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Design Method for Cemented Sand and Gravel Mix Proportion Using Jaw-Crushed Material

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Abstract

The construction of massive infrastructure projects in Africa suffers from a shortage in natural aggregate materials, such as coarse sand and gravel for cemented sand and gravel (CSG) for hydraulic projects, which would delay progress and raise costs. In response to the scarcity of CSG aggregates and the challenges in the environment-friendly disposal of excavation waste, a design method for the mix proportion of CSG by using jaw-crushed material was proposed, and this method was suitable for similar projects to be constructed in Africa. First, the target grading for coarse aggregates was set based on Fuller's ideal grading to determine the optimal ratio of jaw-crushed material and smaller stones for gradation adjustment. Second, the target grading for fine aggregates was determined to be the III zone fineness modulus and obtained by seeking the proper ratio of local ultrafine river sand and artificial sand produced from rock grinding. Then, considering the compressive strength, the optimal CSG mix proportion was determined, where both volcanic ash and cement were added as cementitious materials. Finally, the proposed design method for jaw-crushed-material-based CSG was applied in the construction of a temporary overflow cofferdam at the Julius Nyerere hydroelectric power station in Africa, and its feasibility and effectiveness were verified. The results indicate that the optimal ratio between the jaw-crushed material and small stones for the coarse aggregate of CSG is 0.85:0.15 (by weight by default unless otherwise specified), the best ratio of ultrafine river sand and artificial sand for the fine aggregate of CSG is 4:6 by weight, the optimum sand content of CSG is 30%, the water-cement ratio is 1.11, and the optimal dosage of volcanic ash is 58.3 kg per cubic meters of CSG (kg/CSG m^3). The engineering practice of the temporary CSG overflow cofferdam demonstrates that the use of jaw-crushed material for CSG is feasible, and the proposed CSG mix proportion design method achieved the efficient utilization of jaw-crushed material, which can reduce the environmental impact of excavation waste and ensure the completion of temporary high-quality overflow cofferdam for seasonal floods. This study provides valuable scientific and engineering references for similar CSG projects that may use jaw-crushed material for the design and construction and has important scientific and engineering significance.

Keywords: jaw-crushed material, cemented sand and gravel, mix proportion design, overflow cofferdam

1. Introduction

Cemented sand and gravel (CSG) was first introduced for construction by J. M. Raphael in the United States in 1970. CSG involves the addition of a suitable amount of cementitious material (e.g., cement and fly ash) to natural sand and gravel to enhance the bond strength between aggregate particles. After simple mixing, spreading, and compacting via vibration and rolling, the mixture forms a construction material with apparent physical and mechanic properties between those of aggregate fill and roller-compacted concrete (RCC) [1]. In 1992, Londe and Lino [2] proposed the use of CSG for dam construction to reduce the slope angles of upstream and downstream faces and save construction materials compared with typical earth or rock-fill dams. In 1993, the first permanent CSG dam, Marathia Dam, was constructed in Greece and has been operational since then [3]. In Turkey, A 100-meter-high Cindere Dam was constructed using roller-compacted CSG in 1994 [4]. Afterward, the study on CSG material and the associated dam construction technology have developed rapidly in Japan [5, 6]. Since 1990, China has been exploring the use of roller-compacted CSG for dam construction and has been further applying this concept in concrete-faced rock-fill dams [1, 7].

Coarse and fine aggregates for CSG dams are mainly obtained from natural sand and gravel in riverbeds, and excavated residue at dam sites can also be used. Cementitious materials such as cement and fly ash are typically available locally. The requirements for CSG materials are minimal, allowing for the maximum utilization of local materials. This utilization effectively avoids damage to land vegetation caused by the disposal of construction waste and reduces the risk of geological hazards associated with waste accumulation. Therefore, CSG construction is simple and fast, which reduce resource consumption, environmental disturbance, and construction costs. It exhibits significant characteristics of "rationalization of materials", "rationalization of construction", and "rationalization of design" [8]. CSG dams are commonly referred to as "zero-discharge dams" (non-polluting dams) and are environment-friendly hydraulic infrastructures [9]. Additionally, the cement consumption during the construction of CSG dams is 40%–50% of that in RCC dams. The displacements of CSG dams are only approximately 1/20 to 1/10 of those observed in concrete panel rockfill

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dams of the same height [3, 10]. The internal stresses of CSG dams exhibit minimal changes during construction and operation, making them highly reliable, resistant to earthquakes, and having low foundation requirements [11, 12].

With the increasing demand for dam construction worldwide, especially in the developing countries in Africa and South America, numerous CSG dams have been built or are being constructed. CSG dams require a substantial supply of coarse and fine aggregates and cementitious materials. However, the types and properties of materials for CSG remarkably differ across different work zones and regions. Consequently, no specific standardized guideline is available for CSG material proportioning and construction. Therefore, suitable sources of coarse and fine aggregates need to be selected by testing based on the specific construction conditions and site environment to achieve zero discharge of waste residue, efficient and green construction, and economic and beneficial outcomes. This study addresses the issue of aggregate scarcity in a massive hydraulic project by using CSG in Africa. It proposes a mixed proportion design method of jaw-crushed-material-based CSG suitable for local construction conditions in Africa to provide a guideline for similar CSG projects.

The detection of communities in a network can be regarded as a clustering problem, i.e., one of clustering a network into different groups. The essence of clustering is an optimization problem. Evolutionary algorithms (EAs), inspired by principles from biology, ethology, etc., are a class of intelligent optimization algorithms. They have been successful in solving a wide range of optimization problems. Therefore, it is natural to apply EAs to solve the network-clustering problem. Based on this idea, many single-objective and multiobjective EA-based network-clustering methods have been proposed. Pizzuti [7] proposed a genetic algorithm to discover communities in networks, using a community evaluation criterion called the community score. Gong et al. [8] proposed a memetic algorithm-based approach in which a hill-climbing-based local search tactic was suggested for improving the search performance of the algorithm. Cai et al. [9] introduced a clonal-selection algorithm-based method in which an effective local search strategy based on vertex neighborhoods was developed.

Many optimization problems involve multiple objectives. For the network-clustering problem, many multiobjective optimization models have been proposed. Pizzuti [10] presented a multiobjective genetic algorithm to uncover communities in networks. Recently, Gong et al. [11] proposed a multiobjective discrete particle swarm optimization algorithm for network clustering. Experiments have demonstrated that the proposed algorithm is very effective.

The main contribution of the work described by Gong et al. [11] was the proposed discrete particle swarm optimization (PSO) framework. PSO was proposed by Eberhart and Kennedy [12]. It is an intelligent optimization algorithm and is well known for its fast convergence and concise framework. PSO is attracting attention and has found broad applications in diverse domains [13].

2. State of the art

CSG materials, including coarse and fine aggregates and cementitious materials, vary significantly across different project sites. This property leads to noticeable differences in the mechanical properties of CSG under different construction conditions. Factors such as aggregate gradation, sand ratio, moisture content, water-cement ratio, fly ash content, and admixture content determine the mechanical properties of CSG. The mechanical performance, impermeability, and thermal conductivity of CSG have been widely studied under different microstructural compositions. For example, Masafumi et al. [13] investigated the influence of repeated wetting and drying on the strength of weakly bonded CSG, and the strength of CSG reached the maximum after undergoing three wetting and drying cycles during curing. Aghajani et al. [14] conducted compaction, strength, and permeability tests on CSG with varying cement contents to identify appropriate blending proportions for CSG in cold climates. The compaction of CSG did not depend on the cement content, but the cement content significantly affected the compressive strength, stiffness, and permeability of CSG. Subsequently, Karimi et al. [15, 16] studied the influence of kaolin content on the strength and modulus of deformation of CSG and found that CSG materials with 10% kaolin content exhibited optimal performance in all aspects regardless of the type of cementitious material used in the mixture. Zhao Xin et al. [17] established an inverse analysis method for the non-steady-state seepage field of CSG by using field measurements from the temporary cofferdam of Dahua Bridge. They found that CSG exhibits a "self-healing" phenomenon in terms of permeability, and the seepage characteristics of CSG dams tends to stabilize over time. Furthermore, Jie Yang et al. [19-20] found that the content of cementitious materials and confining pressure affects the deformation characteristics of CSG. As the cementitious material content increases, the failure strain decreases and the brittleness of CSG materials increases.

Fly ash has good mineral activity and can effectively strengthen soil and rock materials. For example, Furlan et al. [20, 21] conducted numerous experiments and found that fly ash can improve the microstructure and enhance the mechanical strength, especially when mixed with cement. Fly ash has low heat of hydration and is commonly used to mitigate the effect of hydration heat cracking on CSG materials. Chai Qihui et al. [22] conducted extensive experiments and found that the compressive strength of CSG at 90 days is usually 10%–30% higher than that at 28 days, in which the optimal fly ash content is 50% by weight of the total cementitious materials (cement + fly ash). Furthermore, Jiang Minmin et al. [23] performed CSG adiabatic temperature rise tests and found that CSG with a higher cementitious content have longer hydration reaction time, which is linearly related to the final adiabatic temperature rise. Other ash materials also exhibit similar strengthening effects. Munirwan et al. [24] found that through the formation of slag activity and hydration process, coffee husk ash has the same strengthening effect as fly ash, thereby expanding the range of choices for CSG cementitious materials. Solomon et al. [25] used the concept of reactivity index to estimate the flexural strength of concrete with cashew nut ash addition, which showed high accuracy and could estimate the strengthening effect of ash materials.

Considering the lack of constitutive models suitable for CSG, the accurate numerical simulation of CSG dam deformation and stress is limited. To address this issue, Feng Xinjun et al. [26] developed a non-linear constitutive model for CSG with different cementitious contents based on previous findings. However, the accuracy of discrete element simulation for CSG is low. To overcome this problem, Cui Chunyang et al. [27] used a hybrid cohesive model to describe the cohesive bond damage of CSG materials, enabling the three-dimensional discrete element simulation of CSG materials. Furthermore, to account for the strength loss of CSG, Ren Honglei et al. [28] established a statistical damage constitutive model that reflects the strain hardening-softening properties of CSG materials through a series of laboratory tests and discrete element analysis. By combining the Monte Carlo method and fuzzy finite element simulation, Noorzad et al. [29] found that an elastoplastic constitutive model is more suitable for the safety prediction of CSG dam stability than the other models.

The aforementioned studies primarily focus on the mechanical properties, permeability coefficient, constitutive models, and numerical simulations of CSG materials. However, studies on specific engineering practices related to CSG material selection, optimization of aggregate grading, mix design, and the selection of cementitious materials, remain lacking, particularly the study of alternative building materials in the region of Africa with a scarcity of natural aggregates and fly ash. Therefore, in this study, considering the challenges faced in massive CSG projects in African water conservancy construction, such as aggregate shortages and the pressure for environment-friendly engineering, and considering the local abundance of volcanic ash but scarcity of fly ash, a jaw-crushed-material-based CSG mix design method suitable for local construction conditions in Africa was proposed. This study aimed to provide guidance for similar CSG projects.

The remainder of this study is organized as follows. Section 3 describes the composition of jaw-crushed-material-based CSG mix design and proposes the method and design process for jaw-crushed-material-based CSG mix design. Section 4 focuses on the specific design of jaw-crushed-material-based CSG mix design for the overflow cofferdam at the Julius Nyerere Hydropower Station in Africa. The optimal composition and mix design of CSG materials that meet the strength design requirements were obtained, and the proposed method was validated through the implementation in the construction of the CSG cofferdam. The final section summarizes the relevant conclusions.

3. Methodology

CSG consists of coarse aggregates, fine aggregates, cementitious materials, water, and chemical additives. The ideal filling and wrapping theory of concrete suggests that coarse aggregates such as gravel are coated by the cementitious paste, and the voids between coarse aggregates are filled by the cementitious mortar. Moreover, fine aggregates such as sand are wrapped by the cementitious slurry, and the voids between fine aggregates are filled by the slurry. Therefore, the core of CSG mix design lies in achieving the maximum compactness of the mixture, in which the cementitious paste precisely fills the voids in the aggregates. Accordingly, this study proposes a jaw-crushed-material-based CSG mix design method, and the technical route of the proposed method is illustrated in Figure 1.

3.1 Coarse Aggregate Design

To reduce costs, shorten the construction period, and utilize local resources, project engineers adopt the production of jaw crushing to process the excavated stone materials. Considering the rock-breaking characteristics of the jaw crusher, the mixed jaw-crushed materials may contain needle-like particles. If the coarse rock obtained from jaw crushing is directly used in CSG mix design, the needle-like aggregates in the CSG will create many voids, resulting in decreased strength, more paste, and difficulty in compactness, thereby reducing the overall strength of the cofferdam. The grading of jaw-crushed materials was optimized by determining the ideal grading passing zone based on the formula for ideal grading passing rate in the American Standard ACI 211.1 (the Fuller formula). This information helps in determining the required ratio of available aggregate particle sizes to approach the optimal particle grading for the coarse aggregate, and the formula is expressed below.

$$P = 100\frac{d^x - 0.1875^x}{D^x - 0.1875} \tag{1}$$

$$\begin{cases} E = \sum_{i}^{n} L_i \\ L_i = \begin{cases} A_i - U_i & if \quad U_i \le A_i \\ D_i - A_i & if \quad D_i \ge A_i \end{cases} \end{cases} \tag{2}$$

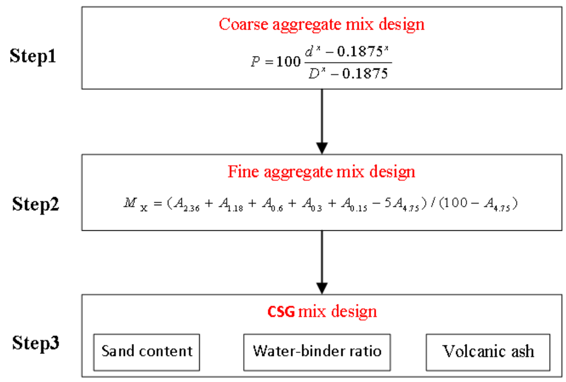


Fig. 1. CSG mix ratio design process

In the formula, *P* represents the cumulative percentage passing through the sieve with diameter *d*, which represents the sieve opening diameter (mm), *D* represents the nominal maximum aggregate size (mm), and *x* is a constant (0.5 for rounded gravel and 0.8 for crushed stone). Equation 1 can be used to calculate the interval of the ideal grading curve. Given that the jaw-crushed material is difficult to satisfy the ideal Fuller formula, a certain proportion of small stones from rock grinding is mixed to ensure that the mixed coarse aggregate meets the interval of the ideal grading curve. The specific optimal ratio was determined by exhaustive optimization by using the cumulative absolute deviation as the objective function, as expressed in Equation 2. *E* represents the cumulative deviation value, L_i is the deviation oversize ratio corresponding to the sieve opening *i*, A_i is the actual oversize ratio corresponding to the sieve opening *i*, U_i is the upper limit oversize ratio corresponding to the ideal grading for the sieve opening *i*, and D_i is the lower limit oversize ratio corresponding to the ideal grading for the sieve opening *i*.

3.2 Fine Aggregate Design

During construction, CSG mixture should have good workability. Therefore, the addition of retardants is selected during mixing to meet the workability requirements of the construction project. Considering the site conditions, previous engineering experience, and the need for cost-effectiveness and environmental protection, local volcanic ash was chosen as a mineral admixture instead of fly ash. By ensuring the required strength, cement material substitution was achieved, thus reducing the cost of CSG production. According to the Chinese national standard "Technical Guidelines for Cemented Granular Material Dam Construction" (SL 678-2014) and project technical requirements, the required strength of the CSG mixture was calculated using the following formula:

$$M_X = \frac{A_{2.36} + A_{1.18} + A_{0.6} + A_{0.3} + A_{0.15} - 5A_{4.75}}{100 - A_{4.75}} \quad (3)$$

In the formula, $A_{0.15}$ represents the cumulative sieve retained percentage (%) for particles with a diameter of 0.15 mm. Grade III fine sand was selected as the target gradation for fine aggregates, and the optimal sand proportion was determined by mixing natural river sand with artificial sand produced from rock grinding by using Equation 2.

3.3 CSG Strength Design

During construction, CSG mixture should have good workability. Therefore, the addition of retardants is selected during mixing to meet the workability requirements of the construction project. Considering the site conditions, previous engineering experience, and the need for cost-effectiveness and environmental protection, local volcanic ash was chosen as a mineral admixture instead of fly ash. By ensuring the required strength, cement material substitution was achieved, thus reducing the cost of CSG production. According to the Chinese national standard "Technical Guidelines for Cemented Granular Material Dam Construction" (SL 678-2014) and project technical requirements, the required strength of the CSG mixture was calculated using the following formula:

$$f_{cu,o} = f_{cu,k} + t \cdot \sigma \quad (4)$$

In the equation, $f_{cu,0}$ represents the designed strength of the CSG mixture (MPa), $f_{cu,k}$ represents the standard value of strength at the design age for CSG (MPa), and t represents the coefficient of probability level. For temporary structures, the value of 0.84 is generally selected at the 80% confidence level, and σ is the standard deviation of the compressive strength of CSG (MPa). Once the parameters for coarse and fine aggregates and the mineral admixtures were determined, CSG trial mixing and strength testing were conducted to determine the mix proportions for construction.

4. Result Analysis and Discussion

The Julius Nyerere Hydropower Station is located in the southeastern part of the United Republic of Tanzania within the Nyerere National Park, and it is one of the largest wildlife reserves in the world. The construction of the overflow cofferdam is a crucial early-stage milestone of the project, and it is of vital importance to the overall construction quality. In accordance with the engineering requirements, CSG was chosen as the primary filling material for the overflow cofferdam. Based on the site survey, the river valley area in the project site was heavily mixed with boulders, large rocks, and gravels. As such, the availability of natural sand and gravel that could be used as CSG aggregates is limited. Moreover, the vegetative soil in the region is only a few meters thick, and large-scale excavation near the project area would cause significant damage to the vegetation. During the early stages of the project, some excavation materials were obtained during the preparation of the foundation pit and the excavation of diversion tunnels. However, the particle size of the majority of these materials was greater than 300 mm, and the particle size distributions did not meet the requirements for CSG. On-site material utilization and reduced excavation and waste disposal were achieved by efficiently utilize the locally available materials for CSG. By employing the method described in this study, the overall application process and results are summarized below.

First, the excavation materials obtained from the foundation pit and diversion tunnel excavation were processed via jaw crushing and were used to prepare artificial small stones and artificial sand. Second, jaw-crushed materials, artificial small stones, and artificial sand were sieved to obtain the particle size distribution curves. Subsequently, after obtaining the size distribution curves of natural river sand available on-site and the mix designs of coarse and fine aggregates, and the final CSG strength design was carried out.

Fig. 2. Jaw-crushed material sieving

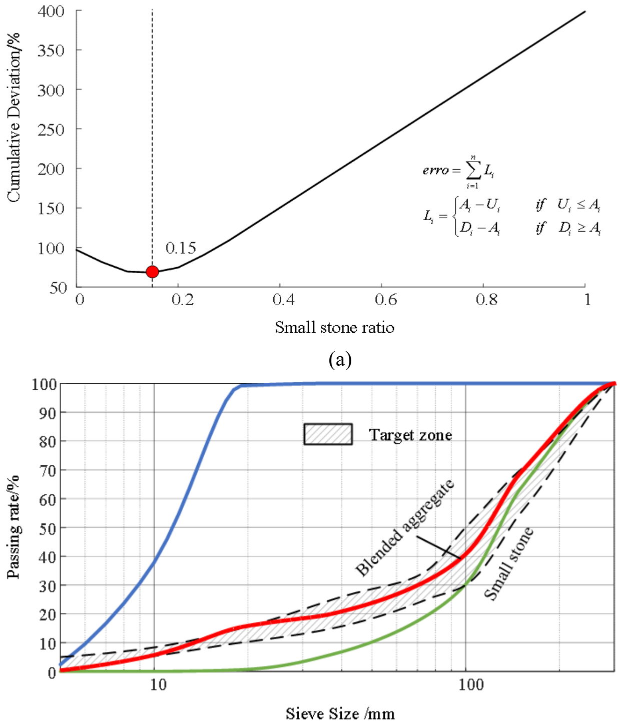
4.1 Coarse Aggregate Composition

The jaw-crushed materials were mixed with smaller-sized aggregates for optimization. Based on extensive laboratory mixing tests, the optimal mass ratio of coarse jaw-crushed material to small-sized stones was determined to be 0.85:0.15. The particle size distribution of the mixed aggregate obtained from sieve analyses is shown in Table 2 and Figure 3. The figures show that the particle size distribution of the crushed material does not meet the requirements of the Fuller equation for ideal gradation and cannot be directly used. However, the mixed gradation curve lies within the ideal gradation range in compliance with the dense packing theory. At this stage, the gaps between the mixed coarse aggregates are smaller than those of the jaw-crushed material, resulting in good compactness and homogeneity of the mixture.

Table 1. Aggregate gradation

Particle size (mm)	Passing rate (%) 19.0–300 (mm)	Passing rate (%) 4.75–19.0 (mm)	Original grading (%)	Targeted grading (%)	Optimal grading (%)
300	100.0	100	100.0	100.0	100
150	63.5	100	68.9	55–70	57.3
100	30.3	100	40.8	30–50	41.4

75	19.4	100	31.5	25–35	32.8
37.5	6.0	100	20.1	15–25	18.7
19	0.6	99.2	15.4	10–15	10.8
9.5	/	34.2	5.1	5–8	6.1
4.75	/	2.4	0.4	0–5	3.4



(b)

Fig. 3. Gradation curves of mixed coarse aggregates. (a) Cumulative deviation at different small stone blending ratios. (b) Illustration of the optimal mixed coarse aggregate grading curve

4.2 Fine Aggregate Composition

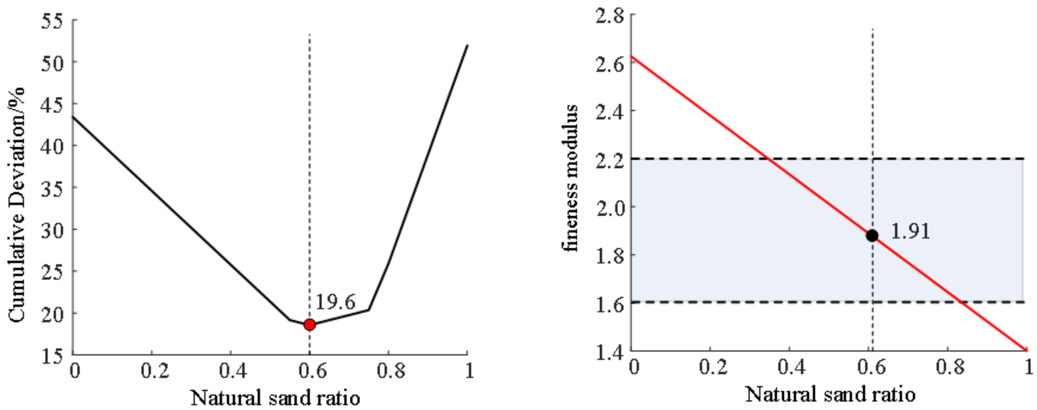
According to the Chinese national standard "Quality Standards and Test Methods for Ordinary Concrete Sand" (JGJ 52-92), the Grade III sand was selected as the target gradation. Grade III sand consists of fine sand and a portion of slightly finer medium sand. Its characteristics are high viscosity, good water retention, and low sand content. The gradation of natural river sand is shown in Table 3, and its fineness modulus is 1.42 based on Equation 3. The composition is too fine and does not meet the gradation requirements of the Grade III sand.

Table 2. Sand gradation

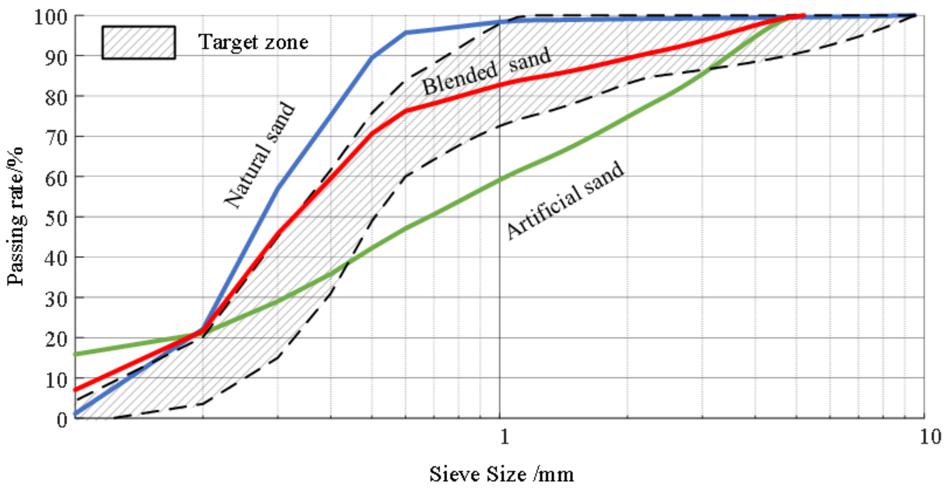
Particle size (mm)	Passing rate (%)		Mixed sand (%)	Targeted grading (%)
	Artificial sand	Natural sand		
4.75	100	100	100	90–100
2.36	78.9	99.2	91.1	85–100
1.18	62.7	98.8	84.3	75–100
0.6	47.1	95.7	76.3	60–84
0.3	29.0	57.0	45.8	15–45
0.15	17.9	7.4	11.6	0–10
0.075	13.8	2.27	6.9	/
Fineness modulus (FM)	2.65	1.42	1.91	1.6~2.2

In compliance with the requirements of CSG workability and for the reduced unit water consumption and efficient utilization of local resources, natural ultra-fine river sand was mixed and optimized with a small amount of artificial crushed sand to increase the coarse sand content and bring the fineness modulus within the allowed range. Considering the characteristics of temporary structure of the overflow cofferdam, Grade III sand was selected as the target for the mixture optimization, and the gradation range of the Grade III sand is shown in Table 3. The artificial crushed sand and natural ultra-fine river sand were sieved and subjected to ratio calculation and analysis. The technical results are shown in Figures 4a and 4b. The optimal proportion of artificial sand and natural ultra-fine river sand was mixed at a mass ratio of 4:6.

The final mixed sand gradation curve for find aggregates is shown in Figure 4c, in which the gradation curve of the natural river sand is not within the Grade III sand gradation range and cannot be directly used for construction. By mixing coarser artificial sand with a fineness modulus of 2.65 and natural river sand at a ratio of 6:4, the majority of the gradation curve of the mixed sand falls within the Grade III sand gradation range, meeting the technical requirements for CSG fine aggregate materials.



(a) (b)



(c)

Fig. 4. Gradation curves of fine aggregates. (a) Cumulative deviation with different natural sand. (b) fineness modulus with different natural sand. (c) Mixed fine aggregate grading curves

Table 3. CSG design strength parameters of the cofferdam in the Nyerere dam project

Design strength (MPa)	Design age (days)	Maximum aggregate size (mm)	Mix design strength (MPa)
5	90	300	8.0

Table 4. Trial tests of different mixing ratios

Mix design label	Water-cement ratio	Sand content (%)	Fly ash content (%)	Water reducing agent dosage (%)	Retarder dosage (%)	Quantities of various materials in single-component CSG (kg/CSG m^3)							
						Water (kg)	Cement (kg)	Volcanic ash (kg)	Mixed sand (kg)	4.75–19 mm small stones (kg)	19–300 mm jaw-crushed material (kg)	SN-2 water reducing agent (kg)	SN-GH retarding agent (kg)
TCSG-1	1.110	30	31.8	1	0.9	110	68	32	642	225	1,266	4.955	4.459
TCSG-2	1.110	30	35.9	1	0.9	110	64	36	642	225	1,266	4.955	4.459
TCSG-3	1.110	30	41.2	1	0.9	110	58	41	642	225	1,266	4.955	4.459
TCSG-4	1.110	30	48.3	1	0.9	110	51	48	642	225	1,266	4.955	4.459
TCSG-5	1.110	30	58.3	1	0.9	110	41	58	642	225	1,266	4.955	4.459
TCSG-6	1.110	30	73.7	1.1	0.9	110	26	73	642	225	1,266	5.450	4.459

4.3 CSG Cementitious Materials

The cementitious material used in CSG is the CEM II/B-L42.5N cement, which was sourced from the local Twiga cement factory in Tanzania. Considering the remote project site and the difficulty in material transportation, water-reducing agents were used to reduce the cement consumption per unit, thus improving the workability of CSG and saving costs. The strength design requirement for the coffer dam is that the compressive strength of concrete cubes should be no less than 5 MPa at 90 days. Considering that no previous domestic projects are available as references for normal-state mixed CSG, the design followed the Chinese standards of "Code for Mix Design of Ordinary Concrete" (JG J55-2011) and "Technical Guidelines for Cemented Particle Material Dam Construction" (SL 678-2014), with a standard deviation of 4.0 MPa. The calculation table for CSG test strength parameters is shown in Table 3, and the required CSG test strength is 8.0 MPa.

Considering the working conditions of the overflow cofferdam, and referring to the principles of concrete mix design experiments and the technical requirements of the project, the following parameters were determined for mixing tests. Given that the gradations of coarse and fine aggregates were optimized in the design stage, the sand content can be appropriately reduced, and a sand ratio of 30% was selected. The water-cement ratio was set to 1.11. The dosage of water-reducing agent was set to 1%–1.1%. The dosage of the retarder is 0.9%. The water content was 110 kg/CSG m^3, the fine aggregate content was 642 kg/CSG m^3, and the coarse aggregate content was 1,491 kg/CSG m^3. The mixing process was simplified by keeping the water-cement ratio and sand ratio unchanged, and only the dosage of volcanic ash was varied for the mixing experiments to determine a CSG mix design that meets the required strength and is economically feasible. The mix designs are shown in Table 4.

According to the mixture proportions shown in Table 4, fresh CSG was prepared and subjected to multiple vibrations and molding to obtain standard cubic specimens with a side length of 150 mm. These specimens were then cured in a standard curing room and tested for 7, 28, 45, and 90 days for the CSG materials. This study selected the compressive strength of CSG as the design control indicator, and Figure 5 shows the compressive strength curves for different water-cement ratios and different ages of CSG specimens. The results show that the compressive strength of CSG specimens at the same age is negatively correlated with the amount of volcanic ash. As the amount of volcanic ash increased, the compressive strength of the specimens decreased. When the amount of volcanic ash reached 73.7 kg/CSG m^3, the compressive strength of the 90-day-old specimens dropped to 7.4 MPa, which does not meet the design strength requirements of the project. Based on the comparison of the compressive strength of single-factor specimens with different amounts of volcanic ash at different ages, a similar trend can be observed. The longer the curing time, the higher the compressive strength of specimens. When the amount of volcanic ash was 58.3 kg/CSG m³, and the curing time was 90 days, the compressive strength of the specimens was 9.6 MPa, which exceeds the required value of 8.0 MPa for CSG strength, satisfying the strength requirements. The above result shows that an appropriate amount of volcanic ash can reduce the influence of age on the compressive strength of CSG materials while achieving the desired compressive strength. This condition ensures that the construction is easy to control, safe, and feasible while also improving the economic efficiency of CSG materials. Therefore, for this project, the final selection of volcanic ash was set to 58.3 kg/CSG m³, and the design mixture proportion of TCSG-5 was chosen for construction.

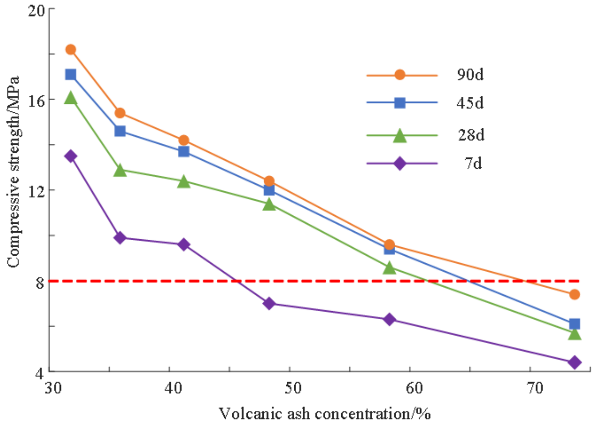


Fig. 5. Relationship between water-cement ratios and compressive strength changes

4.3 Engineering Application

As shown in Figure 5, the actual application results indicate that the CSG mixture produced meets the quality requirements in terms of compaction and compaction density, as verified by testing. The average strength obtained at 28 days is 10.2 MPa, which meets the design requirements. Additionally, the constructed cofferdam exhibits excellent impermeability, providing assurance for the smooth construction of the hydropower station. It also complies with the environmental requirements of the African grassland nature reserve, contributing to the reduction of carbon emissions. The project has received positive feedback and recognition from the owner and consultants.

Based on the results, in practical applications, the CSG mix design method presented in this study considers both strength and cost-efficiency, achieving the use of locally available materials for embankment construction, reducing environmental disturbance, and significantly reducing project works. The cofferdam construction was successfully completed. The CSG material design also avoided the need for post-flood diversion construction, saving time for the excavation and construction of other key components of the project. The CSG material design method provides an economically viable solution for CSG construction in the Julius Nyerere Hydropower Station's overflow dam and serves as a reference for material mix design in similar complex conditions in other engineering projects, demonstrating its significant practical value.

(a)

(b)

Fig. 6. Application of CSG in Dam construction. (a) On-site CSG Mixing. (b) On-site CSG Compacting

5. Conclusions

In response to the frequent shortage of aggregates and the environmental concern of disposal of excavated waste in massive infrastructure projects in Africa, this study proposes a new CSG mix design method that utilizes on-site jaw-crushed materials for coarse aggregates, local fine river sand for fine aggregates, and local volcanic ash and cement for the cementitious material in mixed proportions. The proposed CSG mix design method was applied for the construction of a temporary overflow cofferdam at the Julius Nyerere Hydropower Station in Africa, and the following conclusions were obtained.

1) A new CSG mix design method based on jaw-crushed materials was proposed. This method involves jaw-crushing and optimizing the stone materials from excavation by using the ideal grading formula. The method was validated through laboratory mixing tests, ensuring the workability and compaction of CSG and achieving the efficient utilization of excavated materials. It also solves the shortage of quality building materials in the project region and the disposal issue of excavated waste, providing significant economic and environmental benefits.

2) The optimal ratio between jaw-crushed materials and small stones was determined to be 0.85:0.15 by weight, and the optimal ratio between ultrafine river sand and artificial sand is 4:6. The optimal CSG sand ratio is 30%, the water-cement ratio is 1.11, and the optimal volcanic ash content is 58.3 kg per CSG m^3. Under these parameters, the CSG material exhibited a compressive strength of 9.6 MPa after 90 days of curing, meeting both the requirements of engineering construction and environmental protection, while also addressing the shortage of quality building materials and maximizing economic benefits.

3) The proposed CSG mix design has been successfully applied in the construction of the overflow cofferdam at the Julius Nyerere Hydropower Station, ensuring smooth construction for seasonal floods. The successful

implementation of this CSG mix design method provides an important reference for similar engineering projects.

In summary, this study presents an effective solution for the shortage of quality building materials and the disposal of excavated waste in massive CSG construction sites. The new CSG mix design method based on jaw-crushed materials has potential for further improvement, considering that the jaw-crushed materials contain a significant amount of needle-like and flaky particles, offering room for improvement in the strength of CSG materials. Future research will focus on the refined utilization and screening methods of jaw-crushed materials to enhance their quality and improve the strength of CSG for the improved construction of hydraulic infrastructure projects.

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References

1. Cai, X., Zhang, Y., Guo, X., Zhang, X., Li, F., Zhang, T., "Review on research progress of cemented sand and gravel dam". *Science and Engineering of Composite Materials*, 29(1), 2022, pp. 438-451.
2. Londe, P., "The faced symmetrical hardfill dam: a new concept for RCC". *Water Power and Dam Construction*, 1992, pp. 19-24.
3. Hirose, T., Fujisawa, T., Kawasaki, H., Kondo, M., Hirayama, D., Sasaki, T., Design concept of trapezoid-shaped CSG dam, in Roller Compacted Concrete Dams. 2018, *Routledge*. pp. 457-464.
4. Batmaz, S., Cindere dam–107 m high roller compacted hardfill dam (RCHD) in Turkey, in Roller Compacted concrete Dams. 2018, *Routledge*. pp. 121-126.
5. Thompson, R., "Haul road design considerations". *Engineering and Mining Journal*, 2009, 2009, pp. 36-43.
6. Arefian, A., Noorzad, A., Ghaemian, M., Hosseini, A., "Seismic evaluation of cemented material dams-A case study of Tobetsu Dam in Japan". *Earthquakes and Structures*, 10(3), 2016, pp. 717-733.
7. Peng, Y., He, Y. Study on application of CSG cofferdam in hydropower station construction. *2009 Asia-Pacific Power and Energy Engineering Conference*. IEEE,2009. pp.1-4
8. Tolstikov, V. V., Tareq, S. S., "Investigating the External and Internal Stability for CSG Dams". *Construction Materials and Products*, 5(3), 2022, pp. 45-54.
9. Friol Guedes de Paiva, F., Tamashiro, J. R., Pereira Silva, L. H., Kinoshita, A., "Utilization of inorganic solid wastes in cementitious materials – A systematic literature review". *Construction and Building Materials*, 285, 2021. doi.org/10.1016/j.conbuildmat.2021.122833
10. Hirose, T., Fujisawa, T., Yoshida, H., Kawasaki, H., Hirayama, D., Sasaki, T., Concept of CSG and its material properties, in Roller Compacted Concrete Dams. 2018, *Routledge*. pp. 465-473.
11. Chen, J., Cai, X., Lale, E., Yang, J., Cusatis, G., "Centrifuge modeling testing and multiscale analysis of cemented sand and gravel (CSG) dams". *Construction and Building Materials*, 223, 2019, pp. 605-615.
12. Pratiwi, Y. E., Naharudin, N., Ilham, I., Wibowo, D., "Eligibility of Nickel Slag Waste Combined with Stone Ash for Manufacturing Paving Block". *Journal of Rehabilitation in Civil Engineering*, 10(4), 2022, pp. 33-44.
13. Kondo, M., Sasaki, T., Kawasaki, H. Characteristics of stress distribution in trapezoid-shaped CSG dam during earthquake. in *Proceedings of the 13th World Conference on Earthquake Engineering*. 2004, pp. 33-92
14. Farshbaf Aghajani, H., Soltani-Jigheh, H., Salimi, M., Karimi, S., Estekanchi, V., Akbarzadeh Ahari, R., "Investigating the strength, hydraulic conductivity, and durability of the CSG (cemented sand-gravel) check dams: a case study in Iran". *SN Applied Sciences*, 4(6), 2022. doi.org/10.1007/s42452-022-05062-4
15. Karimi, S., Farshbaf Aghajani, H., "The strength and microstructure of cemented sand-gravel (CSG) mixture containing fine-grained particles". *International Journal of Geo-Engineering*, 14(1), 2023. doi.org/10.1186/s40703-023-00182-1
16. Karimi, S., Farshbaf Aghajani, H., "A new solution for water-tightening of the cemented sand-gravel (CSG) hardfill dams". *Innovative Infrastructure Solutions*, 8(6), 2023. doi.org/10.1007/s41062-023-01137-2
17. Zhao, X., He, Y., "The Permeable Character of CSG Dams and Their Seepage Fields". *Complexity*, 2018, 2018, pp. 1-14.
18. Yang, J., Cai, X., Pang, Q., Guo, X.-w., Wu, Y.-l., Zhao, J.-l., "Experimental Study on the Shear Strength of Cement-Sand-Gravel Material". *Advances in Materials Science and Engineering*, 2018, 2018, pp. 1-11.
19. Yang, J., Yang, A.-y., Shan, Y.-g., Yang, M.-m., Zhao, J.-l., Yu, H., Pavlík, Z., "Experimental Study on Mechanical Behavior of Lean Cemented Sand and Gravel Material in Unloading and Reloading Paths". *Advances in Materials Science and Engineering*, 2021, 2021, pp. 1-12.
20. Furlan, A. P., Razakamanantsoa, A., Ranaivomanana, H., Levacher, D., Katsumi, T., "Shear strength performance of marine sediments stabilized using cement, lime and fly ash". *Construction and Building Materials*, 184, 2018, pp. 454-463.
21. Furlan, A. P., Razakamanantsoa, A., Ranaivomanana, H., Amiri, O., Levacher, D., Deneele, D., "Effect of fly ash on microstructural and resistance characteristics of dredged sediment stabilized with lime and cement". *Construction and Building Materials*, 272, 2021. pp. 1-12
22. Chai, Q., Wan, F., Xiao, L., Wu, F., "The Influence of Fly Ash Content on the Compressive Strength of Cemented Sand and Gravel Material". *Crystals*, 11(11), 2021. doi.org/10.3390/cryst11111426
23. Jiang, M., Cai, X., Guo, X., Liu, Q., Zhang, T., "Adiabatic Temperature Rise Test of Cemented Sand and Gravel (CSG) and Its Application to Temperature Stress Prediction of CSG Dam". *Advances in Materials Science and Engineering*, 2020, 2020, pp. 1-12.
24. Munirwan, R. P., Taha, M. R., Mohd Taib, A., Munirwansyah, M., "Shear Strength Improvement of Clay Soil Stabilized by Coffee Husk Ash". *Applied Sciences*, 12(11), 2022. doi.org/10.3390/app12115542
25. Oyebisi, S., Owamah, H., Alomayri, T., Ede, A., "Modelling the strength of cashew nutshell ash-cement-based concrete". *Magazine of Concrete Research*, 74(10), 2022, pp. 487-496.
26. Feng, X., Zhang, F., Guo, L., Zhong, L., "A new nonlinear constitutive model of CSG". *Australian Journal of Structural Engineering*, 23(1), 2021, pp. 51-58.
27. Cui, C., Wang, W., Jin, F., Huang, D., "Discrete-Element Modeling of Cemented Granular Material Using Mixed-Mode Cohesive Zone Model". *Journal of Materials in Civil Engineering*, 32(4), 2020. doi.org/10.1061/(ASCE)MT.1943-5533.000306
28. Ren, H., Cai, X., Wu, Y., Jing, P., Guo, W., "A Study of Strength Parameter Evolution and a Statistical Damage Constitutive Model of Cemented Sand and Gravel". *Materials*, 16(2), 2023. doi.org/10.3390/ma16020542
29. Noorzad, A., Badakhshan, E., Barari, A., Zameni, S., "Modeling an environment-friendly and antiearthquake dam by probabilistic-FEM approach". *Modeling Earth Systems and Environment*, 8(1), 2021, pp. 823-836.