh concrete, given the necessary and required suitability for its correct applicability and use. Workability is a property composed of at least two main components: fluidity, which describes the ease by which fresh mortar and concrete flow; and cohesion, which describes the resistance to exudation or segregation [13]. Technical standards specify different test methods for its evaluation, though none are able to cover the wide range of workability used in practice. Among the existing test methods is the slump test, specified by the ABNT NBR NM 67:1998 [14].
It is not usual to make use of rheology to study the workability of concrete. Generally, the slump is the only parameter measured and it is related to the yield stress. Additional information is rarely provided on the flow behavior of mixtures, i.e., the behavior of concrete under high shear rates.
In the case of mortars, in traditional tests normally used to control the consistency during application in works, the spread on the flow table, impact tests (cone penetration and dropping-ball [15], vane test [16]), squeeze flow [17], among others, are cited. In general, these tests characterize the mortars in a single condition of stress or shear rate. According to PILEGGI *et al.* [11], in the spreading tests, the applied stress is proportional to the density of the material, while in the impact tests the shear rate applied is defined by the velocity of mobile element. In turn, the vane test is a test that quantifies the yield stress of the compositions. Therefore the results obtained from these methods do not provide a complete rheological characterization of the mortars, which can lead to misinterpretations about their behavior in the fluid state under different application conditions.

3. Methods to determine the rheological parameters of mortar and concrete in the fresh state

In the case of mortars, rheometric practices have been increased, hence bringing promising results either through tests called multipoint, which rheologically characterize fluids and suspensions under different conditions of stress and shear rate that enable the simultaneous identification of fundamental rheological parameters (yield stress, viscosity and rheological profile), or with the test method called squeeze flow [11, 17, 18]. However, in the case of concretes, the rheological evaluation has encountered some problems due to the difficulties in developing tests that can directly measure the correct values of rheological parameters, particularly due to the maximum size of coarse aggregate, among other factors [4]. Moreover, special rheometers for concrete are very expensive, which to some degree have precluded their use in the complete characterization of these materials' behavior. Thus, some alternatives have been proposed and used with promising results. Among the test methods developed, the method proposed by PASHIAS *et al.* [19] for mortar, and the modified slump test proposed by FERRARIS; de LARRARD [20] for concretes can be highlighted.

3.1 Modified slump method proposed by PASHIAS et al. [19]

The method by PASHIAS *et al.* [19], initially developed for fresh concrete, was later modified to include a wide range of materials. The test consists of measuring the height loss of the composite initially inserted into a cylinder that, once removed, makes the material flow on a horizontal surface. Then the difference is measured

between the sample's initial and final heights, associating it with the yield stress of the material tested. Moreover, the introduction of additional bulk on the sample in this technique aims to overcome the material's possible high yield stress.
The advantage of the modified slump technique proposed by PASHIAS *et al.* [19] is the small volume of material required to perform the test that, from an analytical model, allows estimating the fluid's yield stress. The design illustrated in Figure 1 shows the equipment used for the modified slump test, with the additional bulk, as well as the equipment constructed and used in this study.
The yield stress is determined indirectly in the method of PASHIAS *et al.* [19], from the Equations (3) to (8). The pressure exerted by the presence of the bulk added on top of the sample is given in Equation (3):

$$\rho = \frac{m_o}{\pi R^2} g \quad (3)$$

where ρ_0 is the specific gravity of the mixture; g is the gravity; R is the radius of the cylinder; and m_0 is the additional bulk. The resulting total pressure (p) in the material is characterized by Equation (4):

$$p = \rho g z + p_o \quad (4)$$

where p_0 is the pressure due to the additional bulk and z at any height. The bulk addition is equivalent to the sample's "increase in length", and z_0 is the gap. Thus, according to the arguments of PASHIAS *et al.* [19], the determination of yield stress is set by Equations (5) and (6):

$$z_o = \frac{m_o}{\rho \pi R^2} \quad (5)$$

$$h_o = \frac{2\tau_c}{\rho g} - z_o \quad (6)$$

where h_0 is the non-deformed length, z_0 is the gap and t_c is the yield stress.In the research of PASHIAS *et al.* [19] it is observed that if bulk m_o is large, the sample is deformed across its length, which is not interesting when determining the yield stress. From the length h_1 of the deformed region, using the equivalent length of the sample ($H + z_o$), it follows that:

$$h_1 = \frac{2\tau_c}{\rho g} \ln\left(\frac{\rho g}{2\tau_c}(H + z_o)\right) \quad (7)$$

Thus, from Equations (6) and (7), the modified slump test can be written as Equation 8, namely:

$$s = H - (h_o + h_1) = H + z_o - \frac{2\tau_c}{\rho g}\left(1 + \ln\left(\frac{\rho g (H + z_o)}{2\tau_c}\right)\right) \quad (8)$$

where *s* is the slump.

Figure 2 – Device of the modified slump test. Rod in the center of the metal base and the sliding disc

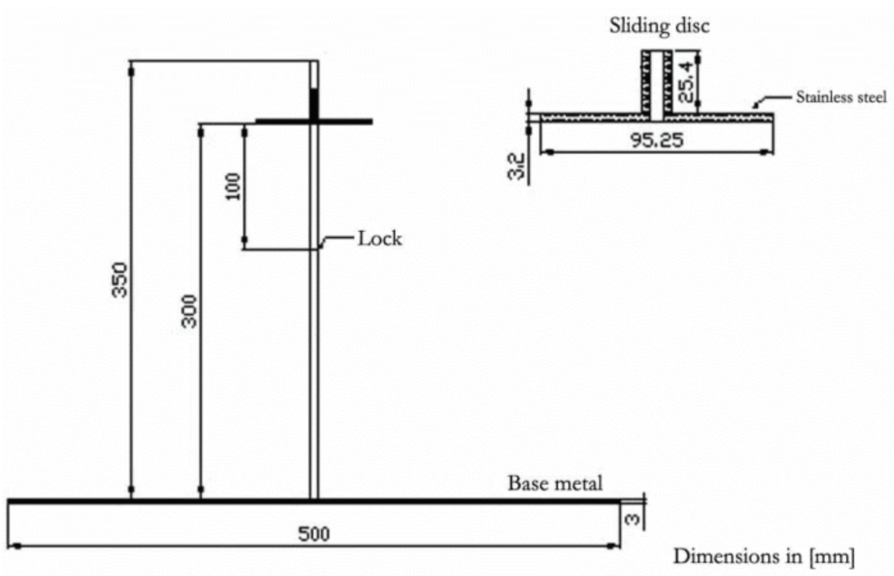
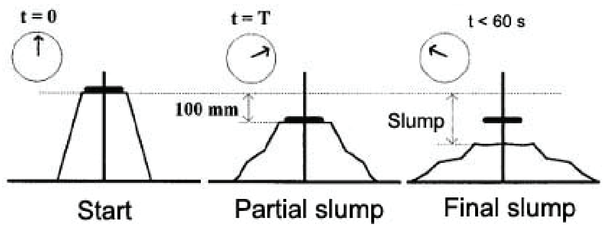


Figure 3 – Design of the modified slump test



3.2 Modified slump test

Seeking equipment that supplied the need to provide two rheological parameters that characterize the behavior of a fresh concrete (Bingham proposal), the modified slump test was proposed by FERRARIS; de LARRARD [20]. This test method has been used in some research centers as an alternative testing method capable of determining the two rheological parameters of concrete, namely, plastic viscosity and yield stress. The plastic viscosity is based on an average slump rate during the test and the yield stress on the final slump itself. Thus, time intervals needed to reach an intermediate height between the initial and final slump values seemed, a priori, a good way to describe the viscosity of concretes [22].

During the choice of the intermediate slump height, two potential problems were considered: first, an excessively low partial slump value could lead to very small slump times, thus resulting in low accuracy measurements; and a very high partial slump value could exclude all concretes with lower final slump values. Thus, as the range of slump values of the concretes capable of being evaluated with rheometers is greater than 100 mm, this value was considered for the partial slump value [20].

The yield stress of concrete is related to the total slump value, while viscosity is related to the material's partial slump time. The modification in the device of the standard truncated cone, for the slump test to the device of the modified truncated cone consists of placing a rod in the center of the base metal and using a sliding disc, as seen in Figure 2.

For timekeeping, a disk that slides along the rod at a height of 100 mm is used. When the disc reaches the height of 100 mm, it is locked by the rod (Figure 3). An operator keeps time and can use a stopwatch, image capture, electronic devices, as well as camera resources (capture and image processing) associated with electronic devices, the option used in this paper.

To evaluate the yield stress, FERRARIS; de LARRARD [20] proposed Equation (9), which is a modification of the equations proposed by Hu *et al.* [1]. This equation relates the slump value of concrete with the yield stress (τ_c).

$$\tau_c = \frac{\rho}{347}(300 - s) + 212 \quad (9)$$

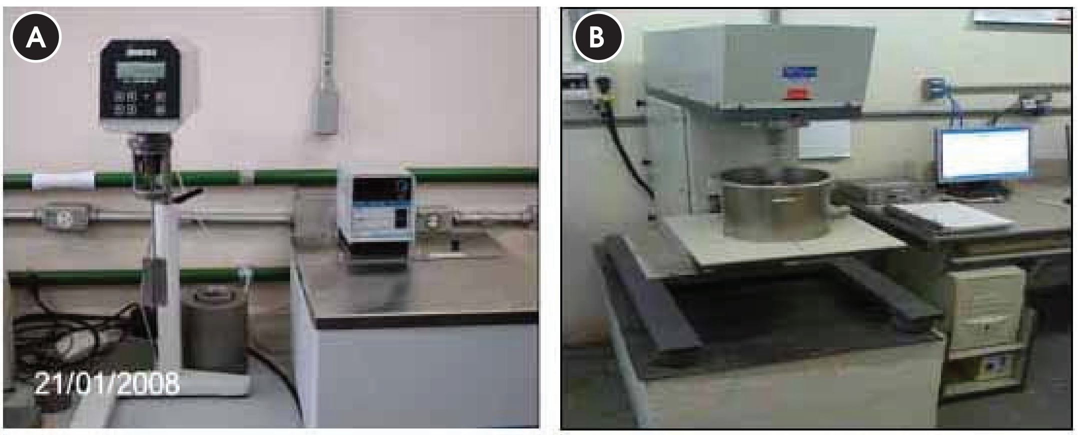
where ρ is the specific gravity of the material (kg/m³), τ_c is the yield stress (Pa) and *S* is the slump value (mm). To evaluate the plastic viscosity, FERRARIS; de LARRARD [20] proposed the Equations (10) and (11) for concretes with a slump value ranging from 100 mm to 260 mm.

$$\mu = 1{,}08x10^{-3}(s - 175)\rho T \quad \text{for } 200\text{ mm} < s < 260\text{ mm} \quad (10)$$

$$\mu = 25x10^{-3}\rho T \quad \text{for } s < 200\text{ mm} \quad (11)$$

where μ is the plastic viscosity (Pa.s) and T is the time of the partial slump value (s).

Figure 4 – (a) R/S Brookfield rheometer (FEIS/UNESP); (b) Rheometer based on planetary model (UFSCar)



3.3 Classic rheometry: use of rheometers

The objective of rheometry is to determine the characteristics of the fluid in the state of strain, from measurements performed in simple and controlled flows. In these tests the fluid is stressed in a simple way, so that few parts of its stress tensor are nonzero. Thus, from the components of shear stress and shear rate, a characteristic equation can be obtained.

Rheometers are precise equipment not only for research, but also for practical studies and quality control measures of the material, aimed at evaluating the rheological properties of fluids and suspensions. According to PILEGGI *et al.* [11], the basic operating principle of rheometers is to evaluate the shear stress generated by cement-based composites due to their shear by rackets that, in an axial or planetary rotational movement, induce them to flow. They provide a higher amount of information when compared to conventional empirical tests, lowering the material and personnel expenses. Also, the information is more objectively obtained, since the test is fully automated and computer-controlled [2].

The compositions of the mortars of this study were tested by the R/S Brookfield rheometer (shear rate *versus* shear stress). This type of rheometer can be used both by controlling the strain and measuring the corresponding stress, as well as controlling the stress and measuring the resulting strain. The yield stresses of mortars measured by the two methods - Pashias and rheometry - were analyzed and a validation study of the technique was performed. The rheometer and the thermal bath used in the tests are shown in Figure 4a.

The first concrete rheometer was conceived by POWERS [23] in a coaxial cylinders concept. With the technological evolution of rheometers, equipment that adopts new concepts for shearing material appeared, among which the BTRHEOM rheometer, developed in the *Laboratoire Central des Ponts et Chaussées* (LCPC), France [24], stands out. The test via classical rheometry of this study was performed in the concrete rheometer available in the *Laboratório de Cerâmicas Especiais e Refratários, Universidade Federal de São*

Table 1 – Physicochemical parameters of cement CPV ARI used

Property		Results	Specifications (ABNT NBR 5733:1991) (26)	
			minimum	maximum
Fineness Sieve 200 (% retained)		0.33	-	6.0
Fineness Sieve 325 (% retained)		0.7	-	-
Specific surface Blaine (cm²/g)		4526	3000	-
Density (g/cm³)		0.93	-	-
Absolute density (g/cm³)		3.15	-	-
Compressive resistance (MPa)	03 days	45.4	24.0	-
	07 days	50.6	34.0	-
	28 days	52.3	-	-
Loss on ignition (%)		3.12	-	4.5
Insoluble residues (%)		0.48	-	1.0
Chemical analysis (%)	SiO_2	18.91	-	-
	Fe_2O_3	2.72	-	-
	Al_2O_3	5.68	-	-
	CaO	65.15	-	-
	MgO	0.87	-	6.5
	SO_3	2.90	-	3.5
	Na_2O	0.15	-	-
	K_2O	0.87	-	-
Equivalent alkaline Na_2O		0.72	-	-
Free lime in CaO		1.35	-	-

Table 2 – Size distribution of sand used (sieved and fine sands)

Maximum size (mm)	Fineness modulus	% Cumulative retained						
		Sieve (mm)	0.075	0.150	0.300	0.600	1.180	2.360
0.60	1.46	Sieved sand	100	92	54	0	0	0
1.18	1.86	Fine sand	100	99	77	10	0	0

Carlos (UFSCar). The design of this rheometer was based on a planetary mixer originally composed of an alternating current motor, a four-speed gear and a cylindrical bowl with a mixing capacity of up to 10 kg of concrete (Figure 4b). The advantage of considering the planetary model is that it allows evaluating both high fluidity concretes and concretes with reduced fluidity and without cohesion [25].

4. Experimental procedure

4.1 Mortar mix design

The mortars were prepared with Portland cement CPV ARI and two types of fine aggregates, sieved sand (sieve No. 30) with maximum size of 0.60 mm and fine sand with maximum size of 1.18 mm. Table 1 presents some physicochemical parameters of cement CPV ARI and Table 2 the size distribution of the two types of fine aggregates used.
In the mix design of the mortar used in the tests, five different water/cement ratios (w/c) were employed, namely 0.40, 0.43, 0.45, 0.47 and 0.50, by adopting the following mixing procedure:

- first, the cement and water were mixed for thirty seconds in a mixer under low speed;
- next, the fine aggregate was added for one full minute with the mixture in motion;
- then mortar was allowed at rest for two minutes and, afterwards the process of mixing was restarted for another minute under high speed, totaling ten minutes of mixing in the mixer.

Figure 5 – (a) Mortar mixing in the mixer; and (b) rheometer test

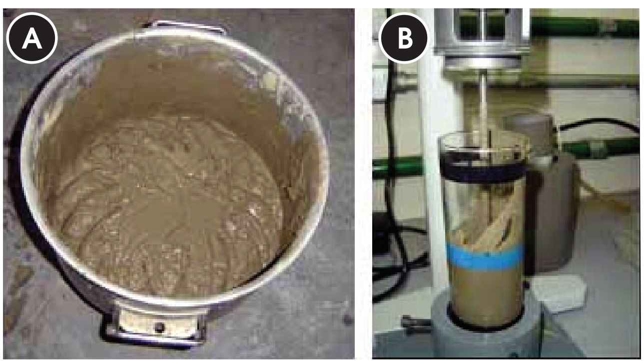


Table 3 – Composition of the mortars tested

Mix design	Consumption of the constituent materials		
Cement (kg/m^3)	425.0		
Sand (kg/m^3)	670.0		
Water (kg/m^3)	170.0	191.25	212.5
a/c ratio	0.40	0.45	0.50

At the end of this process, the mixture was simultaneously tested by the method of Pashias and by the rheometer for three time intervals (t = 0s, t = 15s and t = 30s), leaving this sample to rest between the successive time intervals, as illustrated in Figure 5.
The experimental test device used to determine the yield stress by the method of Pashias, illustrated in Figure 6, consists of a PVC cylinder with 30 cm in height and 150 mm in diameter, a horizontal metal plate (50 cm x 50 cm), with a 35 cm-height vertical axis and a metal disc (additional bulk) of 142.61 g attached to the center. The procedure used for the equipment's correct use is described below:

- after the PVC cylinder is properly cleaned and moistened, it should be placed on the metal base, also clean and moist, which in turn must lay on a rigid, flat, horizontal surface;
- the cylindrical mold is filled with three layers of approximately equal volume of a given composite (concrete or mortar), and in the last layer, the composite must completely fill it, each layer is compacted with 25 uniformly distributed strokes. After compaction, the excess material is removed by skimming the surface;
- next, the metal plate around the mold is cleaned, then, the demolding is done by rising carefully lifting the mold by the handles in a vertical position, with constant and uniform velocity;
- the slump of the cylindrical mold is measured, which corresponds to the distance between the upper mold base and the center of the upper base of the slumped sample using a metal ruler. This procedure to measure the slump of material placed into the cylinder is repeated for the same sample at three different times (0, 15 and 30 minutes), which remains at rest between the successive measurements;
- with the sample slump values, the yield stress is calculated by Equation (8) and the calculated values are compared with those obtained via classical rheometry (rheometer) for the same sampling.

Figure 6 – Test procedure steps used for the method of Pashias:
(a) cylinder ready to be lifted; (b) cylinder removal and slump measurement

Table 4 – Characterization of fine and coarse aggregates used (27; 28)

Maximum size (mm)	Fineness modulus	Specific gravity (g/cm^3)	Absorption (%)
4.8	–	–	–
9.5	6.02	2.934	0.37
16	6.51	2.917	1.23

Table 5 – Physicochemical characteristics of the silica fume used

Specific gravity	2.220 g/cm^3
Specific surface	20.000 m^2/kg
Particle shape	rounded
Mean size	0.2 μm
SiO_2 content	≥ 85%
Moisture	≤ 3%
Equivalent alkaline in Na_2O	≤ 0.5%

4.2 Concrete mix design

The concretes were prepared with Portland cement CPV ARI, crushed basaltic (maximum sizes of 16 mm and 9.5 mm), natural river sand (maximum size of 4.76 mm and fineness modulus of 2.4), and replacing the cement by silica fume (10% by weight). The compositions differed only in the superplasticizer content: for concrete prepared with 16 mm gravel, the admixture content varied from 0.1% to 0.2%, while for concrete with 9.5 mm gravel, the admixture content was 1.1% in relation to the weight of the binders. The admixture used was the third generation based on polycarboxylate, with specific gravity of 1.087 g/cm^3 and solid content of 30%. Tables 4 and 5 show the characteristics of the aggregates and silica fume used.

Concretes CAD1 and CAD2 were prepared with gravel (maximum size of 16 mm) and differed only in the amount of superplasticizer, which ranged from 0.1% to 0.2%. Table 6 presents the compositions of the concretes evaluated, noting that the concrete prepared with gravel (maximum size of 9.5 mm), called MCAD, was used to compare the rheological properties obtained by the modified slump

Table 6 – Composition of the concretes tested (29)

Concrete mixtures	a/c ratio	Water (kg/m³)	Cement (kg/m³)	Silica fume (kg/m³)	Coarse aggregate (kg/m³)	Fine aggregate (kg/m³)	Admixture (kg/m³)
CAD1	0.30	160.1	466.7	51.8	1088.6	763.1	5.160
CAD2	0.30	160.1	466.7	51.8	1088.6	763.1	5.676
MCAD	0.30	160.1	466.7	51.8	957.1	848.7	5.676

Figure 7 – Shooting apparatus

test [20], with those obtained by the planetary rheometer (available in UFSCar).

4.3 Concrete tests by FERRARIS; de LARRARD method [20]

The rheological behavior of fresh concrete was evaluated through the modified slump test by varying the resting time of the concrete. The modified slump test, proposed by FERRARIS; de LARRARD [20], provides the two rheological parameters, viscosity and yield stress, necessary for the evaluation of rheological properties of fresh concrete. For the comparison of results obtained by this test method, tests were performed via classical rheometry, using the rheometer available in the *Laboratório de Cerâmicas Especiais e Refratários* of *Departamento de Engenharia de Materiais/UFSCar*. Due to the existing limitations in the rheometer used, which allows tests with coarse aggregates with size up to 9.5 mm, it was necessary to develop a new composition of high performance concrete using only aggregates in accordance with the allowed size limit.

The mixing procedure distinctively influences the properties of concrete, both in the fresh and hardened state. For CAD, the superplasticizer was added at the end of the concrete's resting time, unlike the standard procedure used in conventional concretes. Both had a total mixing time of 10 minutes. For MCAD, the procedure differed, starting with the sequence of mixing the materials until the total time of concrete production, which in this case was of 12 minutes. The test procedure was identical for all concretes.

Once the concrete mixing was completed, the material rested for 5 minutes. After this period, a sample of the concrete was tested by the modified slump test. During the tests the residual concrete remained within the mixer, and the opening of the device was protected with a wet cloth to prevent water loss through evaporation.

To measure the partial slump time, a high resolution camera was used. This camera was set to maintain a constant view of the disc from the beginning to the end of its 100 mm falling, as shown in Figure 7. Note that the camera was properly positioned above the apparatus of the modified slump test. This position was defined as the point with the best view of the disc falling. To edit the images captured by the professional digital camera (JVC DY-DV500 camcorder), a computer software program, specific for this type

Figure 8 – Test in concrete rheometer

Figure 9 – Computer for data acquisition obtained by the rheometer

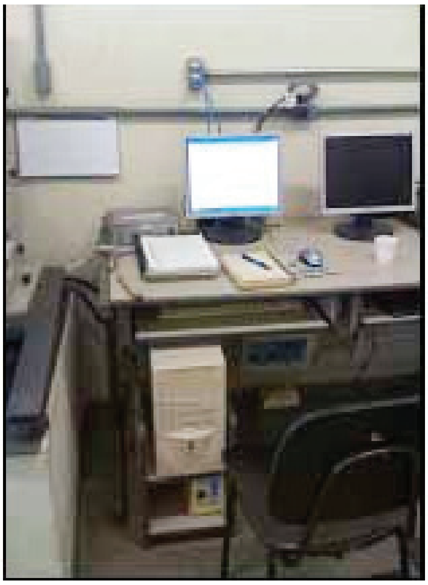


Table 7 – Method of Pashias: parameters needed to calculate the yield stress of the mortars with w/c = 0.40

Test	g (m/s^2)	Time (min)	w/c	H (cm)	Sieved sand			Fine sand		
					Zo (m)	ρ (kg/m^3)	S (cm)	Zo(m)	ρ (kg/m^3)	S (cm)
1					0.000963	2,096.00	10.80	0.000905	2,230.00	9.00
2	9.81	T = 0	0.40	30.0	0.000963	2,095.00	11.00	0.000909	2,219.00	9.00
3					0.000964	2,093.00	11.30	0.000917	2,200.00	8.80
1					0.000967	2,086.00	9.50	0.000965	2,090.00	6.00
2	9.81	T = 15	0.40	30.0	0.000966	2,089.00	9.60	0.000913	2,210.00	6.70
3					0.000964	2,092.00	9.70	0.000938	2,150.00	6.50
1					0.000965	2,090.00	8.50	0.000961	2,100.00	4.50
2	9.81	T = 30	0.40	30.0	0.000964	2,093.00	9.00	0.000897	2,250.00	5.00
3					0.000966	2,088.00	8.80	0.000930	2,170.00	4.70

of work, was used. The software used was *Ulead Video Studio 8*. With this software, the beginning and the end of the partial slump of the concrete was seen with precision, namely; the duration of the disc falling.
The procedure considered for the rheometric tests was done in order to have the greatest similarity as possible to the procedure used in the modified slump test, thus avoiding large variations in the results to be compared. The equipment is completely automated, hence facilitating its handling and the test execution, enabling the least human interference possible and thereby providing a reliable result, close to the actual behavior of the tested sample. To operate the rheometer, a schedule was developed for the applied torques and resting time of the concrete, simulating that performed in the modified slump test. The rheometer bowl containing the MCAD under test and the computer used for the data acquisition obtained by the equipment are shown in Figures 8 and 9.

5. Results

5.1 Mortar tests – Method of PASHIAS *et al.* [19]

The experimental results presented here, the specific gravity and slump range by the method of PASHIAS *et al.* [19], refer to the mortars whose compositions were established with different water/cement ratios. Two different yield stress values are presented:

- the first is the yield stress value calculated from Equation (8);
- the second is the yield stress value obtained by the tests performed in the rheometer.

With these two values, one from the method of PASHIAS *et al.* [19] and the other from more accurate and precise measures (rheometer), it was possible to compare the results and to assess the validity or not of the alternative method of PASHIAS *et al.* [19] as a low-cost solution for determining the rheological parameter yield stress.

The results presented in 5.1.1 are arranged according to the variation of water/cement ratio (w/c), the two types of fine aggregates, the cement used in the mixtures and the range of superplasticizer content.

5.1.1 Mortars with water/cement ratio of 0.40 produced with cement CPV ARI

Tests performed to determine the yield stress by the method of PASHIAS *et al.* [19] and by the rheometer, for mortars produced with both types of fine aggregates, are presented in Table 7 for w/c ratio of 0.40. Table 8 shows the two values for the yield stress as well as the percentage of error between both results obtained in different tests.
The comparison between the yield stresses obtained by the method of PASHIAS *et al.* [19] and those obtained by the rheometer according to the number of tests performed, for mortar produced with both types of fine aggregates, is shown in Figure 10. The behaviors of the yield stress as a function of the material's resting time are shown in Figure 11.
The mean values for the yield stress were higher for the mortars produced with fine sand in the test method of PASHIAS *et al.* [19] and in the rheometric test. For these same mortars, according to Table 8, it appears that the calculated errors were higher than those of mortars produced with sieved sand, which can also be seen in Figure 10, where a greater spread of points for mortars produced with fine sand for the three times (T = 0min, T = 15min and T = 30min) can be observed. From Figure 11 it is clear that the stress behaviors, as a function of time, are very similar, with a deflection only for the rheometry of the mortar produced with fine sand from a resting time of about 20 minutes, even surpassing the curve of the stresses calculated by the method of Pashias for mortars produced with sieved sand after 30 minutes.

Table 8 – Comparison of yield stress calculated by the method of Pashias and by classical rheometry with their respective errors for mortars with w/c ratio = 0.40

Test	Sieved sand				Fine sand			
	Time (min)	Yield stress (Pa)			Time (min)	Yield stress (Pa)		
		Pashias	Rheometer	Error (%)		Pashias	Rheometer	Error (%)
1		877.996	641.074	36.96		1,101.310	722.278	52.48
2	T = 0	861.381	620.180	38.89	T = 0	1,081.667	689.027	56.98
3		836.732	601.336	39.15		1,106.451	687.996	60.82
1		984.794	750.320	31.25		1,355.440	808.869	67.57
2	T = 15	977.253	733.220	33.28	T = 15	1,344.055	802.320	67.52
3		969.757	713.271	35.96		1,331.783	775.068	71.83
1		1,080.370	773.762	39.63		1,567.754	1,127.525	39.04
2	T = 30	1,034.026	798.772	29.45	T = 30	1,593.905	1,096.364	45.38
3		1,050.436	760.131	38.19		1,601.009	1,131.626	41.48

5.1.2 Mortars with water/cement ratio of 0.45 produced with cement CPV ARI

Table 9 shows the data obtained in the tests performed to determine the yield stress by the method of PASHIAS *et al.* [19] for the mortar produced with both types of fine aggregates and w/c ratio equal to 0.45. The yield stress values obtained by classical rheometry are compared with those obtained by the method of PASHIAS *et al.* [19] as well as the percentage error present in Table 10.
Figure 12 shows the comparison between the yield stresses obtained by the method of PASHIAS *et al.* [19] and those obtained by the rheometer, considering the two types of fine aggregates, and Figure 13 shows the behaviors of yield stress as a function of time. Analyzing Figure 12, it can be noted that there is a lesser dispersion of the yield stress values obtained by classical rheometry, suggesting that these values are presented in the same range of magnitude. Again, the mortars produced with fine sand showed a higher percentage of error in most tests. By observing the curves in Figure 13, referring to the yield stress values calculated by the method of Pashias, it appears that the curve corresponding to the mortars produced with fine sand starts with lower values than those of the curve corresponding to the mortars produced with sieved sand for the time T = 0min,

Figure 10 – Comparison between the yield stresses obtained for mortars with w/c = 0.40

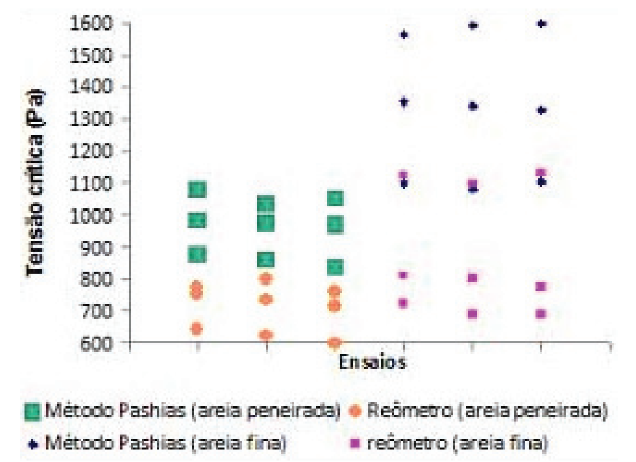
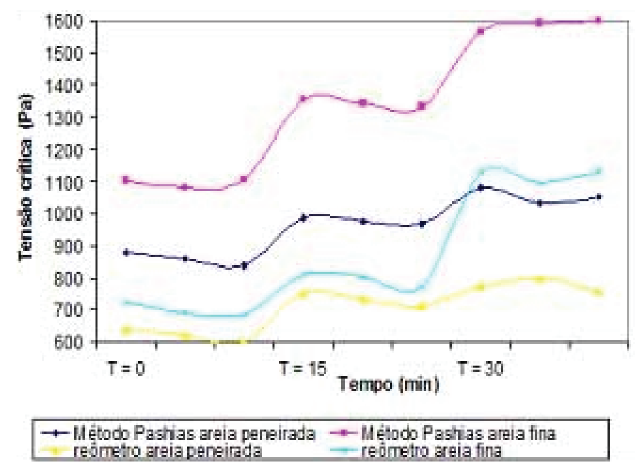


Figure 11 – Behavior of the yield stress as a function of time for mortar with w/c = 0.40



and over time (T = 15min and T = 30min), their yield stress values are greater. What is quite evident in Figure 13 is the more linear behavior for the rheometric tests, whereas for the method of Pashias some instability of the stress behavior is observed, as a function of time.

5.1.3 Mortars with water/cement ratio of 0.50 produced with cement CPV ARI

Tests performed to determine the yield stress by the method of PASHIAS *et al.* [19] for mortars produced with both types of fine aggregates and w/c ratio equal to 0.50 are presented in Table 11, while the two values of yield stress obtained by the method of PASHIAS *et al.* [19] and by the rheometer are compared in Table 12, as well as the percentage error between them.

Statistical analyses of the results were carried out for all the tested mixtures. For the mixtures with w/c ratio equal to 0.50, Tables 13 and 14 exhibit the yield stress average, as well as the coefficient

Table 9 – Method of Pashias: parameters needed to calculate the yield stress of the mortars with w/c = 0.45

Test	g (m/s^2)	Time (min)	w/c	H (cm)	Sieved sand			Fine sand		
					Zo (m)	ρ (kg/m^3)	S (cm)	Zo(m)	ρ (kg/m^3)	S (cm)
1					0.000985	2,048.00	17.50	0.000985	2,048.00	18.00
2	9.81	T = 0	0.45	30.0	0.000984	2,050.00	17.00	0.000984	2,050.00	18.50
3					0.000983	2,053.00	17.50	0.000988	2,043.00	18.00
1					0.001001	2,016.00	16.00	0.000979	2,060.00	15.00
2	9.81	T = 15	0.45	30.0	0.000997	2,023.00	16.00	0.000980	2,058.00	14.70
3					0.000995	2,027.00	15.50	0.000978	2,063.00	15.00
1					0.000996	2,026.00	14.50	0.000963	2,095.00	13.50
2	9.81	T = 30	0.45	30.0	0.000994	2,030.00	14.50	0.000968	2,084.00	13.50
3					0.000990	2,037.00	14.00	0.000971	2,077.00	13.00

Table 10 – Comparison of yield stress calculated by the method of Pashias and by classical rheometry with their respective errors for mortars with w/c ratio = 0.45

Test	Sieved sand				Fine sand			
	Time (min)	Yield stress (Pa)			Time (min)	Yield stress (Pa)		
		Pashias	Rheometer	Error (%)		Pashias	Rheometer	Error (%)
1		428.489	279.055	53.55		403.175	309.494	30.27
2	T = 0	455.033	300.795	51.28	T = 0	378.990	298.814	26.83
3		429.522	297.453	44.40		402.199	314.277	27.98
1		501.395	299.029	67.67		570.769	330.124	72.90
2	T = 15	503.117	324.626	54.98	T = 15	588.494	339.064	73.56
3		532.452	327.453	62.60		571.325	347.555	64.38
1		591.607	352.175	67.99		677.074	373.810	81.13
2	T = 30	592.765	351.080	68.84	T = 30	673.545	378.154	78.11
3		626.115	357.840	74.97		705.398	391.332	80.26

Figure 12 – Comparison between yield stresses obtained for mortars with w/c = 0.45

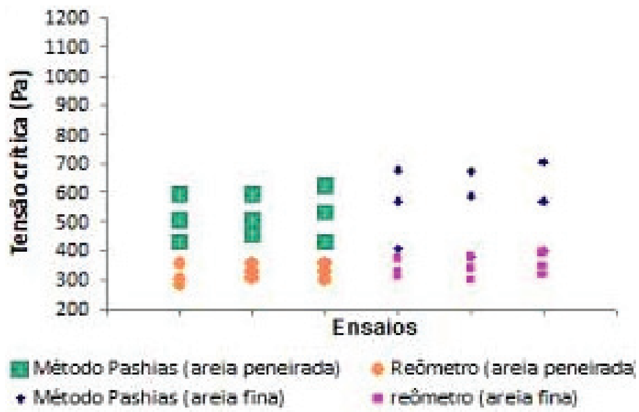


Figure 13 – Behavior of the yield stress as a function of time for mortars with w/c = 0.45

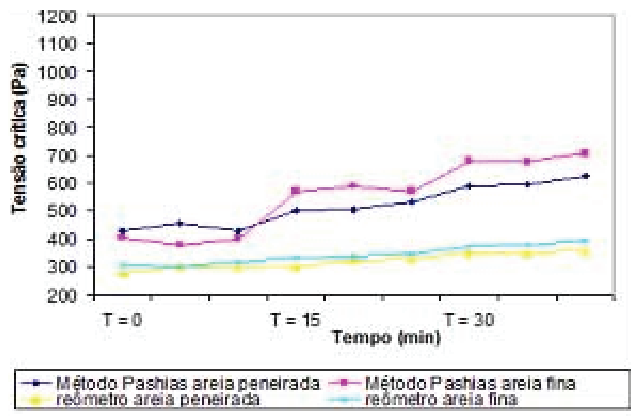


Table 11 – Method of Pashias: parameters needed to calculate the yield stress of the mortars with w/c = 0.50

Test	g (m/s²)	Time (min)	w/c	H (cm)	Sieved sand			Fine sand		
					Zo (m)	ρ (kg/m³)	S (cm)	Zo(m)	ρ (kg/m³)	S (cm)
1					0.000987	2,045.00	26.00	0.000985	2,040.00	23.70
2	9.81	T = 0	0.50	30.0	0.000984	2,050.00	26.00	0.000984	2,036.00	24.00
3					0.000981	2,057.00	25.50	0.000988	2,042.00	24.00
1					0.001004	2,010.00	24.50	0.000979	2,090.00	23.00
2	9.81	T = 15	0.40	30.0	0.001001	2,015.00	24.50	0.000980	2,085.00	23.30
3					0.001000	2,018.00	25.00	0.000978	2,093.00	23.00
1					0.000975	2,070.00	24.50	0.000963	2,010.00	21.50
2	9.81	T = 30	0.50	30.0	0.000977	2,065.00	24.00	0.000968	2,014.00	21.50
3					0.000980	2,059.00	24.50	0.000971	2,019.00	21.70

of variation and standard deviation for the two cases (Pashias and rheometer) and for both types of fine aggregates used.
Figure 14 shows the comparison between the yield stresses obtained by the method of Pashias and that obtained by the rheometer, considering the two types of fine aggregate. Figure 15 shows the behavior of the yield stresses as function of time.
Observing the line referent to the mean yield stress in Tables 13 and 14, one can see that the mean yield stress values verified for the mortars produced with fine sand are superior to those produced with sieved sand. Figure 15 shows that the order of magnitude between the yield stress values calculated by the method of Pashias and by the rheometer for mortars produced with sieved sand for T = 30 min is almost the same. This is also evident for the mortars produced with fine sand, but for T = 0 min, as seen in Table 14, there is a considerable reduction of the error for this time.

5.2 Discussion of the results

5.2.1 Mortars – Method of Pashias et al. [19]

When comparing the yield stress values of the mortars produced with a single cement type, taking into account only the range in the w/c ratio, it is observed that the higher the water/cement ratio, the lower the value of the yield stress. A mixture with higher w/c ratio has a higher water content and hence higher fluidity, which ensures higher values for the slump (*S*), being this value a major factor for calculating the yield stress by the

Table 12 – Comparison of yield stress calculated by the method of Pashias and by classical rheometry with their respective errors for mortars with w/c ratio = 0.50

Test	Sieved sand				Fine sand			
	Time (min)	Yield stress (Pa)			Time (min)	Yield stress (Pa)		
		Pashias	Rheometer	Error (%)		Pashias	Rheometer	Error (%)
1	T = 0	91.462	77.856	17.48	T = 0	163.704	153.328	6.77
2		91.680	73.095	25.43		153.213	150.454	1.83
3		106.728	78.002	36.83		153.655	153.078	0.38
1	T = 15	135.040	95.902	40.81	T = 15	192.893	165.975	16.22
2		135.366	108.814	24.40		181.490	162.186	11.90
3		119.855	101.548	18.03		193.167	163.742	17.97
1	T = 30	138.977	146.246	4.97	T = 30	241.792	181.163	33.47
2		155.347	144.507	7.50		242.266	179.246	35.16
3		138.254	135.815	1.80		235.009	195.834	20.00

Table 13 – Statistical analysis of the results for mortars with w/c = 0.50 and sieved sand

Sieved sand	Method of Pashias			Rheometer		
	T = 0 min	T = 15 min	T = 30 min	T = 0 min	T = 15 min	T = 30 min
Mean yield stress (Pa)	96.62	130.09	144.19	76.32	102.09	142.19
Standard deviation	8.75	8.86	9.67	2.79	6.47	5.59
Maximum yield stress (Pa)	106.73	135.37	155.35	78.00	108.81	146.25
Minimum yield stress (Pa)	91.46	119.86	138.25	73.10	95.90	135.82
Coefficient of variation (%)	9.06	6.81	6.70	3.66	6.34	3.93

Table 14 – Statistical analysis of the results for mortars with w/c = 0.50 and fine sand

Fine sand	Method of Pashias			Rheometer		
	T = 0 min	T = 15 min	T = 30 min	T = 0 min	T = 15 min	T = 30 min
Mean yield stress (Pa)	156.86	189.18	239.69	152.29	163.97	185.41
Standard deviation	5.93	6.66	4.06	1.59	1.90	9.07
Maximum yield stress (Pa)	163.70	193.17	242.27	153.33	165.98	195.83
Minimum yield stress (Pa)	153.21	181.49	235.01	150.45	162.19	179.25
Coefficient of variation (%)	3.78	3.52	1.69	1.05	1.16	4.89

method of Pashias. In figure 16 this fact can be verified for two of the three w/c ratios used.
Analyzing Figures 11, 13 and 15, regarding the behavior curves of the yield stress as a function of time, it is observed that the stress increases with increasing resting time of the mortar sample. This can be explained by the several chemical reactions involved during

Figure 14 – Comparison between yield stresses obtained for mortars with w/c = 0.50

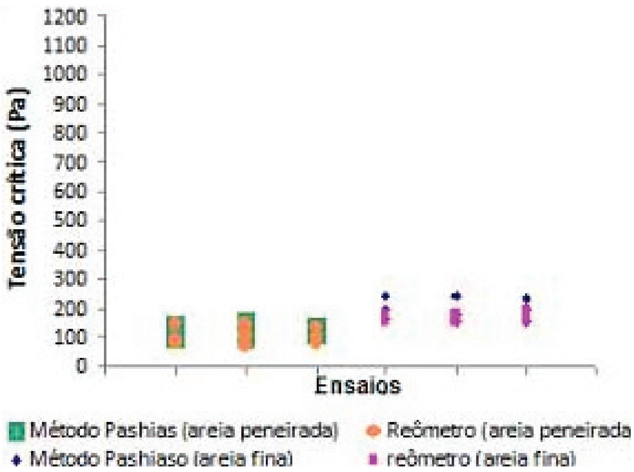


Figure 15 – Behavior of the yield stress as function of time for mortars with w/c = 0.50

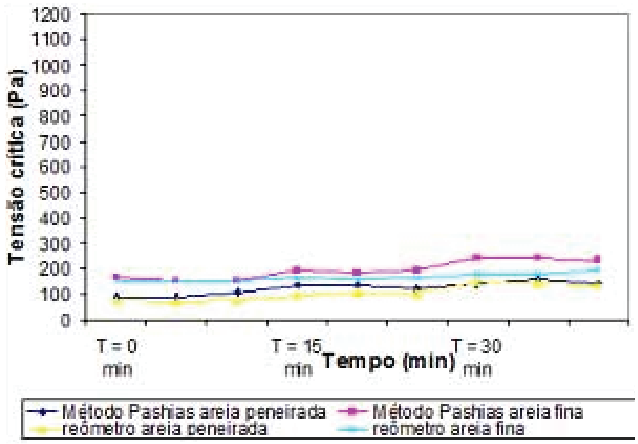


Figure 16 – Mortars produced with w/c ratio equal to (a) 0.40 and (b) 0.45, without superplasticizer addition

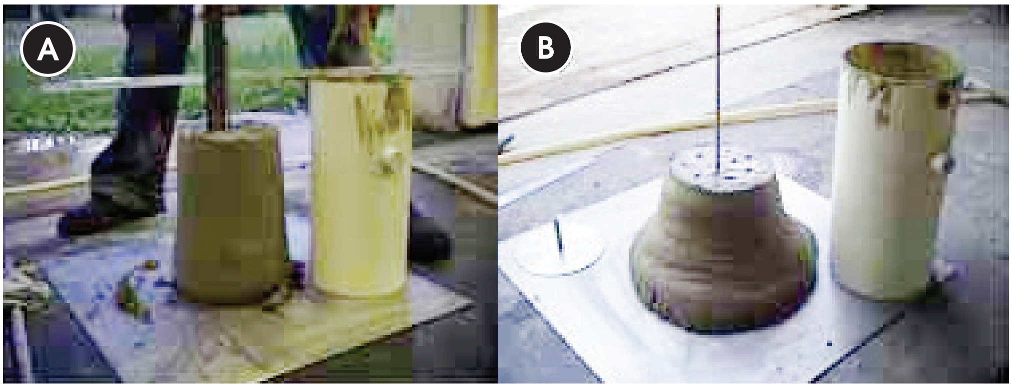
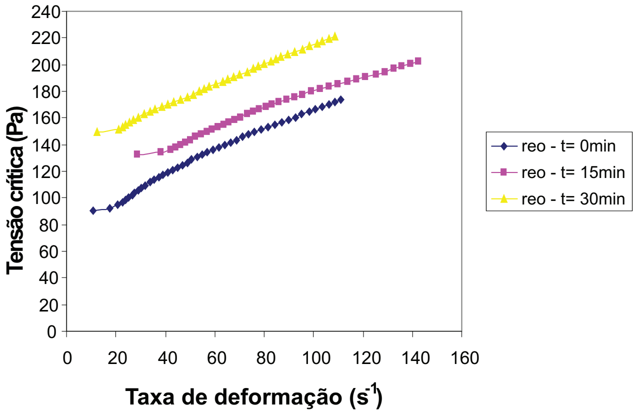


Table 15 – Comparison of the yield stress calculated by the method of Pashias and by classical rheometry with their respective errors, for mortars produced with CPV ARI, w/c = 0.50 and sieved sand

Test	Time (min)	w/c	S (cm)	Z_o (m)	ρ (kg/m³)	Yield stress (Pa) Pashias	Yield stress (Pa) Rheometer	Yield stress (Pa) Error (%)
1	T = 0		26.50	0.000988	2,043.00	77.328	69.480	10.15
2	T = 15	0.50	25.00	0.001010	2,040.00	121.141	102.864	17.87
3	T = 30		24.30	0.000985	2,085.00	146.633	136.817	6.70

Figure 17 – Rheological curves for the mortar produced with CPV ARI, w/c = 0.50 and sieved sand without superplasticizer, for the times T = 0, 15 and 30 min



cement hydration, when the setting of the material occurs, causing its fluidity loss over time.
The rheological curves were determined for the mortars produced with cement CPV ARI, w/c ratio equal to 0.50 and only with sieved sand, without superplasticizer addition. Table 15 presents the yield stress values calculated by the method of Pashias and by classical rheometry with their respective errors.
Figure 17 presents the rheological curves obtained for the mortar described above, with the R/S Brookfield rheometer endowed with vane geometry by controlling the shear stress and measuring the resulting shear rate.
The yield stress and strain rate values obtained by the rheometer were filtered by removing the strain rate values below 10 s^{-1} and above 160 s^{-1}, in order to determine more reliable values, also given the limitations of the rheometer at low shear rates. It should be noted that controlling the rheometric tests eliminates any possible slipping on the walls of the spindles. Observing Figure 16 and Table 15, it is noted that the values of yield stress increase gradually over time. The results showed a good fit to the Herschel-Bulkley rheological model with a very slight concavity, since the values of the flow coefficient *n* (Equation 12) practically ranged from 0.70 to 0.90, characteristic of shear thinning materials, reaching close to 1 (Bingham behavior, as elucidated in section 2.1). Table 16 shows the values of the parameters of this equation for each curve obtained.

$$\tau = \tau_c + K\dot{\gamma}^n \quad (12)$$

where *K* is the flow consistency index.

5.2.2 Concretes – Method of Ferraris; de Larrard [20]

5.2.2.1 Determination and evaluation of the yield stress

Table 17 shows the values of the slump obtained for the three concretes (CAD1, CAD2 and MCAD), determined by the modified slump test. Figure 18 shows the evolution of the slump as a function of time for the three concretes.

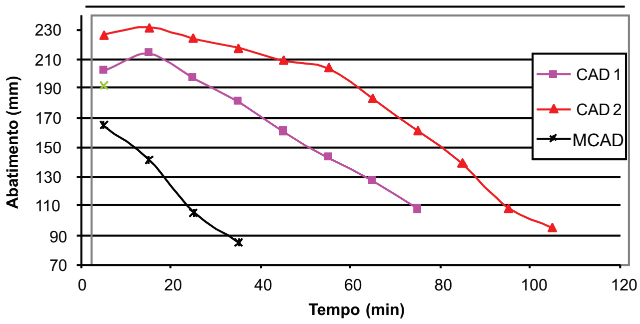
Table 16 – Rheological parameters obtained for the rheological curves of the mortar produced with CPV ARI, w/c = 0.50 and sieved sand, without superplasticizer

Measure time (min)	τ_c	K (Pas^n) Flow consistency index	n Flow coefficient
T = 0	69.480	2.498	0.684
T = 15	102.864	2.276	0.867
T = 30	136.817	1.749	0.905

Table 17 – Slump values obtained by the modified slump test as a function of time for the tested concretes

Concretes	Measure time (minutes)										
	5	15	25	35	45	55	65	75	85	95	105
CAD 1	202	214	197	181	161	143	127	108	-	-	-
CAD 2	226	231	224	218	209	204	183	161	139	109	95
MCAD	165	142	105	85	-	-	-	-	-	-	-

Figure 18 – Slump curves obtained by the modified slump test as a function of time for the tested concretes



A continuous and gradual slump loss over time is observed for all the concretes. However, in the first fifteen minutes of the test, except for the MCAD, it can be seen that the slump increased with time and, thereafter, there was a gradual slump loss as a function of time. This behavior can be justified because the mixing procedure used for the production of CAD1 and CAD2 do not provide enough energy for a complete dispersion and reaction of the superplasticizer with the cement. Superplasticizer molecules need more time to react with the cement, promoting this initial slump gain. For the MCAD, the mixing procedure was differentiated, offering enough energy to disperse the superplasticizer molecules, unlike the other CADs.

Although concretes have different levels of slump loss, the curves obtained are parallel, i.e., they showed the same rheological behavior. It was not possible to analyze the influence of other materials on the concretes' behavior, since it was decided to only alter the content of superplasticizer used.

Figure 19 shows this slump loss in three different phases: at first, soon after mixing, the concrete slump is high due to the low yield stress needed to initiate its flow; subsequently, over time, it is noted that the yield stress of the concrete increased by decreasing its slump; and at the last moment, when the concrete had very low slump, displaying a high yield stress.

The slump loss is considered a normal phenomenon in concretes because it is a result of their setting and hardening process. For the CADs and MCAD analyzed, only the superplasticizer content was changed. Therefore, it is noted that the concrete called CAD2, that received the highest content of superplasticizer, it represented the concrete with the most fluid behavior, with the highest initial setting time.

For the MCAD, the superplasticizer content is the same as for the CAD2, however, by using a coarse aggregate with maximum size less than that of the CAD2, the specific surface increased. The use of crushed gravel of 9.5 mm resulted in a lower slump value for MCAD than for CAD2.

The yield stresses of the evaluated concretes are presented in Table 18. Figure 20 illustrates the development of the yield stresses as a function of time for the tested concretes.

The yield stress of the concrete is inversely proportional to its

Table 18 – Results of yield stress over time for the tested concretes

Yield stress (Pa)		Concretes		
		CAD1	CAD2	MCAD
Measure time (min)	5	872	709	1,121
	15	791	675	1,278
	25	906	726	1,525
	35	1,013	768	1,660
	45	1,148	827	-
	55	1,269	860	-
	65	1,377	1,003	-
	75	1,505	1,146	-
	85	-	1,298	-
	95	-	1,500	-
	105	-	1,593	-

Figure 19 – Continuous and gradual slump loss over the test measure time

Figure 20 – Yield stress curves over time for the tested concretes

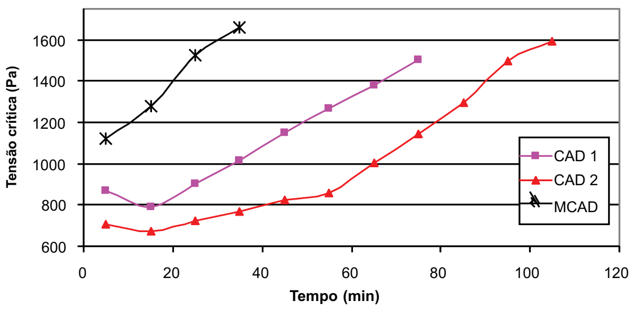


Figure 21 – Evolution of the partial slump time for the tested concretes

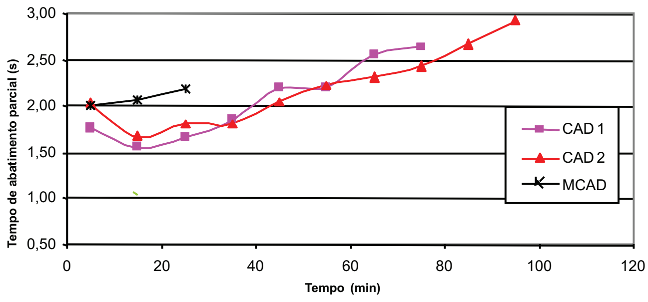


Table 19 – Partial slump time determined by the modified slump test over time for the tested concretes

Concretes	Measure time (minutes)										
	5	15	25	35	45	55	65	75	85	95	105
CAD 1	1.77	1.56	1.66	1.86	2.19	2.20	2.56	2.64	-	-	-
CAD 2	2.03	1.68	1.81	1.81	2.05	2.23	2.32	2.43	2.68	2.93	-
MCAD	0.90	1.03	1.51	1.67	1.76	-	-	-	-	-	-

slump, according to Equation 9 proposed by FERRARIS; de LARRARD [20]. The yield stress curves of both concretes CAD1 and CAD2 are proportional, but they are at different levels of stress. According to TATTERSALL [30] this fact is related to the deflocculation of the cement particles. This behavior was also obtained by Castro [22]. The superplasticizer content of MCAD was identical to that used in CAD2, but the stress levels were different. This difference was due to the change of the coarse aggregate used in MCAD (crushed gravel of 9.5 mm). This modification caused an increase of the specific surface of aggregates, resulting in a concrete with a higher yield stress. The behavior of MCAD in the first fifteen minutes was different from the behavior of the CADs, this is because the mixing procedure was different, using a more efficient procedure for the dispersion of superplasticizer molecules.

It is worth noting that concrete workability losses associated with the increase of the yield stress are related to the setting processes of the concrete. Over time, the concrete hardens due to the reactions of cement hydration.

5.2.2.2 Determination and evaluation of the viscosity

Table 19 shows the values of the partial slump time for the high performance concretes (CADs and MCAD), determined by the modified slump test. Figure 21 shows the evolution of the partial slump time as a function of time for the tested concretes.

The plastic viscosity of concrete with slump exceeding 200 mm is only proportional to the partial slump time of the concrete and, for final slumps between 200 mm and 260 mm, the viscosity is proportional to the ratio of the final slump and the partial slump time, according to Equations 10 and 11 proposed by FERRARIS; de LARRARD [20].

It is noted that in Equation 10 for final slumps ranging from 200 mm to 260 mm, the viscosity is overvalued. These values did not fit the actual situation of the concrete mixture tested. CASTRO [22] found this difference in their concretes and concluded that the value of viscosity calculated from this equation was overvalued with respect to its development over time. As a correction measure, the author considered only Equation 11 for all determinations, a procedure also adopted here. Table 20 shows the viscosity values of the concretes, for all the extent of the final slumps. The development of the viscosity as a function of time for this new relationship is illustrated in Figure 22.

Based on the results of Figure 22, it can be observed that the addition of superplasticizer to the concrete had little influence on its viscosity. The literature [20; 22; 29] emphasizes that the concrete's viscosity variation depends on the proportions of materials used in its composition and also on its setting time. The high performance concrete is a more viscous concrete than the conventional one, called "sticky". This is due to the water/binder ratio and the proportion of admixtures added to it.

6. Conclusions

Regarding the determination of the rheological parameters of cement-based mixtures, especially for the mortars and concretes tested in this study, it can be concluded that the devices or alternative techniques (Pashias for mortars and modified slump test for concretes) provided acceptable values of yield stress and viscosity

Table 20 – Results of the viscosity over time for the tested concretes

Viscosity μ (Pa.s)	Concretes		
Measure time (min)	CAD1	CAD2	MCAD
5	103	119	117
15	91	98	120
25	97	106	127
35	109	106	-
45	128	120	-
55	129	130	-
65	150	136	-
75	154	142	-
85	-	157	-
95	-	171	-

when using this type of material in construction applications. The classical rheometry, based on the use of rheometers, pointed rheometric parameters values of the same order of magnitude as the devices tested. Errors or distances detected in the experiments, for this type of research and within the prescribed experimental conditions, are acceptable. Moreover, it could be inferred indirectly that the Bingham rheological model, with two rheological parameters (yield stress and viscosity), proved to be a necessary and sufficient condition to represent well the concrete compositions tested in this study. For the tested mortars, in particular the use of fine sand in the composition, the yield stress increases, when compared to that of sieved sand, with the result in agreement with the literature [11; 20]. The rheological behavior for the specific case tested seemed to fit better a Herschel-Bulkley model with three rheological parameters.
For the high performance concretes tested, the slump value varied proportionally to the content of superplasticizer used, confirming the influence of the percentage of superplasticizer addition on the workability of concretes. The high performance microconcrete (MCAD) obtained lower slump values than CAD2, although the superplasticizer contents of both mixtures are equal. The possible cause for this is that MCAD is composed by coarse aggregate with higher specific surface (smaller size) which results in a mixture with a more efficient packing of materials than the other CADs.
An important fact regarding the slump value was that all concretes had the slump curve with the same slope, i.e., the slump loss of the concretes as a function of the measure time is in the same proportion. The slump loss and the increase of yield stress were continuous and gradual for the compositions of the concretes tested.
The viscosity of the concrete had little variation during the test (same order of magnitude). Thus, it is noted that the influence of the superplasticizer on the viscosity of the concrete is negligible when compared to the influence on the yield stress. This fact is in agreement with what is presented in the literature [5; 6; 22].

The shooting apparatus used to capture the slump time, using the modified slump test, was very useful, since the uncertainties measured at the end of the test data collection were minimized due to the new resources used.
The MCAD was tested with the concrete rheometer (available at UFSCar) and some adjustments were made on the upward and downward parts of the flow curve. Using these data, the rheological behavior of the mixture was identified, which showed that the MCAD behaves as a Bingham fluid. The upward part of the flow curve was the best suited one, as it had the highest correlation coefficients and also for corresponding to the period in which the yield stress is exceeded [29]. It is also observed that the hysteresis area for the MCAD tested indicated a thixotropic behavior, as some other authors have observed (topic not explored in this paper).
Finally, the process of workability loss of the high performance mixtures (CADs and MCAD), evaluated using the modified slump test by the determination of rheological parameters, was represented by an increase in the yield stress, while the plastic viscosity varied little during the test. The increase in the yield stress of the concrete indicates the mixtures' workability loss over time, i.e., to begin the flow, the resistance to be exceeded increases and its fluidity decreases over time. This behavior is in agreement with the results found in the literature. The results obtained by the concrete rheometer to evaluate the workability of the mixture are: yield torque and torque viscosity. According to REIS [29], the yield torque of MCAD increased and the torque viscosity did not change, both over time, after the end of concrete mixing. This shows that the effect of cement hydration and the chemical effects of the admixtures and mineral additions meant that the mixture lost workability over time, and this behavior is also in agreement with the literature.

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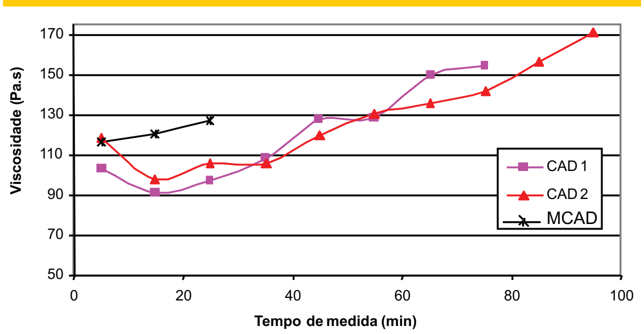
Figure 22 – Curves of the viscosity as a function of time for the tested concretes



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