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Prediction of the yield stress of concrete considering the thickness of excess paste layer

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HIGHLIGHTS

- A model to predict the yield stress of concrete is proposed adopting the excess paste theory.
- The thickness of excess paste is assumedly constant for fine and coarse aggregates while it is dependent on the properties of binder.
- A concrete equivalent mortar having 90%-volume-fraction aggregates content in concrete mix or a wet-sieved mortar can be used to measure the yield stress of the corresponding mortar.
- Finally, based on the measured yield stress of the corresponding mortar, the model acceptably predicts the yield stress of a concrete mix.

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ABSTRACT

Polycarboxylates in chemical admixtures are adsorbed onto the surface of cement particle, and the degree of their adsorption is related to the performance of concrete. Measuring total organic carbon (TOC), we demonstrated the amount of the consumed carbon is consistent regardless of the existence of aggregates. This result allows us to consider the effect of aggregates inclusion in a superplasticized cement paste. In a multiscale approach, concrete or mortar is considered as suspension of aggregates in cement paste. Excess paste layer covering aggregates in cement-based materials is considered taking a material property of the layer thickness in addition to the volume fraction of the aggregates. Finally, the yield stress of mortar or concrete can be predicted assuming that the layer thickness is constant regardless of the aggregate volume fraction.

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1. Introduction

High-range water-reducing admixture (HRWRA) is inevitable to improve the workability and fluidity of freshly mixed concrete. HRWRA reduces the water demand for concrete mixing, which contributes to a higher strength and durability by decreasing the water-to-cement ratio. As the demand for HRWRA increases in field, various kinds of polycarboxylates (PCE), the main polymer in HRWRA, have been developed and produced. Due to the diversity and uncertainty of PCEs, the performance of HRWRA is evaluated empirically through a direct application to trial batches every time. However, the trial tests in field are cumbersome and limited in time. A lab test method is therefore needed to evaluate many numbers of promising PCEs or HRWRAs [1].

One of the solutions is concrete equivalent mortar (CEM) proposed to predict the workability of the corresponding concrete mixture [2]. CEM is produced by substituting the coarse aggregates with the fine aggregate as much as the surface area of the coarse aggregate. A correlation between the flow of a CEM, by the flow table test, and the slump of the corresponding concrete was empirically developed [3]. Another correlation between the mini-slump flow of the CEM and the slump flow of the corresponding concrete was also developed [4]. In further study, the excess paste theory was considered to relate the flowability of the concrete and CEM [5]. Nevertheless, the empirical correlations for CEM were often erroneous, and a correction factor was then introduced to fit the model into field conditions [6].

In this paper, we will derive a theoretical model to predict the yield stress of self-consolidating concrete with that of the corresponding mortar. The model adopts the excess paste theory [7,8] for both concrete and mortar. One of the simplest multi-scale

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models considers concrete or mortar mixture as a suspension of the aggregates, where the suspending fluid is a cement paste. The excess cement paste covers aggregate particles, and the remainder fills the pore space of the packed aggregates. The excess paste therefore affects the frictional (lubricating) or hydrodynamic interaction between the aggregates, which is effective on normal concrete or self-consolidating concrete, respectively [9].

The resultant rheological properties of the concrete were possibly predicted with the solid volume fraction and maximum packing density of aggregates [8,9]. Recently, Mahaut et al. [10] accurately predicted the yield stress of concrete using a noncolloidal-particles suspension model [11]. Saar et al. [12,13] also derived a numerical model to predict the yield stress of magma, a crystal-melt suspension, based on the percolation theory. Such a reliable prediction has been accomplished with a *priori* information of the excess paste, and the evaluation on the thickness of the excess paste was inductive [14,15]. A comprehensive deductive evaluation on the thickness of the excess paste is therefore proposed in this paper. Firstly, it is assumed that the binder in cement-based materials thoroughly determines the characteristics of the excess paste. The assumption is supported by the comparison of PCE consumption in cement paste and mortar. The relationship between the thickness of the excess paste and the dosage of used HRWRA is then derived. Finally, an updated volume fraction including the excess paste is discussed with the yield-stress prediction model based on the percolation theory.

2. The proposed model

2.1. Quantification of excess paste layer

Excess paste layer in cement-based materials surrounds all aggregate particles. Cement paste becomes the suspending fluid as well as the cover layer of the suspended particles in a mortar or concrete suspension. The thickness of excess paste is assumed to be constant regardless of the dimension of aggregates while it is dependent on the properties of the binder (cement paste). The excess paste layer is a fictitious concept to address the frictional and hydrodynamic interaction of aggregates in concrete. The cohesion of the binder and its adhesion to the aggregates obviously affect the interaction of aggregates. We here assumes its effective adhesion is proportional to the distance from the surface of an aggregate particle. The thickness of excess paste layer is then the same regardless of the dimensions of the aggregates' particles even though its adhesive potential is unknown. Most importantly the thickness of the excess paste layer, denoted by b hereafter, is assumed to be constant in the case.

Fig. 1 shows a generalized suspension system composed of n-categorized rigid-body grains. The grains, representing aggregates in cement-based materials, take a constant diameter at each category: d_1, d_2, ..., and d_n. The volume of excess paste layer is then

$$V_e = \varphi_1\left(\frac{b}{d_1}\right)^3 + \varphi_2\left(\frac{b}{d_2}\right)^3 + \cdots + \varphi_n\left(\frac{b}{d_n}\right)^3, \quad (1)$$

where φ_1, φ_2, ..., and φ_n are the volume fractions of each grade of the multi-sized grains. The grains covered by b-thick layer interact each other, and the properties of the layer affect the frictional and hydrodynamic behavior of the grains. Excess paste layer is dragged together with each grain in the suspension, and then the volume fraction of grains needs to be updated in a rheological view. The effective volume fraction (φ') of the suspension is then obtained by adding the volume of excess paste layer:

$$\varphi' = \sum_{i=1}^{n}\varphi'_i = \varphi_1\left(1+\frac{b}{d_1}\right)^3 + \varphi_2\left(1+\frac{b}{d_2}\right)^3 + \cdots + \varphi_n\left(1+\frac{b}{d_n}\right)^3. \quad (2)$$

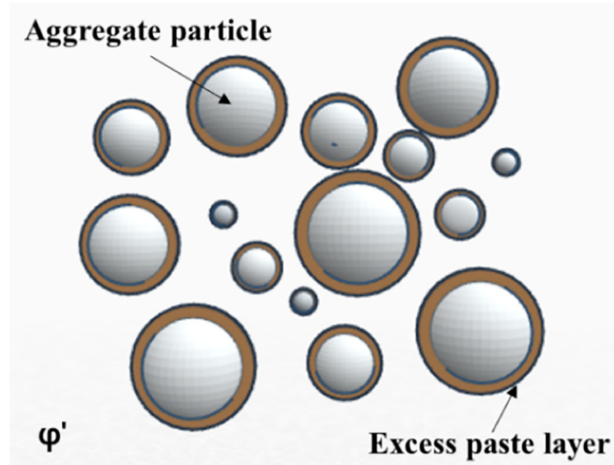

Fig. 1. A generalized suspension composed of multi-sized grains.

The properties of excess paste layer affect the rheology of the suspension while the effective volume fraction of the grains is dominant. A theoretical approach on percolation considering interlocking of particles allows us to have a power-law model for the yield stress prediction:

$$\tau_y/\tau_0 = k(\varphi - \varphi_c)^n, \quad (3)$$

Where τ_y and τ_0 is the yield stress of suspension and suspending fluid, respectively and φ_c is the percolation threshold [12,13]. Here the prediction model takes the volume fractions for grains and their percolation threshold, while the original derivation was given by the number density of grains. The volume fraction-based model was valid to represent the rheology of the suspension system [16]. The parameters of k and n are addressed with the properties of excess paste layer and grains. Prediction of viscosity can be similarly obtained using a structural model such as the Krieger-Dougherty equation [17] and the Quemada's model [18].

2.2. Application to a mortar suspension: Mono-sized grains

Aggregates in mortar or concrete are graded having an acceptable distribution in its dimension. Their size distribution controls the packing of aggregates, but for evaluating their percolation it is hard to assume randomly-distributed grains due to its narrow range in size. For example, fine aggregates are usually bounded within 0.08 to 4.75 mm, and standard sand specified in ISO 679 [19] is within 0.08 to 1.6 mm.

Assuming sand particles in mortar are spherical and their diameter are constant, mono-sized grains, the volume of excess paste layer is given by Eq. (1): $V_e = \varphi_1(b/d_1)^3$ where b, φ_1, and d_1 are the thickness of excess paste layer, the volume fraction and the diameter of the sand, respectively. The effective volume fraction in Eq. (2) becomes $\varphi' = \varphi_1(1 + b/d_1)^3$, and the yield stress is finally given by

$$\tau_y/\tau_0 = k\left(\varphi_1\left(1+\frac{b}{d_1}\right)^3 - \varphi_c\right)^n. \quad (4)$$

The percolation threshold for a spherical mono-sized system is 0.29 and it tends to decrease with irregular shape of the particles [20].

2.3. Application to a concrete suspension: Binary-sized grains

Aggregates for concrete are usually classified in dimension. Fine and coarse aggregates were divided by 4.75 mm in dimension, and

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