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Evaluating the distance between particles in fresh cement paste based on the yield stress and particle size

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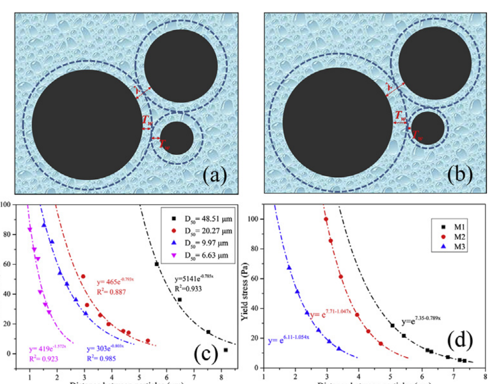
HIGHLIGHTS

- The coarser particles needed larger λ to achieve same yield stress of paste.
- The relationships between yield stress and λ were established.
- λ in binary-cement pastes was evaluated in consideration of particle size.
- Reliability of the evaluation of λ was validated experimentally.
- This paper gives a deeper insight into initial packing and bridging of particles.

GRAPHICAL ABSTRACT



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ABSTRACT

The distance between particles (λ) plays a key role in the flowability of fresh cement pastes. λ given in available literatures is an average value and independent with the particle size. Actually, coarse particles in cement paste need a larger λ to achieve same yield stress compared with fine particles. In the present study, relationship between yield stress and λ for single-fraction cement pastes was established by introducing an exponential-type function. Then the function was theoretically deduced to evaluate λ in binary-fraction cement pastes. For cement pastes with yield stress of 30 Pa, distance between coarse particle (48.51 μm) and fine particle (6.63 μm) was 5.00 μm, while distance between mid-sized particle (20.27 μm) and fine particle (6.63 μm) was only 2.57 μm. Finally, the reliability of λ in binary-fraction cement paste was experimentally validated. This method can be applied in multi-fraction cement pastes, and λ in consideration of particle size will give a deeper insight in the flowability and microstructural development of cement pastes.

1. Introduction

The workability of fresh concrete, which is one of the concerns in engineering applications, is driven by the flowability (or rheological properties) of fresh cement paste (the fluid phase of concrete). Fresh cement paste mainly consists of water and cement particles, and its flowability generally attributes to the initial

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Nomenclature

PSD	particle size distribution
H-B model	Herschel-Bulkley model
D_{50}	volume median diameter (μm)
λ	distance between particles (μm)
λ_f	distance between particles in fine-fraction cement paste (μm)
λ_c	distance between particles in coarse-fraction cement paste (μm)
T_w	water coating thickness (μm)
T_{wf}	water coating thickness of fine particles in binary-fraction cement paste (μm)
T_{wc}	water coating thickness of coarse particles in binary-fraction cement paste (μm)
SSA	specific surface area (m^2/cm^3)
SSA_f	specific surface area of fine fraction (m^2/cm^3)
SSA_c	specific surface area of coarse fraction (m^2/cm^3)
ρ_p	wet density of cement paste (g/cm^3)
ρ_c	density of cement (g/cm^3)
ρ_w	density of water (g/cm^3)
M_t	total weight of container and cement paste (g)
M_c	weight of container (g)
V_c	volume of container (cm^3)
τ	shear stress (Pa)
τ_c	yield stress (Pa)
y	shear rate (s^{-1})
W_e	Volume of excess water (cm^3/cm^3)
W_w	volume ratio of water to cement (dimensionless)
φ	solid volume concentration of cement paste (dimensionless)
φ_m	maximum solid volume concentration of cement paste (dimensionless)
V_m	minimum void ratio (dimensionless)
μ	size ratio of finer fraction to coarser fraction in binary-fraction cement (dimensionless)
X_L	volume proportion of coarser fraction in binary-fraction cement (dimensionless)
k,n	coefficients of H-B model (dimensionless)

packing of particles in fresh cement paste. Compared with the packing of dry particles (particles are assumed to be contacted with their neighbor ones as shown in Fig. 1), the voids among particles in cement paste are filled up by part of water (filling water), then particles are separated by the residual water (excess water) [1,2]. Thus particles in cement paste do not directly contact with their neighbor particles, and the water coated around particles contributes greatly to the fluidity of fresh cement paste [3–6].

Many attempts have been made to evaluate the rheological properties from the initial packing of particles in fresh cement paste. For instance, the yield stress of cement paste can be predicted from the solid volume concentration (φ) of cement pastes by the YODEL based on first principles, in which particle size distribution (PSD), inter-particle forces, and microstructural features were taken into account [7,8]. Bentz reported that the relationship between yield stress and particle number density (the number of particles in unit volume of powder) shows a percolation-type trend [9]. Silva presented the yield stress of cement paste increases with the decrease of particle size [10], while Ferraris pointed out that yield stress increases and then drops with the decrease of particle size, and the yield stress reaches maximum value when the mean size of particles equals to 5.7 μm [11].

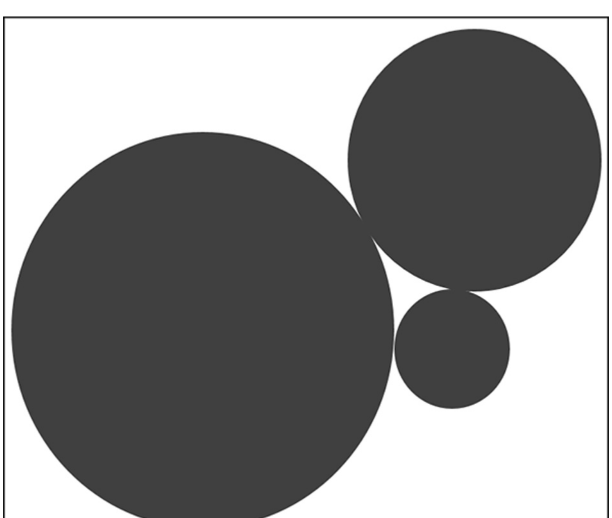

Fig. 1. The packing of dry particles.

Actually, major factors influencing the yield stress of fresh cement pastes, such as particle size, particle number density, solid volume concentration, etc. can be attributed to the distance between particles (λ) in fresh cement paste. A larger λ generally means more water coated around particles, which provides better lubrication and eventually contributes to the flowability of fresh cement paste. For fresh cement pastes with same flowability, small λ is beneficial to the cluster and bridging of hydration products and densification of microstructure [12,13], and then contributes to strength development and deformation resistance [14], especially at very early age. Therefore, beside the flowability of fresh cement paste, the mechanical properties and volume stability of cement paste during hardening are subject to λ either.

Ferraris introduced the distance between aggregates in concrete and pointed out that higher torque is necessary for maintaining constant rotation speed of the plate when the distance between aggregates is decreasing [15]. Thus, there must be a similar relationship between λ and rheological properties of cement paste. It is observed that the yield stress of fresh cement paste is proportional to λ [16]. Commonly, λ is calculated from φ of cement paste and the specific surface area of particles in cement paste [17,18].

$$\varphi = \frac{\rho_p - \rho_w}{\rho_c - \rho_w} \tag{1}$$

where, ρ_p is the wet density of cement paste (g/cm^3), ρ_c and ρ_w are the densities of cement and water (g/cm^3), respectively.

For the maximum solid volume concentration (φ_m) of cement paste, the corresponding minimum void ratio (V_m) is defined by Eq. (2):

$$V_m = \frac{1 - \varphi_m}{\varphi_m} \tag{2}$$

The volume of excess water (W_e) can be evaluated by the following equation:

$$W_e = W_w - V_m \tag{3}$$

where, W_w is the volume ratio of water to cement, which can be calculated from φ.