Stone-concrete – material for rockfill dam face zone

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Abstract. The main limitation of the construction of high rockfill dams with a reinforced concrete face is the inevitability of high tensile stresses in the face due to deformations of the dumped rockfill. Modern means of “struggle” consist in face reinforcement, in the face cut by deformation seams, in placing of the “sliding seam” on the border of the screen with the sub-screen zone, but all of them are associated with a significant increase in the cost of the dam. The article presents the results of experimental work on the creation of a special material based on a quarry stone, called stone-concrete, which makes it possible to create a harder, in comparison with the stone outline, base for a reinforced concrete face. The technology of creating such material in the construction of dams consists of watering a layer of crush-stone or gravel-pebbly with a height of up to 0.6 m with a cement-sand mix of a specially selected composition in order to create a uniform conglomerate with predetermined properties.

1. Introduction

The purpose of the experimental work was to select the optimum in terms of cost and strength properties of the cement-sand mix composition with the additives of the mineral powder MP, which would allow the layer of crushed stone to be watered into a given depth.

The task of experimental work was to conduct several series of experimental studies based on methods of factor analysis. As the factors influencing the composition of stone concrete, the following quantitative ratios were chosen: the weight (kg) of cement per 1 m³ of stone-concrete, the weight of sand in 1 m³ of stone-concrete, the weight of the mineral powder MP, in 1 m³ of stone-concrete, the volume of water was set in the amount required to bring the mixture up to a predetermined volume (pore volume of 1 m³ of the backfill). In the course of the experiments, the boundaries of the factor space were determined and further refined. The criteria and their values were chosen for the optimal composition of the cement-sand mix, the strength and deformability of the stone-concrete samples were studied, regression dependences for the strength parameters of the material, its cost, viscosity and stability of the casting mixture.

The practical meaning of experimental work consists in the possibility of controlling the stress-strain state of the face, reducing the maximum tensile stresses in it by selecting the required properties in the face zone made from stone-concrete, which is achieved by varying the composition of the cement-sand mix for stone-concrete.

Formulation of the problem. The construction of rockfill dams with reinforced concrete face is cost-effective, but for high dams is limited due to the inevitable cracking in the face. Joint performance of the reinforced concrete face and the stone shoulder can be represented as a slab lying on a flexible foundation. The more strained the shoulder material is, the larger deflections the face acquires. This condition requires arranging a transitional “damping layer” at the face and shoulder.
junction – the face zone, which is traditionally made of tightly compacted gravel-pebbly soil, and the construction practice shows that it is a mandatory element of dams with reinforced concrete faces. Due to insignificant thickness of the reinforced concrete face and great difference in the stress-strain behavior of the face and stone materials, the face acquires both high tensile and compression stresses. Provisional stress-strain (SS) analysis of the reinforced concrete face dam has shown that the increase of the face layer hardness above the shoulder hardness allows reducing the face tensile stresses. Moreover, if the face zone hardness exceeds some “threshold” value, this results in longitudinal cracks, similar to “flaw” cracks on the dam ridge and shoulder strains, occurring separately from the face zone strains, which may affect the stability of the dam downstream side [1]. The increase of the face zone width beneficially impacts both its own strain-stress state and stressed state of the face; in this case, only minimum dam cost may serve as limitation of the face zone width.

Repair of the face usually requires reservoir storage decrease, which is associated with large economic losses. To prevent unpredictable cracking in the face within the area of maximum tensile stresses, expansion joints fitted with sealing splines, which have a rather complicated design, shall be arranged, but their arrangement causes face appreciation. In addition, to reduce tensile stresses in the face, a “sliding layer” structure may be used. The purpose of this layer is to give “greasing” properties to a geotextile bed running under the face, along a shaping course on the upstream side. To improve the stress state of the reinforced concrete face, to increase its reliability, to create conditions that allow repairing to be carried out without reservoir storage decrease, it is suggested to arrange a high-tech zone of stone-concrete, to serve as a transitional solid between the reinforced concrete face and the dumped rockfill. This zone becomes a new line to protect the dam against through filtration, if water tightness of the face is compromised. The stone-concrete face zone width should be sufficient to fit in cementing galleries, which can be used to perform repair works to restore water tightness in the zone of cracking. The cementing galleries shall also allow controlling the dam performance, by installing instrumentation in them.

In this case, stone-concrete composition, which affects the strength and deformation properties of the material, can be simulated for specific construction conditions and dam design. Face zone material, called stone-concrete, is material with a low content of cement (not more than 100 kg/m³), made by watering crush-stone or gravel-pebbly soil backfill with cement-sand mix, with the layer between 0.5 to 0.8 m, depending on the size composition. Such technique, classified as a preplaced gravitation concreting method, allows achieving a high rate of facility construction [2]. The upstream side of the reinforced concrete face may be made of precast concrete units, up to 1.5 m high, with upstream sloping corresponding to the upstream siding. Installed units act as stoppers, a kind of “formwork” to prevent the cement-sand mix from running out to the side, when the stone is watered. The upstream side of the “formwork” units may be used to arrange both the “sliding joint” and “fixed” joint of the face and the face zone. It is required to find the best solution for each specific case through a computational analysis. The use of the stone-concrete material, produced as a result of watering the stone with the sand-cement mix, requires to perform provisional studies of its processing technique and strength properties of such material.

2. Experimental program

The first stage of experimental research. First pilot studies were performed for a 0.6x0.5x0.3-m³ pilot sample. Designing of the cement-sand mix composition was based on the concept of a minimum cost of produced material and minimum toxic hazard of additives, used to improve the cast concrete structure, hence, first experiments were conducted with the cement-sand mix free from water-reducing agents. The technique to manufacture the pilot sample is described in detail [3]. After the stripping of the stone sample, it became clear that the produced mix filled the pores of crush-stone backfill rather
evenly along the full height (figure 1). Average density of the produced material amounted to 2.17 t/m³, cement consumption per 1 m³ of the produced material was approximately 87 kg/m³.

![Figure 1. Sample block of stone-concrete after stripping](image)

First series of experiments to determine the stone-concrete strength and elastic properties by non-destructive testing methods (GOST 22690-2015) were performed 28 days after the material hardening. The surface strength of the stone-concrete was evaluated by rebound resilience values, measured with a Schmidt hardness tester during the series of experiments, ranged between 10 to 15 MPa. To determine elastic properties of the sample, an ultrasonic scanning technique with a UD2V-P defect detector was used. Instrument sensors were located on the opposite sides of the sample, along its longest side 0.6 m. Based on the propagation time of elastic waves, propagation velocities of the elastic waves were calculated, and using ratios known in the elasticity theory, a stone-concrete elasticity modulus \( E_{SC} \) was computed. Average elastic wave propagation velocities in the sample measured on the faces amounted to \( V_p = 1,400-1,600 \text{ m/s} \). Average material elasticity modulus was \( E_{SC} = 4,000-5,000 \text{ MPa} \) (figure 2).

Second series of experiments by destructive testing methods (GOST 10180-2012) were performed at the age of 180 days. To study strength properties of the produced material, the sample was sawn into “puzzles” - 15x15x15 cm³ cubes. As one can see on the presented photo (figure 1), the upper layer of the unit became exposed as a result of water bleeding, and it had to be excluded from the compression experiment. Visual examination of the produced stone-concrete cubes allows to see that the cement-sand mix successfully penetrated through the backfilled crush-stone layer. The graphs show the results of uniaxial compression testing of the sample strength (figure 3). The samples were destructed into cement and sand material, despite a weak limestone aggregate. It was found that the samples of the lower layer had higher strength than the samples of the middle layer. The ultimate compression strength for the samples of the lower layer ranged between 4 and 7 MPa, of the middle layer – between 3 and 4 MPa (30-40 kg/cm²). The noted variation of material strength with regard to backfill height, related to a gravitational disintegration of the cement-sand mix, led to the conclusion that it was required to use special-purpose plasticizing agents to enhance stability of the cement-sand mix with high water/cement ratio.
The second stage of experimental research. The second stage of studies was aimed at the expedient selection of composition of the “casting mixture” for crush-stone backfill, which should meet the prescribed strength, apparent viscosity and stability of the cement-sand mix. Experiments performed at the first stage of studies have shown that the stone-concrete strength depends on the casting mixture strength. An optimal composition of the casting mixture for stone-concrete was selected, based on its full penetration through pores of the backfill, pore filling and creation of a conditionally "solid-cast" structure. A high water-cement ratio, which allowed for the “cast concreting” technique, required to use plasticizing agents to prevent disintegration of the mix; for this purpose, environmentally friendly material – the mineral powder MP1 [4] was applied.

Method of factor analysis. The existence of 3 independently variable factors that made up the casting mixture for stone-concrete required to find the optimal composition (in terms of its cost and technological criteria) by the method of factor analysis [5], creating a quadratic polynomial $3^3$. 

![Figure 2](image1.jpg)

**Figure 2.** Modulus of elasticity of the sample according to UD2V-P

![Figure 3](image2.jpg)

**Figure 3.** Testing of the strength of rock stone-concrete samples

FORM 2018 IOP Publishing
IOP Conf. Series: Materials Science and Engineering 365 (2018) 032024 doi:10.1088/1757-899X/365/3/032024
Table 1 shows factors and levels of their variation per 1 m$^3$ of stone-concrete.

| Factors             | Identification | Variation levels, (kg/m$^3$ of stone concrete) |
|---------------------|----------------|-----------------------------------------------|
|                     |                | Lower (-1)  | Basic (0)  | Upper (+1) |
| Cement content      | $X_1$          | 50          | 75          | 100        |
| Sand content        | $X_2$          | 200         | 300         | 400        |
| Mineral powder MP$_1$ | $X_3$         | 100         | 175         | 250        |

The main criteria to select the optimal composition of the casting mixture for stone-concrete are as follows:

1. Apparent viscosity of the casting mixture, determined by the time required for the mix to flow through a viscosity meter dip ($t_{av}$). Apparent viscosity of the mix was chosen to meet the consistency of the mix with adequate fluidity, which allowed watering of 0.5 m high naturally compact crush-stone backfill.

2. Stability of the casting mixture, regulated by adding the mineral powder MP$_1$ and evaluated by the height of clear water layer, which seeped to the surface of the cement-sand mix, as compared to the initial height of the mix poured into a dosing cup measured after 5, 10 and 20 minutes.

3. Strength of 10x10x10 cm$^3$ cubes measured during uniaxial compression tests.

As part of full factorial experiment $3^3$, 27 casting mixture compositions were prepared, which had different quantities of cement, sand and mineral powder. On the assumption that all pores of crush-stone backfill would be filled with the mix, a formula was formed for cement-sand mix with MP$_1$ additive for the mix volume, which took up 1 m$^3$ of stone-concrete, and for 1 liter of the mix taken up by the formwork. Using the mixture formula, (1) water volume required to make a prescribed quantity of the casting mixture for 1 m$^3$ of stone-concrete was computed for each composition:

$$\frac{Water}{1} = 440 - \frac{X_1}{C} - \frac{X_2}{S} - \frac{X_3}{MP} \quad (1)$$

where $X_1$, $X_2$, $X_3$ – weight in kg for cement ($X_1$), sand ($X_2$), mineral powder($X_3$);

$C$, $S$, $MP$ – specific gravity for cement, sand, MP$_1$.

*Studies of the strength of stone concrete samples*. Each prepared composition was repeated in 2 replicas, and apparent viscosity and disintegration were defined for each composition. Strength parameters of samples of casting mixture for stone-concrete (figure 4) were studied in the Construction Materials, Products and Structures Testing Laboratory of the Center of Shared Usage of Equipment NRU MGSU [6].
To find the optimal composition of the casting mixture for stone-concrete requires searching for the composition, which has a minimum cost and conforms to prescribed parameters – limitations of the prescribed properties. As part of factor analysis \(3^3\), mathematical dependencies were drawn up, in the form of quadratic regression equations, and adequacy of these equations was checked (the maximum discrepancy does not exceed 5\%) for the target cost function, technological limitation functions and performance function (compressive strength). Verification of the adequacy of the regression equations, with regard to the cost function (prices of 2017 were used to calculate the cost) and the water bleeding function has revealed their high accuracy, even as part of the factorial plan \(2^3\) (not more than 1\%), however, with regard to the strength and apparent viscosity function, the adequacy was ensured only for a quadratic polynomial with the matrix plan \(3^3\).

The regression equation for obtained functions may be written as:

- for the cost of casting mixture, 1 liter:
  \[
y_1 = 1,532 + 0,228 \cdot x_1 + 0,125 \cdot x_2 + 0,202 \cdot x_3 + 0 \cdot x_1 \cdot x_2 + 0,0025 \cdot x_1 \cdot x_3 + 0 \cdot x_2 \cdot x_3 + 0 \cdot x_1 \cdot x_2 \cdot x_3 \quad (2)
\]

- for apparent viscosity:
  \[
y_2 = 6,4 + 0 \cdot x_1 + 0,1 \cdot x_2 + 0,2 \cdot x_3 + 0,4 \cdot x_1 \cdot x_2 + 0,25 \cdot x_1 \cdot x_3 + 3,3 \cdot x_2 \cdot x_3 + 4,1 \cdot x_1 \cdot x_2 \cdot x_3 - 0,4 \cdot x_1^2 - 0,1 \cdot x_2^2 - 0,2 \cdot x_3^2 + 0,6 \cdot x_1^2 \cdot x_2 + 0,3 \cdot x_1^2 \cdot x_3 + 0,45 \cdot x_2^2 \cdot x_1 + 3,25 \cdot x_2^2 \cdot x_3 + 0,4 \cdot x_3^2 \cdot x_1 + 3,6 \cdot x_3^2 \cdot x_2 + 0,85 \cdot x_1^2 \cdot x_2^2 + 0,85 \cdot x_1^2 \cdot x_3^2 + 3,45 \cdot x_2^2 \cdot x_3^2 + 1,6 \cdot x_1^2 \cdot x_2 \cdot x_3 + 3,775 \cdot x_1 \cdot x_2^2 \cdot x_3 + 3,5 \cdot x_1 \cdot x_2 \cdot x_3^2 + 1,325 \cdot x_1^2 \cdot x_2 \cdot x_3 + 0,9 \cdot x_1^2 \cdot x_2 \cdot x_3^2 + 3,225 \cdot x_1 \cdot x_2 \cdot x_3^2 + x_1^2 + 0,375 \cdot x_1^2 \cdot x_2^2 \cdot x_3^2 \quad (3)
\]

- for stability:
  \[
y_3 = 16,053 - 9 \cdot x_1 - 9,5 \cdot x_2 - 14 \cdot x_3 + 1,875 \cdot x_1 \cdot x_2 + 2,375 \cdot x_1 \cdot x_3 + 2,875 \cdot x_2 \cdot x_3 - 2,125 \cdot x_1 \cdot x_2 \cdot x_3 + 0,938 \cdot x_1^2 - 0,563 \cdot x_2^2 + 1,938 \cdot x_3^2 + 4,875 \cdot x_1^2 \cdot x_2 - 0,125 \cdot x_1^2 \cdot x_3 + 5,375 \cdot x_2^2 \cdot x_1 \quad (4)
\]

- for axial compression strength function:
\[ y_4 = 1.08 + 1.645 \cdot x_1 + 0.375 \cdot x_2 - 0.275 \cdot x_3 - 0.132 \cdot x_1 \cdot x_2 - 0.02 \cdot x_1 \cdot x_3 + 0.237 \cdot x_2 \cdot x_3 + 0.311 \cdot x_1 \cdot x_2 \cdot x_3 + 1.085 \cdot x_1^2 + 0.845 \cdot x_2^2 + 0.575 \cdot x_3^2 - 0.422 \cdot x_1^2 \cdot x_2 + 0.28 \cdot x_2^2 \cdot x_3 - 0.632 \cdot x_2^2 \cdot x_1 + 0.343 \cdot x_2^2 \cdot x_3 - 0.92 \cdot x_3^2 \cdot x_1 - 0.182 \cdot x_3^2 \cdot x_2 - 1.532 \cdot x_1^2 \cdot x_2^2 - 1.26 \cdot x_1^2 \cdot x_3^2 - 1.087 \cdot x_2^2 \cdot x_3^2 + 0.056 \cdot x_1^2 \cdot x_2 \cdot x_3 - 0.039 \cdot x_1 \cdot x_2^2 \cdot x_3 + 0.564 \cdot x_1 \cdot x_2 \cdot x_3^2 - 0.284 \cdot x_1^2 \cdot x_2^2 \cdot x_3 + 0.769 \cdot x_1^2 \cdot x_2 \cdot x_3^2 + 1.339 \cdot x_1 \cdot x_2^2 \cdot x_3^2 + 2.274 \cdot x_1^2 \cdot x_2^2 \cdot x_3^2 \] (5).

Values, obtained as a result of test watering of crush-stone backfill, were adopted as limitations for the functions in the following form:

1. For the apparent viscosity function. Test watering has shown that the apparent viscosity measured by a 5 mm dip viscosity meter (30 ml cup capacity) should not exceed 20 seconds. At the same time, if the casting mixture composition is too fluid (less than 10 s), the watered mixture is not retained by stone backfill pores and runs through it, without forming an internal solid in the material (figure 5, a).

2. For the mix stability. Water bleeding of the casting mixture, measured 20 minutes after settling, was limited to 5%, which created a slight evenness on the backfill surface after evaporation of the bled water.

3. For the strength property. During the uniaxial compression tests, 28-days old cube strength was limited to 1.3 MPa, which related to searching the leanest casting mixture composition that could ensure structural strength in the material.

Target function (2) minimization in MathCad allows creating an “optimal” solution for the plan \(3^3\) (Table 2), provided that the conditions for limitations of each function (3, 4, 5) are observed. As can be seen, the composition with the maximum content of sand and MP (practically in equal proportions) and 2.71 water/cement ratio has the lowest cost, provided that the prescribed minimum material strength is observed.

### Table 2. Casting Mixture Composition Meeting the Optimal Solution

| No. | Factors | Composition for 1 of stone-concrete | W/(C+\(S+\) MP) | W/(C+\(S\) MP) | W/C |
|-----|---------|-------------------------------------|----------------|----------------|-----|
| X1  | X2      | X3 | C, kg | S, kg | MP1, kg | W, l |  |  | |
| Optimal | -0.275 | 1 | 0.927 | 68 | 400 | 245 | 184 | 0.26 | 0.59 | 2.71 |

Control watering of the sample with the optimal casting mixture composition confirmed that the mix satisfactorily penetrated into the stone backfill pores and was adequate in terms of the prescribed criteria (figure 5, b).

![Figure 5](image_url) Test watering of the samples with a different viscosity: a) \(t_w=10\) s; b) \(t_w=20\) s
3. Discussion of results

The conducted studies have allowed determining the dependencies of technological criteria for the casting mixture composition, expressed as quantitative ratios of cement, sand, mineral powder and water.

Analysis of the results has shown that mathematically, the viscosity parameter might be described by the ratio \( \frac{W}{C + S + MP} \) (figure 6). The thickest mix, in terms of watering, may be obtained by the ratio \( \frac{W}{C + S + MP} \) of not more than 0.3.

Mix stability (water bleeding) is properly described by \( W/(C+MP) \) dependency (figure 7), which, unlike the previous one, has no sand, because cement and mineral powder have a water hydration property. The best compositions of the casting mixture comply with the ratio \( W/(C+MP) \) of not more than 0.8.

As could be expected, the strength depends only on the \( W/C \) parameter, as shown in the graph (figure 8). At the same time, the MP content in the casing mixture is determined by the parameter of its stability, but does not participate in the choice of material by strength parameter.

![Figure 6. Graph for the viscosity function](image)

![Figure 7. Graph for the water bleeding](image)

![Figure 8. Graph for the strength function](image)
4. Conclusions
1. The test results of the produced stone-concrete sample make it possible to draw the conclusion that this material, called stone-concrete, has adequate structural cohesiveness, sufficient strength, and can be used as a supplementary “line of protection” for the reinforced concrete face against cracking, not only as a “filling” transitional zone, but as a solid, which allows carrying out repair, restoration and injection works at the tiers of different heights.
2. Results of the conducted studies have allowed determining the casting mixture composition to make stone-concrete at the construction site, with a high degree of predictability;
3. The most critical criteria for the casting mixture are apparent viscosity and stability of the cement-sand mixture, because they limit the selection of the composition, based on the proposed cast gravitation concreting method of stone-concrete production;
4. The conducted studies have allowed determining the dependences of technological criteria on the casting mixture composition, expressed in the quantitative ratios of cement, sand, mineral powder and water. The best solutions include the ratio of $W/(C+S+MP_1) < 0.27$ and $W/(C+MP1) < 0.75$. In this case, $W/C$ ratio may reach 2.5 or even 3.
5. The use of the factor analysis techniques has allowed defining the optimum casting mixture compositions in terms of their cost, meeting the prescribed technological criteria, their cost being a little different from each other and ranging between 1.65-1.85 RUB/liter.
6. Strength properties of the best composition samples range between 1.3 and 1.6 MPa. Cement content per 1 m$^3$ of stone-concrete amounts to 65-70 kg/m$^3$.
7. Strength parameters of the “stone-concrete” material differ from strength parameters of the casting mixture by not more than 10%, which allows using the casting mixture graphs to predict the “stone-concrete” properties.

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