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Effect of coarse aggregate characteristics on concrete rheology

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ABSTRACT

In the present study, concrete was considered as a two-phase material, consisting of coarse aggregate (CA) and mortar. Coarse aggregate properties were characterized by fineness, uncompacted void and friction angle. The combined effects of CA characteristics and mix design on the rheological properties of the corresponding concrete were investigated using a portable IBB concrete rheometer. Experimental results indicated that a higher CA and fine aggregate content normally result in higher concrete rheological parameters (yield stress and viscosity). For a given type and amount of mortar, concrete yield stress and viscosity generally increase with the uncompacted void content and friction angle but decreased with the size (or fineness) of CA. Well graded CA, generally having low uncompacted void content, provides concrete with considerably reduced yield stress and viscosity when compared with single-sized CA. In addition, a multiple-parameter linear regression analysis was conducted to evaluate how different CA characteristics (fineness, uncompacted void and friction angle) and mix design parameters (mortar composition, and CA volume fraction) affect concrete rheological behavior.

1. Introduction

Aggregate characteristics, such as size, gradation, shape, surface texture and volume fraction, all have significant effects on concrete rheology [1–3]. These effects result from the aggregate interparticle forces (such as interlocking and friction among solid particles) and the particle movement in the liquid phases of fresh concrete [4–6]. Geiker et al. have shown that the relative yield stress and viscosity of concrete significantly increase with increased coarse aggregate (CA) volume fraction [7]. The water requirement for concrete decreases with increased aggregate particle size. Very fine aggregate requires more water for a given consistency. An optimal aggregate gradation provides a higher degree of packing and requires less paste to reach a given consistency since less cement paste is needed to fill the space among the aggregate [8–10]. Previous research also indicates that friction among aggregate has a significant contribution to concrete rheology [11]. Particles with a nearly spherical shape and a smooth surface texture provide more workable concrete. However, compared with the study of cement paste and mortar, the study of concrete rheology is still limited due to the difficulties in characterizing concrete aggregate and the limited equipment available for concrete rheology measurements. Very few aggregate parameters are applied in concrete rheology study.

In the present study, concrete was considered as a two-phase material, composed with mortar and CA. The two-phase approach can not only reduce the error of analysis caused from the wide range of aggregate size, but also provide practical advantages in concrete mix design since fine aggregate (FA) and CA are usually proportioned separated [12]. In addition to proportions of concrete, CA properties were studied. The CA was characterized by gradation, uncompacted void and aggregate friction angle tests. The effects of concrete material properties (CA characteristics) as well as mix design parameters (mortar composition and CA content) on concrete rheological behavior were studied. A multi-parameter linear regression analysis was conducted to study effects of different material and mix design parameters on concrete rheology. Based on the regression analysis, the degree of importance of the aggregate properties and mix design parameters in concrete rheology were evaluated.

2. Research significance

Aggregate characteristics and content significantly influence rheology of concrete. Rational characterization of concrete aggregate has been challenging. In the present paper, test methods for characterizing coarse aggregate were explored, and the aggregate property parameters obtained from these tests were further used to quantify the influence of aggregate (properties and content) on concrete rheology. Based on the experimental results, a statistical analysis was used to evaluate the effect of original mix design and aggregate properties on rheological properties of concrete.

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These test and analysis results can provide researchers and engineers with useful tools to evaluate and predict the effects of aggregate on concrete rheology.

3. Experimental work

3.1. Material properties

ASTM Type I cement was used as a binder in present study, and its chemical composition and physical properties are listed in Table 1. Natural graded river sand with a fineness modulus (FM) of 2.92 was used as fine aggregate (FA). The absorption of FA was 1.60%, and specific gravities were 2.59 and 2.63 at the oven-dried (OD) and saturated surface dry (SSD) condition respectively. Crushed limestone with a 25 mm (1 in.) normal maximum size of aggregate (NMSA) was used as CA. As seen in Fig. 1, three CA gradations (G1, G2, and G3) were employed, where G1 and G3 are the high and the low limits of ASTM C33 "Standard Specification for Concrete Aggregates" and G2 is the middle point gradation between G1 and G3. In addition, four single-sized CAs, retained on the 19.0 mm (3/4 in.), 12.5 mm (1/2 in.), 9.5 mm (3/8 in.), and 4.75 mm (no. 4) sieve but passed the sieve one size higher than the specified sieve, were also used. The specific gravity of the CA was 2.53 at SSD condition and 2.45 at OD condition. Absorption of the CA varied from 2.76% to 3.77%, depending on the aggregate particle sizes. The uncompacted void content and friction angle of the CA was also measured, the test procedures and results will be described later.

3.2. Mix proportions

Different mortar proportions, CA gradations, and CA volume fractions (Vca) as shown in Table 2 were considered in the concrete mix design. A total of 23 concrete mixes with three different mortar proportions (M1: $s/c = 1.75$, $w/c = 0.45$; M2: $s/c = 2.21$, $w/c = 0.45$; and M3: $s/c = 2.60$, $w/c = 0.50$), three CA contents (Vca = 35%, 38% and 41%), and seven CA gradations (four single sizes at 19 mm, 12.5 mm, 9.5 mm and 4.75 mm and three gradations at G1, G2 and G3) were prepared. Note that the mortar proportions were originally designed with the same water-to-cement rations (w/c) but different sand-to-cement ratios (s/c). However, mixes with the highest s/c (M3) was chosen to have slightly higher w/c than mixes with lower s/c so as to achieve acceptable flow ability.

3.3. Mixing procedure

The concrete was mixed using a pan mixer based on ASTM C192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory". CA and FA both at the SSD conditions and tap water at 23 ± 2 °C (73 ± 3 °F) were used.

3.4. Aggregate property measurement

CAs used in present study were sieved and recombined to obtain the designed gradation as described earlier. The uncompacted void content tests were performed according to ASTM C29 "Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate". The void contents of CAs were calculated according to the mass of the aggregate required to fill a container of a specified unit volume. Generally, angularity increases void contents while well-graded aggregate decreases void content. The void content between aggregate particles affects paste and mortar requirements in mix design. While a higher void content of aggregate usually requires more paste and mortar to provide concrete with the same workability, with the same mix design, aggregate with higher void content usually results in concrete with lower workability [3].

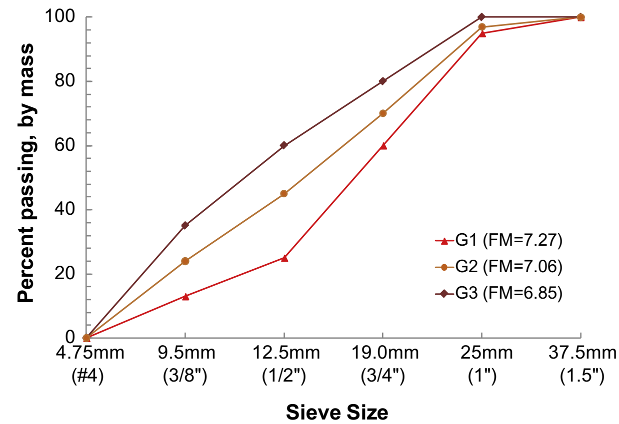

Fig. 1. Coarse aggregate gradation curves.

A simple method was also developed to estimate the friction angle of CA based on a basic soil mechanics concept. Using the infinite slope stability analysis for dry conditions, the angle of repose at limit equilibrium conditions is equal to the angle of internal friction of the material forming the slope [13,14]. The maximum angle formed by the particle pile (i.e., angle of repose) can be considered as a constant and correlated to the friction angle of the particles [15,16]. ASTM C1444, "Standard Test Method for Measuring the Angle of Repose of Free-Flowing Mold Powers," also describes a friction angle test based on the measurement of the angle of repose. With the same concept, a series of tests was conducted in present study to measure the friction angle of various air-dry CAs using slope stability test, the friction angles of tested CAs were estimated from loosely-falling aggregate piles that formed a maximum slope.

As shown in Fig. 2, a piece of paper was marked with a series of circles, up to one meter (40 in.) in diameter, and placed on a ground base. CA samples (18–36 kg, or 40–80 lb, depending on the need for forming a maximum angle) were slowly poured onto the ground base from a given height that was kept approximately 1 cm (3/8 in.) above the formed cone. The height was selected in order to form a pile with a maximum angle under least disturbing. A cone-shaped aggregate pile was gradually formed because of the internal friction angle of particles. When the pile reached a height that no slope change could be visualized as more aggregate was added onto the pile (usually about 20–30 cm or 8–12 in.), the test was stopped. The slope of the aggregate pile was calculated from the diameter and height of the cone and defined as the friction an-

Table 1
Chemical composition and physical properties of cement.

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	$(Na_2O)eq.$[a]	SO_3	LOI[b]
(%)	64.2	20.8	5.55	2.25	1.91	0.50	0.19	0.52	2.96	0.82
Mean size = 23.7 µm			Fineness = 399 m2/kg				Specific gravity = 3.15			

[a] $(Na_2O)eq. = (Na_2O) + 0.658\ (K_2O)$.
[b] LOS = loss of ignition.