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# Effects of admixtures on the rheological properties of high-performance wet-mix shotcrete mixtures

Kyong-Ku Yun [a], Sung-Yong Choi [a], Jung Heum Yeon [b,*]

[a] Department of Civil Engineering, Kangwon National University, Chuncheon 200-701, South Korea
[b] Department of Civil and Environmental Engineering, Gachon University, Seongnam 461-701, South Korea

## HIGHLIGHTS

- Effects of various admixtures on the rheological properties of HPWMS were examined.
- Rheological properties such as yield stress and plastic viscosity were measured using IBB rheometer.
- The measured rheological properties were correlated to shootability and pumpability.
- Silica fume is the most effective admixture for enhancing the rheological properties of HPWMS.

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## ABSTRACT

This study investigates the effects of various admixtures on the rheological properties of high-performance wet-mix shotcrete (HPWMS) in an attempt to resolve practical issues faced in conventional wet-mix shotcrete processing. The admixtures used in this study were silica fume, air-entraining agent (AEA), superplasticizer, synthetic fiber, powdered polymer, and a viscosity agent. Representative rheological properties such as yield stress and plastic viscosity were measured using an IBB rheometer to evaluate the pumpability and shootability of HPWMS with varying admixture types and contents. The results demonstrated that the use of AEA tended to reduce both flow resistance and torque viscosity of HPWMS almost proportionally. A superplasticizer had a relatively greater impact on the flow resistance rather than torque viscosity. Also, it was observed that silica fume led to a remarkable increase in flow resistance while it slightly reduced torque viscosity. This behavior trend indicates that silica fume is quite effective in enhancing the rheological properties of HPWMS, particularly in terms of shootability and pumpability.



## 1. Introduction

Fresh concrete exhibits an elastic behavior at a low-stress range, and it begins to show a plastic flow once a certain level of deviator stress is reached. Because of such nature, from a rheological perspective, fresh concrete is classified as a Bingham fluid rather than a Newtonian fluid [1–3]. It is well known that, in fresh concrete, the shear stress is not in perfect linear proportion to the shear strain rate. However, if assumed that their correlation is approximately linear, the Bingham model can be an effective tool to characterize the flow behavior of fresh concrete. Applications of the Bingham model require at least two parameters, yield stress and plastic viscosity, as indicated in Eq. (1):

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

where $\tau$ is the shear stress; $\tau_0$ is the shear yield stress; $\mu$ is the plastic viscosity; and $\dot{\gamma}$ is the shear strain rate.

The Bingham model has been primarily applied to high-concentration viscous fluids such as fresh cement paste. However, over the years, this well-defined model has been accepted to fresh concrete containing various-sized aggregates as the development of cutting-edge test apparatuses, such as rotational and oscillatory rheometers [4–7], allowed easy measurements of yield stress and plastic viscosity of fresh concrete. In particular, the Bingham model yields a strong fitness when applied to fresh concrete with a high slump (over 15 cm) and consistency because, in such highly workable concrete, the flow characteristics largely depend on the properties of cement paste matrices [8].

Previous research on shotcrete often focused on wet-mix types; a number of studies attempted to document the strength characteris-

* Corresponding author. Tel.: +82 31 750 5498.
*E-mail address:* jyeon@gachon.ac.kr (J.H. Yeon).

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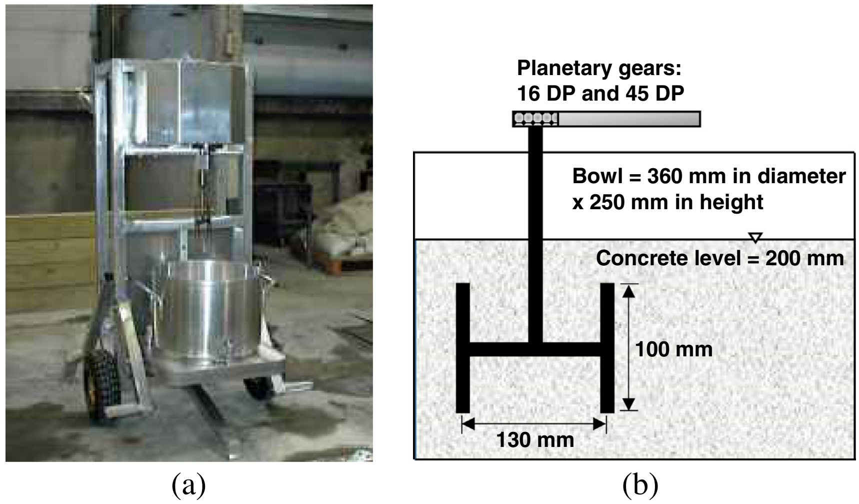


**Fig. 1.** IBB rheometer: (a) front view; (b) details of H-shape impeller, bowl, and planetary gear.

**Table 1**
Experimental variables and target levels.

| Variables | Target levels |
|---|---|
| *w/cm* (–) | 0.50, 0.55, 0.60 |
| AEA (% of cement content) | 0, 0.01, 0.02, 0.05 |
| Superplasticizer (% of cement content) | 0, 0.1, 0.2 |
| Silica fume (% of cement content) | 0, 9 |
| Polymer (% of cement content) | 0, 4 |
| Synthetic fiber (% of cement content) | 0, 0.2 |
| Viscosity agent (% of cement content) | 0, 0.3 |

**Table 2**
Chemical compositions of cement (unit: %).

| $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ |
|---|---|---|---|---|---|
| 20.8 | 6.3 | 3.2 | 61.2 | 3.3 | 2.3 |

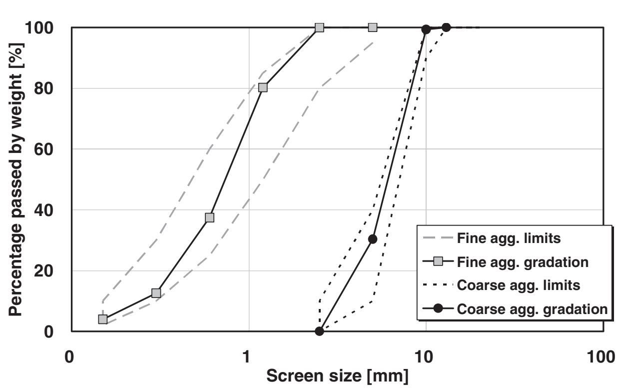


**Fig. 2.** Aggregate gradations with recommended limits.

tics and rebound rate of fiber-reinforced wet-mix shotcrete [9,10]. Also, over the years, there has been an increasing interest in high-strength and high-durability shotcrete [11–15]. Only few studies are available that address pumpability and shootability, as well as other rheological properties of high-performance shotcrete. Beaupre [7] studied the rheological properties of high-performance shotcrete using a self-developed UBC rheometer, in which pumpability and shootability of fresh shotcrete were evaluated. Another study

**Table 3**
Physical properties of polymer.

| Solid content (%) | Ash content (%) | Bulk density (kg/m$^3$) | Min. film forming temp. (°C) | Particle size (μm) | Appearance | Protective colloid/ emulsifier system |
|---|---|---|---|---|---|---|
| 98–100 | 9–13 | 490–590 | 4 | 400+ (max. 4%) | White powder | Polyvinyl alcohol |

[8] has confirmed that flow characteristics of fresh concrete largely depend on the rheological properties of cement paste matrices. Moreover, Ko et al. [16] evaluated how the binder type, water-to-binder ratio, admixture content, and time of testing initiation affect the mechanical and rheological properties of mortar to provide some basic information on high-fluidity concrete. Szecsy [17] found the effects of fine aggregate fraction, water-to-cement ratio, coarse aggregate type, fly ash replacement, and superplasticizer addition on the rheological properties of fresh concrete. Kang et al. [18] developed a theoretical mixture design for high-fluidity concrete by assessing the influences of microfine and mineral admixtures on the rheological properties of cement paste. Other former research studies incorporate modeling of pump pressure considering the rheological properties and frictional conditions [19] and experimental investigations on the effects of silica fume [20] and accelerators [21].

The key components affecting the rheological properties of fresh concrete include: (1) binder formulations including the type and content of chemical and mineral admixtures; (2) type, shape, and gradation of aggregates; (3) water-to-cementitious ratio (*w/cm*); and (4) properties of cementitious materials. Even similar mixtures could display quite different flow characteristics with slight variations in those components. In this study, the effects of various types of additions (i.e., silica fume, air-entraining agent (AEA), superplasticizer, synthetic fiber, powdered polymer, and viscosity agent) on the rheological properties of high-performance wet-mix shotcrete (HPWMS) are comprehensively evaluated. Also, the identified rheological properties were correlated to the practical indicators of shotcrete behavior, such as shootability and pumpability. The outcomes of this study are expected to provide valuable information to resolve practical issues faced in conventional wet-mix shotcrete processing.