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Development of two new anti-washout grouting materials using multi-way ANOVA in conjunction with grey relational analysis

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HIGHLIGHTS

- The purpose of this study is to develop two new composite anti-washout grouting materials.
- Taguchi design of experiments and grey relational analysis were used to achieve the desired yield stress and plastic viscosity at the same time.
- The less influential control factors in rheological properties identified by the multi-way ANOVA can be used to adapt the other performances.

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ABSTRACT

Two new types of anti-washout cementitious grouts, named "AWG-1" and "AWG-2" (anti-washout grout) respectively, have been developed for different geological conditions. Separate addition tests were performed to study the effects of certain accelerating agents and flocculating agents on the cement based grout comparatively. Based on the results of separate addition tests, two new formulations were proposed for further investigations. Both formulations involved three admixtures respectively. Grey relational analysis, coupled with Taguchi design of the combined addition experiment, was performed to determine the optimal admixture dosages for simultaneously achieving the desired yield stress and plastic viscosity of the cementitious grout. Multi-way ANOVA was employed to identify the insignificant factors ($p > 0.05$) which could be used to adjust the setting time and the compressive strength while not compromising the optimum rheological properties. The optimization algorithm was thus developed to achieve a faster set time, higher durability but lower workability for AWG-1, as well as sufficient washout resistance for both formulations according to their geotechnical applications. In addition, AWG-1 requires a high-pressure grout pumping system. Finally, the washout resistance of the newly developed grouts was validated by anti-washout simulation experiments.

1. Introduction

The idea of applying grouts in hydraulic engineering to solve foundation problems is not new, such as improving water tightness of underground soil mass, strengthening of weak soils or rock mass. Nevertheless, the development of new grouting materials has been much slower since the 1990s, failing to keep up with the rapid grouting application development in China.

Traditional cement-based grouts present poor performance from functional [1] perspectives. As a result, they are unable to form an effective seepage-preventing curtain under complex ground conditions such as large leakage [2] and water gushing of high pressure and large flow. Moreover, although chemical grouts possess many advantages such as rapid gain in high strength and good groutability, these materials are likely to pollute the environment [3], and they are less cost-effective [4]. Therefore, there is a need to develop a new cementitious grouting material. That should meet several critical user requirements as follows: (1) It is well resistant [5] to water dilution and rushing; (2) The setting time of the grouting material should be adjustable within a certain range; (3) Must have a desired level of impact strength and bond strength after gelling [6]; (4) It should be non-toxic, tasteless and harmless to the environment. To meet these requirements, the principal difference between the new and traditional anti-washout cement-based grouts is that the newly-developed grouting material adopts more suitable types of admixtures [7,8] with optimal mixing proportions as compared to the traditional ones.

Two types of non-toxic admixtures were used in this study: the accelerating agent and flocculating agent. The former is employed

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to adjust the setting time [9] of the grouts, and the latter is used for the control of the fluidity, the mechanical strength and plastic viscosity of the grouting material.

The accelerating agent is referred herein to as set-accelerating admixture, the addition of which could decrease the setting time of cementitious slurry and improve [10,11] its initial strength. The accelerating agents on the market at present can be divided into groups based on their composition: inorganic accelerator [12–15] and organic accelerator. The mechanism of their acceleration is complicated [16–19]. These accelerating agents have their respective advantages and disadvantages depending on specific applications.

The flocculating agent is also known as viscosity-enhancing admixture (VEA), which is used to enhance the cohesion and stability of cement-based systems. The flocculating agents can be categorized into five classes [20] according to their physical actions in the cementitious grout [21–24]. The reaction mechanism of flocculating agents is a very complicated physical and chemical process. It is mostly considered that flocculation is attributed to two processes: coagulating and flocculating [25,26].

The setting time, fluidity and rheological property of cement grouts have been generally modified by using one or both of the two types of admixtures [27–31]. However, most of recent studies aimed to understand and evaluate the influence of the admixtures and their proportions on the cementitious material separately. The optimization of several parameters simultaneously is relatively few. In this study, two types of new cement-based grouts designated as AWG-1 and AWG-2 (anti-washout grout) were developed for different geotechnical applications. AWG-1 is applied to conditions [1] where there is running groundwater and it must feature a high yield stress, high plastic viscosity and relatively fast set time. It is worth noting that a high-pressure grout pumping system is necessary when AWG-1 is adopted because the cement-based grout has a high yield stress, which, in turn is at the origin of a low workability. When the grouting material is used for strata of neither cavern nor super-high hydrodynamic pressure, the greater workability and fluidity is needed rather than rapid initial setting, and AWG-2 meets this requirement.

Grey relational analysis was used to optimize the fluidity and washout resistance of the newly-developed grouting material at the same time. Multi-way ANOVA allowed the assessment of the significance of the ratios of the admixtures for the rheological properties and thereby adapted them adequately to achieve the desired performance.

2. Experimental

2.1. Method

The experimental study involved three stages.

The purpose of the first stage of this study was to evaluate the effects of two accelerating agents (AA-1 and AA-2) on the setting time and those of four flocculating agents (CPAM, hydroxyethyl cellulose ether, UWB-II and bentonite) on the fluidity separately. These effects will serve as basis for the classification of admixtures in the next stage. In addition, the influence of the six independent variables on the compressive strength was not ignored.

In the second stage, two new types of anti-washout cementitious grouts were proposed due to the practical application, "AWG-1" and "AWG-2". AWG-1 will be developed for conditions [1] where there is running groundwater. A high-pressure grout pumping system is necessary when AWG-1 is adopted because the cement-based grout presents a high yield stress which means a low fluidity. AWG-2 was developed to achieve greater workability and fluidity for strata of neither cavern nor super-high hydrodynamic pressure. AWG-2 is supposed to suit the case. Based on the results of the separation addition test in the first stage, suitable admixtures were carefully chosen for AWG-1 and AWG-2 respectively for the further development according to their set-accelerating capability and fluidity assuming that combination of admixtures induced some interactions but not interventions between their respective effects on the cementitious grout. And the ratio ranges of admixtures were set for further combined addition tests considering the specification recommended by the admixture producers. The interactions of the accelerating agent and flocculating agent dosages on the rheological characteristics, setting time and fluidity were evaluated to confirm the hypothesis. Taguchi method is combined with Grey relational analysis (GRA) to optimize AWG-1 and AWG-2′s rheological characteristics. Multi-way ANOVA was employed to identify the relatively insignificant process parameters whereby we could adjust the properties other than the yield stress and the plastic viscosity. The results of thorough optimization proposes two set of specific admixture dosages for AWG-1 and AWG-2 respectively.

The last step is to validate the results of optimization through the anti-washout experiment on the newly-developed AWG-1 and AWG-2 (anti-washout grout). The residual rate of grout by weight after washout is recommended as the index of the anti-washout performance for the optimal formulations.

The scheme for a structured grout development and analysis is illustrated in Fig. 2.1.

2.2. Materials

The cement used in the mixture was Portland Cement [32] (CEM I 42.5N) at a water to cement ratio of 0.5:1. Admixtures adopted in the first step included two types of accelerating agents and four types of flocculating agents. To be specific, the accelerating agents were named after "AA-1" and "AA-2" in our study as they don't have exact scientific names yet. And the flocculating agents were cationic polyacrylamide (CPAM), hydroxyethyl cellulose ether (HEC), UWB-II (underwater binder) and bentonite. Bentonite is often used to help good fluid properties without occurring segregation during injection [12]. Fig. 2.2 shows the molecular structure of CPAM and hydroxyethyl cellulose ether (HEC). The molar substitution ratio (MS_{HE}) represents the number of moles of hydroxyethyl groups per mole of anhydroglucose unit and is 2 for the investigated HEC samples. So-called UWB-II is a type of polysaccharide flocculating agent. AA-1 is a type of inorganic modified mineral accelerating agent, AA-2 is a composite accelerator comprised of organic and inorganic matter. The chemical characteristics of AA-1 and AA-2 are presented in Table 1.

2.3. Mixing and testing procedures

All grouts were prepared in laboratory, and mixed using a high-shear mixer rotating at 2500 rpm. Water was first introduced in the mixer along with the accelerating agents. The cementitious materials were then added over 1 min, followed by the flocculating agent or nothing, and the grout was mixed for 1 min. After a rest period of 30 s, the mixing was resumed for 1 additional minute. The w/c ratio of the grout was 0.5. Fig. 2.3 shows the mixer and an example of the premixed cement based grout.

Following the end of mixing, the setting time, yield stress, compressive strength, plastic viscosity and fluidity were tested as described below.

2.3.1. Setting time measurements

The Vicat method was used to evaluate the setting time of the mixtures conforming to the standard ASTM C953.