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Mix Ratio Design of Geopolymer Self-Compacting Concrete

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Abstract: Based on the literature survey of the mix design methods of geopolymer concrete, the steps and advantages and disadvantages of each method were analyzed. At the same time, the literature research on the design methods of self-compacting concrete mix ratio is conducted to compare the advantages and disadvantages of various methods. Based on the advantages of the design method of the mixture ratio of the geopolymer concrete and the self compacting concrete, the characteristics of the geopolymer self compacting concrete materials are analyzed, and the suggestions on the design method of the mixture ratio are given, which provides a reference for the design and engineering application of the mixture ratio of the geopolymer self compacting concrete.

1. Introduction

Due to the rapid development of engineering construction, significantly more concrete is used, with the demand for Portland cement increased simultaneously. According to statistics, about 1 ton of CO_2 is emitted in every ton of cement production, and the cement industry's CO_2 emissions account for about 7% of the global CO_2 emissions [1]. Cement production is also accompanied with elimination of a large amount of harmful substances such as NO_x, SO_x and dust particles. Hence, cement production not only consumes abundant energy, but also causes serious pollution. Assisting in the frequent occurrence of geological disasters and meteorological anomalies, such as landslides and debris flows [2-4], it threatens the environment for survival of the entire human beings. It is a problem demanding urgent solution to seek green, environmentally friendly, fast-hardening and early-strengthening cement material substitutes. The emergence of geopolymers provides a solution for this, which carries important social practical significance and enjoys broad market application prospects for creating a green environment by promoting low carbon environmental protection, energy conservation and emission reduction.

Geopolymer, a new material developed rapidly in recent decades, is mainly composed of raw materials and basic catalysts. Wastes such as fly ash, red mud, copper slag, and rice husk ash are used as raw materials, while sodium-based or potassium-based alkaline solutions are used as alkaline catalysts in geopolymers. The polymerization process is to activate the alumina and silica in the waste by the alkaline solution to form a three-dimensional amorphous polymer chain [5]. The concrete thus prepared has the same appearance and mechanical properties as Portland cement. Literature [6-8] studies the basic properties, while literature [9-12] studies the durability performance. Some conclusions of the above-mentioned geopolymer concrete performance are still controversial, and the mineral compositions vary greatly in different regions, so a lot of research work is still needed to implement large-scale popularization and application. In particular, there is still scarce theoretical research on mix ratio design.

Self-compacting concrete (SCC for short) means that under the action of its own gravity, concrete can flow and compact without additional vibration. Even in the presence of dense steel bars, the formwork can be completely filled with good homogeneity to form concrete with design strength grade and good durability after hardening. Compared with ordinary concrete demanding vibration, self-compacting concrete has high fluidity, high cohesion, high water retention, and good durability [13,14]. Literature [15,16] studies the working and mechanical properties of self-compacting concrete, with some suggestive conclusions given.

With the rapid development and application of geopolymer materials, the research, development and application of geopolymer self-compacting concrete will inevitably become a new engineering demand. This paper mainly analyzes the mix ratio design of geopolymer concrete and self-compacting concrete. Based on the existing research results, it puts forward suggestions for the mix ratio design of geopolymer self-compacting concrete, in order to provide help for the engineering application of geopolymer self-compacting concrete.

2. Analysis on Existing Design Methods of Geopolymer Concrete

An important difference between geopolymer concrete and ordinary concrete lies in different cementitious materials. The key point in mix ratio design of geopolymer concrete, which is more complicated compared to ordinary concrete, is to consider the content of alkali activator [17]. At present, there are two main methods for designing the mix proportion ratio of geopolymer concrete: the quantity ratio method and the mass ratio method.

2.1. The Material Quantity Ratio Method

The material quantity ratio method refers to a mix ratio design method with the material quantity ratio relationship among compounds such as Na_2O, SiO_2, H_2O and Al_2O_3 as the control parameter. For instance, in mix ratio design with Na_2O /Al_2O_3, SiO_2/Al_2O_3 and H_2O / Na_2O as control parameters, the substance mass ratio of the related compounds is given. The principle of this method is that when Si/Al = 2 for the geopolymer concrete raw material, dense and high-strength PSS-type geopolymer concrete can be formed. The research finds that the red mud + metakaolin-based polymer concrete designed with SiO_2/ Al_2O_3=1, Na_2O/Al_2O_3=1, H_2O/Na_2O=17 as the control parameters can acquire higher strength, while SiO_2/ Al_2O_3 is the main factor influencing the slag-based polymer concrete strength. When SiO_2/Al_2O_3=1.8 ～ 2.2(3.3～4.5), geopolymer concrete with higher compressive strength is also possible [18].

2.2. Mass Ratio Design Method

The mass ratio design method is similar to that of ordinary silicate concrete [18]. That is, according to the design value of compressive strength, the peptization ratio and the amount of cementitious materials are initially decided, and the volume and dosage of sand and gravel are determined by the principle of volume equivalence. This method requires extensive mix ratio design experiences to determine the relationship between peptization ratio and compressive strength. The dosage and peptization ratio of raw materials (solution-solid ratio) are the main factors affecting the strength, and related scholars have also made a preliminary design of the mix ratio. However, due to many influencing factors, the mix ratio design methods proposed by different scholars have different parameter values, and a mix design method generally recognized by the majority of scholars has not yet been formed [19].

If the mass ratio of the geopolymer concrete is known, the content of Na_2O, SiO_2, CaO and Al_2O_3 in the slag and the content of Na_2O, SiO_2 and H_2O in the water glass can be used to calculate the mass ratio of the corresponding compounds, so that the mix ratio indicated by substance mass ratio can be calculated.

However, if the substance mass ratio of the compound is known, it is generally impossible to infer the mass ratio between the materials. Existing literature only gives the substance mass ratio of the compounds, and no mix ratio information of the geopolymer concrete convenient in practical application can be gathered. Moreover, if coarse and fine aggregates are added, it is more impossible to accurately determine the corresponding mix ratio.

3. Analysis of Existing Mix Ratio Design Methods for Self-Compacting Concrete

The related research on SCC started as early as the 1970s in Japan, France, etc. which enjoys broad applications at present. In China, related research was started in the 1990s, and a complete industry standard was issued in 2012. In 2018, Hangxiao Steel Structure conducted an experimental study of self-compacting concrete pouring in concrete-filled steel tube shear walls, further expanding the research scope of self-compacting concrete [20]. With the research of various scientific research schools, institutions, and concrete production units, continuous advancement is achieved in the preparation technology of SCC, and many mix ratio design methods are found. SCC production is no longer difficult [21]. However, each has its own characteristics in the selection of SCC coordination design methods. For example, fixed aggregate method and absolute volume method require hypothesis of aggregate dosage; parameter method and aggregate specific surface area demand parameters setting; simple mix ratio method demands empirical determination of certain constants. Their design principles and methods vary.

3.1. Fixed Aggregate Method

This method is improved according to the characteristics of mix ratio design proposed by Japanese scholar H. Okamura [22]. The specific process is as follows:

(1) Set the loose pile volume of stones in $1m^3$ concrete to $0.5\text{-}0.55m^3$, and calculate the amount of stones.

(2) Set the volume content of sand in the mortar to 0.42-0.44, and calculate the sand amount and the slurry content.

(3) Set the water-binder ratio and the amount of slurry, and calculate the amount of cementitious material and water used.

(4) Set the ratio of admixture to cement dosage, and calculate the respective dosages of cement and admixture.

3.2. Absolute Volume Method

According to JGJ/T283-2012, the percentage of each material in SCC is determined to find out the value range of each parameter. The water-to-binder ratio and water consumption in the absolute volume method can be determined by the calculation formula. The specific design steps are as follows:

(1) Calculate the mass according to the absolute volume (0.28-0.35m^3) and apparent density of coarse aggregate in 1m^3 concrete.

(2) Mortar volume=total volume-coarse aggregate volume. Calculate the absolute volume of sand in 1m^3 concrete from the volume fraction of sand in the mortar (0.42-0.45), and then calculate the mass of sand from the apparent density of sand.

(3) Volume of slurry = volume of mortar - volume of sand. The total dosage of mineral admixtures in the slurry should be no less than 20%. Calculate the water-binder ratio, and its value should be no less than 0.45.

(4) Calculate the total amount of cementitious materials from the slurry volume, water-binder ratio, and air content, and the range of cementitious materials should be 400-550kg/m^3.

(5) Determine the water consumption from the water-binder ratio and the dosage of cementitious materials.

(6) Calculate the usage of the admixture from the dosage of the admixture and the total amount of the cementitious material.

3.3. Simple Mix Ratio Design Method

The principle of this method is to fill the gaps of loosely packed aggregate with cementitious material slurry. When water and cementitious material are mixed and filled into the aggregate, the aggregate will be more compactly accumulated [23]. In the simple mix ratio design method, the compaction factor of the aggregate can be defined as PF, which means the mass ratio of the aggregate in the compacted state to the aggregate in the loosely packed state [24]. The specific design steps are as follows:

(1) Select the compaction factor PF, and calculate the amount of coarse and fine aggregates Wg and Ws.

$$Wg = PF \times W_{gL}\ [l- S/a] \quad (1)$$

$$WS = PF \times W_{SL} \times S/a \quad (2)$$

W_{gL} and W_{SL} are the bulk density of coarse and fine aggregates respectively (kg/m^3); S/a-sand rate

(2) The amount of cement C is calculated from the concrete preparation strength.

(3) Select the water-cement ratio to calculate the water consumption W_{WC}.

$$W_{WC} = [W/C]C \quad (3)$$

(4) Calculate the mineral admixture amount, and the specific amount is determined after the fluidity test according to ASTMC230.

(5) Calculate the total water consumption.

In the mix ratio design of SCC, the value of each material parameter, the selection of raw materials, and the subtle changes in the mixing amount will affect the final result and usage effect. Among the above three SCC mix ratio design methods, the absolute volume method involves simple calculation. Those without experience in SCC mix ratio design can choose this method for trial mixture, and then perform mechanical property tests to check the mix results. To prepare concrete with stable mechanical properties, the fixed aggregate method can be used to measure the strength. The simple mix ratio design method is simple and fast, which can be used to assist in the first SCC mix design.

4. Mix Ratio Design of Geopolymer Self-Compacting Concrete

Based on the analysis of the existing mix ratio design methods of geopolymer concrete and self-compacting concrete, the suggestions for the mix ratio design of geopolymer self-compacting concrete are proposed. The specific design steps are as follows:

4.1. Determining the Dosage of Coarse Aggregate and Fine Aggregate in Unit Volume Concrete

The volume of coarse aggregate is an important factor affecting the workability of concrete mixtures. Too low volume content of coarse aggregate will significantly reduce the mechanical properties such as the elastic modulus of concrete, while too high volume content of coarse aggregate will significantly reduce workability of the concrete mixture, making it impossible to meet the requirements of self-compacting properties. In addition to coarse aggregates, the volume fraction of fine aggregates can significantly affect the mortar consistency and thus the workability of concrete mixtures. Too high volume fraction of fine aggregate will reduce the concrete strength and affect the self-compacting performance of concrete, while too low volume fraction will cause concrete shrinkage and poor volume stability.

(1) Determine the dosage of coarse aggregate. By selecting the volume of coarse aggregate in each cubic meter of concrete and measuring the apparent density of coarse aggregate, the amount of coarse aggregate in each cubic meter of concrete can be calculated. The calculation formula is:

$$Mg = \rho g \cdot Vg \tag{4}$$

Where: Mg—the dosage of coarse aggregate in each cubic of concrete, kg; ρg—the apparent density of the coarse aggregate, kg/m^3; Vg—the volume of coarse aggregate in each cubic of concrete, m^3.

(2) Determine the dosage of fine aggregate. The mortar volume is calculated by the following formula:

$$Vm = 1 - Vg \tag{5}$$

Where: Vm — volume of mortar in each cubic of concrete, m^3; Vg — volume of coarse aggregate in each cubic of concrete, m^3.

By selecting the volume fraction θs of sand in the mortar, and determining the apparent density ρs of the fine aggregate, it is possible to calculate the volume Vs and mass Ms of the sand in each cubic of concrete with formula:

$$Vs = Vm \cdot \theta s \tag{6}$$

$$Ms = \rho s \cdot Vs \tag{7}$$

In formula (6) (7): Vs — volume of sand in each cubic of concrete, m^3; Vm — volume of mortar in each cubic of concrete, m^3; θs — volume fraction of sand in mortar, ranging from 0.42 to 0.45; Ms— mass of sand in each cubic of concrete, kg; ρs — apparent density of fine aggregate, kg/m^3.

4.2. Calculate the Alkali Activator Volume of Geopolymer Self-Compacting Concrete

After determining the volume of coarse aggregate and fine aggregate in each cubic meter of concrete, the amount of alkali activator in each cubic meter of concrete can be calculated with formula:

$$V_J = 1 - Vg - Vs \tag{8}$$

Where: V_J - the volume of alkali activator in each cubic of concrete, m^3. The alkali activator is prepared by fly ash, slag, water glass, sodium hydroxide and water [25].

4.3. Admixture Dosage

Since each admixture creates different effects on the filling performance, anti-segregation performance, gap passing performance and mechanical performance of geopolymer self-compacting concrete, adjustment can be made according to experience, working performance and mechanical performance in the test.

4.4. Trial Design and Adjustment of Mix Ratio of Geopolymer Self-Compacting Concrete

Trial mix of geopolymer self-compacting concrete was carried out according to the above calculated mix ratio, and the self-compacting properties of the mixture were checked for filling, gap passing and segregation resistance. When the self-compacting properties met the requirements, 28-day-old concrete compressive strength specimens were prepared. Adjustment is needed if the self-compacting properties of the mixture cannot meet the requirements. The material dosage should be adjusted reasonably while keeping the cementitious material volume of alkali activator unchanged until the requirements are met.

5. Conclusions

By investigating relevant literatures on the existing design methods of geopolymer concrete, analysis and comparison are made and suggestions for mix ratio design are proposed. The existing mix ratio design methods of self-compacting concrete are investigated to analyze the advantages and disadvantages of various methods, so that suggestions can be proposed for mix ratio design. By analyzing the mix ratio design method of self-compacting concrete and geopolymer concrete, the mix ratio design method is proposed for geopolymer self-compacting concrete.

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