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Correlating rheological properties to the pumpability and shootability of wet-mix shotcrete mixtures

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HIGHLIGHTS

- This study examines the performance of the wet-mix process in relation to fresh materials' rheological properties.
- There was no clear relationship between flow resistance and piston pressure.
- A meaningful relationship was identified between torque viscosity and piston pressure.
- The build-up thickness tended to increase as the flow resistance increased.
- Both flow resistance and torque viscosity had no clear relationship with rebound rate.

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ABSTRACT

The pumpability and shootability of fresh wet-mix shotcrete (WMS) mixtures are important factors determining the quality of applied wet-mix shotcrete. Currently, one of the simplest and most accepted methods for estimating the performance of the pumping and shooting process is the slump test. It is well known that the slump test, however, has some limitations in its ability to reasonably evaluate pumping and shooting performance, since it exhibits large variations even among mixtures with the same slump. This paper presents efforts to provide a quantifiable means of estimating the pumping and shooting performance of WMS mixtures in relation to fresh materials' rheological parameters such as flow resistance and torque viscosity, focusing on investigating the effects of various additives and admixtures. The findings of this study reveal that fairly good statistical correlations exist between torque viscosity and piston pump pressure, flow resistance and build-up thickness, and rebound rate and build-up thickness. By contrast, it was quite challenging to define clear relationships between flow resistance and piston pump pressure, torque viscosity and build-up thickness, and rebound rate and rheological parameters.

1. Introduction

The wet-mix shotcrete process is a concreting technique that transports fresh wet-mix shotcrete (WMS) mixtures with a pump and projects the mixtures onto application surfaces using compressed air for purposes such as construction and surface protection, slope stabilization, tunnel lining, underground construction, and/or structural renovation [1]. In this process, ensuring appropriate fluidity and viscosity of the mixture is considered a critical factor to determine the degree of mobility and stability of fresh WMS mixtures delivered through a closed hose system under pressure, which is commonly referred to as "pumpability" [2] or "pressure workability" [3]. Currently, one of the simplest and most accepted evaluation methods for determining the pumpability of fresh concrete is the slump test. However, it has been recognized that the slump test is insufficient to directly assess the pumpability of fresh concrete because pumpability could significantly vary even among mixtures with an identical slump value. Furthermore, advancements in modern concrete technology by means of incorporation of a variety of additives and chemical admixtures in the mixture have made the behavior of fresh concrete even more complex, which in turn has made the pumpability and workability much less consistent with respect to slump; in other words, having a mixture with a good slump does not guarantee good pumpability and vice versa. There have been several research efforts to develop feasible measures to estimate the pumpability of fresh concrete mixtures. Browne and Bamforth [4] proposed a method to predict the

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pumpability of fresh concrete based on the results of slump and pressure bleed tests. Beaupre [5] developed a test device, namely UBC rheometer, to capture fresh concrete's rheological parameters (i.e., flow resistance and torque viscosity) and correlated these parameters to pumpability by measuring the required piston pressure. Recently, Burns [6] experimentally examined the relationships among rheology, tribology, and pump pressure to characterize WMS mixtures pumpable through a small-diameter hose. In 2000, McAskill [7] suggested some technical tips to troubleshoot pumping problems faced in the wet-mix shotcrete process.

Another important consideration with the wet-mix shotcrete process is the concept of "shootability" of fresh concrete mixtures, the definition of which encompasses: (1) the ability of a material (which had been shot) to adhere to or build-up on vertical/overhead surfaces (i.e., adhesion), (2) the degree to which a material sticks to itself (i.e., cohesion), and (3) the degree to which a material bounces off the shooting surface (i.e., rebound). A variety of research efforts have been undertaken to improve the shootability of fresh WMS mixtures. Previous studies [5,8] have shown that the use of silica fume, accelerator, and synthetic fiber increases the build-up thickness of WMS. Jolin and Beaupre [9] reported that introducing a large amount of initial air in the as-batched mixture could be an effective way to increase the build-up thickness of WMS because the loss of the high initial air content during shooting results in better compaction and adhesion of materials during the shotcreting process; Beaupre described this as a "slump killer" effect. Beaupre [5] investigated the relationship between rheological parameters and build-up thickness and confirmed that the build-up thickness had no strong correlation with the torque viscosity while it had an almost proportional relationship to the flow resistance. In addition, Beaupre [5] reported that the use of an air-entraining admixture (AEA) significantly improved shootability because a substantial amount of entrained air bubbles was naturally lost during the shooting process, increasing the build-up thickness. Recently, Ballou [10] suggested practical solutions to mitigate wasteful rebound during the shooting process.

Shootability is considered to be mutually complementary with pumpability; that is, shootability is reduced as pumpability increases, and shootability increases as pumpability decreases. Accordingly, keeping an optimum balance between shootability and pumpability is a key to a satisfactory wet-mix shotcrete operation. While pumpability and shootability are such important factors for the wet-mix shotcrete process, little information is currently available that sheds light on the relationships between fresh material properties and resulting pumping and shooting performances. This has made predictions of a mixture's pumpability and shootability quite subjective. In order to provide a quantifiable means of estimating the pumpability and shootability of WMS, this paper presents the results of efforts to identify the relationships between rheological properties of fresh WMS mixtures and their pumpability and shootability, with a special emphasis on examining the effects of various admixtures such as AEA, polymer, and viscosity agent and additives such as silica fume and synthetic fiber. It is expected that this paper will provide useful information for improving the quality and effectiveness of the wet-mix shotcrete process.

2. Experimental

2.1. Materials

ASTM C150 Type I ordinary Portland cement with a fineness of 3200 cm^2/g, a specific gravity of 3.15, and a chemical composition of 20.8% SiO_2, 6.3% Al_2O_3, 3.2% Fe_2O_3, 61.2% CaO, 3.3% MgO, and 2.3% SO_3 was used. For coarse aggregate, washed crushed rock with a specific gravity of 2.65 and a fineness modulus of 5.70 was used. Washed river sand with a specific gravity of 2.57 and a fineness modulus of 2.66 was used as fine aggregate. The gradation chart for the coarse and fine aggregates used is shown in Fig. 1, along with the upper and lower gradation limits suggested by ASTM C33 (for the coarse aggregate, size number 8 grading requirement was used). The silica fume included had a specific surface area of 150,000–300,000 cm^2/g, a specific gravity of 2.22, and a chemical composition of up to 97% SiO_2 and less than 1% CaO. The polymer used was a powdered admixture prepared by polymerizing vinyl acetate and ethylene, which is known to improve the consistency of mixtures. The physical properties of the polymer are presented in Table 1. As a reinforcement, nylon synthetic fiber with a specific gravity of 1.16, a melting point of 260 °C, a filament diameter of 23 μm, and a length of 12 mm was used. The tensile strength, elastic modulus, and toughness of the synthetic fiber were 890 MPa, 5.1 GPa, and 107 MPa, respectively. In addition, this study utilized superplasticizer, AEA, and viscosity agent (all of which were in powder form) as chemical admixtures, and their physical properties are shown in Tables 2–4, respectively.

2.2. Mixture proportions

Nine WMS mixtures were prepared with a fixed water-to-cementitious ratio (w/cm) of 0.435, a cementitious content of 440 kg/m^3, a maximum coarse aggregate size of 10 mm, and a fine aggregate-to-total aggregate fraction (S/a) of 0.7. The silica fume was incorporated using a mass replacement basis. The addition rate of superplasticizer varied from 0.12% to 0.27% of the total cementitious material content by weight in order to obtain a target slump of 120 ± 30 mm. The mixture proportions of the WMS used in this study are given in Table 5.

2.3. Methods

2.3.1. Air content and slump

The air content in fresh WMS mixtures was measured, following the test method specified by KS F 2421 (*Standard test method for air content of fresh concrete by the pressure method*). The slump was measured as per KS F 2402 (*Method of test for slump of concrete*) using fresh concrete samples collected in accordance with KS F 2401 (*Sampling method for fresh concrete*).

2.3.2. Rheological properties

The rheological properties of fresh WMS mixtures prior to shotcreting were measured using an IBB rheometer (see Fig. 2), originally devised at The University of British Columbia [5], later modified by IBB Rheology Inc. The testing procedure was initiated by calibrating the torque resolution to ±0.5 N m and setting the built-in strain gage to a null position. Subsequently, fresh concrete was poured into the 21-l mixing bowl up to a height of 200 mm. The bowl was then lifted using the lever to completely bury the H-shaped rotary impeller in the fresh concrete mixture. Finally, the torque exerted on the impeller was continuously monitored using a load cell as the impeller stirred the mixture with a rotational speed varying from 0 to 1.2 rev/s (held for about 10 s for every 0.3–0.4 rev/s). The testing was performed under a controlled temperature condition of ±23 °C to minimize the temperature influence on the experimental results.

Fig. 3 shows an example of experimental data obtained from the IBB rheometer, which represents the impeller rotational speed in the x-axis and the torque exerted on the impeller in the y-axis. From this figure, rheological material parameters, namely torque viscosity and flow resistance, can be estimated based on a linear regression analysis of the collected data points; the slope of a linear regression line corresponds to the torque viscosity (H in Fig. 3), and the y-intercept corresponds to the flow resistance (G in Fig. 3). The torque viscosity and flow resistance determined by the IBB rheometer have a comparable physical meaning to the yield stress and plastic viscosity in the Bingham model, respectively.

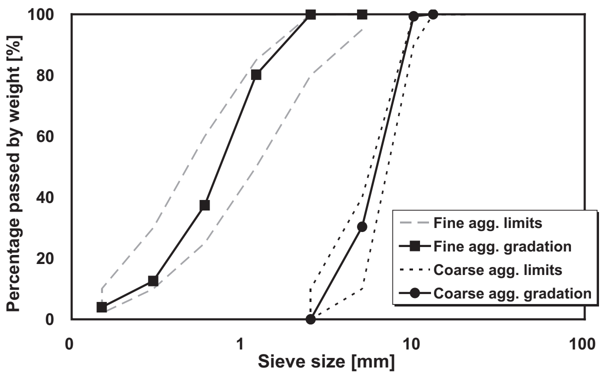

Fig. 1. Gradation curves for coarse and fine aggregates used.