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The Cemented Material Dam: A New, Environmentally Friendly Type of Dam

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ABSTRACT

The first author proposed the concept of the cemented material dam (CMD) in 2009. This concept was aimed at building an environmentally friendly dam in a safer and more economical way for both the dam and the area downstream. The concept covers the cemented sand, gravel, and rock dam (CSGRD), the rockfill concrete (RFC) dam (or the cemented rockfill dam, CRD), and the cemented soil dam (CSD). This paper summarizes the concept and principles of the CMD based on studies and practices in projects around the world. It also introduces new developments in the CSGRD, CRD, and CSD.

1. The concept of the cemented material dam

Reservoirs are important infrastructures with functions such as flood control, irrigation, power generation, and water supply. Dams were being built to store water before 1000 AD. Early dams were constructed out of local materials, but most of these dams failed and brought unmitigated disaster to the people living downstream. The development of dam construction theories laid a foundation for dam safety, allowing higher and higher dams to be built. Dam safety has been improved significantly, especially since the 1990s. However, dam engineers continue to seek new technologies to build dams in a safer, more economical, and more environmentally friendly way.

The concrete gravity dam has a high degree of safety [1]. A serious secondary disaster will not occur in this type of dam, even if a dam block breaks or if overtopping occurs due to an earthquake or to unexpected flood events (e.g., Shigang Dam [2] in Taiwan had no serious secondary disaster, even when it was broken during an earthquake). This characteristic makes the concrete gravity dam stand out from other dam types. However, concrete gravity dams are much more costly, so that there is less than 5% of these dams in dams higher than 15 m. An idea for a new type of dam—partway between a concrete dam and an earth-rockfill dam—was first proposed in 1941 by an American engineer, Homer M. Hadley, but the idea was not taken into practice. The symmetric gravity dam (optimal gravity dam) was proposed by Jérôme Raphaël in 1970 [3], but no dams were constructed based on this concept. In 1992, Pierre Londe and Michel Lino [4] proposed the concept of the symmetric concrete-faced hardfill dam; this concept was reported in the International Commission on Large Dams (ICOLD) Bulletin No. 117 under the title "The gravity dam: a dam for the future" [5]. Marathia Dam, completed in 1993 (Fig. 1), was the first hardfill dam. From that point on, several dams of this type were built in Greece, the Dominican Republic, Peru, Turkey (Fig. 2), the Philippines, and Algeria [6–8].

Based on the concept of the symmetric hardfill dam, Japan proposed the trapezoid cemented sand and gravel (CSG) dam, with new progress in material preparation, mix proportion de-

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sign, and the utilization of a "trapezoid" section [9]. The cofferdams of Nagashima, Tokuyama, and Takizawa, some slope treatment projects, and some sediment control dams were built using this method, as were Okukubi Dam ($H = 39$ m) and Tobetsu Dam ($H = 52$ m) (Fig. 3), which were completed in 2012 [10,11].

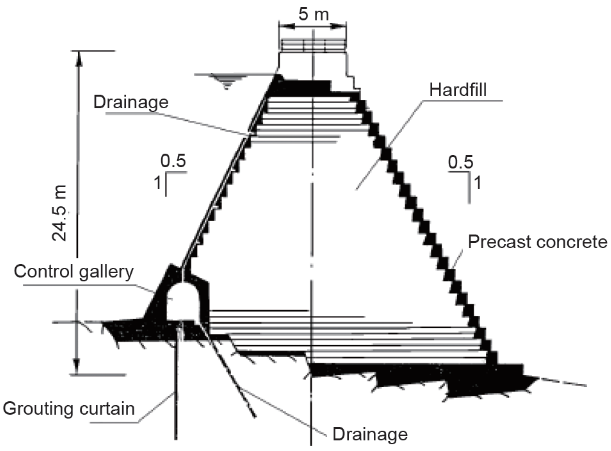

Fig. 1. Marathia Dam in Greece.

Based on the concept and practice of the hardfill dam and the trapezoid CSG dam, Jia et al. [12] put forward the concept of the cemented sand, gravel, and rock dam (CSGR dam, or CSGRD) in 2004. The Jiemian and Hongkou CSGR cofferdams were completed in 2004 and 2005, respectively. The CSGRD further broadens the scope of local material utilization, with the maximum particle diameter increased from 80 mm to 150 mm, and with similar way of mixing sand, gravel, and excavated rock as aggregates. It can be built with artificial sand and rock when no sand and gravel is available for a steep river. The dam structure can be designed according to the material properties of the CSGR in order to make full use of local materials. For a CSGRD, a "symmetric" or "trapezoid" structure is not always necessary based on research and project practice; especially for some low dams, a traditional gravity dam section can be used when the dam stress level is very low. At present, the Shunjiangyan CSGRD with a gravity dam section ($H = 11.6$ m) has been built, and the Shoukoubu CSGRD with a symmetrical section ($H = 61.4$ m) is under construction (Fig. 4). Several CSGRDs in China that use artificial sand and rock material are under design.

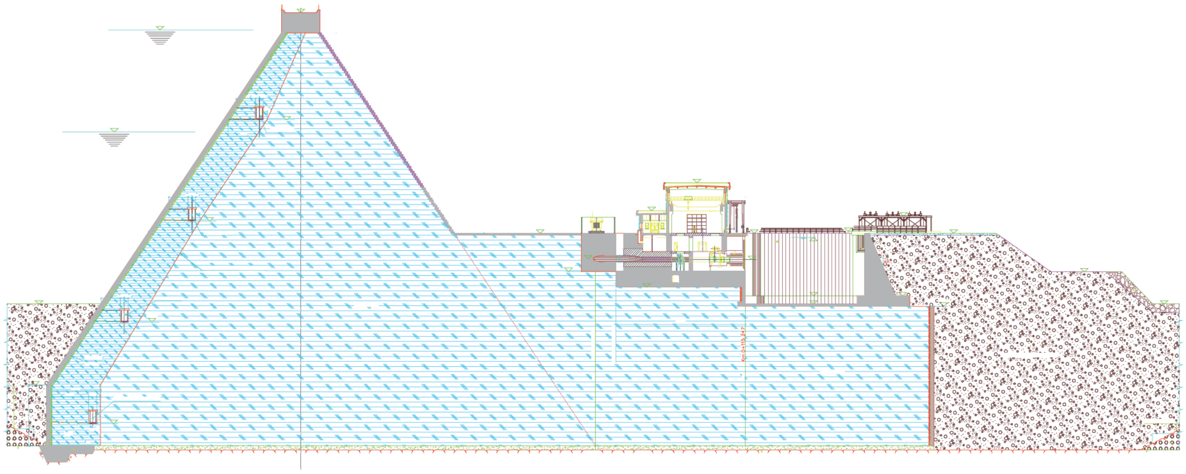

Fig. 2. Cindere Dam in Turkey ($H = 107$ m).

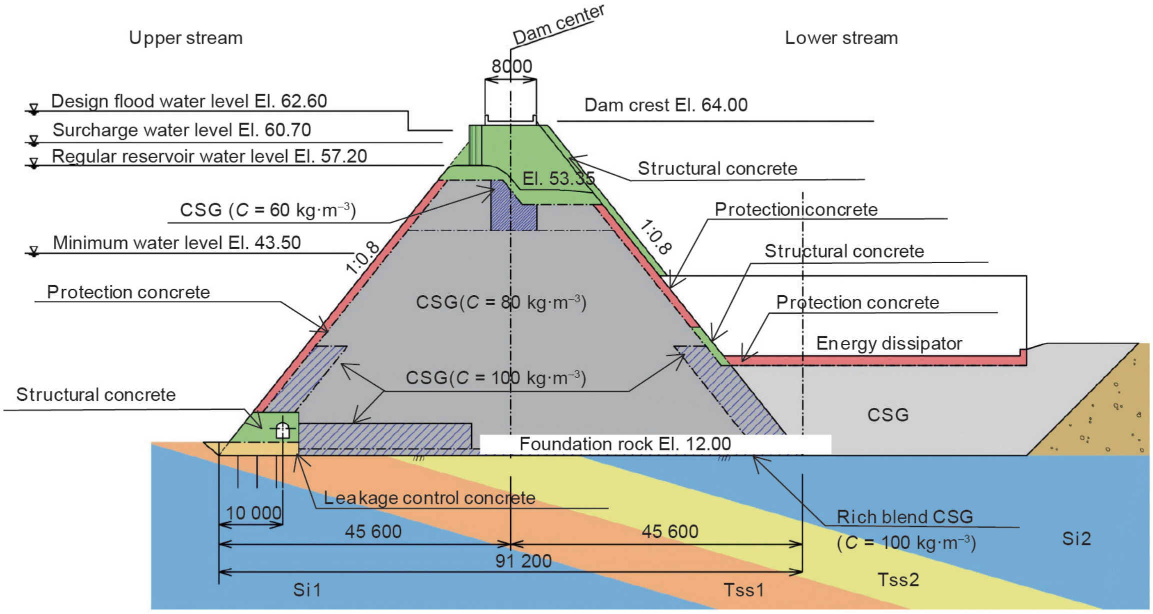

Fig. 3. Tobetsu Dam in Japan ($H = 52$ m).

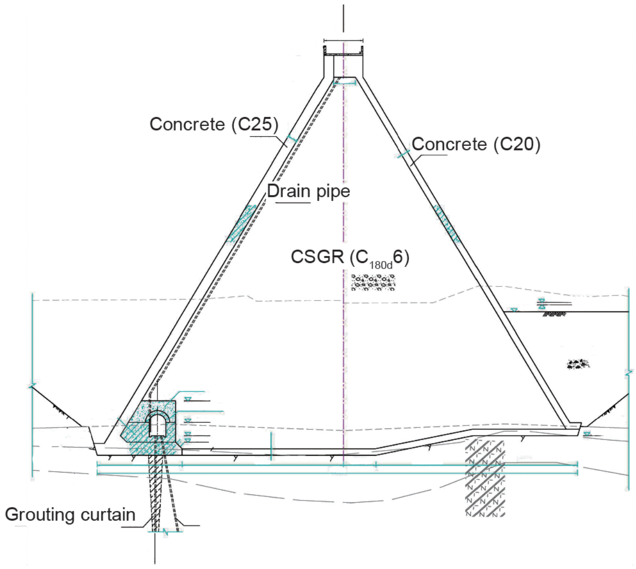

Fig. 4. Shoukoubu Dam under construction (H = 61.4 m).

One reason for the high cost of a gravity dam is that the strength of the concrete for most parts of the dam is much higher than necessary. To make better and full use of local materials, and based on the practices of the hardfill dam, trapezoid CSG dam, and CSGRD, Jia put forward the concept of the cemented material dam (CMD) in 2009 and published a paper in 2012 [13] based on the above developments. ICOLD established a technical committee on CMDs in 2013, and the Chinese technical guidelines prepared by Liu et al. for CMDs were published in 2014 [14].

The CMD is defined as a new dam type, partway between an embankment dam and a concrete dam, and having the character of a gravity dam. Its main characteristics are as follows:

(1) The dam structure is optimized in order to make better use of local materials. A cemented soil dam (CSD) can be built when earthfill or fine material is possible, and a CSGRD can be built when material with a diameter less than 300 mm is possible. A cemented rockfill dam (CRD) can be built when material with a diameter larger than 300 mm is possible.

(2) Proper materials can be selected for the different parts of the dam in order to realize better function of structures.

(3) The shape or type of the dam can be adjusted for better use of materials. Symmetric or trapezoidal dam section is not always necessary.

It should be emphasized that the safety of CMD is similar or close to gravity dam. It should be safe even when overtopping occurs; in addition, no serious secondary flood disaster would occur for the area downstream, even if the dam breaks during an earthquake.

2. Progress of the cemented sand, gravel, and rock dam

2.1. Studies on the CSGRD

For the CSGRD, sand, gravel, and rock are mixed with cementitious materials in order to improve the cohesive strength. The stable slope ratio for a CSGRD can be calculated according to the material cohesive strength, which is determined by lab tests. The stable slope ratios are about 1∶0.75, 1∶0.3, and vertical, respectively, when the amount of cement per cubic meter is 30 kg, 50 kg, and 80 kg. The material of a CSGRD has good compressive properties. The dam cross-section can be symmetrical, trapezoidal, or traditional gravity shape. The shape should be determined based on the material properties and the requirements of the dam structure.

Many existing hardfill dams adopt a symmetrical section. Compared with a traditional gravity dam section, the advantages of a symmetrical section are as follows:

(1) Homogenization of stress. Under the same load case, the stress at the dam heel is half of that of a gravity dam when the reservoir is empty. The maximum normal stress and shear stress at the contact between the dam and foundation are approximately 60% of those of a traditional gravity dam. The resultant hydrostatic force on the upstream face passes approximately through the centerline of the dam foundation section. Therefore, it causes no rotation of the section, and the stresses of the foundation at the filling or emptying of the reservoir experience little change.

(2) High degree of safety due to anti-sliding stability. The anti-sliding stability is less sensitive to pore pressure at the contact between the dam and foundation. This allows the drainage of the contact with the foundation to be simplified, and permits the hydraulic gradient between the watertight curtain and the drainage curtain to be decreased. It is possible to build a symmetrical dam for an erodible foundation or for a poor foundation, even though a traditional gravity dam would not be acceptable.

The CSGRD was proposed based on experiences with hardfill and CSG dams, but following the concepts of optimizing the dam structure to make better use of local materials and of selecting proper material for different parts of the dam in order to realize better function of structures. Raw materials include not only natural sand and gravel, but also excavated materials and artificial aggregates. Symmetrical and trapezoidal sections are no longer a requirement. A rational section and structure can be adopted for a dam according to the properties of the materials used. The structural partition must be emphasized and an appropriate material selected in order to adapt to the requirements of the structure. Rich CSGR material, roller-compacted concrete (RCC), concrete, and other materials can be used in dam parts for seepage control and freezing/thawing resistance. The main progress that has occurred in the practice of this type of dam is as follows:

- The maximum diameter of the aggregates has increased from 80 mm to 150 mm (for dams) and to 300 mm (for cofferdams). Sand and gravel from the riverbed, excavated material, artificial aggregate, or a mixture of all of these can be used as the aggregate, which extends the usage of local materials.
- Rich-mix CSGR and grouting-enriched vibrated CSGR are used for seepage control, freezing/thawing resistance, and anti-carbonization zones.
- Dam function partition is considered in the structure design.
- Low CSGR dams can be built on a non-rock foundation.
- Cemented artificial sand and gravel (CASG) dams can be built.
- New equipment and systems, such as the material continuous mixer and the digital automatic quality-control system, have been developed.

2.2. Mix design of the cemented sand, gravel, and rock material

The aggregate of a CSGRD is processed very simply. In order to guarantee strength reliability, which usually has a large discreteness, a mix design of CSGR based on the mix design method developed in Japan is improved and proposed as follows:

(1) The gradation envelope of sand, gravel, and rock material is plotted according to the screening tests in order to obtain the coarsest gradation, finest gradation, and average gradation using sample raw materials in the material field.

(2) Sand, gravel, and rock materials used for the mix propor-

tion test are screened into four grades of coarse aggregate: 150–80 mm, 80–40 mm, 40–20 mm, and 20–5 mm diameters, as well as sand with a diameter less than 5 mm.

(3) For each quantity of cementitious materials, the relationship between compressive strength and water consumption for different gradation at the design age is established (Fig. 5). The determined mix ratio needs to satisfy the requirement that the minimum strength of the average CSGR gradation be no less than $f_{\mathrm{cu},0}$ and that the minimum strength of the finest CSGR gradation be no less than the design strength, $f_{\mathrm{cu,k}} \times f_{\mathrm{cu},0} = f_{\mathrm{cu,k}} + t\sigma$, in which t is the probability coefficient and σ is the standard deviation of compressive strength.

The cementitious materials used in the project should be no less than 80 kg, of which the cement content is no less than 40 kg. For conditions such as a sand ratio above 35% or below 15%, or soft rock aggregate, the proportion can be adjusted using tests to find the optimal utilization of the materials.

Permeable dissolution testing results indicate that strength obviously decreases with long-term dissolution; it is very important to perform seepage control and drainage. Lab test results show that the permeability resistance grades of grout-enriched vibrated CSGR and rich-mix CSGR can reach S8, and that their frost resistance marks can reach F300; thus, they can be used as the impermeable layer for CSGRDs.

2.3. Special mixing equipment and quality-control system

For cofferdams, CSGR material can be mixed by backhoes. It is necessary to use mixers to guarantee mixture quality for dam construction, because the CSGR aggregate, including any material with a maximum size of 150 mm, has greater dispersion and a high mud content. In order to ensure mixing efficiency and quality, a continuous rotary-drum-type mixer and a related mixing system have been developed, with a maximum mixing capacity of 200 $\mathrm{m}^3 \cdot \mathrm{h}^{-1}$.

The transportation, unloading, spreading, and rolling of CSGR and the treatment of placed layers are similar to those of an RCC dam. The placing thickness, rolling thickness, and rolling times must be determined through on-site production tests.

Due to the high dispersion of the raw material, quality should be controlled during the whole construction process. For raw material, the gradation range should be controlled; for mixing, the vibrating compacted (VC) value of the mixture should be controlled; and for spreading and rolling, the density and compressive strength of the CSGR should be controlled. In order to realize whole-process and automatic control, a construction quality monitoring system has been developed, which can utilize ultra-wideband positioning technology to monitor the mixing proportion and process, rolling times, paving thickness, and time interval between layers. The apparent density of CSGR in the field can be detected by adopting a nuclear moisture density meter in combination with the water replacement. Sampling should be taken at the mixer outlet, and the compressive strength of a 150 mm reference cube specimen with a standard curing of 28 d is adopted as the criterion. In addition, CSGR strength testing of a 450 mm cube specimen (full graded) should be conducted.

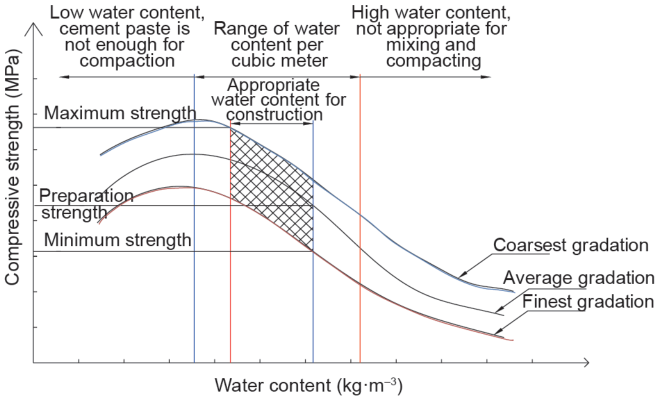

Fig. 5. Relationship curve between unit water consumption and compressive strength at the design age.

The developed construction quality monitor system was used to control the mixing and rolling of CSGR construction for the Shoukoubu and Shunjiangyan CSGRDs.

2.4. The Qianwei CSGR dike on a non-rock foundation and the Naheng cemented artificial sand and rock dam

The Qianwei dike, located along Minjiang River in Sichuan Province, China, is to be built on a foundation composed of sand and gravel, with a length of 2.77 km and a maximum height of 14.1 m. Concrete-faced rockfill dams (CFRDs) have been practiced on similar foundations with poor results due to overtopping and leakage problems. A CSGR dike has therefore been selected to improve the safety. Fig. 6 shows the cross-section of the Qianwei dike; construction on the dike will commence in 2016.

The Naheng Reservoir is located in Yunnan Province and has a dam height of 71.4 m. There is no natural sand or gravel near the damsite, so cemented artificial sand and rock (CASR) has been investigated. Results show that it is much simpler to build a CASR dam than an RCC dam, and that the construction cost of the former could be more than 10% lower. Compared with CSGR, which contains natural sand and gravel from the riverbed, the properties of CASR (Table 1), with its artificial aggregates, are much better—especially its durability.

The strength of CASR is much higher and more uniform than that of CSGR, and its quality is more easily controlled. A CASR dam cross-section could be similar to that of a gravity dam for most low dams.

3. The concept and main progress of the rock-filled concrete dam and the cemented rockfill dam

3.1. Concept of RFC dam and CRD

The rock-filled concrete (RFC) dam was proposed and developed by Jin et al. [15]. Rockfill can be cemented with a high-quality self-compacting concrete to build gravity dams and arch dams. Stones with particle diameters larger than 300 mm are placed in layers that are 1.5–2.5 m in height. A high flow of high strength self-compacting concrete (HSCC) is poured at the top of the rockfill to fill the voids in the rockfill. The stone size should be at least 10–15 times greater than the aggregate size (which is usually less than 20 mm) in the HSCC to ensure the filling performance of the HSCC; however, the preferable size is generally less than 1/8 of the minimum size of the structural section. In some cases, if a heavy vehicle can be employed to transport the stones to the working face, a few stones larger than 1 m (or even 2 m) can be used; these are usually placed in the middle part of the structure. The saturated compression strength of the stone is generally required to be greater than double the compressive strength of the RFC, so as to ensure higher safety factors of the prepared rockfill concrete.

RFC technology combines the advantages of masonry and concrete, decreasing cement consumption, lowering the temperature rise of hydration heat, and reducing the shrinkage of the concrete. According to statistics from more than 50 projects in China, the

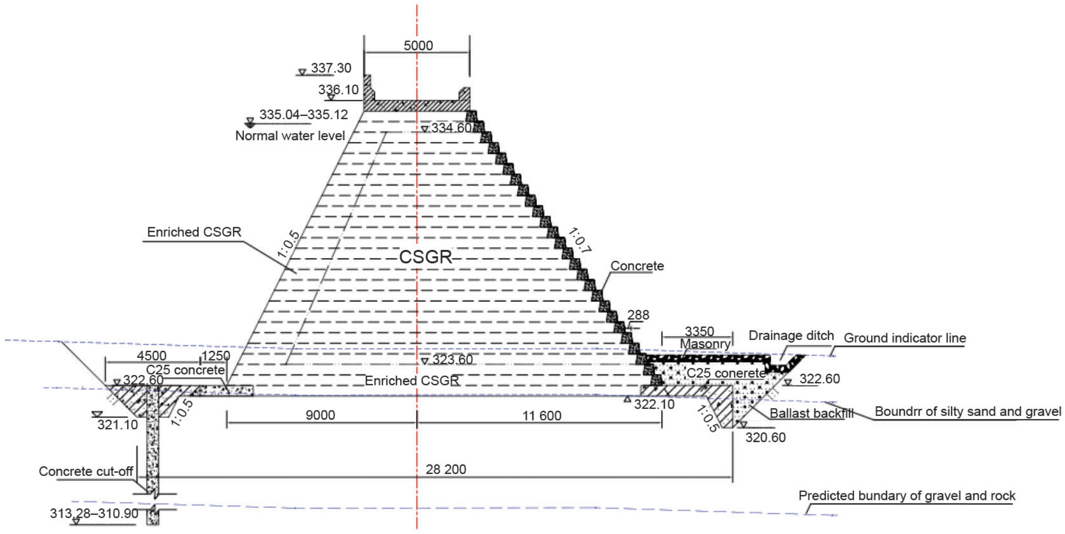

Fig. 6. A typical cross-section of the Qianwei dike.

HSCC in RFC accounts for only 40%–45% of the volume. Much less cement is used in RFC than in mass concrete.

The CRD was proposed by Jia based on RFC, although it can be built with a greater choice of material and of construction methods than an RFC dam. The CRD requires further investigation with real practice to continue its development.

3.2. Strength of RFC

Generally, the mix proportion of HSCC shall conform to the following requirements:

- The volume ratio of coarse aggregate is between 0.27 and 0.33;
- The water consumption is 170–200 kg·m^{-3};
- The water-cement ratio varies from 0.80 to 1.15 by volume;
- The volume ratio of mortar is between 0.16 and 0.20; and
- The air content of HSCC is 1.5%–4.0%, and shall be determined according to the frost resistance, if there is a frost resistance requirement.

The working behavior indexes of HSCC shall meet the requirements listed in Table 2.

For C10 RFC, the cement content is 160 kg·m^{-3}; for C30 RFC, the cement content is 280 kg·m^{-3}. According to the material property test, the ratio of tensile strength to the compression strength of RFC is 0.075–0.085. The shearing coefficients along the interface between two layers can be f' = 1.71 and c' = 1.59 MPa. The strengths of RFC are listed in Table 3 and Table 4.

3.3. Design of RFC dam

The macro properties of RFC are similar to those of concrete. The design criteria used in a concrete gravity dam can be adopted in

Table 1
Material testing results of cemented artificial sand and rock (CASR) and roller-compacted concrete (RCC).

No.	Materials (kg·m^{-3})					Compressive strength (MPa)			Tensile strength (MPa)			180 d anti-permeability grade
	Cement	Fly ash	Water	Sand	Rock	28 d	90 d	180 d	28 d	90 d	180 d	
CASR-1	45	75	78	651	1694	13.7	20.3	26.7	1.14	2.04	2.44	> W6
CASR-2	40	80	78	651	1693	11.1	17.7	22.4	0.90	1.68	2.31	> W6
RCC	65	84	82	755	1558	22.4	28.1	33.8	1.73	2.43	2.87	> W6

Table 2
Working performance requirements of HSCC.

Test item	Acceptable index
Slump (mm)	260–280
Slump flow (mm)	650–750
Passing time of V-funnel (s)	7–25
Self-compacted stability (h)	≥ 1

Table 3
Comparison of compression strengths of HSCC and RFC.

Type	Dimension (mm)	Compression (MPa)	Average value (MPa)	Effect of specimen size (%)
RFC	600	15.6/22.4/22.0	22.0	–
HSCC	600	17.8/19.2/23.3	19.2	68.8
HSCC	150	–	28.0	100.0

Table 4
Compression strength of core specimen in RFC projects.

Project name	Location	Design grade	Compression strength of core specimen (MPa)			RFC/HSCC
			Rock	RFC	HSCC	
Changkeng III Reservoir	Dam body	C20	100.4	52.2	34.0	1.54
Wudongde Station	Cofferdam	C15	61.0	32.7	27.0	1.21

order to determine the cross-section and recheck the anti-sliding stability and dam stress for an RFC gravity dam. Due to the low cement content, the distance between two transverse joints—that is, the width of a monolith—of an RFC dam could be larger than that of a normal concrete gravity dam; it could reach 30 m or more, depending on the amount of aggregate and cement in the HSCC, the property of the stone in the RFC, the temperature condition, and the geological condition of the damsite. Similar to an RCC dam, an RFC dam usually has an impervious layer arranged upstream.

Only two recently built RFC arch dams have been completed. Although the behavior of both has been very good during the impound process, more attention should be paid to the design of an RFC arch dam. Since the stress level in an arch dam is higher than that in a gravity dam, a cemented rockfill with a compression strength of C20 or higher should be adopted in the arch dam body. The tensile strength of RFC should be 90% of that of HSCC; a factor that is important in the design of an RFC arch dam. Because much more fly ash is used in HSCC, the temperature rise of hydration heat will last a long time. The grouting time of the transverse joint should be determined cautiously.

In 2005, RFC technology was first adopted in a project. To date, it has been successfully applied in more than 80 projects (including dam rehabilitation) in China, for dam heights between 30 m and 70 m. Of these RFC projects, 40.3% have dam heights between 30 m and 50 m, and 48.6% have dam heights between 50 m and 70 m. Based on the practice in China, the cost of an RFC dam can be reduced by 10% to 30% under the same conditions when compared with a concrete dam or an RCC dam.

4. Concept and development of cemented soil dam

4.1. Concept of CSD

Soil treatment with lime and/or cement is a profitable technique that is widely and successfully used in transport infrastructures. Applications also exist in hydraulic works (in the US, Australia, South Africa, and European countries). The use of CSD was first proposed in 2014. CSD uses natural soils—generally silty-clayey materials—with almost no processing aside from eventual screening for the maximum size of aggregate before it is mixed with adequate content of lime and/or cement and, when necessary, with water. Hydraulic binders (such as cement) behave as a glue to bind the particles of a granular material. Pozzolanic binders need lime to set and harden (i.e., natural pozzolanas, siliceous fly ashes, etc.). Once mixed with lime, they behave like hydraulic binders [16].

Calcium air lime can be in the form of either quicklime (CaO) or hydrated lime ($Ca(OH)_2$). It reacts differently than a cement, particularly in the presence of soil that contains clay. Cement is effective in the presence of "clean" materials (i.e., those with a very low content of clay, such as sand and gravel). Thanks to its combination with clay, lime is effective in the presence of clayey materials. The limit between the fields of application of cement and lime depends on the proportion and activity of the clay. As these cannot be predetermined, performance tests are necessary to choose the right binder and the right proportions.

In general, the final mechanical performance of a cement-treated granular material is higher than the performance of a lime-treated clayey material. However, it is possible to enhance the performance of a clayey material, thanks to a double treatment: lime treatment first, to flocculate the clay and reduce its activity, followed by cement treatment, to rapidly obtain a higher level of performance.

From the kinetics point of view, the hardening of lime-treated soils is slower than the kinetics of the cement-treated soils (or lime-plus-cement-treated soils). Fig. 7 gives an example of the increase of the unconfined compressive strength, R_c, with time for a silty soil (PI = 7, 24% of clay). A threshold between 4 MPa and 5 MPa at 90 d is shown, which corresponds to the minimum performance commonly accepted for hardfill/CSG.

In parallel with the increase of R_c, the cohesion also increases with time. Several tests have been performed in the lab and in the field to compare the permeability of non-treated soils with the same soils treated with lime [17,18]. The results show that the same order of magnitude can be obtained for a lime-treated soil as for natural soil, provided the compaction is made on the wet side of the Proctor curve (w = 1.15 OMC, OMC is short for optimum moisture content) with a sheep-foot roller. The resistance to internal erosion has also been measured according to the hole erosion test (HET) treated mixtures. In spite of the slow kinetics of reaction between lime and clay, the critical stress increases rapidly with time, even in the case of a silty soil (PI = 9) treated with only 2% quicklime.

4.2. Design of CSD

The lime treatment of a soil increases the cohesion of the material. Tests show the results on clayey silt treated with 3% quicklime: The cohesion grows from 10 kPa to 20 kPa just after treatment and to 100 kPa after one year. It should be noted that the friction angle is not modified by the lime treatment and is in the range of 28°–35°. It is very suitable to build small to medium height dams with lime-treated material because it is known that the stability of small dams relies on the cohesion. In this

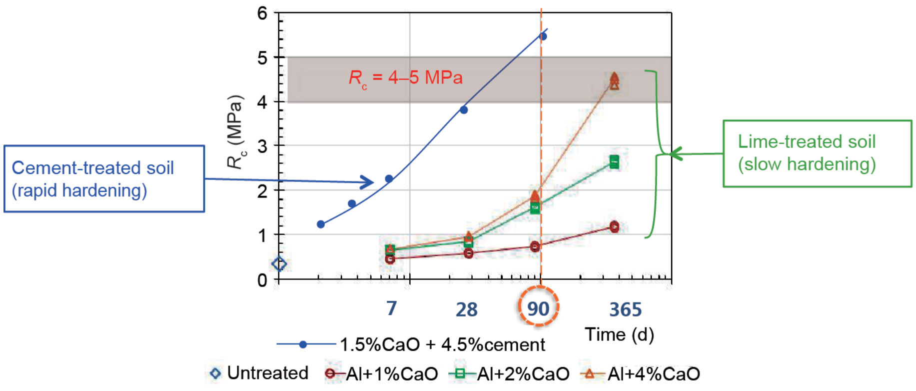

Fig. 7. An example of the hardening kinetics of a silty soil treated with lime and lime plus cement.

paper, we discuss dams with heights up to 50 m as a reference. The cohesion of cemented soil is one of its main differences from granular materials treated with cement, such as hardfill or CSG, for which the cohesion increases in the hours or days following placement. As a result, the slopes of a CSD will be basically determined by its stability during construction.

The stability of an embankment built with fine materials depends greatly on the pore pressure building during construction. Pore pressure building is also a concern for a CSD. Pore pressure building depends on the permeability of the material and its deformability. To reduce the risk of pore pressure building, it is convenient to place the cemented soil close to the optimum Proctor curve, such as [OMC – 1, OMC + 1]. In this range, the quantity of free water in the soil is reduced; also, the permeability of the treated material is higher than for natural soil, which is favorable for low pore pressure building.

Oedometric tests have been performed on cemented soil. The general trend is as follows:

- The expansion index, C_s, of the natural clay soil is divided by a factor of 5–10 after treatment;
- The yield strength, p_s, of the natural clay soil is multiplied by a factor of 5–10 after the addition of lime (from 50 kPa to 400–500 kPa with 2% lime addition, in the example cited); and
- The compressibility index, C_c, of the natural clay soil is not explicitly affected by the treatment.

Thus, the cemented soil deformability is low for a charge of fill up to 20–25 m, compared to 2.5 m for untreated soil. This low deformability tends to limit the pore pressure building for a dam height lower than 50 m. This preliminary analysis must be confirmed by further laboratory and *in situ* tests. The profile is symmetrical, with upstream and downstream slopes in the range of 1H/1V to 1.5H/1V. A watertight facing, with drainage underneath, is provided on the upstream face of the dam (Fig. 8). In this manner, the CSD body is mainly out of the water and has no watertightness function. Cracking of the dam body during construction or first filling is not a problem, provided that the cracking of the dam can be accommodated by the upstream facing.

The upstream facing can be a concrete slab, as in a hardfill dam, but the sliding stability of the slab is questionable if the foundation is soft. A geomembrane anchored in the dam body can also be considered, as was designed for Filiatrinos Dam in Greece and the Quatabian hardfill dam in Iraq.

The objective of this replacement is to improve the stability of the dam and also to limit the settlement of the foundation. It is considered as a basic component for CSD in order to accommodate poor foundation conditions. The stability analysis of a 30 m high CSD has been checked. Two types of analysis have been carried out: a circular slip plane analysis as an embankment dam, and a limit equilibrium analysis along horizontal planes as a concrete or hardfill dam. The results prove that the slope (circular plane) method is the most relevant.

4.3. Application procedures

Two procedures are possible to achieve soil treatment: in place (or *in situ*) and in central plant. The most common way is in place, layer by layer, either in the cut, followed by earthmoving, or in the fill, after earthmoving. The thickness of each layer depends on the capacity and performance of the mixer and the roller. It is currently limited to 35 cm after compaction.

The technology has improved dramatically over the last 50 years and allows for good quality mixtures with a good accuracy in the binder dosage. The output depends on the type and amount of equipment used (mainly the number of mixers). One mixer is able to mix 200–300 $m^3 \cdot h^{-1}$.

For 10–15 years, it has also been possible to treat humid and/or clayey soils with lime or cement in a central plant. In this case, moisturizing, spreading, and mixing are achieved by the plant. This procedure allows for very homogeneous mixtures with a high accuracy in the binder dosage and the water content. The output depends on the size of the plant, and can be from 50 $m^3 \cdot h^{-1}$ to more than 500 $m^3 \cdot h^{-1}$.

5. Conclusions

Based on research and worldwide practice on the hardfill dam, CSG dam, CSGRD, and RFC dam, the main progress and new principles are summarized as follows.

(1) Safety performance. The safety of the CMD is similar to that of a gravity dam with a larger dam section. Although it can be overtopped or broken, it results in much less secondary disaster for the downstream area compared with other type of dams when suffering from an extraordinary flood or earthquake. The Hongkou CSGR cofferdam, with a height of 35.5 m, demonstrated well during an 8 m overtopping flood. Many other CSGR or RFC cofferdams have suffered similar loading cases and shown good performance. A CMD can be built in a very strong earthquake area with a height over 100 m, such as Cindere Dam (107 m) in Turkey, and have good performance.

(2) Economic and construction advantages. Work on CSGRDs and RFC dams indicates that 10% to 20% of the cost could be saved and the construction period could be significantly reduced by the use of cemented material. Cemented material is usually prepared in a very simple way, involving much less processing, screening, grading, and mixing than concrete. The consumption of cementitious material such as cement and fly ash is much lower compared with that of a concrete dam or RCC dam. Thermal stress control measures are not necessary in most construction cases. A digital system based on Global Positioning System (GPS) and other information technologies (ITs) has been developed for the CSGRD in order to conduct whole-process and real-time monitoring and quality control for raw material, mixing, and construction. It demonstrates the ability to improve construction quality, and can be used for other CMDs.

(3) Environmental benefits. A CSD can be built with local earth material. A CSGRD can be built with sand, gravel, or artificial rock material when the material diameter is less than 300 mm, and an RFC dam (or a CRD) can be built when the material diameter is larger than 300 m. A dam can be built even on a non-rock foundation when the dam height is lower than 50 m. Therefore, a CMD

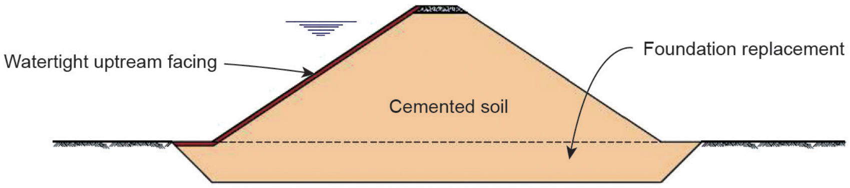

Fig. 8. Cemented soil dam section.

can be built in a very environmentally friendly way.

(4) Design concept for a CMD. A new design concept has been proposed. The shape design of a CMD is based on the concepts of optimizing the dam structure to make better use of local materials and of selecting proper material for different parts of the dam in order to realize better function of structures. A "symmetrical" or "trapezoidal" shape is not always necessary. It is better to keep the material of the CMD inner dam body under a dry and compressive stress status for all load cases. A material with good tensile strength, such as enriched CSGR, concrete, or reinforced concrete, can be used for the dam's outer parts with possible tensile stress during construction or operation.

(5) Structural analysis and calculation method. The dam cross-section is basically determined as being between those of a concrete dam and an embankment dam. The dam cross-section of a CMD is enlarged compared with that of a gravity dam, in order to decrease the stress level, expand the range of material usage, and decrease the requirement on the foundation.

Generally, the stress and stability of a CMD must satisfy the requirements of a gravity dam. For a CSD, compared with other CMDs, the stability should be rechecked based on the criteria for an earth dam. CMDs with heights less than 50 m can be built on a non-rock foundation through investigation. The CMD can be widely used, especially for the large number of small- or medium-sized projects that will be built in future.

Compliance with ethics guidelines

Jinsheng Jia, Michel Lino, Feng Jin, and Cuiying Zheng declare that they have no conflict of interest or financial conflicts to disclose.

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