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New model to estimate plastic viscosity of eco-friendly and conventional concrete

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HIGHLIGHTS

- A new model for calculating the plastic viscosity of eco-friendly and ordinary concrete was developed.
- The proposed model taking into account the impact of mineral addition and superplasticizer.
- The experimental results are obtained with a new rheometer concrete.

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ABSTRACT

This paper presents a new rheological model for estimating plastic viscosity of eco-friendly concrete (concrete with a high rate of mineral addition) and ordinary concrete. The proposed model is based on the assumption that the concrete is divided into two scales: paste (water, cement, addition and superplasticizer) and aggregate (sand and gravel). Model predictions are evaluated using large experimental results of 44 mixtures. The used results have been obtained with recent developed rheometer witch new blade geometry (in form of a perpendicular double U) was used. This new geometry minimizes segregation of concrete during the rheological test. The evaluation of the proposal model with experimental results showed that, the model fits well with viscosity of eco-friendly concretes (with mineral addition) as well as ordinary concrete (without addition). The developed model describes well the concrete viscosity depending on the nature and the rate of replacement with mineral addition and the effect of the superplasticizer. The validation showed that this model predicts concrete viscosity with an error of about ±11%.

1. Introduction

Concrete is the most commonly used material in construction field. The quality of the concrete is depending on the quality of each constituent used in the mix. Nowadays, new concretes such as self-compacting concrete (SCC), high performance concrete (HPC), and environmental friendly concretes have been developed and widely used. In order to improve the quality and to optimize the placement into the formwork of these concretes, the control of rheological parameters becomes crucial [1,2]. To describe the rheological behaviour of fresh concrete, terms like workability, consistency, flowability and mobility have been used to reflect personal viewpoints than scientific precision [1–5]. Slump value has been used to characterize concrete workability. However, several studies have shown that slump value is necessary but not a sufficient measurement to characterize the fundamental rheological properties of concrete, namely plastic viscosity and yield stress [6–8].

The rheological behaviour of fresh concrete can be considered as a Bingham fluid given by the following equation [9–13]

$$\tau = \tau_0 + \mu\dot{\gamma} \quad (1)$$

With:

τ (Pa) is the shear stress.
τ_0 (Pa) is the yield stress.

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List of symbols

SCC	self-compacting concrete
HPC	high performance concrete
τ	shear stress
τ_0	yield stress
$\dot{\gamma}$	shear rate
Φ/Φ^*	relative (normalized) solid concentration of mixtures
μ	concrete viscosity
μ_0	viscosity of water
SP	the dosage of superplasticizer
SP*	the saturation dosage of superplasticizer
Φ_F	the solid volume of silica fume
Φ_c	the solid volume of cement
Φ_g	the solid volume of aggregate
Φ_F^*	maximum solid concentration of silica fume
Φ_c^*	maximum solid concentration of cement
Φ_g^*	maximum solid concentration of aggregate
Φ	the solid volume of concrete
Φ^*	the maximum solid concentration of mixture
D_{max}	maximum diameter of aggregate
Φ_{us}^*	the maximum concentration of the structural unit
Φ_{us}	the solid volume of the structural unit
k	constants to adjust
Ω	rotational speed
M	torque
h	vane height
R_1	vane radius
mse	the mean squared error
$\Omega_{calculated}$	calculated rotational speed
$\Omega_{mesured}$	measured rotational speed
V_A	volume of air
Φ_P	the solid volume of powder
Φ_p^*	maximum solid concentration of powder
f_{paste}	the factor of the viscosity of paste
$f_{aggregate}$	the factor of the viscosity of aggregates
Φ_{SP}^*	the maximum solid concentration of powder with superplasticizer dosage
$\mu_{measure}$	the experimental viscosity
μ_{model}	the calculated viscosity

μ (Pa.s) is the plastic viscosity.
$\dot{\gamma}$ (1/s) is the shear rate.

In practice, the determination of rheological parameters is obtained by the so-called rheometers tests, which measure the shear stress at varying shear rates [13–19]. However, this technique is expensive and requires more time and materials. an alternative approach for modeling the rheological behaviour of fresh concrete was proposed. These models use the material characteristics and the mixture proportion for predicting the plastic viscosity of fresh concrete [15,20–26].

Several investigations have shown that the changes of plastic viscosity are depending on relative solid concentration (Φ/Φ^*) of mixtures [25]. This theory has been validated by Chan on binary mixtures of spheres [27] and also by Ferraris on mortars and concretes [23,24]. Currently, there are several viscosity models.

Based on the model of Krieger- Dougherty [28], Farris proposed a viscosity model of bimodal or trimodal suspensions [29]. Then this model was modified by Hu [21,22] to adapt it to the fluid high performance concretes, taking into account the effect of the superplasticizer. The modified model is written as follows (Eq. (2)):

$$\mu = \mu_0\left(1 + k_s\frac{SP}{SP^*}\right)\left(1 - \frac{\Phi_F}{\Phi_F^*}\right)^{-2.5\Phi_F^*}\left(1 - \frac{\Phi_c}{\Phi_c^*}\right)^{-k\Phi_C^*}\left(1 - \frac{\Phi_g}{\Phi_g^*}\right)^{-k\Phi_g^*}. \quad (2)$$

μ is the concrete viscosity,
μ_0 is the viscosity of water (0.001 Pa.s at 20 °C),
SP and SP* are respectively, the dosage and the saturation dosage of superplasticizer,
Φ_F, Φ_c, Φ_g are respectively, the solid volume of silica fume, cement, and aggregate,
$\Phi_F^*, \Phi_c^*, \Phi_g^*$ are respectively, maximum solid concentration of silica fume, cement, and aggregate.

The model is validated with results obtained with the BTRhéom for three high-performance concrete series. The values for the constants are 4.2 for k and 33, 81 and 53 for k_s for series 1, 2 and 3, respectively [21].

Using the experimental results achieved with the rheometer BTRhéom, Ferraris and De Larrard [23,24] proposed a concrete viscosity model (Eq.3), which mainly depends on the relative solid concentration expressed as the ratio (Φ/Φ^*).

$$\mu = \exp\left[26.75\left(\frac{\Phi}{\Phi^*} - 0.7448\right)\right] \quad (3)$$

μ is the concrete viscosity,
Φ is the solid volume of concrete,
Φ^* is maximum solid concentration of mixture.

The model was validated with seventy-eight mixtures (thirty-three mortars and concretes without superplasticizer and forty-five concrete with superplasticizer) made with the same components [23–25].Toutou [26] proposed a model of multi-scale viscosity applied to micro- concrete with aggregate of maximum diameter $D_{max} < 630$ µm (Eq. (4)).

$$\mu = \mu_0\prod_{j=1}^{i}\left(1 - \frac{\Phi_{us}}{\Phi_{us}^*}\right)^{ki\Phi_{us}^*} \quad (4)$$

μ is the viscosity of concrete,
μ_0 is the viscosity of water at 20 °C (0.001 Pa.s),
Φ_{us}^*, Φ_{us} are the maximum solid concentration and the solid volume of the structural unit, respectively.
k is a constant to adjust.

The proposed model is based on the model of Krieger and Dougherty [28]. The model is validated with results obtained with a rheometer Rhéologica, Couette type, whose gap is 0.8 mm for cement paste and 2.5 mm for micro- concrete [26].

In previous study, a rheometer concrete was developed and validated by Soualhi et al. [13] with new vane geometry in form of a perpendicular double U, which allows to minimizing segregation during the test. The device was then used in an experimental program to analyze the influence of each composition parameters on the plastic viscosity of ordinary and a low environmental impact concrete with mineral additions (slag, limestone and fly ash) [30]. The results will be used in this work as a database to construct and validate a model for calculating the plastic viscosity of concretes (ordinary and those with additions) from their mix design parameters.