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Investigating and optimizing the mix proportion of pumping wet-mix shotcrete with polypropylene fiber

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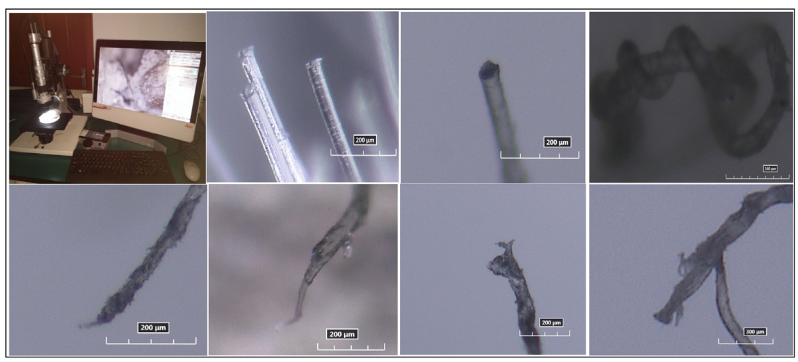
HIGHLIGHTS

- The situation of breakage fiber in broken shotcrete was observed by digital microscopy.
- Three types of fiber breakage in broken shotcrete were proposed and analyzed statistically.
- The pumpability, shootability and hardenability of wet-mix shotcrete was comprehensively investigated by Taguchi method.

GRAPHICAL ABSTRACT



Leica Digital Microscopy and the types of fiber breakage

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ABSTRACT

In order to obtain the optimum mixture proportions of wet-mix shotcrete, the tests of shotcrete properties with different fiber length were firstly conducted and the situation of breakage fiber was analyzed statistically. Secondly, mix proportion factors of wet-mix shotcrete were analyzed by using the Taguchi method. Results showed that increasing fiber length enhanced the shear and tensile failure of fibers. According to the analysis of variance (ANOVA), the water/binder (W/B) ratio was the most effective parameters on the slump and compressive strength, whereas the polypropylene fiber (PF) was the dominant factor on the splitting tensile strength and water permeability. Finally, based on the multi-factor comprehensively considering, the final mix design was determined.

1. Introduction

Wet-mix shotcrete is today a well-known technology. The application of wet-mix shotcrete is prevalent in support in China because dry-mix shotcrete, owning a great deal of dust during the process, is forbidden in China' mining supporting now [1,2]. However, it is difficult for the traditional wet-mix shotcrete technique to meet the high support requirements especially under the complicated geological conditions such as high pressure water pouring and large geostress that generally cause shotcrete layer cracking and large rebound. Hence, it is needed to obtain a high performance wet-mix shotcrete, owning high pumpability and shootability and harden characteristics together, by optimizing the mixture proportions based on the fiber reinforced shotcrete.

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Fiber is known to have significant effects on properties of shotcrete and the addition of fibers to normal shotcrete can improve the toughness or energy absorption capacity efficiently [3–7]. In wet-mix shotcrete technique, fibers are added to the fresh concrete and then the mixtures are pumped to the nozzle, where it is accelerated by high pressure wind and sprayed to the surface. Setting accelerator is normally added at the nozzle for reaching the certain stiffness upon arrival on the surface area. Furthermore, silica fume as a highly pozzolanic mineral admixture can improve concrete mixture durability and strength. The addition of superplasticizer and appropriate fine aggregate to total aggregate (s/a) percent are also helpful to improve the shootability and pumpability of fresh concrete.

Austin et al. [8,9]reported that fiber addition nor fiber geometry or fiber mass had no significant influence on the rebound whereas the variations in spray conditions had a larger effect. John et al. [10] studied the influence of addition of three forms of silica fume (uncompacted, compacted low density, and compacted high density) on the properties of plastic and hardened shotcrete, compared to the performance of plain control Portland cement shotcretes. Results showed that three different silica fume can be successfully used to substantially improve both the properties of the shotcretes studied. Cheng et al. [11] added both silica fume and fibers in wet-mix shotcrete in order to increase the flexural strength of shotcrete and reduce rebound in the engineering of diversion tunnel where water pouring was serious. Dufour et al. [12] found that the macro-synthetic polypropylene fibers can increase shotcrete layer built-up thickness and the rebound may cause a reduction of fiber loss. Yun et al. [13] investigated the effects of various admixtures (like silica fume, superplasticizer and air-entraining agent) on the properties of wet-mix shotcrete in order to resolve practical issues faced in the process of conventional wet-mix shotcrete. Masahiro et al. [14] also investigated the effect of superplasticizer on the balance between viscosity and flowability of mortar in concrete quantitatively. Su et al. [15,16] researched the effect of fine aggregate to total aggregate (s/a) percent on the properties of concrete and found that increasing s/a can increase the flowability of fresh concrete.

There are also other ways to improve the properties of shotcrete. For example, Zeng et al. [17] used magnetized water that was mixed in premixed concrete to increase the compressive strength and reduce the rebound rate of shotcrete. Literature [18,19] found that the addition of fine particles and lower aggregate density may reduce aggregate rebound efficiently. Ginouse et al. [20] studied the effect of equipments on spray velocity distribution in shotcrete applications by using a high-speed imaging system.

The key components affecting the properties of shotcrete include: (1) properties of cementitious materials; (2) type, shape, and gradation of aggregates; (3) water/ binder (W/B) ratio; and (4) binder formulations including the type and content of chemical and mineral admixtures (like silica fume and superplasticizer). To evaluate the effect of various factors on concrete properties comprehensively, the common measuring test is Taguchi method. Turkmen et al. [21] studied on the effect of the admixtures of silica fume and blast furnace slag on the mechanical properties of high strength concrete by using the Taguchi method. Fauzan et al. [22] used Taguchi design of experiment method to identify the most influencing factor of concrete mixing on the properties of concrete. Hinislioglu et al. [23] analyzed the optimal mix proportion for flexural strength of pavement concrete with fly ash and silica fume by using Taguchi method.

Although several other researchers applied Taguchi method to study the properties of concrete, they generally changed one or two parameters of concrete to investigate the effect of those parameters on concrete. Few studies had examined the comprehensive properties of wet-mix shotcrete including pumpability, shootability and hardenability. In addition, the relative study on the type of fiber breakage in the broken shotcrete was few.

The main purpose of this study was to analyze the types of fiber breakage in the cracked shotcrete for selecting the optimal fiber length, then to find the optimum mix proportions and ranking of the effective factors on the fresh and hardened properties of wet-mix shotcrete, finally improving the harden characteristics of wet-mix shotcrete with the better pumpability and shootability.

In this study, the tests of shotcrete properties with different fiber length were conducted and the types of fiber breakage was observed by Leica Digital Microscopy and analyzed statistically. Then the experimental work was designed by using the Taguchi method. The slump and rebound rate of fresh concrete were tested, along with their compressive strength, splitting tensile strength and water permeability of hardened shotcrete. The tested results were analyzed by the method of analysis of variance (ANOVA). Using Taguchi method, the significance of the seven factors, water to bonding materials ratio (W/B), water content (W), fine aggregate to total aggregate percent (s/a), silice fume (SF), superplasticizer (SP), accelerator (AC) and polypropylene fiber (PF), affecting the properties of shotcrete was determined, mix proportions were set to best possible levels for the maximization of slump, compressive strength, and splitting tensile strength results and for the minimization of rebound rate and depth of penetration of water. Finally, according to the multi-factor comprehensively considering, the final mixture proportions was determined and verified for improving both fresh and hardened properties of wet-mix shotcrete.

2. Experimental program

2.1. Materials

2.1.1. Cement

The cement was standard PO 42.5 cement produced from China United Cement CO., LTD with a fineness of 3100 cm^2/g, a specific gravity of 3.14. Moreover, the chemical characteristics of the cement is listed in Table 1.

2.1.2. Aggregates

For coarse aggregates, crushed limestone with a maximum size of 10 mm was used. Natural river sand was employed as fine aggregate. The specific gravities of the fine and coarse aggregates were 2.61 and 2.67, respectively. In addition, the fineness moduli of the fine and coarse aggregates were 2.66 and 5.70, respectively. The amount of mixing water was corrected to take into account the water absorbed by the fine and coarse aggregates. The water absorption of the fine and coarse aggregates were 7.1% and 1.6%, respectively. The gradation curves shown in Fig. 1 for both coarse and fine aggregates are along with the gradation limits recommended by the national standard GB50086-2001 (Specifications for Bolt-Shotcrete Support).

2.1.3. Admixtures

2.1.3.1. Silica fume. This study included silica fume with a specific surface area of 160,000–300,000 cm^2/g and a specific gravity of 2.21. The silica fume consisted of up to 95% SiO_2 with less than 1% CaO.

2.1.3.2. Polypropylene fiber. Polypropylene fibers with a specific gravity of 0.93 were used as a reinforcing material. The fiber length used for the study was 3, 9, 15, 21 and 29 mm and its melting point was approximately 180 degrees Celsius. The specific physical properties of polypropylene fiber are listed in Table 2.