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Influence of the Granular Mixture Properties on the Rheological Properties of Concrete: Yield Stress Determination Using Modified Chateau et al. Model

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***Abstract*—**The prediction of the rheological behavior of concrete is at the center of current concerns of the concrete industry for different reasons. The shortage of good quality standard materials combined with variable properties of available materials imposes to improve existing models to take into account these variations at the design stage of concrete. The main reasons for improving the predictive models are, of course, saving time and cost at the design stage as well as to optimize concrete performances. In this study, we will highlight the different properties of the granular mixtures that affect the rheological properties of concrete. Our objective is to identify the intrinsic parameters of the aggregates which make it possible to predict the yield stress of concrete. The work was done using two typologies of grains: crushed and rolled aggregates. The experimental results have shown that the rheology of concrete is improved by increasing the packing density of the granular mixture using rolled aggregates. The experimental program realized allowed to model the yield stress of concrete by a modified model of Chateau et al. through a dimensionless parameter following Krieger-Dougherty law. The modelling confirms that the yield stress of concrete depends not only on the properties of cement paste but also on the packing density of the granular skeleton and the shape of grains.

***Keywords*—**Crushed aggregates, intrinsic viscosity, packing density, rolled aggregates, slump, yield stress of concrete.

I. Introduction

SINCE its invention, concrete remains the most efficient and economical building material. Concrete is made by mixing a solid phase which is composed of a mixture of aggregates (the size may range from a few millimeters to a few centimeters) and a liquid phase which is the cement paste (consisting of a mixture of water, cement, additives, admixtures...). The cement paste bonds the aggregates to ensure good short-term workability as well as a long-term resistance (transition from the liquid state to the solid state of the concrete). However, the cement paste increases the cost of concrete and the cement industry generates a significant impact on the environment of our globe. For this, we often seek to minimize the amount of paste in the concrete.

Several rheological studies of concrete have shown that the concrete behavior at the short time could be assimilated to yield stress fluid [1], [2]. The yield stress of a cementitious material indicates the critical stress value at which the material will start or stop flowing, which is an important property when placing the material [3]. The yield stress of concrete is impacted not only by the granular skeleton (packing density, grain shape, particles size distribution ...) but also by the quality of the cement paste that fills the voids between the grains [4].

In the literature, studies of various suspensions have shown that the yield stress of these latter depends mainly on the packing density of the solid particles, their volume fraction, their size and shape as well as the yield stress of the suspending fluid [4]-[6]. In the case of non-concentrated suspensions immersed in a suspending fluid, Einstein [7] and Krieger-Dougherty [8] have proposed two models ((1) and (2) respectively) expressing the viscosity of suspensions as a function of the maximum density (the packing density of the suspension) as well as to an intrinsic parameter controlled by the morphology of the suspensions (intrinsic viscosity).

$$\eta/\eta_0 = 1 + [\eta] \times \emptyset \tag{1}$$

$$\eta/\eta_0 = \left(1 - \frac{\emptyset}{\emptyset_{max}}\right)^{-[\eta]\times\emptyset_{max}} \tag{2}$$

η is the dynamic viscosity of the suspensions (in Pa.s), η_0 is the dynamic viscosity of the suspending fluid (in Pa.s), $[\eta]$ is the intrinsic viscosity of solid grains (dimensionless parameter, equal 2.5 for a sphere), ϕ is the volume fraction of solid grains and ϕ_{max} the maximum packing density of solid grains. Moreover, the study of the flow of non-colloidal particles immersed in yield stress fluid has made it possible to estimate the yield stress of suspensions [4], [9], [10]. Chateau et al. [9] have proposed a law for calculating the yield stress of suspensions in the case of spheres (3). However, the results of these studies cannot be extrapolated in the case of concrete because the shape of the aggregates (the suspensions) is often random.

$$\tau(\phi)/\tau_0 = \sqrt{1-\phi}\Big/\left(1 - \frac{\phi}{\phi_{max}}\right)^{1,25\times\phi_{max}} \tag{3}$$

where $\tau(\phi)$ is the yield stress of the suspensions (in Pa) and τ_0 is the yield stress of the suspending fluid.

In order to generalize the model of Chateau et al. [9] in the case of grains of any shape, in the present study we will present the factor of morphology of aggregates in the model of Chateau et al. This factor is taken into account through the

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intrinsic viscosity parameter of the Krieger-Dougherty model (2). Our goal is to propose a modified Chateau et al. model which makes it possible to estimate the yield stress of concrete in the case of crushed aggregates and rolled aggregates.

II. Materials and Methods

In Table I are listed the aggregates of the present study and few characteristics. The shape and the packing density of the grains are the parameters that affect the yield stress of concrete [11], [12]. Therefore, rolled aggregates from “Chevrières” quarry (“Hauts-de-France” region) and crushed aggregates from “Boulonnais” quarry (“Nord Pas-de-Calais” region) were used to conduct the present work. For each type of aggregates, three granular classes were chosen: 0/4 mm sand, 4/10 mm gravel and 12/20 mm (or 11/22 mm) gravel. In order to measure the packing density of the aggregates, the “Laboratoire Pont et Chaussées” (LPC) procedure No. 61 was followed [13]. It consists of applying a series of shocks to a granular material placed in a cylinder (shaking table) allowing it to be into a more dense configuration [21]. The process is characterized by a compaction index K = 9 [13]. The absolute density and the water absorption were measured according to the European standard NF EN 1097-6.

In this research work, Portland cement type CEM I 52.5 R from LafargeHolcim Saint-Pierre-La-Cour is used. The particle size distribution of the cement is measured using laser diffraction particle sizing analyzer of type Beckman Coulter LS 13 320. A superplasticizer CHRYSO®Fluid Optima 206 was also used in order to limit the water content of the concrete.

For the measurement of the rheological characteristics of cement pastes, ANTON PAAR MCR102 rheometer is used. The adjustments made before starting the tests are the temperature of the test (20 °C) and the inertia system. During this study, the coaxial cylinder geometry, with a fixed gap between the shearing surfaces of 1 mm is used.

The procedure of rheological measurements of cement pastes starts 5 minutes after the beginning of mixing with a pre-shearing at 100 s^{-1} to eliminate any influence of the sample build-up history. Then, the shear rate applied varies from 100 s^{-1} to 0.01 s^{-1}. The yield stress is defined as the minimum value reached by the shear stress. This value corresponds to the critical stress that allows the fluid to remain in a stable flow [14], [15].

The experimental program of this work aims to estimate the yield stress of concrete through the slump test (Abrams cone test according to the European standard NF EN 12350-2) and the rheological models presented above. For each type of aggregates (crushed and rolled), the water/cement (w/c) ratio and the superplasticizer (SP) dosage are fixed (w/c = 0.5 and SP = 0.12% in dry extract) and the volume of cement paste varies at different levels. This allows us to determine the evolution of the yield stress of concrete as a function of the solid volume fraction and to evaluate the influence of the parameters of morphology and packing density of the aggregates on the yield stress. The volume proportions of sand, intermediate gravel and coarse gravel are fixed at 40%, 20% and 40% of the total aggregates volume respectively, i.e. the Gravel/Sand (G/S) ratio is equal to 1.5 and the Intermediate gravel/Coarse gravel (G_2/G_1) ratio is equal to 2. Otherwise, we have implemented a concrete mix design methodology that allows us to control the parameters of the different rheological models used. This methodology consists of choosing the proportions of the liquid phase (cement paste) and solid (granular mixture) before determining the composition of each of these phases. Fig. 1 shows the different stages of the concrete mix design method.

TABLE I
Properties of the Aggregates of the Study

Type of aggregates	Granular class d/D	Density (t/m^3)	Water absorption (%)	Packing density
Crushed	Sand 0/4	2.69	0.43	0.751
	Gravel 4/10	2.67	0.59	0.583
	Gravel 12/20	2.67	0.49	0.574
Rolled	Sand 0/4	2.55	1.18	0.695
	Gravel 4/10	2.43	3.06	0.628
	Gravel 11/22	2.54	1.79	0.604

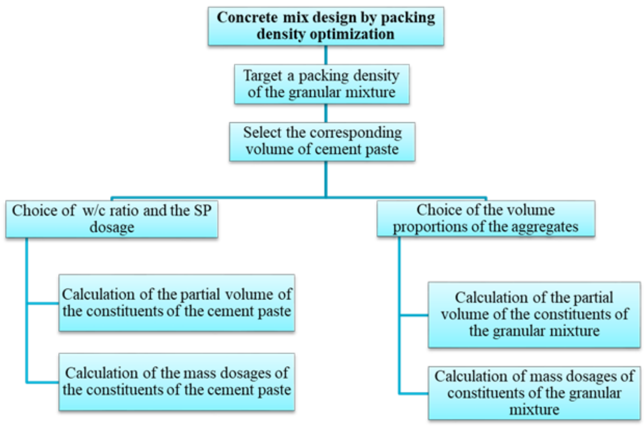

Fig. 1 Concrete mix design methodology

III. Results and Discussions

The particle size distribution of the different materials of the study is shown in Fig. 2. The particle size analysis of crushed aggregates (Fig. 2 (a)) and rolled aggregates (Fig. 2 (b)) was carried out according to the European standard NF EN 933-1. It showed a high fines content of crushed sand (16% of grains are smaller than 125 microns) in comparison with rolled sand (only 7% of grains are smaller than 125 microns). For packing densities measurement (using the compaction table), the aggregates were used in their raw state without any prior sieving to remove the fine fraction (particles smaller than 63 microns as recommended by the LPC procedure No. 61 [13]). The use of the aggregates in their raw state without any prior sieving did not influence the accuracy of the packing density measurements by the compaction table [16], [17]. For the concrete mix design of the present study, we target high packing densities of the granular mixtures. For this reason, we have fixed the proportions of the granular mixtures at 40% of Sand, 20% of fine gravel (G_1) and 40% of coarse gravel (G_2). The packing density of these mixtures is equal to 0.719 for crushed aggregates mixture and 0.796 for rolled aggregates mixture. On the other hand, the particle size analysis of the cement (Fig. 2 (c)) gives a maximum diameter of the cement grains of 50 microns. This result is conforming to some studies undertaken on this type of cement [18]. For the coaxial cylinder geometry used in the rheological measurements of cement paste, the gap is 1 mm which respects the condition that the gap is greater than 10 times the maximum diameter of tested materials in the rheometer [19]. The yield stress of the cement paste was measured by the rheometer following the experimental protocol described above. The w/c ratio was fixed at 0.5 and the SP dosage at 0.6%. The yield stress determined according to the prescribed test and method of determination (shown in Fig. 3) is equal to 1.42 Pa.

Following the determination of the different parameters relating to granular mixture (packing density) and the parameter relating to the cement paste (yield stress), several concretes were cast. These concretes differ by the volume of granular fraction used (ϕ). For each type of aggregates (crushed aggregates and rolled aggregates), we have varied the volume fraction in cement paste $(1-\phi)$ by targeting consistency classes S2 to S4 as defined in the European standard NF EN 206 (the corresponding slump test values varies from 50 mm to 210 mm). The results of slump test measurements (Fig. 4) show that this latter increases when the cement paste volume increases (volume fraction in aggregates decreases). Furthermore, a greater packing density of the rolled aggregates makes it possible to achieve greater slump value for the same volume of cement paste. By targeting the same slump value, an improvement in the packing density (of 0.07 points) by using the rolled aggregate mixtures allow to reduce the volume of cement paste by 4% in comparison with the crushed aggregate mixtures.

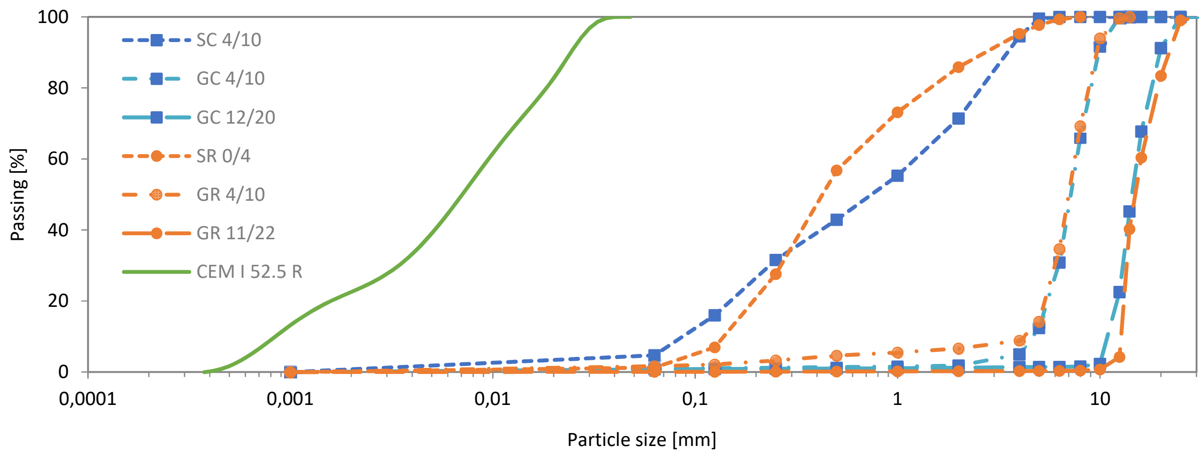

Fig. 2 Particle size distribution of the materials of the study

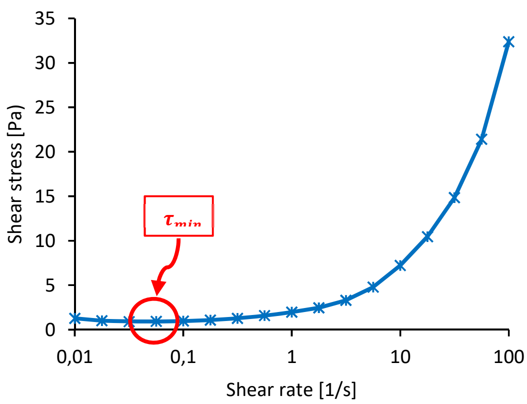

Fig. 3 Identification of the yield stress of cement paste for w/c = 0.5 and PC = 0.12%

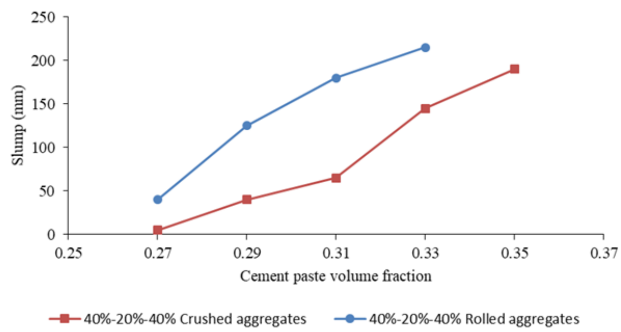

Fig. 4 Variation of slump with cement paste volume fraction for crushed aggregate mixtures and rolled aggregate mixtures

In order to predict the effect of the packing density and the aggregate morphology on the slump and the yield stress of concrete, we realized a modeling of the yield stress of concrete through a modified model of Chateau et al. [9]. We introduced the intrinsic viscosity parameter (defined by (1) and (2)) in the basic model (3) in order to take into account the morphology of aggregates. The modified model is given by (4). The values of the intrinsic viscosity and the maximum packing density of the concrete are calibrated on the experimental data using (4). However, this calibration requires knowledge of the yield stress of the concrete. For this, we used the model of Saak et al. (5) [20] which makes it possible to calculate the yield stress of concrete from slump measurements.

$$\tau(\phi)/\tau_0 = \sqrt{1-\phi} \Big/ \left(1-\frac{\phi}{\phi_{max}}\right)^{\frac{[\eta]}{2}\times\phi_{max}} \quad (4)$$

$$S = H - h_0 - h_1 \quad (5)$$

h_0 and h_1 are two functions depending on $\tau(\phi)$, H is the height of the Abrams cone.

The results of the modeling are given in Fig. 5 where the concrete yield stress to cement paste yield stress ratio is plotted as a function of the solid volume fraction. We note that this ratio increases when the solid volume fraction increases. This confirms the effect of the solid volume fraction (or cement paste volume) on the yield stress of concrete which increases by the effect of contact forces between the aggregates. Moreover, it is shown that the basic model of Chateau et al. underestimates the yield stress since it has been validated in the case of spherical particles (for which [η] = 2.5).

TABLE II
DETERMINATION OF THE PARAMETERS OF THE MODIFIED MODEL OF CHATEAU ET AL. AND THE PREDICTION ERROR

	40%-20%-40% Crushed aggregates mixtures	40%-20%-40% Rolled aggregate mixtures
ϕ_{max}	0.901	0.793
[η]	5.415	3.942
RMSE (mm)	27.6	

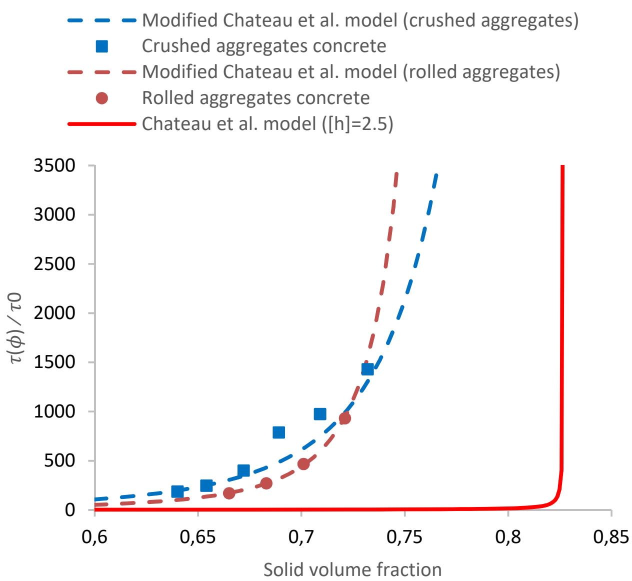

Fig. 5 Modified Chateau et al. model applied in the case of crushed and rolled aggregates

The calculated parameters of the modified Chateau et al. model (4) and the Root Mean Square Error (RMSE) of the predicted slump values are given in Table II. Moreover, the curves of variation of the modelled yield stress by (4) as a function of the measured slump and the comparison between this later with the modelled slump (using (4) and (5)) are shown in Figs. 6 and 7 respectively.

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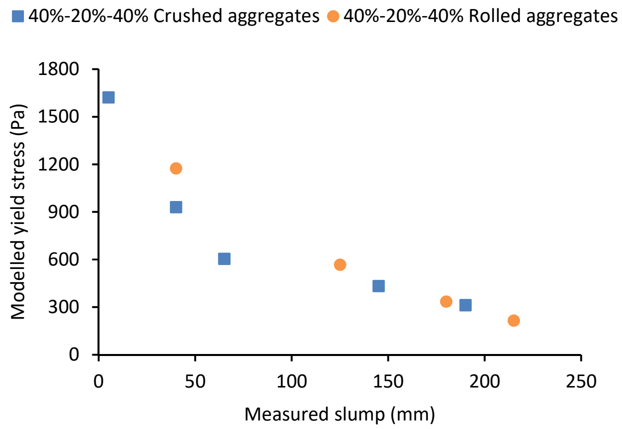

Fig. 6 Variation of modelled yield stress with measured slump

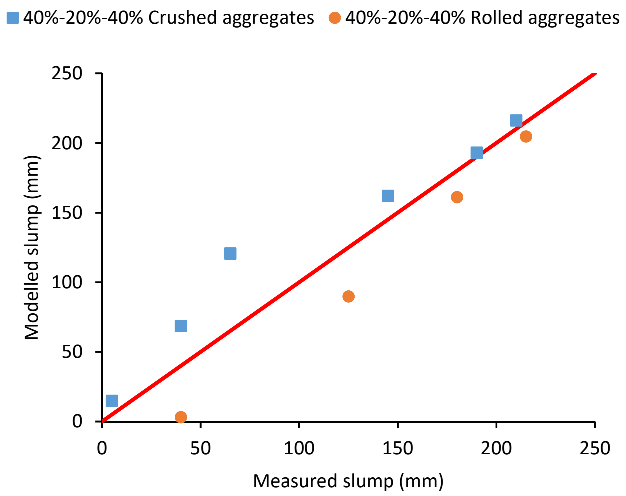

Fig. 7 Measured slump vs. modelled slump

From the results of the modelling presented in Table II, we notice that the introduction of the cement paste increases the packing density of the concrete. The latter is more important in the case of crushed aggregates. For rolled aggregates, the maximum packing density was not affected by the introduction of the cement paste. This observation can be explained by the difficulty of optimizing the model on two parameters. Otherwise, with regard to the intrinsic viscosity, we note that it is influenced by the morphology of aggregates. Its value is smaller for the rolled aggregates, which is explained by the fact that the rolled aggregates are closer to the sphere (for which $[\eta] = 2.5$) in comparison with the crushed aggregates. Otherwise, the modelled yield stress is plotted versus measured slump in Fig. 4. We note from Fig. 4 that the modelled yield stress decreases when the slump increases. This result shows that the modified Chateau et al. model is able to correlate the workability of the concrete with the modelled yield stress. This is confirmed by the results shown in Fig. 5 in which the modelled slump values correspond to the measured values especially in the range of high slumps.

IV. Conclusion

In this paper, a predictive model of the yield stress of concrete has been proposed. The parameters of this model were calibrated on crushed and rolled aggregates mixtures. From this study, we can draw the following conclusions:

- The flow of the concrete through the slump test requires a minimum volume of cement paste. This minimum volume (around 250 to 270 liters per cubic meter of concrete) varies according to the granular mixture (especially its packing density).
- The slump of concrete can be improved by two ways: either by increasing the volume of cement paste, or by improving the packing density of the granular mixture by using rolled aggregates. This allows to reduce the amount of cement paste required to achieve given workability of the concrete.
- It has been confirmed through the results obtained by the modified Chateau et al. model that the parameters of the granular mixture affecting the yield stress of concrete are:
  - The morphology of the aggregates;
  - The maximum packing density of the concrete.
- The proposed model gives a good precision in the prediction of the yield stress of concrete especially in the range of lower yield stress values (higher slump values). Furthermore, the model takes into account the parameters of the granular mixture and has been validated for crushed and rolled granular mixtures.

As perspectives to the present study, the proposed model will be validated on other granular mixtures in order to analyze the variation of the parameters of the model (packing density, intrinsic viscosity ...). Moreover, other parameters influencing the rheology of concrete will be studied (such as the quality of the cement paste, sand/ gravel ratio, etc.). Finally, given the large number of parameters that control the rheology of concrete, the use of Artificial Intelligence models can be a better solution for predicting the rheological properties of concrete. These models can even be extended to predict the long-term properties of concrete (resistance and durability).

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