Study on quantification method for aggregate gradation of discrete Cemented Sand Gravel and Rock

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Abstract: As a new damming technique, Cemented sand gravel and rock damming technique could fill the gap between the earth-rock dam and the concrete dam in material and improve the construction system. The largest characteristic of this material is that it directly adopts the aggregates in the engineering field and only aggregates with a particle size above 150 mm are screened. The aggregate gradation is discrete and fluctuating, so it is significant to study the methods of quantization and characterization of aggregate grading. Based on Fuller curve, this paper quantified the variation and dispersion of aggregate gradation via using similarity coefficient of aggregate gradation, average similarity coefficient, mean average similarity coefficient and standard deviation of similarity coefficient, which has provided significant guidance for the real practice. Relevant quantization methods not only assist to differentiate the grading boundary including the thinnest and roughest graded aggregate, but also master the grading changes and predict the dispersion degree of strength of Cemented sand gravel and rock from the dispersion degree of aggregate, which could provide a scientific reference for the mixing design of Cemented sand gravel and rock.

1. Introduction

Earth-rock dam (including rockfill dam) and concrete dam (including roller compacted concrete dam) are two main types of dams at home and abroad. From the characteristics of material, rockfill dam is the granular material dam while Cemented sand gravel and rock is the consolidating material dam. If there is a transition material dam between the rockfill dam and Cemented sand gravel and rock, the dam material system could be improved. With a small number of cementing material and aggregate, the Cemented sand gravel and rock has low intensity and shear performance after mixing, spreading, vibrating and rolling. The Cemented sand gravel and rock dam exists between rockfill dam and concrete dam. The main concept of Cemented sand gravel and rock dam is to make full use of the material on construction field as well as rapid and convenient construction methods, thus lessening the abandoned material of dam construction.

The Cemented sand gravel and rock dam has many advantages, such as economy, rapidity, safety, environmental protection [1-5], which has been widely used in China, Japan, Turkey, Greece, France, Philippines and other countries [6-9]. The first Cemented sand gravel and rock project in China, Shunjiangyan Project in Sichuan, was completed in 2016 and the first construction project in Shanxi Province with the highest dam height was capped in 2018. After that, several engineering projects are in the design or construction and the Cemented sand gravel and rock dam has a wide application prospect in the construction of small and medium-sized water conservancy construction.
2. Characteristics of mixing design of Cemented sand gravel and rock

The biggest characteristic of Cemented sand gravel and rock is that its adopted aggregate is not screened so that the aggregate gradation is discrete and fluctuating. In the engineering with a wide range of materials, the grading changes of aggregate is relatively larger, thus influencing the design of mixture proportions. Besides having the basic characteristics of concrete, the mixture of Cemented sand gravel and rock also has some construction characteristics of soil compaction. However, the principle of concrete characteristics is more suitable for the research of Cemented sand gravel and rock. The maximum density method in the mix ratio theory of concrete requires that the stone, sand and cementing material to make up concrete firstly should have a reasonable gradation, thus guaranteeing that the concrete has the maximum density and minimum voidage. When the particle size distribution of coarse and fine aggregate as well as cementing material is unreasonable, many voids would occur inside the concrete. The maximum density and minimum target void ratio of the concrete could be achieved based on the continuous gradation theory, whose formula (1) is as follows:

\[ P_d = 100 \sqrt{\frac{\%}{D}} \]

where \( P_d \) represents the percentage passing through a screen hole; \( D \) represents the maximum diameter of coarse aggregate; \( d_i \), represents the pore size of screen hole.

Only according with Fuller gradation curve, the materials with different-size pellets have the largest bulk density and the smallest void content. The requirements for the graduation of sand stone concrete are based on the Fuller gradation curve in the concrete construction code of many industries in China. In term of material, two most obvious characteristics of Cemented sand gravel and rock are that the aggregate does not need to be sieved and mixed and the consumption of cementing material is less, which could be approximately regarded as the combination of low adhesive roller compacted concrete with different aggregate gradation.

By the experimental study on mixture ratio parameters of Cemented sand gravel and rock, it is found that the changes of water consumption would result in the large discreteness of the strength of Cemented sand gravel and rock despite fixing the amount of adhesive material. On the whole, the aggregate gradation of Cemented sand gravel and rock would not be the optimal proportion and the less amount of adhesive material makes the embedding efficiency of adhesive material slurry in aggregate low. The corresponding high water-binder ratio and water-cement ratio are the low glue concentration and the difference in the material components results in the difference between the properties of the gelled gravel and those of traditional concrete. The later design method of mix proportion could be achieved by optimizing sand rate and aggregate gradation. At the same time, its water consumption is relatively fixed, which is the “point” control. The original material of Cemented sand gravel and rock comes from the engineering site. The aggregate just requires to remove the certain size particles without screening so that it is impossible to proceed the optimal selection. Only adjusting the content of cementing material, fixing the amount of adhesive material and controlling the water consumption could meet the requirements of the engineering design strength [10]. The mix proportion design of Cemented sand gravel and rock is similar to the mix proportion design of low binder roller compacted concrete with different aggregate gradation in the collection engineering site. Therefore, how to quantify discrete aggregate gradation and evaluate the suitability of aggregate on site not only relates to the economy of the preparation of dam material, but also influences the safety degree of dam, which is of great significance to study.

3. Furrer similarity coefficient of aggregate

One of the largest characteristics of Cemented sand gravel and rock is that the aggregate is not screened so that the aggregate gradation is variational. The whole aggregate gradation is made up by different gradations, resulting in fluctuation of water consumption within a certain range and the difference in strength. When the amount of adhesive material is certain, different aggregate gradations have different strength of Cemented sand gravel and rock with the same water consumption and certain water-binder ratio. The first task for the test on the mix ratio of Cemented sand gravel and rock is to analyze the
aggregate gradation so as to master the situation of aggregate gradation. Most of the aggregate of Cemented sand gravel and rock is natural gravel, whose grain shape is smooth. Since the Cemented sand gravel and rock is dry hard concrete with a large volume, it is more in line with the Fuller gradation curve derived from spherical or elliptical particles. From the distribution of aggregate gradation, it is seen that the closer to or the more similar to the aggregate gradation of the gradation curve, the greater compactness and smaller void volume. To quantify the proximity and similarity between aggregate gradation and Fuller curve, the similarity coefficient of aggregate gradation was obtained, as shown in formula (2).

\[ S_i = 100 - \sqrt{(P_i - P_{di})^2} \]  

(2)

Where \( S_i \) represents the similarity coefficient between the screen through a certain stage and the corresponding Fuller curve. \( P_i \) represents the percentage of screen holes passing through a certain stage. \( P_{di} \) represents the percentage of screen holes passing through a certain stage according to Fuller curve.

The average similarity coefficient is the average value of similarity coefficient at all levels, as shown in formula (3).

\[ \bar{S}_i = \frac{\sum S_i}{n} \]  

(3)

where \( n \) represents the progression. The graded grain size areas for the hydraulic four grade aggregate were divided into 150~80mm, 80~40mm, 40~20mm, 20~5mm and below 5mm, so that the progression \( n \) equals to five and the progression for three grade aggregate \( n \) equals to four. The average similarity coefficient represents the similarity between aggregate and Fuller curve under a certain gradation condition and the larger average similarity coefficient, the better gradation ratio. To further verify the reliability of similarity coefficient, the similarities of graduation of 12 groups of aggregate in the site of solidified gravel dam of Shoukoubao, Shanxi province were analyzed and the aggregate gradation and Fuller curves of 12 groups were shown in Figure 1. From the figure, it is seen that gradations and Fuller curves of the aggregate in each group have larger deviation and lower degree of similarity, which shows that the gradation of aggregates in engineering site is poor, causing the large water consumption. The test has proved this phenomenon further. The aggregates in group 1 (sand ratio is 29.2%) and group 3 (sand ratio is 34.0%) are close to the Fuller curve and the aggregates in group 10 (sand ratio is 46%) and group 12 (sand ratio is 53.2%) have the maximum deviation from Fuller curve. The similarity coefficients of aggregate classification between 12 groups of graded aggregate and average aggregate are shown in Figure 2, the comparison of the average similarity coefficient is shown in Figure 3. In the hierarchical similarity coefficients of each group reflected in Figure 2, besides two groups (sand ratios are 29.2% and 34.0% respectively), the distribution of average graded aggregate in the rest 10 groups is more concentrated. The similarity coefficients of large stone, medium stone and sand are below 80% and the lowest similarity coefficient of medium stone aggregate is 64.5% with the sand ratio of 46.0%.
The average similarity coefficient for 12 groups of aggregate is within the range of 75.7% ~ 80.4% and the similarity coefficient of average grading aggregate is 80.4%. After judging by the average similarity coefficient, its maximum and minimum were obtained. The largest similarity coefficient of graduation with the minimum sand ratio or closeness to the minimum sand ratio is selected as the roughest gradation, while the smallest similarity coefficient of graduation with the maximum sand ratio or closeness to the maximum sand ratio is regarded as the finest gradation. Under the special condition, the gradation with the largest similarity coefficient might be larger than that with the smallest similarity coefficient so that the references of the roughest gradation and finest gradation will lose their meaning. The gradation with the largest and smallest similarity coefficient should be used as the gradation boundary in the mix proportion control range test of Cemented sand gravel and rock. In these 12 groups, the aggregate with the largest similarity coefficient is the aggregate with 34% sand rate, followed by 29.2% sand rate and the similarity coefficients of both are close. The aggregate with the smallest similarity coefficient is the aggregate with 46% sand rate, followed by 53.2% sand rate and the similarity coefficients of both are also close. The design of mix proportion of Cemented sand gravel and rock could replace the roughest aggregate gradation and the finest aggregate gradation.

The similarity coefficients of aggregate with sand ratio of 29.2% and 34.0% are above 87.9% and the similarity coefficients of the rest groups are concentrated in about 80%. To compare the degree of deviation average value of similarity coefficient in each group, the standard deviation of aggregate similarity coefficient was calculated, as shown in formula (4).

$$\sigma_s = \sqrt{\frac{\sum_{i=1}^{n} S_{cu,i}^2 - n \overline{S_{cu}}^2}{n - 1}}$$  \hspace{1cm} (4)$$

where $\sigma_s$ is the standard deviation of similarity coefficient. $S_{cu,i}$ is average similarity coefficient for the i graded aggregate. $\overline{S_{cu}}$ is average similarity coefficient for the group n.
From formula (4), the standard deviation of similarity coefficient in the site of solidified gravel dam of Shoukoubao, Shanxi province is small, whose value is 4.2%. From Figure 3, it is seen that apart from two larger similarity coefficients, the rest similarity coefficients are concentrated around the average similarity coefficient of the whole aggregate. The standard deviation of similarity coefficient could reflect the dispersion degree of gradation aggregate, thus predicting the discreteness of the strength of Cemented sand gravel and rock and providing the references to control the strength.

The tests of water consumption and strength of Cemented sand gravel and rock of the roughest gradation and finest gradation in the site of solidified gravel dam of Shoukoubao, Shanxi province were carried out for 28 day.

The cement consumption is 50kg/m³ and second level fly ash is 40kg/m³. From the figure, it is found that the strength of the roughest gradation aggregate decreases with the increasing of water consumption.
and its strength is higher than the finest gradation aggregate. As the water consumption increases, the difference of both gradation aggregates is shortened because with the less amount of Cemented sand gravel and rock, the Cemented sand gravel and rock of all levels aggregate has significant differences in the margin of wrapping, porosity and compactness under the condition of less water consumption. With the same water binder ratio and different graduation, the difference of the strength of Cemented sand gravel and rock with larger difference of similarity coefficient is bigger. With the increasing of water consumption, the difference between package margin and void volume is shortened, that is, when the sand is all wrapped by adhesive material slurry and rough aggregate is all wrapped by mortar, the void in Cemented sand gravel and rock is shortened. Therefore, the key influence factor of the strength of Cemented sand gravel and rock is the mortar strength decided by water binder ratio and boundary strength. With the same water binder ratio, the difference is relatively small as the water consumption increases, thus reducing the difference of the strength of Cemented sand gravel and rock at each levels of aggregate.

4. Conclusions
The biggest characteristic of Cemented sand gravel and rock is that it directly adopts skeletal materials in the engineering field, most of which are the natural gravels in river bed with requirements of maximum particle diameter and without screening of aggregate. The aggregate gradation is discrete and fluctuating so that it is hard to be controlled by people. Therefore, it is of great significance to master the gradation change of aggregate and study the methods of quantization and characterization of aggregate grading.

The similarity coefficient of aggregate gradation, average similarity coefficient, overall average similarity coefficient and standard deviation of similarity coefficient proposed in this paper quantify the variation and dispersion degree of aggregate gradation. Those coefficients not only could assist to distinguish the gradation boundary of aggregate (the roughest gradation aggregate and the finest gradation aggregate) and master the gradation change of aggregate, but also could predict the dispersion degree of Cemented sand gravel and rock from dispersion degree of aggregate, thereby providing reference to the design of mix proportion of Cemented sand gravel and rock

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