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Optimization of alkali-activated mortar utilizing ground granulated blast-furnace slag and natural pozzolan from Germany with the dynamic approach of the Taguchi method

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HIGHLIGHTS

- Dynamic approach of the Taguchi method was applied to optimize design system.
- Volume ratio of powder to alkaline activating solution is suitable as input signal.
- System optimization was made using SN ratio and sensitivity.
- Effect of design parameters on SN ratio and sensitivity of AAGT mortar are clarified.
- Optimized linear input–output relationships have been established.

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ABSTRACT

This paper presents an investigation into the applicability of the dynamic approach of the Taguchi method to optimize alkali-activated mortar utilizing ground granulated blast-furnace slag and natural pozzolan from Germany called trass (hereafter, AAGT). The volume ratio of powder to alkaline activating solution (V_p/V_{aas}) was chosen as an input signal, while flow value and flexural and compressive strengths were considered as output values. The concentration of sodium hydroxide solution, mass ratio of sodium silicate to sodium hydroxide solution, ground granulated blast-furnace slag replacement ratio, mixing regime, mixing time, curing temperature, and cumulative temperature in heat curing were taken into account as design parameters. Based on the experiments conducted using an L_{18} orthogonal array and the calculated results of signal to noise (SN) ratios and sensitivities, input–output relationships between V_p/V_{aas} and the output values were optimized. Long-term tests on the optimized specimens revealed the applicability of AAGT as a construction material; however, expansion cracks due to a gypsum formation were noticed after long-term immersion in a 10% sulfuric acid solution.

1. Introduction

The use of geopolymer binders has increasingly attracted attention in recent years. A geopolymer is an inorganic polymer devised by Davidovits [1]. Compared with Portland cement concrete, the amount of CO_2 emitted in the manufacturing of a geopolymer is estimated to be lower by 80% [2]. In the field of construction materials, a geopolymer is defined as a hardened body resulting from polymer reactions among sodium silicate, sodium hydroxide, and metallic ions such as Si^{4+} and Al^{3+}, leached from active fillers. Coal fly ash from thermal power plants and calcined kaolin are some examples of active fillers. There is a great deal of research on geopolymers formed using coal fly ash and metakaolin. There is also research on geopolymers that utilize blast-furnace slag, sewage sludge slag [3], ferronickel slag [4], and so on.

Aside from industrial by-products, the majority of natural resources such as volcanic ash and other pozzolanic materials remain unused. It is important to make use of these natural resources in construction materials, from the standpoints of not only disaster mitigation in mountainous regions but also conservation of limited resources. Natural pozzolans are intrinsically rich in

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SiO_2 and Al_2O_3; thus, they could function as active fillers in geopolymer systems.

Several published research papers on geopolymers that utilize natural pozzolan such as volcanic ash or trass [5–10] suggest that they are indeed suitable as active fillers. However, there remain matters such as mixture proportion, manufacturing method, long-term strength, and durability.

Some of the many design parameters in the manufacturing of geopolymers include type and mixture of alkaline activator, type of active filler, content of active filler, and mixing and curing regimes. The number of variables makes it difficult to achieve an optimum geopolymer design. In addition, there can be interactions among the design parameters. For example, approaches where one parameter is varied while other parameters remain fixed are widely adopted to find the optimum condition. The solution obtained in this manner may not be the optimum one, however, when the fixed parameters are changed.

To solve such problems, the methods of "The Design of Experiments" or the parametric design of "The Taguchi Method" is expected to be helpful. The design of experiments is an important on the subject of quality control, originating from studies on experimental methods by Fischer [11]. It describes a method to evaluate the effect of multiple factors statistically with a small number of experiments. The Taguchi method is a series of techniques and concepts developed by Dr. Taguchi since the 1950 s, based on ideas introduced in the design of experiments. It is essentially a preventive design technique that can eliminate problems due to data scattering or system deterioration.

The main objective of the present study is to establish a reasonable input–output system for manufacturing alkali-activated mortar utilizing ground granulated blast-furnace slag as well as natural pozzolan from Germany called trass (hereafter, AAGT). Special emphasis is placed on the dynamic approach of the Taguchi method [12,13], which was employed in the optimization. In the dynamic approach, relationships between a range of input signals and the corresponding output values are determined, through an optimization of design parameters based on signal to noise (SN) ratios and sensitivities. Although there are actually several reports on geopolymers optimized with the static approach of the Taguchi method or the design of experiments [14–21], none of the studies has focused on the application of the dynamic approach. Fig. 1 presents the difference between the static and dynamic approaches of the Taguchi method. The static approach is applied to cases where the quality characteristic's target has a fixed level. On the contrary, the dynamic approach is applied to cases where the quality characteristic operates over a range of values [12]. The goal in the dynamic approach is to optimize a system's quality characteristic as a function that generates a range of outputs, and thus, the input parameter in the dynamic approach is an adjustment factor [12]. In the field of construction materials, target values such as workability and strength are normally varied depending on the purpose of each construction project. Furthermore, it has been shown that the reproducibility of the dynamic approach is usually higher than that of the static approach [13].

First, optimized linear relationships between the input signal (V_p/V_{aas}: volume ratio of powder to alkaline activating solution) and output values (flow value and flexural and compressive strengths) were determined based on experiments conducted using an orthogonal array of L_{18}. This step was followed by long-term tests on the optimized AAGT mortar specimens.

2. Experimental outline

2.1. Materials

Commercially available ground granulated blast-furnace slag (GGBFS) (density = 2.93 g/cm^3, specific surface = 4086 cm^2/g) and natural pozzolan from Germany (trass) (density = 2.34 g/cm^3, specific surface = 5980 cm^2/g) were used as activated powders. The major chemical compositions and the particle size distributions of the GGBFS and trass are shown in Table 1 and Fig. 2, respectively. It can be seen that the trass is rich in SiO_2 and Al_2O_3; thus, it is expected to function as an active filler.

Standard sand (CEN-Normsand DIN EN 196-1 [22]) (density = 2.64 g/cm^3) was used as fine aggregate. Combination of sodium silicate solution (specific gravity = 1.37) and sodium hydroxide solution was used as the alkaline activating solution. Sodium hydroxide was dissolved in tap water to produce sodium hydroxide solutions of 3 M, 6 M, and 9 M, with specific gravities 1.12, 1.22, and 1.31, respectively.

2.2. Design parameters

The design parameters in the present study are summarized in Table 2. Concentration of sodium hydroxide solution, mass ratio of sodium silicate solution to sodium hydroxide solution, GGBFS replacement ratio, mixing regime, mixing time, curing temperature, and cumulative temperature in heat curing were taken into account as design parameters. The parameters and the levels were selected with reference to Ken et al.'s review [23]. The GGBFS replacement ratio in the present study is defined as follows:

$$\text{GGBFS replacement ratio} = GGBFS/(GGBFS + Trass) \quad (1)$$

where *GGBFS*: mass of GGBFS (g); *Trass*: mass of trass (g).

The mixing regimes are shown in Fig. 3. The cumulative temperature in heat curing is defined as the product of curing temperature (°C) and curing period (hour).

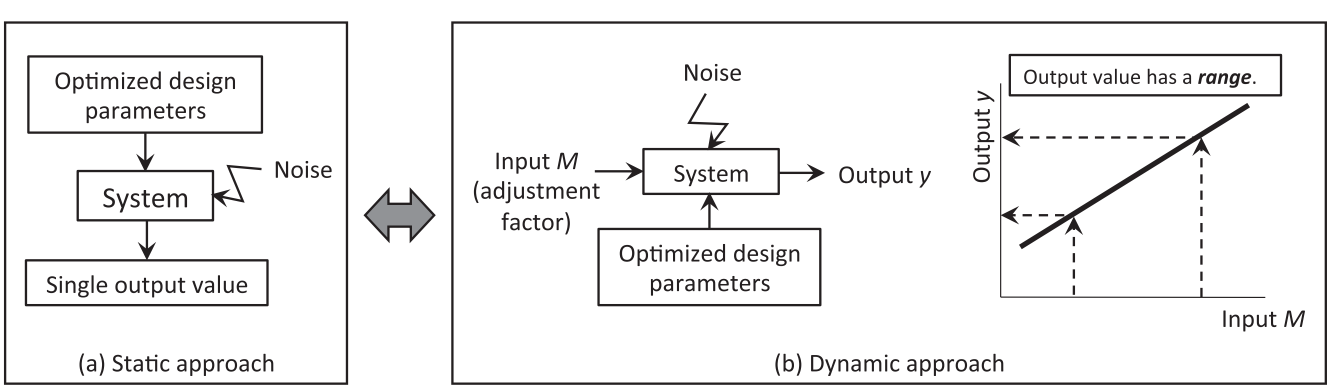

Fig. 1. Static and dynamic approaches of the Taguchi method.