The application of rheological concepts on the evaluation of high-performance concrete workability

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THE APPLICATION OF RHEOLOGICAL CONCEPTS ON THE EVALUATION OF HIGH PERFORMANCE CONCRETE WORKABILITY

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Synopsis: Traditionally, concrete workability is associated with its consistency, expressed in terms of the value measured by the slump test that, in spite of being quite a used test, does not quantify it totally. It happens because, from a rheological point of view, the fresh concrete flows as a liquid and its behavior is similar to a Bingham fluid, and is described by two rheological parameters: the yield stress and the plastic viscosity. Thus, this paper presents the evaluation of high performance concrete workability by the traditional slump test widely used in the construction practice and by more recent equipment such as the rheometer. It can be observed that the slump test measures a single value (slump), which can be the same for two mixtures with different rheological behaviors, while with a rheometer, it is possible to determine both rheological parameters that describe the fresh concrete properties, causing two mixtures with different behaviors to be erroneously considered equal in terms of workability. The process of workability loss is associated with the increase of rheological parameter values and to a corresponding reduction of the slump value over time. The correlation among the parameters obtained by the rheometer and the value measured by the slump test, of great importance for practical purposes, showed that the slump value is much more sensitive to the yield torque than the torque viscosity.

Keywords: High performance concrete, rheology, slump value, workability.

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INTRODUCTION

Traditionally, the behavior of fresh concrete is associated with its workability, a term that refers to properties of the material before it has set and hardened. It does not correspond to an intrinsic property of the material, but it is related to the construction type and the methods of placement, compaction and finishing. Thus, the workability level required for a concrete depends on the situation for which the material will be designed.

The importance of workability in the concrete technology is very obvious, because apart from the sophistication used in the mix design procedures, a concrete that cannot be placed easily or totally compacted will probably not present the desirable characteristics of strength and durability [1].

Due to the workability definition, the composed nature of this property and its dependence on the construction type and practical processes involved, no single test can be designed to measure this property. However, the tests developed to measure workability – slump test, flow-table test, compacting-factor test, Vebe consistometer etc. – constitute useful tools for the quality control of concrete, even being qualitative measures based on scales which are randomly defined.

Most national standards specify several different tests for the workability evaluation and the reason for this is that none of them are capable of dealing with the whole range of workabilities that are of interest in the construction practice. Results from empirical tests should be mentioned quantitatively, but indicating the test. Such tests do not measure workability and it is a mistake to quote results as if they do [2].

Concrete workability is mainly evaluated by the slump test; however, the validity of this test is recommended for concretes with a slump value ranging from

25 mm to 175 mm, corresponding to consistency ranging from low plastic to medium plastic stage. Therefore, this test does not seem to correctly characterize the workability of high performance concrete with high flowability, since its slump value is usually more than 200 mm. Moreover, in practice, it is known that concretes with the same slump value or flow value are able to present different workabilities [3].

So that advances are made in the comprehension and control of the fresh concrete workability, the test procedures and the industrial standards should be directed for more fundamental quantitative bases. Thus, the demand for the estimative of fresh concrete workability in terms of rheological constants in the place of the results from empirical tests has increased significantly in the last years.

Rheology of fresh concrete

Concretes are composite materials, with cement, aggregates and water being the main components. In high performance concrete (HPC), chemical admixtures and mineral additions are incorporated to the traditional mixture so that a greater variety of properties and characteristics can be achieved.

From the rheological point of view, fresh concrete can be considered as a concentrated suspension of solid particles (aggregates) in a viscous liquid (cement paste). In turn, the cement paste does not represent a homogeneous fluid, which is composed of particles (cement grains) and a liquid (water). On a macroscopic scale, concrete can flow as a liquid [4]. Therefore, as the concrete is a viscous fluid, in order to study its fresh behavior, there is nothing more appropriate than finding its rheology concepts, the science which concerns the study of deformation and flow of a fluid under stress influence.

All the standard tests, as well as any other empirical tests, try to assess workability in terms of a single quantity, be it a slump value, a Vebe time etc., so that all of them take into account the implicit consideration that concrete behaves in the simplest way possible, such as water. However, the most casual observation of the behavior of this material shows that this assumption cannot be true.

It can be observed that the concrete requires the imposition of a minimum stress or force to start its flow, which indicates that there is a yield stress [5]. Therefore, the concrete behavior cannot be described by a unique constant. To discover what the form of the flow curve of a material is, some experiments should be developed in which the measures are evaluated under different flow speeds [2].

In the literature, due to extensive experimental evidence of the flow properties of fresh concrete, it was concluded that the material behaves as a Bigham fluid [2,4,5] for the range of shear rate involved in the practical process of the material, that is, concrete does not flow until a particular stress is exceeded. Thus, the stress which is necessary for a material flow – shear stress (τ) – is equal to the sum of yield stress (τ_o) and of another term proportional to the shear rate ($\dot{\gamma}$) (Eq. 1). The proportionality factor in the second term is called plastic viscosity (μ) and its reciprocal, fluidity or mobility.

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

Evaluation of workability by rheological concepts

The workability of HPC is evaluated using the same tests as were used for ordinary concrete; however its specific characteristics incorrectly interpret the results [4]. As an example, the slump test is mentioned: how this test results in a single value (slump value), critically based on the argument that the same slump value can be measured for two concretes with different rheological behaviors.

Thus, the necessity for the description of fresh concrete behavior in terms of fundamental physical quantities has been widely discussed. Any test that describes the flow behavior of this material should measure, at least, the two rheological parameters – yield stress and plastic viscosity.

Unfortunately, most existing tests only measure one of these parameters. That being so, the single-point tests can only reflect the answer of the fresh concrete to a particular shear rate. To obtain a more pertinent description of the flow behavior of HPC, it is necessary to test the properties in a certain range of the shear rates while concrete flows [3].

In recent years, the workability of fresh concrete has been studied from rheological concepts, with measurements that vary from simple and practical tests, such as the slump test, to more sophisticated equipment, such as the rheometers.

Rheometers are equipment developed to evaluate rheological properties of fluids and suspensions. They are special instruments not only for research, but also for practical studies and quality-control measurements of the material. With their use, it is possible to obtain much more information than with the conventional empirical tests, lowering the material and personnel expenses. Moreover, the information is more objective, as the test is fully automated and computer-controlled [6].

Rheometers evaluate the behavior of yield stress and plastic viscosity as a function of other variables, such as time, temperature etc. Moreover, they allow the user not only to detect losses of workability, but also to discover the origin of the phenomenon.

The measurements obtained from a rheometer can be interpreted only if the fluid is homogeneous. Due to the broad particle size distribution present in a concrete and the air trapped in the suspension, this material cannot be considered as such. Thus, it is inaccurate in describing the characteristics of this class of material in terms of shear stress and shear rate. A better approach would be the direct analyses of the forces (torque) that result from the shearing (rotation speed) of the concrete [7]. So, the flow curve has been built giving the torque as a function of the rotating speed and the two parameters that describe the fresh concrete behavior are normally expressed in torque units. The relationship between torque (T) and rotation speed (N) is given by the equation:

$$T = g + h*N \qquad \text{(Eq. 2)}$$

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 [3].

RESEARCH SIGNIFICANCE

The behavior of fresh high performance mixtures is always critical for a successful construction and a suitable performance along the time. As from rheological point of view the fresh concrete behaves as a fluid, its behavior, associated with workability, can only be correctly evaluated through the application of rheological concepts. Thus, this paper presents a study about the workability of high performance concrete from rheological concepts, evaluated as by simple and practical test procedures – such as the slump test – as by more sophisticated equipments that determine the flow curves of the material – such as the rheometers.

EXPERIMENTAL PROCEDURE

To evaluate the workability of high performance mixtures from rheological concepts, HPC – constituted by portland cement and silica fume commercially available and by aggregates used in the region of São Carlos/SP - Brazil – were studied:

- high early strength and sulfate resistant portland cement (CPV ARI RS – ABNT), of which the specific gravity is 3.08 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 according to Brazilian standard – ABNT);
- 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 0.50% (optimum content for the composition of designed HPC [8]);
- mixing water corresponding to a water/binder ratio of 0.40.

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

For the mix design used (1:*m* = 3.5, being *m* the total of aggregates), the proportions of mixture constituents is presented in Table 1. The HPC1 corresponds to the reference mixture – ordinary concrete, without the incorporation of any chemical admixture or mineral addition; the HPC2 corresponds to the ordinary concrete mix design incorporated only with the optimum quantity of SP; and the HPC3 corresponds to the high performance concrete composed both with chemical admixture and mineral addition.

The concrete workability was evaluated in terms of the slump value measured by the slump test, and of the rheological parameters determined from the flow curve obtained with the rheometer. So it is possible to verify the influence of the constituent materials and the mixture composition on the behavior of fresh concrete both from a test widely used in practice (slump test) as well as from modern and sophistical equipment (rheometer).

Firstly, the slump value was determined by the slump test (Fig. 1). In sequence, the concrete was submitted to step shearing cycles in the rheometer (Fig. 2) to make the flow curve and to determine the rheological parameters that describe its behavior.

When a concrete is designed, especially for an HPC, it is necessary not only to meet the specifications for its initial behavior, but also to ensure that its behavior remains stable as long as necessary for placement [9]. Thus, the behavior of the studied mixtures was followed over time, making measurements 10, 30 and 60 minutes after the initial contact between cement and mixing water.

However, as the use of a rheometer to evaluate HPC workability is not a common practice, it is interesting to determine correlations between the values obtained with this equipment and the values obtained with the slump test which is widely used. Thus, these correlations were made as an attempt to facilitate the study of concrete workability from rheological concepts.

RESULTS AND DISCUSSION

The slump values of the studied mixtures, obtained by the slump test, are presented in Table 2. The evolution of this parameter over time can be observed in Figs. 3 and 4.

The values of the rheological parameters resulting from the flow curve obtained with the rheometer are also presented in Table 2 and their evolution over time can be observed in Figs. 3 and 4. The parameters were obtained adjusting the upward curve (torque *versus* rotation speed) to the Bingham model [8].

From the results, it can be observed that the slump test presents a limitation when the mixture has a low initial slump value, which does not permit the following of this parameter evolution over time. Therefore, the study of constituent materials and mixture composition influence on the behavior of fresh concrete is engaged.

When the rheometer is used, the behavior of all the HPC studied can be analyzed and followed over time, regardless of its composition and of the slump value. This is possible because a planetary rheometer allows both concretes with high fluidity and mixtures with a lower fluidity to be evaluated.

Thus, the influence of constituent materials and mixture composition on the properties of fresh concrete can be observed:

- when comparing HPC1 and HPC2, a great reduction of the yield torque and an increase of the torque viscosity were observed when the SP was incorporated into the mixture. This behavior was also observed in other research [10,11], where the authors relate this comment to the fact of SP having a bigger effect on yield torque than on the torque viscosity;
- when comparing HPC2 and HPC3, it can be observed that the incorporation of silica fume results in the increase of yield torque, while the torque viscosity is reduced. The torque increase is related to the increase in the quantity of fine particles: as the silica particles are very small and, consequently, have a high

specific surface, they are very chemically reactive and adsorb the SP molecules [12]. The viscosity reduction is associated with the better particle distribution of the binder, the change of the C_3S angular particles by silica spherical particles and the lubricating role promoted by silica, reducing the aggregate interlocking and, consequently, this rheological parameter [13];

* a HPC possesses a low yield torque and a high torque viscosity compared to that of ordinary concrete [3]: a lower torque means that this material is apt to flow under the influence of its own weight, while a higher viscosity is required to prevent aggregate segregation. Thus, when comparing the rheological parameters determined for the ordinary mixture (HPC1) and for the high performance one (HPC3), this observation is confirmed.

The process of workability loss is generally reflected by an increase of yield torque, with a correlative reduction of slump value; however, in most cases, the torque viscosity stays practically constant during the period in which the test is developed (generally less than 90 minutes) [9,14].

The increase observed for yield torque over time indicates the concrete stiffening; however, the torque viscosity does not reflect this behavior. As the concrete stays in rest between consecutive rheological tests, the torque for the low rotation speeds increases more than that for the high rotation speeds. This results in a reduction of the slope of the torque *versus* rotation speed curve, which may explain why the torque viscosity does not increase with time and can decrease in some cases [13].

For the HPC studied, the slump value decreases, while the yield torque and the torque viscosity increase over time (Figs. 3, 4). Thus, the process of workability loss is associated with a reduction in the slump value and a corresponding increase of both rheological parameters. The evolution of these parameters resulted in similar behaviors to other results presented in the literature [3,9,12,13,14].

Correlation among slump value and rheological parameters

At present, rheometers are not commonly used in practice, so it is interesting to determine correlations among the values obtained with this equipment and those obtained by the slump test.

As the slump cone is lifted, the concrete sample slumps down by the action of gravity. Considering the concrete as a yield stress fluid, the sample stops flowing downward when the shear stress applied by gravity becomes less than its yield stress. Thus, for these materials, the existence of a strong relationship between the slump value and the yield stress (or yield torque) is expected [15].

Several attempts have been made to find a relationship between the yield stress (or yield torque), the plastic viscosity (or torque viscosity) and the slump value of a concrete. However, most researchers agree that the slump test is essentially a static test, depending specially on the yield stress of the concrete and, to a lesser extent, on the plastic viscosity of the material [16].

In Fig. 5, the results obtained for the HPC studied are presented. As HPC1 did not present a sufficient slump value to be measured over time, it was not possible to obtain the correlation of this value with the rheological parameters obtained for this mixture. For the other mixtures, the correlations between the yield torque and the slump value presented coefficient equals to 0.9847 and 0.8075, respectively, to HPC2 and HPC3. For the torque viscosity, the coefficients of correlation between this rheological parameter and the sump value were 0.9981 and 0.7353, respectively, for HPC2 and HPC3. Thus, this study indicates that the slump value is more sensitive to the yield torque than to the torque viscosity, which is in accordance with the study developed by Wallevik [15].

CONCLUSIONS

As the slump test widely used in practice has its use generally limited to slump values ranging from 25 mm to 175 mm, the rheometer constitutes a very efficient tool to evaluate the behavior of concretes with consistency ranging beyond these limits. With the planetary rheometer, it is possible to involve quite fluid concretes (self-compacting ones) as well as mixtures with a reduced fluidity. Thus, the influence of constituent materials and mixture composition can be observed in any situation, regardless of the slump value presented by the mixture.

Moreover, the study of concrete rheological behavior from a rheometer allows the user not only to detect losses of workability, but also to discover the origin of the phenomenon. The process of workability loss is normally associated to the increase of the rheological parameters over time and, among the main causes of these losses, the abnormal chemical activity of the cement that constitutes the mixture, the water absorption from the matrix by the aggregates and the segregation between mortar and coarse aggregate stand out.

Although the rheometer is not an equipment frequently used in the design and quality control of the concretes, the correlation between the parameters obtained from this equipment and the parameter measured by the slump test is very interesting for practical purposes. From the correlations observed between the slump value and the rheological parameters, it can be seen that the slump is much more sensitive to the yield torque than to the torque viscosity, as observed previously in papers presented in the literature.

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TABLES

Table 1 – *Specific gravity and material's proportions for the HPC studied.*

Concrete	**Specific gravity (kg/dm^3)**	**Material's proportions (kg/ m^3 of concrete)**					
		Cement	**Silica**	**Fine aggregate**	**Coarse aggregate**	**Water**	**SP**
HPC1	2.393	488	---	855	855	195	---
HPC2	2.393	488	---	855	855	194	2.25
HPC3	2.377	454	31	849	849	192	2.43

Table 2 – *Results of the slump test and of the adjustment of flow curve obtained with the rheometer for the HPC studied.*

Concrete	**Time (min)**	**Slump test**	**Rheometer**	
		Slump value [mm]	***g*** **[Nm]**	***h*** **[Nm.s]**
HPC1	**10**	20	3.87	0.601
	30	---	4.19	0.981
	60	---	4.91	0.998
HPC2	**10**	230	0.92	1.956
	30	190	1.13	2.023
	60	125	1.70	2.116
HPC3	**10**	210	1.37	0.685
	30	165	1.51	1.114
	60	135	2.09	1.053

FIGURES

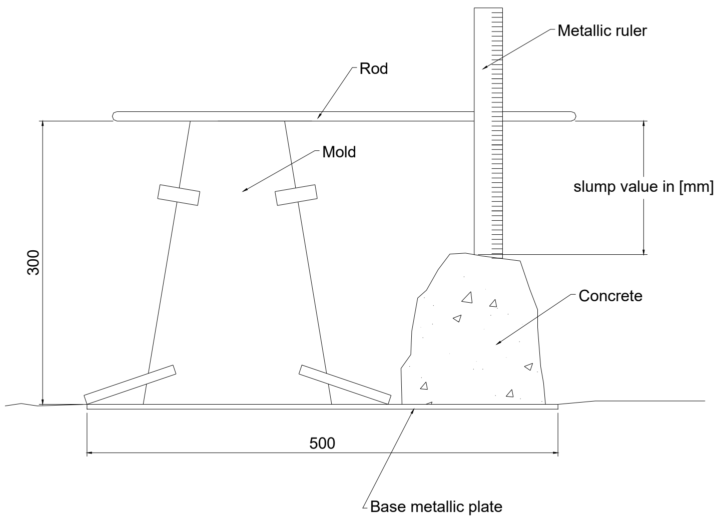

Fig. 1 – *Slump test. Dimensions in [mm].*

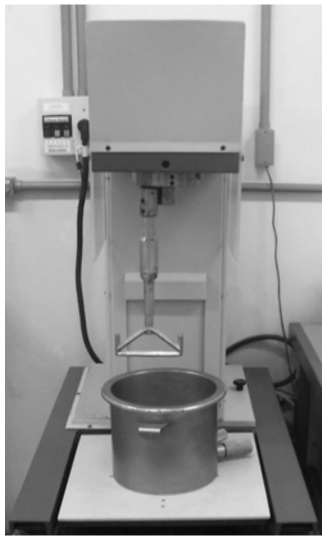

Fig. 2 – *Partial view of the planetary rheometer.*

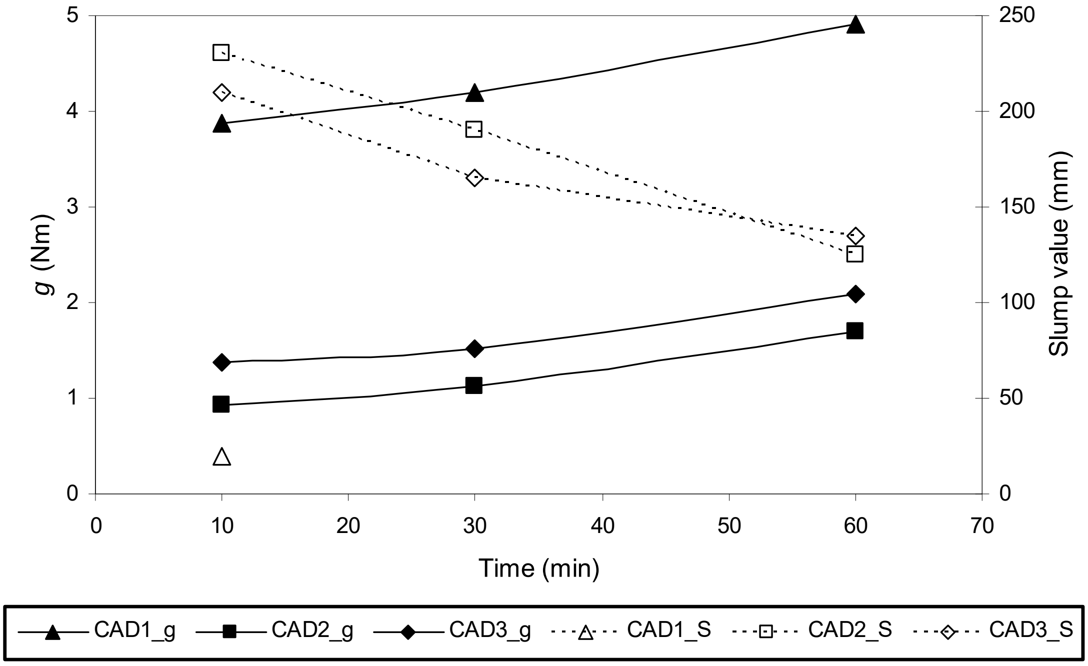

Fig. 3 – *Evolution of yield torque (g) and slump value (S) over time for the HPC studied.*

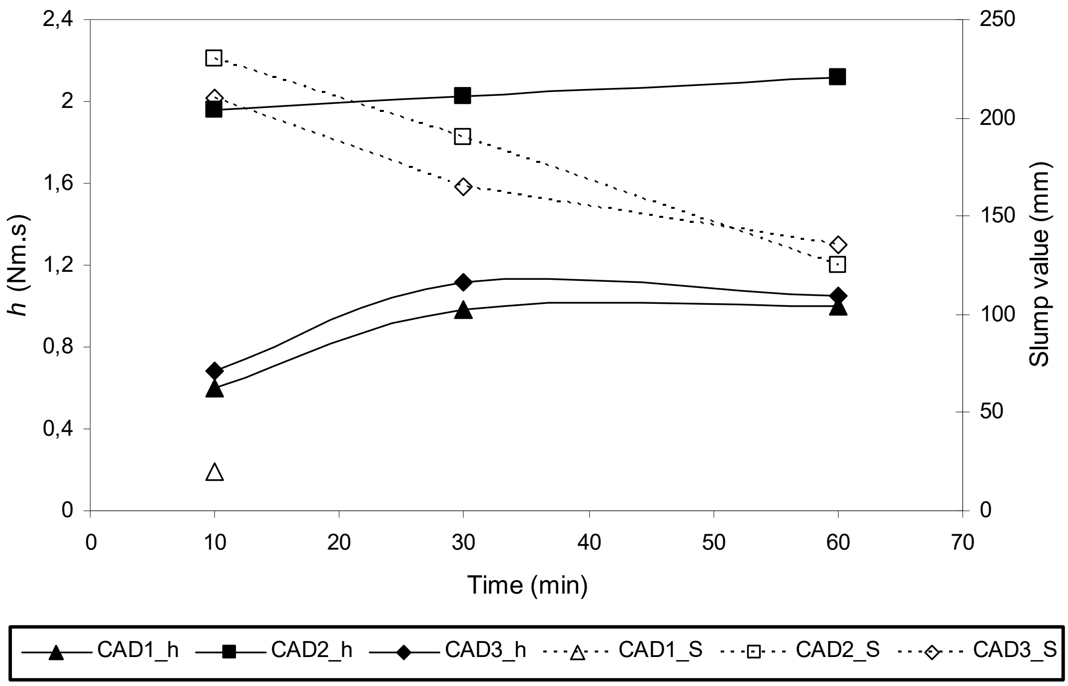

Fig. 4 *– Evolution of torque viscosity (h) and slump value (S) over time for the HPC studied.*

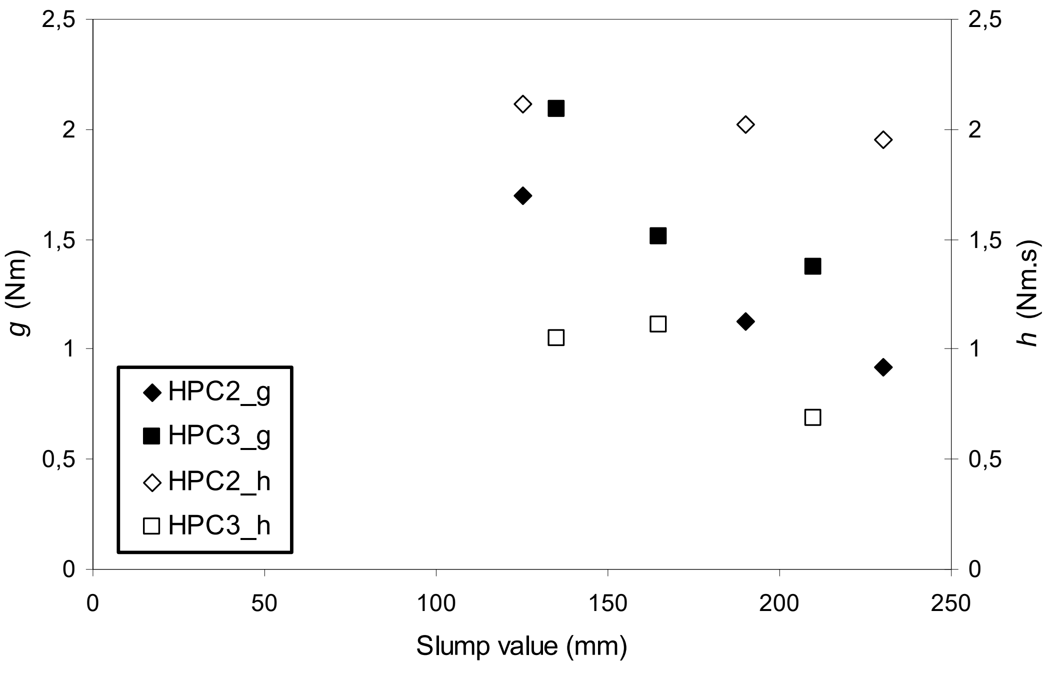

Fig. 5 *– Correlation between the slump value and rheological parameters for the HPC studied.*