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Evaluation of fresh high performance concrete behavior by rheometer assistance

Avaliação do comportamento de concretos de alto desempenho no estado fresco com o auxílio de um reômetro



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Abstract

To study the behavior of fresh concrete, nothing is more appropriate than applying the concepts of rheology. It is known that this material behaves as a Bingham fluid and two rheological parameters are needed to describe it: yield stress and plastic viscosity. In recent years, rheology of fresh concrete has been studied with the aid of the slump test or with rheometers. As the slump test does not seem to describe its rheological behavior correctly, this paper presents an evaluation of fresh high performance concrete behavior using a rheometer. Based on the flow curves, their rheological nature and parameters that describe their behavior can be observed. Moreover, the influence of composition and the mixing procedure can be observed as well as the workability evolution over time.

Keywords: *high performance concrete; workability; rheology; rheometer.*

Resumo

Para se estudar o comportamento do concreto no estado fresco, nada mais adequado do que aplicar os conceitos da reologia. Sabe-se que este material se comporta como um fluido binghamiano, sendo necessários dois parâmetros reológicos para sua caracterização: tensão de escoamento e viscosidade plástica. Nos últimos anos, a reologia do concreto fresco tem sido estudada tanto pelo ensaio de abatimento de tronco de cone quanto com reômetros. Como o ensaio de abatimento não parece caracterizar corretamente seu comportamento reológico, o presente trabalho apresenta a avaliação do comportamento de concretos de alto desempenho no estado fresco com o auxílio de um reômetro. A partir das curvas de cisalhamento é possível identificar sua natureza e parâmetros reológicos que caracterizam seu comportamento. Além disso, as influências da composição e do procedimento de mistura podem ser observadas, bem como a evolução da trabalhabilidade ao longo do tempo.

Palavras-chave: *concreto de alto desempenho; trabalhabilidade; reologia; reômetro.*

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1. Introduction

Terms like workability, consistency, flowability, mobility and pumpability have all been used to describe the behavior of fresh concrete. However, these terms reflect personal points of view more than scientific precision [1]. Thus, to study the behavior of fresh concrete, nothing is more appropriate than applying the concepts of rheology, the science that studies the deformation and flow of a fluid under the influence of stress.

1.1 Fresh concrete rheological behavior

Most of the equations used for concentrated suspensions, such as cement paste and concrete, try to relate the suspension concentration to its viscosity or the shear stress to the shear rate, thus assuming that there is only one value for the viscosity of the whole system [2]. Usually, the equations that relate the concentration to the viscosity are used to describe the behavior of cement pastes, while the equations that relate the shear stress to the shear rate are commonly used to describe the rheological behavior of fresh concrete (Table 1).

In the literature, due to extensive experimental evidence of the flow properties of fresh concrete, it was concluded that the material behaves as a Bingham fluid [2; 3; 4] for the range of the shear rate involved in its practical process. Thus, the stress which is necessary for the material flow – shear stress (τ) – is equal to the sum of yield stress (τ_o) and of another term proportional to the shear rate $(\dot{\gamma})$, called plastic viscosity (*μ*) (Equation 1).

$$\tau = \tau_o + \mu\dot{\gamma} \qquad (1)$$

As fresh concrete is a heterogeneous material, with extreme internal mechanical discontinuities, the consideration of a continuous becomes unacceptable. Thus, the rheological parameters are normally measured as dependents of the equipment used in the test and they are expressed in torque units, resulting in flow curves in which the torque (T) is presented as a function of the rotation speed (N), whose relationship is given by the Equation 2.

$$T = g + h^{*}N \qquad (2)$$

where: *g* – yield torque, in [Nm] – is the intercept on the torque axis and *h* – torque viscosity, in [Nm.s] – is the slope of the line. These two constants are analogous to the yield stress and the plastic viscosity, respectively [5].

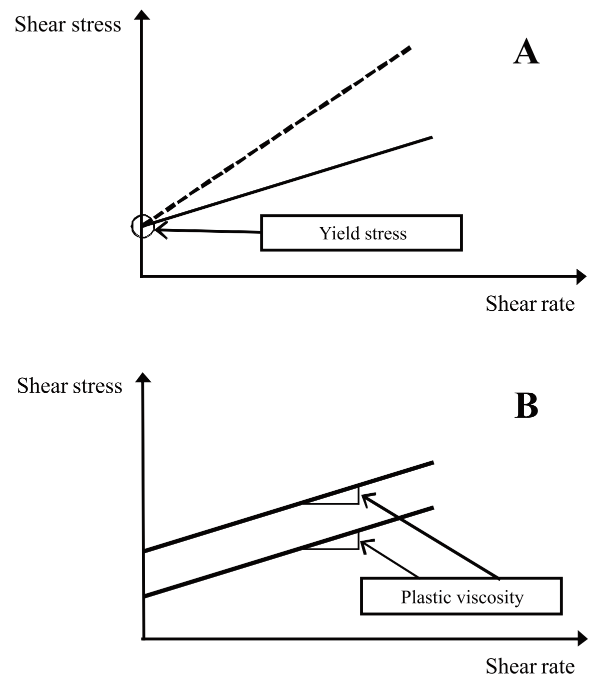
Therefore, as the fresh concrete behavior is similar to that of a Bingham fluid, the material should be evaluated in terms of two rheological parameters: yield stress and plastic viscosity. The first parameter is related to the slump value, while the latter makes the difference between an easily workable concrete from that of hav-

Table 1 – Equations relating shear stress and shear rate to describe the behavior of fresh concretes (2)

Rheological model	Model's equation
Newton	$\tau = \mu\dot{\gamma}$
Bingham	$\tau = \tau_o + \mu\dot{\gamma}$
Herschel-Bulkley	$\tau = \tau_o + K\dot{\gamma}^n$
Power law	$\tau = A\dot{\gamma}^n$ n=1, for Newtonian fluid n>1, for shear thickening n<1, for shear thinning
Vom Berg, Ostwald-de-Waele	$\tau = \tau_o + B\,sen^{-1}(\dot{\gamma}/C)$
Robertson-Stiff	$\tau = a(\dot{\gamma} + C)^b$
Eyring	$\tau = a\dot{\gamma} + B\,sen^{-1}(\dot{\gamma}/C)$
Atzeni *et al.*	$\dot{\gamma} = \alpha\tau^2 + \beta\tau + \delta$

Obs.: τ=shear stress; τ_o=yield stress; μ=viscosity; γ=shear rate;
A, a, B, b, C, K, α, β, δ=constants.

Figure 1 – Concrete rheology: (A) same yield stress and different viscosities; (B) same viscosity and different yield stresses (2)



ing a “sticky” behavior, which is hard to pump and shows coarse bubbling when the mold is removed [6]. Relating to practical applications, the yield stress indicates the flow resistance for low rotation speeds, while the plastic viscosity indicates how the flow resistance increases when the rotation speed up [7].

The relevance in measuring both the yield stress and the plastic viscosity can be observed when the rheological parameters of any two concretes are compared (Figure 1): these materials can have one identical rheological parameter, while the other can be totally different, indicating that these materials present very different rheological behaviors [2].

Therefore, by determining both rheological parameters allows for the immediate differentiation of concretes which could be incorrectly considered identical by the existent standard test methods. Furthermore, the various factors that constitute a concrete mixture and that interfere in its workability influence the yield stress and the plastic viscosity in different ways. Thus, the study of the nature of the changes which take place in the mixture can show which factor is responsible for them.

Normally, the high performance concrete possesses low yield stress and high plastic viscosity compared to an ordinary concrete [5]. A lower yield stress means that this material is capable of flowing under its own weight, while a higher plastic viscosity is required to prevent segregation of aggregates.

1.2 Evaluating fresh concrete rheological properties

When rheological properties are measured in a laboratory, it can be said that rheometry tests are being developed. Taking this into account, there are various available experimental techniques which vary according to the material to be tested.

For fresh concrete, the test methods to determine the flow properties are divided into two groups, which are separated according to the obtained results: one or two rheological parameters. Most current tests measure only one rheological parameter and the relationship between the measured parameter and the second one is not simple. In most cases, it is impossible to calculate the fundamental parameter from the obtained result. In fact, a correlation among them can only be ensured [2].

In particular, for high performance concrete, the flow properties are evaluated by the same test methods used in evaluating an ordinary concrete, however its specific characteristics prevent a correct interpretation of the results. For example, the slump test which is widely used in building practice is mentioned. The test is valid for concretes with a slump value ranging from 25 mm to 175 mm, corresponding to consistencies ranging from low to medium plastic stages; as a high performance concrete usually presents a slump value of more than 200 mm, this test method does not seem to describe its fresh behavior correctly [5]. Furthermore, it is known that, in practice, two concretes with the same slump value can present different rheological behaviors. From this test, it can be demonstrated that the yield stress is within the range desired, but the plastic viscosity, which is not measured by the test, may be so high that the mixture is labeled as “sticky” and considered difficult to be placed even with vibration [2].

Therefore, the requirement for a description of flow properties in terms of fundamental physical quantities has been thoroughly discussed and any test that describes the fresh concrete behavior should measure the yield stress and the plastic viscosity of the material.

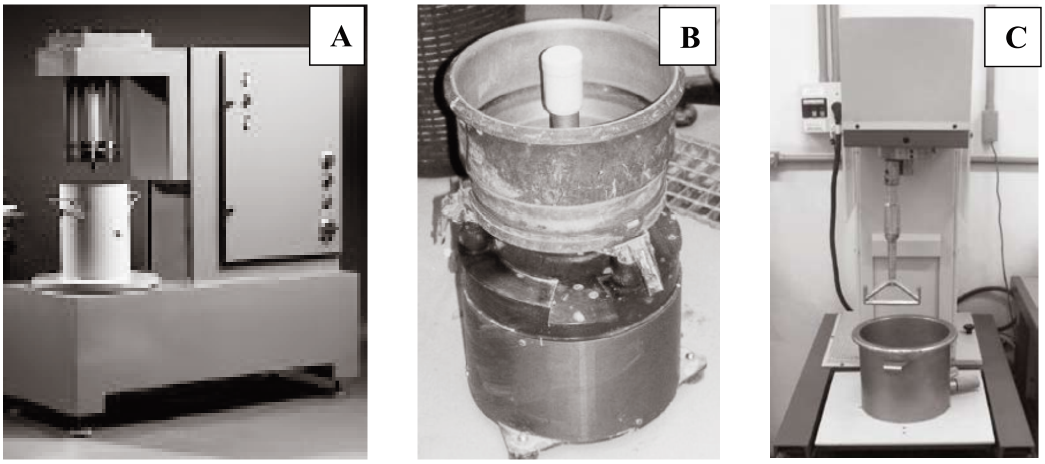
Since Powers and Wiler introduced their “plasticizer” in 1941, several attempts have been made to apply fundamental concepts to the study of fresh concrete properties. Great progress was obtained in 1973, when Tattersall introduced the two-point workability test and, since then, rheological behavior of fresh concrete has continuously been investigated [8]. Over the last years, the rheology of concrete has been studied by determinations which vary from simple and practical test methods, such as the slump test, to more sophisticated equipment which determines the flow curves of the material, such as rheometers.

1.2.1 Rheometer

Rheometers are equipment developed to evaluate rheological properties of fluids and suspensions which enable us to study the behavior of yield stress and plastic viscosity in function of other variables, such as time, temperature etc. Furthermore, this equipment presents geometries which are especially suitable to evaluate mixtures during mixing and transport, simulating conditions of turbulent flow.

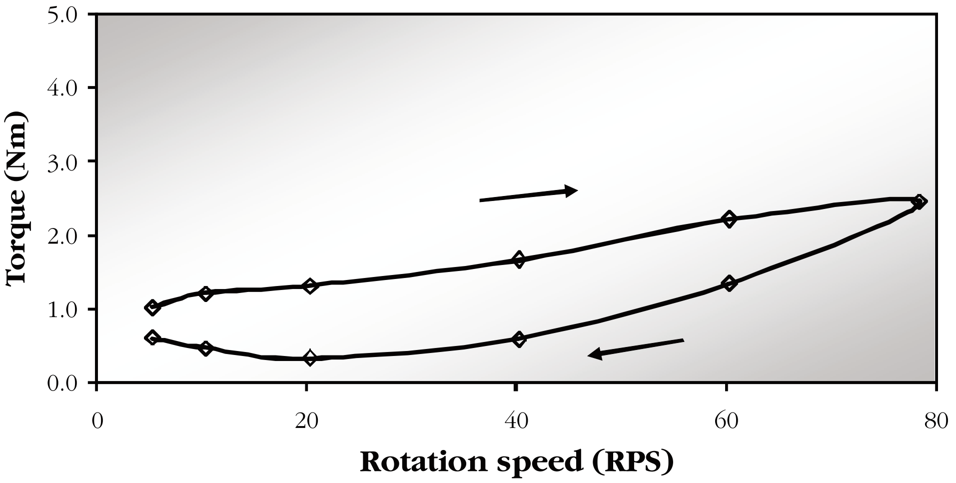
Therefore, rheometers are precise equipment not only for research, but also for practical studies and quality-control measurements of the material. They provide much more information than the conventional empirical tests, lowering material and personnel expenses. Moreover, the information obtained is more objective, as the test is fully automated and computer-controlled [9].

Figure 2 – (A) BML rheometer, based on coaxial cylinders concept (12); (B) BTRHEOM rheometer, based on plate/plate concept (12); (C) rheometer based on planetary model



The first rheometer developed specifically for concrete characterization was conceived by Powers, in 1968, in a coaxial cylinders concept (Figure 2a). With the technological evolution of rheometers, equipment that adopts new concepts for material shear appeared, such as the BTRHEOM rheometer (Figure 2b) developed in the *Laboratoire Central des Ponts et Chaussées* (LCPC), France [12], based on plate/plate concept. In Brazil, a rheometer for the rheological evaluation of refractory castables (Figure 2c) was developed by the Materials Microstructure Engineering Group (GEMM/UFSCar). The project is based on a planetary mixer, which can be used to evaluate rheological properties of self-compact concrete and reduced fluidity mixtures, making possible to enlarge the equipment utilization when compared to the coaxial cylinders rheometers. It also enables the mixing study and simulation of various concrete application techniques [11].
Various commercially available rheometers are based on only two basic principles of operation [11]: the rheometer where the applied torque to the fluid is controlled and the resulting shear is evaluated – suitable for evaluations where the yield stress is the main property to be measured; and rheometers where the applied shear to the material is controlled and the necessary force for such is registered – suitable for evaluations concerning the behavior of the material's viscosity under several shear rates.

Figure 3 – Flow curve of a high performance concrete (16)



Obs.: the narrows indicate the up and down curves, respectively

1.2.2 Flow curves

The rheological behavior of a material depends on the test conditions considered, such as the shear rate, temperature, mixing energy etc. Thus, evaluating the rheological properties of high performance concretes needs special considerations: they require test methods which involve the evaluation of the energy in the mixture and, then, how much the material deforms [13].

Normally, the rheological properties of fresh concrete are determined by plotting flow curves obtained with rheometer assistance. Therefore, it is possible to determine the relationship among the shear stress and the shear rate under conditions which are defined physically. The experimental condition (shear cycle) should be defined before calculating the rheological parameters, keeping in mind that for cement based materials, where certain time dependent phenomena are also involved, the change in the shear rate (rotation speed) should be done in steps and not continually [14].

The flow curves are necessary to appropriately describe the cement based materials such as non-Newtonian fluids, as their viscosity depends on the shear rate and the shear duration [15].

When a concrete is submitted to a gradually upward shear rate and, after this rate is evenly reduced to zero, the resulting flow curve will be able to or not to have its parts – upward and downward – coincident; this graph is called the hysteresis curve, obtained when the material experiences a structural break under a shear action (Figure 3). This hysteresis, whose area represents the work related to the volume of sheared material, can be analysed using a shear qualitative analysis. Afterwards, some conclusions can be drawn concerning the material structural stability [15].

The flow curves vary depending on the total time of the shear cycle, the increase and the reduction rate of the shear rate and the “turning point” of the tests (a moment where the shear rate begins to decrease). Among the parameters which promote variations in the flow curves of the suspensions, the particle coagulation rate is the only factor related to its chemical composition. As the other parameters are simple experimental conditions, it is important to observe that the variation of the flow curve shape does not always describe differences related to the quality of the tested sample [3; 17].

The flow curve of a cement based materials also depends on the features of the equipment used in the test. It is difficult to observe all the possible trends for the flow behavior using only a single rheological model and is made even more complicated when the flow geometry, the gap between the shear surfaces and its friction capacity also vary [18].

The flow curves are useful as a preliminary indicator of the behavior; however they do not provide a good basis for a quantitative analysis. An alternative technique is to study the rate of structural breaks with the time under a continuous shear rate, or more precisely, under a constant rotation speed.

2. Materials and experimental program

To evaluate the behavior of fresh high performance concretes with rheometer assistance, mixtures constituted by Portland cement and silica fume (commercially available), and by aggregates used in the region of São Carlos/SP were studied:

- high early strength Portland cement (CPV ARI), of which the specific gravity is 3.12 g/cm^3;
- fine aggregate: sand quartzous with fineness modulus and maximum size of 2.34 and 4.8 mm, respectively;
- coarse aggregate: crushed rock of basaltic origin with maximum size of 9.5 mm (crushed rock 0);
- mineral addition: silica fume resultant of the metallic silicon and/or Fe-Si alloy production, in the content of 10% in cement volume substitution;
- chemical admixture: polycarboxylate based superplasticizer (SP) with a content of 0.61% (considered as the optimum content for the mixture) [16];
- mixing water corresponding to a constant water/binder ratio of 0.40.

The test conditions were kept constant: relative humidity higher than 65% and a room temperature at 23°C ± 3°C.

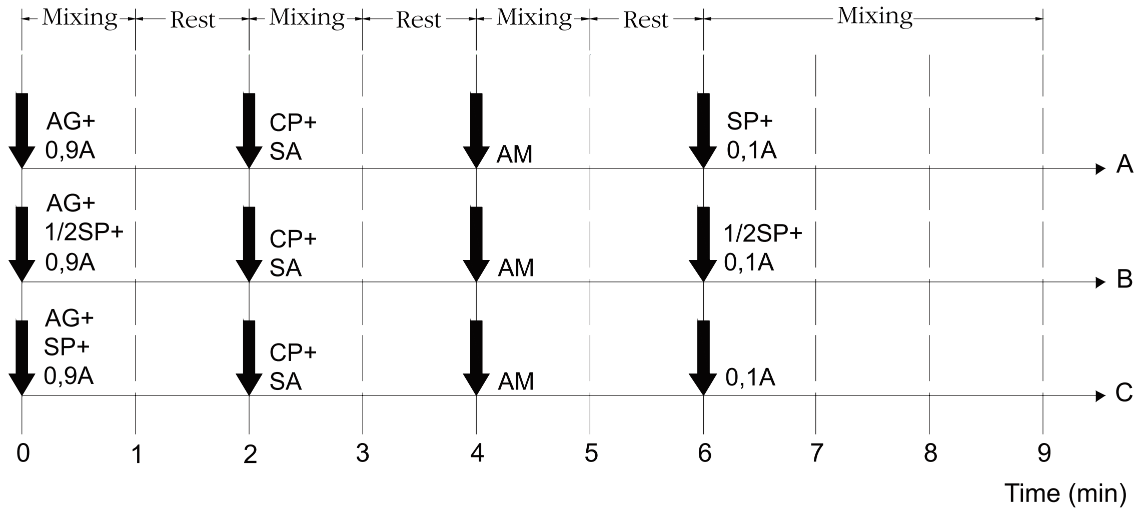
For a better use of the mixture’s constituent materials, a study of the phases that compose the concrete – cement paste matrix and aggregates – was initially carried out. The study of the matrix was done to evaluate the compatibility among the binder materials and the superplasticizer, as well as to determine the admixture’s saturation point. The aggregate phase was studied in order to find the best particle packing by determining the ideal composition among them. After defining the two phases of the concrete, the final composition of the mix design, as well as the necessary fittings were carried out [16].

Thus, for the mix design used (1:m = 3.5; being m the total of aggregates), the consumption of the mixture’s constituent materials is presented in Table 2, where: CC corresponds to an ordinary concrete, without incorporating any chemical admixture or mineral addition; CSP corresponds to the ordinary concrete mix design incorporated only with the optimum quantity of SP; and CAD corresponds to the high performance concrete composed both with chemical admixture and mineral addition. Taking this into account, the influence of the mixture’s composition on its rheological behavior can be observed.

Table 2 – Specific gravity and materials consumption for the concretes studied

Concrete	Specific gravity (kg/dm^3)	Material's consumption (kg/m^3 of concrete)					
		Cement	Silica fume	Fine aggregate	Coarse aggregate	Water	SP
CC	2.393	488	---	855	855	195	---
CSP	2.393	488	---	855	855	194	2.25
CAD	2.377	454	31	849	849	192	2.43

Figure 4 – Mixing procedures used in the production of high performance concretes, where: A=water, AM=fine aggregate, AG=coarse aggregate, CP=cement, SA=silica fume and SP=superplasticizer



To observe the influence of the mixing procedure on the fresh concrete behavior, three different procedures were considered when producing the high performance mixture (CAD), whose order of placing the constituent materials was varied (Figure 4). They were based on the mixing procedure widely used in practice (procedure A) and a variation of the superplasticizer time addition was considered (procedures B and C). The mixing time was kept constant for all the procedures which were followed, and a total of 9 minutes to complete the concrete production was considered.

In this paper, evaluating fresh concrete behavior was carried out by the assistance of the rheometer developed by GEMM/UFSCar (Figure 2c). The design of the rheometer was based on a planetary mixer originally composed by an alternating current motor, a four-speed gear and a cylindrical vat with a capacity to mix up to 10 kg of concrete. The original reduction system was maintained to transfer the motor rotation to the planetarium; however, some changes were made in the original mixer: the mixing vat capacity was reduced to 4 kg of material and entrances for pH and temperature sensors were installed. For the equipment rotation control and, consequently, shear application to the concrete, a direct current relay substituted the original motor and the rotation speed became variable [11].

Introducing the new relay meant constructing a control panel, in which there was a converter from an alternating current to a direct one, a security system that limits the maximum current which can be supplied to the motor, a motor rotation controller and connection points to communicate with a computer. The control panel was connected to a computer and specific software was also developed to control the rheometer and to analyze the collected data [11].

The rheological description of the concretes was carried out by shear tests done using rheometer assistance. Taking this into account, the mixtures were submitted to step shear cycles, with rotation speeds ranging from 5 RPM to 80 RPM after mixing. This kind of test creates flow curves which enable us to observe the efficiency of particle dispersion (mixing efficiency) and to identify the rheological nature of the material.

To identify the rheological behavior, the flow curves were fitted by two rheological models – Bingham and Power law. Both upward and downward parts of the flow curve were evaluated. Thus, the rheological nature was identified by the model which best fitted the flow curve, in other words, by the model which was able to obtain the highest correlation coefficient between its constitutive straight and the data obtained by the rheometer.

The influence of the mixing efficiency and the evaluation of concrete thixotropy were observed by the complete flow curves. These factors were related to the hysteresis area formed in each study condition.

The influence of the concrete composition, as well as the mixing procedure used in its production was evaluated by comparing the rheological parameters determined in each situation.

For high performance concretes, a common problem found in building practices is their fast workability loss. Therefore, when a mixture of this material is designed, it is not just necessary to find the specifications for its early behavior, but also to ensure that it remains stable during the time necessary for its placement [10]. With the rheometer assistance, the workability evolution of the concretes can be monitored over time, associating it with the evolution of the measured rheological parameters. Thus, the behavior of the studied mixtures was followed over time, making measurements of 10, 30 and 60 minutes after the initial contact between the cement and mixing water.

3. Results and discussions

3.1 Identifying concrete rheological nature

Controlling the factors that influence the rheological behavior of high performance concretes can determine their application characteristics. Thus, depending on the mixture composition, the used casting technique can vary from a vibration application to a self-compacting one.

However, the use of these materials does not only involve their compaction process, but also the processes of mixing, transport and placement. Various factors, such as the rheological nature, the tendency to segregate, the cohesion and the heating of the mixture – which influence the behavior of the concrete during the handling processes – are not measured by the slump test widely used in concrete building practices.

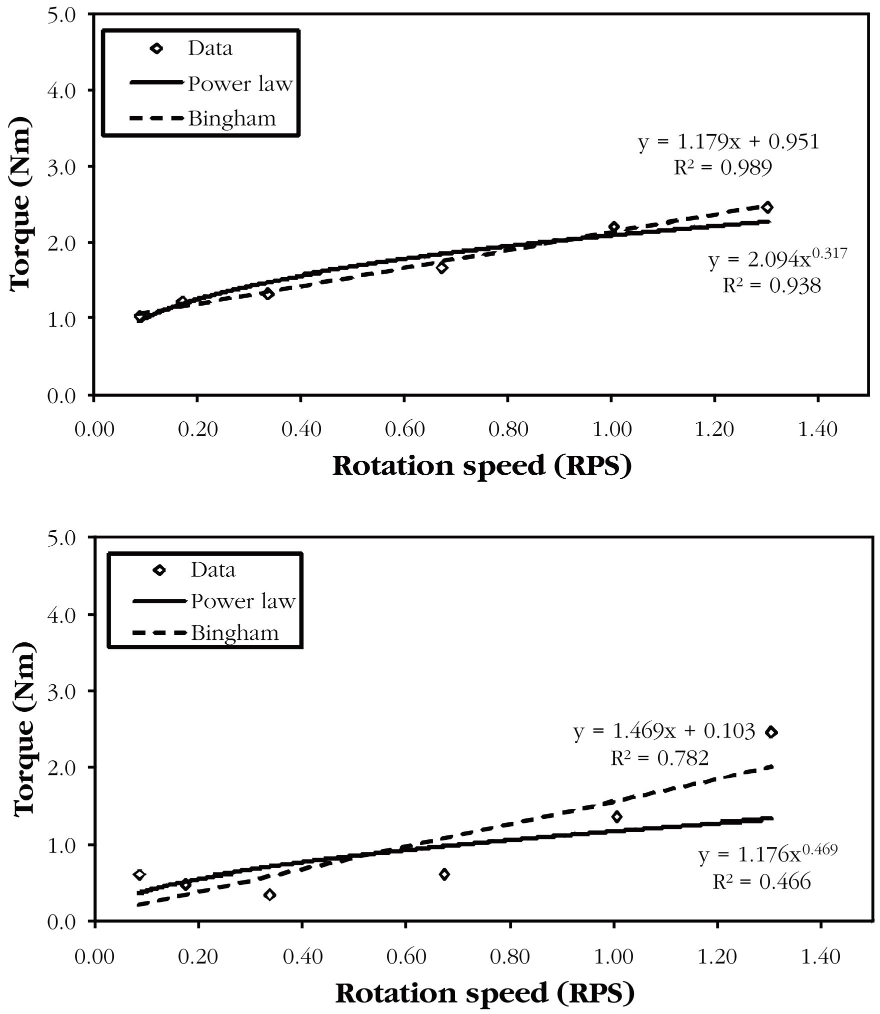
For example, Pileggi [11] mentions the pumpable concrete: a shear thickening concrete, regardless of its fluidity level, which presents difficulties to flow under high shear rates, hindering or preventing its pumping. On the other hand, a shear thinning mixture, even with low fluidity, could be pumped, because as the higher the shear rate applied, the lower its flow resistance. Therefore, a difference between the fluidity level (which defines the casting characteristic) and the concrete's rheological behavior (which determines the most suitable technique for its application) can be observed.

To identify the rheological behavior of the mixtures, fittings were made both in upward and downward parts of the flow curve for two rheological models – Bingham and Power law. From the results (fitting examples presented in Figure 5), the consideration of the upward part of the flow curve showed to be more appropriate (higher correlation coefficients), and corresponded the period in which the yield stress should be exceeded for the beginning of the flow.

It is worth remembering that to plot the flow curves, the speed was considered in rotations per second (RPS) so that the parameter related to the plastic viscosity (torque viscosity – *h*), expressed in Nm.s, was directly determined. Otherwise, by plotting the flow curves with the rotation speed in rotations per minute (RPM), this parameter should be corrected in the constitutive straight.

Thus, the upward parts of the flow curves fitted to identify the rheological nature of the concretes are presented in Figure 6. In Figure 6-A the fittings of the curves obtained for the mixtures with different compositions (CC, CSP and CAD) are shown, while in Figure 6-B the curves re-

Figure 5 – Example of the fitting of the upward (A) and downward (B) parts of a concrete flow curve to the considered rheological models



sulted from the mixtures with a similar composition produced according to different mixing procedures (procedures A, B and C) are presented. From Figure 6, it can be observed that all the mixtures, regardless of their composition and the mixing procedure used in their production, present a behavior similar to a Bingham fluid, which is compatible with the behavior widely observed for high performance concretes studied in the well-respect centers of concrete technology research and found in the literature [2; 3; 4; 19]. Thus, two rheological parameters are necessary for the behavior description of these fresh concretes: the yield stress and the plastic viscosity.

3.2 Influence of mixing efficiency/concrete thixotropy

The flow curves provide two fundamental pieces of information [11]: first, the smaller the hysteresis area, the higher the efficiency of particles dispersion and, consequently, of the mixing; and second, the curve outline indicates the rheological nature of the material.

In Figure 7, the complete flow curves for the studied concretes are presented. It can be observed that the upward and the downward parts of the curves do not coincide, generating a hysteresis area. Initially, this behavior indicates that the mixing was not capable of supplying enough energy to break the agglomerates present in the material and therefore a more efficient mixing process is related to a smaller hysteresis area. In some situations, other factors can also be related to a hysteresis area, such as the characteristics of the matrix and the aggregates that constitute a concrete mixture.

The values of the flow curve hysteresis area of the concretes are presented in Table 3. A small variation of these areas can be observed due to the concrete composition and the mixing procedure used in its production.

Furthermore, when a hysteresis area is observed in the complete flow curve, it is considered that the tested material has a significant thixotropic behavior, i.e., when this material is submitted to a constant shear rate, its apparent viscosity decreases

Figure 6 – Fitting of the flow curve upward part of the concretes with (A) different compositions and (B) same composition produced according to different mixing procedures

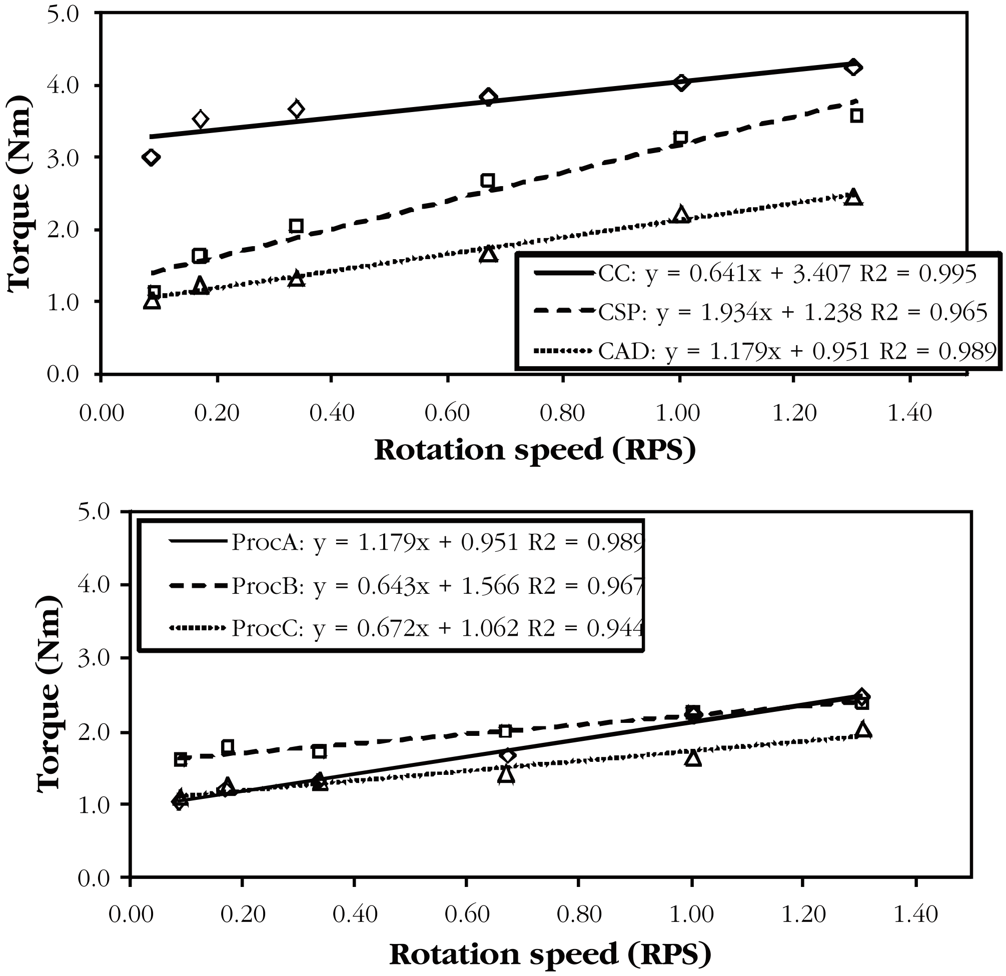
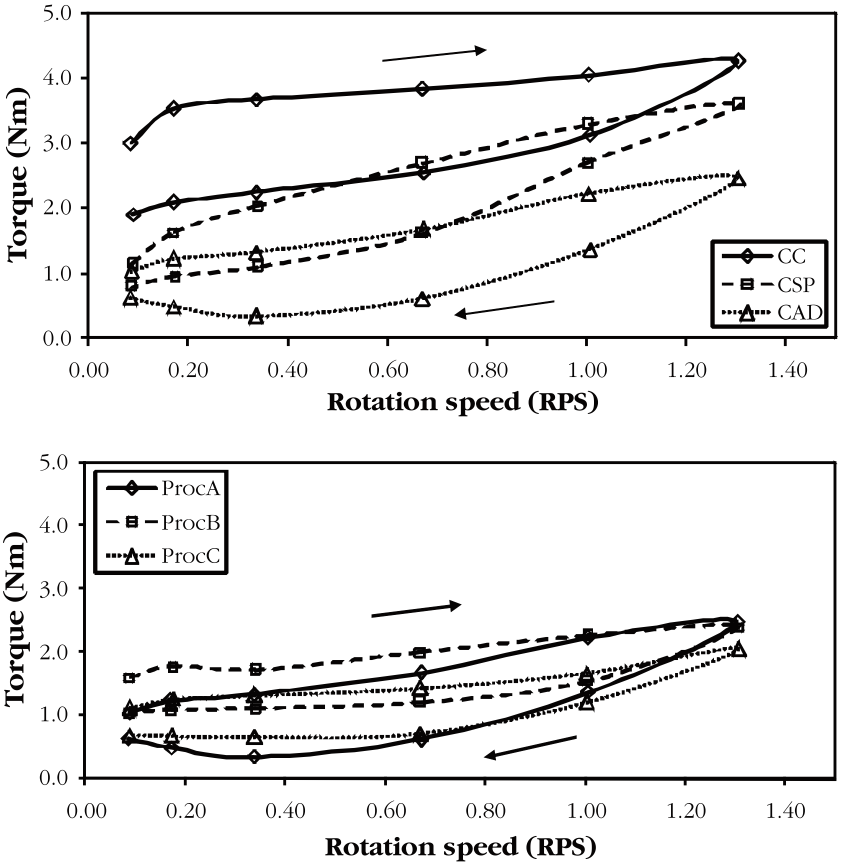


Figure 7 – Flow curves of the concretes with (A) different compositions and (B) same compositions produced according to different mixing procedures.



Obs.: the narrows indicate the up and down curves, respectively

over time. This behavior is due to the existence of an unstable structure in the material, which can be broken when applying a given energy, remembering that this structural break is reversible and quickly recovered.

Thus, it can be observed that the flow curves obtained for the studied concretes have a hysteresis area, proving the thixotropic behavior of these materials. However, determining a hysteresis area does not give an intrinsic value of any rheological parameter, and it is only possible to obtain empirical correlations among the results obtained in the study of thixotropy consequences.

The calculation of a flow curve hysteresis area seems to be a limited way to obtain a relative classification of the concretes or a qualitative comparison of the effect of various additions [20]. Evaluating concrete behavior under a continuous shear rate or, more precisely, under a constant rotation speed, by studying the rate of the material's structural break in function of the time, constitutes an alternative technique to the flow curves [3].

Table 3 – Flow curves hysteresis area of the concretes studied

	Concrete			Mixing procedure		
	CC	CSP	CAD	ProcA	ProcB	ProcC
Hysteresis area (Nm.RPS)	1.325	1.119	1.095	1.095	1.023	0.804

Table 4 – Rheological parameters of the concretes studied, obtained by fitting the upward part of the flow curve to Bingham model

Rheological parameters	Concrete			Mixing procedure		
	CC	CSP	CAD	ProcA	ProcB	ProcC
Yield torque g(Nm)	3.41	1.24	0.95	0.95	1.57	1.06
Torque viscosity h(Nm.s)	0.641	1.934	1.179	1.179	0.643	0.672

3.3 Influence of composition and mixing procedure

The influence of the concrete composition and the mixing procedure used in its production can be observed, in more fundamentals terms, from the analysis of the rheological parameters which describe the behavior of fresh concrete mixtures. The values determined for the rheological parameters in each test condition are presented in Table 4.

From the results presented in Table 4, it can be observed that the rheological parameters vary according to the concrete composition and with the mixing procedure used in its production. Therefore, it is possible to observe different rheological behaviors among the studied concretes, even the considered slump value being the same.

3.4 Workability evaluation from the evolution of the rheological parameters

The evolution of rheological parameters is becoming more and more important as new generations of concrete are shown dependent on the effective conditions during the casting. Changes in the flow resistance over time, when a material presents Bingham behavior, are consequences of the changes in the yield stress and the plastic viscosity, which usually vary exponentially over time. From the technological point of view, it is very important to know how the change in these parameters contributes to the changes in the flow resistance [21; 22]. Therefore, the results of workability evaluation measured over time, based on the evolution of rheological parameters, are presented in Table 5.

From the values presented in Table 5, it can be observed that the yield torque increases with time, while the viscosity stays practically constant. This means that, once the yield stress has been exceeded, its flow resistance stays practically the same for the applied shear rates, within the evaluated period of time. Regardless of the concrete composition and the mixing procedure used in its production, evaluating the rheological parameters over time is similar for the studied mixtures.

The increase in the concrete yield stress over time reflects the stiffening process of this material. However, the same can not be said for the evolution of plastic viscosity. As the samples of concrete remain at rest between the consecutive rheological tests, the torque requirement for the low rotation speeds increases more than that for the highest speeds, probably due to the agglomeration of the particles, the growth of hydration products and the depletion of superplasticizer molecules in the chemical process. This results in a reduction in the slope of the flow curve, which may explain why the

Table 5 – Rheological parameters values considering the upward part of the flow curve and Bingham behavior

	Yield torque (g(Nm))			Torque viscosity (h(Nm.s))		
	Time (min)			Time (min)		
	10	30	60	10	30	60
Concrete						
CC	3.41	3.92	4.48	0.641	0.574	0.976
CSP	1.24	1.41	1.87	1.934	1.969	1.807
CAD	0.95	1.13	1.48	1.179	1.121	1.189
Mixing procedure						
ProcA	0.95	1.13	1.48	1.179	1.121	1.189
ProcB	1.57	1.86	2.31	0.643	0,688	0.663
ProcC	1.06	1.44	1.54	0.672	0,673	0.800

plastic viscosity does not increase over time, tending to decrease slightly in some cases [23].

4. Conclusions

Regardless of their composition and the mixing procedure used in their production, the studied concretes presented a behavior similar to that of a Bingham fluid, indicating the need for two rheological parameters – yield stress and plastic viscosity – for the correct evaluation of their fresh behavior. The behavior observed in this study is compatible with that widely observed for high performance mixtures studied in well-respected centers of concrete technology research and information found in the literature.

Furthermore, it can be observed that the upward and the downward parts of the flow curves of the tested mixtures do not coincide, generating a hysteresis area between them, indicating the thixotropic behavior of these materials.

From the flow curve, with the rheological parameters determination, the influence of the concrete composition and the mixing procedure used in its production in terms of more fundamental physical quantities can be observed.

Evaluating concrete workability over time from the evolution of the rheological parameters shows that the workability loss process of high performance mixtures was characterized by an increase in the yield stress, while the plastic viscosity remains practically constant during the test. The behavior observed is compatible with the results published in the literature.

Thus, the rheometer constitutes an efficient tool to evaluate fresh concrete behavior. It can obtain precise information beyond the evaluation of this material workability, such as the identification of its rheological nature, the observance of mixing efficiency and thixotropy, the verification of the influence of mixture composition and the mixing procedure used in its production. In the case of the use of a planetary shear rheometer, as in the present paper, the rheological properties of the reduced fluidity concretes (ordinary concrete) and mixtures of the high plastic stage (high performance concrete) could be evaluated.

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