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MINERAL MINING TECHNOLOGY

Compositions of Backfill Made of Fine and Very Fine Natural Sand

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Abstract—The strength, elasticity and deformability testing of cemented paste backfill is carried out. The test backfill compositions include fine and very fine natural sand with the increased content of clay and dust, and refined with sifted granular blast-furnace slag 0–5 mm in size. The uniaxial compression strength, elasticity modulus and Poisson's ratio are determined in the test backfill compositions at different stages of curing. The ultimate uniaxial compression strength is correlated with the P-wave velocity and elasticity modulus determined in the static and dynamic tests of the backfill compositions.

Keywords: Cemented paste backfill, very fine natural sand, aggregate grade analysis, sifted granular slag, ultrasonic investigation, ultimate compression strength, elasticity modulus, Poisson's ratio.

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INTRODUCTION

The strength, elasticity and deformation analysis of artificial masses made of cemented backfill enable optimization of the backfill compositions and efficient backfilling technologies for specific geotechnical conditions. The safety of mining improves and the cost of backfilling reduces as a result.

The backfill quality is governed by the strength properties (ultimate strength in uniaxial/biaxial/triaxial compression, shear, tension and bending) and by deformation characteristics (static and dynamic elasticity modulus, Poisson's ratio) [1–3]. Many estimation procedures of physical and mechanical properties of cemented backfill are specified by the state standards [4–7].

The uniaxial compression strength is a principal property to be estimated obligatory for specific compositions of backfill in cubic sample testing. The samples are manufactured from backfill samples taken at the outlets of backfill mixture machines, or by coring in exposed backfill mass. The samples are used in the study and selection of cemented backfill compositions in laboratory conditions.

The other strength properties are also determined experimentally. Such experimentation is laborious and requires specific equipment and many samples of different shapes and sizes. The calculations use the known relations between the unknown parameters and the uniaxial compression strength of a material [1, 2]. The tensile and bending strengths of a material are independent of the type of an aggregate at the same uniaxial compression strength.

A backfill material 1–6 MPa strong features a correlation dependence between the strengths in tension, σ_r, bend, σ_i, and uniaxial compression, σ_s: $\sigma_r = 0.0255\sigma_s + 0.045$ at the correlation factor $r = 0.9$ and reliability factor $\mu = 33$; $\sigma_i = 0.04\sigma_s + 0.01$ at $r = 0.8$ and $\mu = 30$. The cohesion $C = 0.383\sigma_s + 0.5$.

The elasticity and deformation characteristics of backfill are necessary to determine stability of exposed backfill spans in mining of closely spaced ore bodies. The elasticity modulus and Poisson's ratio are the principal characteristics of deformation. The standard static testing [6] needs full-size cylindrical or prismatic samples having the height-to-diameter ration 4.0. It is not always possible to produce the required number of samples of the required size. For another thing, such tests are rather laborious and expensive. In such case, the elasticity modulus and Poisson's ratio are found from the dynamic testing and measurement of P- and S-wave velocities in the samples, with calculations using the known formulas [1–3]. The dynamic tests are simpler and needs no fracture of the samples, which is critical. The same samples are usable for the retesting later, at another age of the backfill material, given proper storage.

The elasticity modulus in dynamics is higher than in statics but these moduli are correlatable. The correlations for different rocks, liquid sand-and-concrete and cemented backfill with a strength to 10 MPa are available [8–21] but are not of general duty, and are validated for specific materials. The cemented backfill strength grows with time and exceeds 10 MPa by the time of undermining. For instance, backfill material grade M100 at an age of 90 days can have a strength more than 14 MPa given all standards are fulfilled.

In case of experimental determination of backfill compositions made of fine and very fine natural sand with high clay content, it is critical to investigate their strength properties and deformation characteristics, and to correlate the indices found in statics and dynamics.

Fine and very fine sand with the fineness modulus less than 0.7, and with the increased contents of clayey and flour particles (to 30%) are below the standard quality to be used in construction. Such sand is often used as an aggregate material in manufacture of cemented backfill mixtures (Portland cement and its varieties). Such backfill mixtures have certain advantages. The finely dispersion structure of the aggregate allows producing uniform and nonstratifiable paste mixtures transportable by gravity in pipelines for long distances (to a few kilometers). Spreadability of such backfill on a Suttard viscometer is to 220 mm. The sand is comparatively cheap, especially when a sand deposit lies in a close vicinity to a backfill preparation plant. The disadvantage is an increased consumption of cement to achieve the required uniaxial compression strength of the cemented backfill (4–10 MPa). As a consequence, the water consumption grows, which increases shrinkage in curing and raises the cost of backfilling.

It is found to be technically and economically expedient to optimize grain compositions of off-standard fine and very fine sand with the increased clay and dust content [22, 23]. Such sand is used in production of cemented backfill with addition of a coarse agent—granulated furnace slag siftings 0–5 mm in size without any pretreatment (washing, re-milling, resifting, etc.). With the increase in the portion of slag, the composition of the aggregate needs less water. The fineness ratio of the aggregate grows, and the content of clayey particles lowers. This allows producing cemented backfill mixtures at the reduced cement consumption (by 11–16%) at the same strength and transportability.

The aim of this study is the analyze the strength, elasticity and deformation characteristics of experimental backfill compositions, and to correlate the static and dynamic indices.

1. SUBJECT OF RESEARCH

The subject of research is the experimental compositions (backfill grades M40 and M100) with fine and very fine sand as an aggregate. The sand was taken from the deposit Bolshie Mayachki in the Belgorod Region, Russia. The coarse agent to optimize the grain composition of the aggregate was the furnace slag siftings 0–5 mm from Severstal.

Table 1. Physicotechnical properties of very fine sand (Bolshie Mayachki) and furnace slag siftings (Severstal)

Material	Overscreen mass percent (as per State Standard 8735-88, screen size, mm)						M_k	S, %	T, kg/m^2	I/N, kg/m^3
	2.50	1.25	0.63	0.315	0.16	< 0.16, including clayey				
Sand	Partial						0.60 very fine	18.29	19.45	2675 / 1630
	0.07	0.04	5.46	4.65	33.66	56.12				
	Total									
	0.07	0.11	5.57	10.22	43.88					
Slag	Partial						2.65 coarse	—	7.69	2700 / 1490
	2.07	10.63	52.35	24.40	6.39	4.15				
	Total									
	2.07	12.70	65.06	89.46	95.85					

M_k—fineness ratio; S—content of clayey and flour particles; T—theoretical specific surface; I/N—true / bulk density.

Table 1 describes the physicotechnical properties of backfill used to prepare the experimental compositions—grade M40 (uniaxial compression strength 4 MPa) and grade M100 (uniaxial compression strength 10 MPa). The sand has a very low fineness ratio (0.60) as it is dominated by fine and flour particles (< 0.16 mm), the content of clayey particles is very high, and the specific surface of the particles is large. An aggregate of such quality is assumed as off-standard even in manufacture of cemented paste backfill as the uniform wetting and cohesion of prevailing ultrafine particles to ensure the standard strength requires the increased consumption of water and, probably, cement. The slag has the quality of coarse sand, is free from clay, has the specific particle surface area 2.0–2.5 smaller than sand has, needs no pretreatment (sifting, milling, etc.) and is comparatively inexpensive. The test sand and slag siftings had close-value true densities, which made it possible to use the siftings as a coarse agent to optimize the off-standard sand and to select compositions of unstratifiable backfill mixtures at the reduced cement consumption.

Table 2. Optimized backfill mixtures with optimized aggregate

Mixture no.	Aggregate composition, %			Consumption per 1 m^3 backfill, kg		Sample density, kg/m^3	Shrinkage, %	Uniaxial compression strength, MPa at different ages, days				
	Sand	Slag	M_k	Cement	Water			28	60	90	180	365
Grade M40												
1	100	0	0.60 very fine	380	500	1920	6.08	6.51	8.00	8.79	10.15	11.50
2	75	25	1.11 very fine	260	450	1920	4.31	6.30	8.07	8.51	9.82	11.13
3	60	40	1.42 very fine	240	410	1930	2.88	6.83	8.85	9.22	10.64	12.06
Grade M100												
4	100	0	0.60 very fine	570	530	1870	5.33	10.20	12.53	13.77	15.89	18.01
5	75	25	1.11 very fine	460	500	1880	3.69	10.40	11.55	14.04	16.21	18.37
6	60	40	1.42 very fine	420	480	1870	3.50	10.23	11.34	13.81	15.94	18.07

Selection procedure sets two obligatory conditions: spreadability at least 220 mm on Suttard's viscometer and design strength development in 28 days of normal curing. Table 2 describes some experimental compositions of backfill grades M40 and M100 with optimized aggregate, and their physical and mechanical properties at different ages of strength.

Optimization of the grain composition of very fine sand allows production of the transportable mixtures of backfill grades M40 and M100 at the reduced cement consumption. The produced samples after curing had shrinkage 2 times lower than the same nonoptimized samples. The strength development keeps the same dynamics in time. For the strength and deformation testing of backfill made of the experimental compositions (Table 2), 15 cubic samples 100×100×100 mm and three cylindrical samples with the height-to-diameter ratio of ~2:1 were manufactured for each test period of normal curing (28, 60, 90, 180, 360 days). All in all, 108 samples were manufactured. They were held in the normal curing cell at a temperature of 20±2 °C and relative humidity of 95%. The deformation testing used the static and dynamic methods.

In the static method, deformation is measured in the test samples subjected to loading. On test and measurement equipment ASIS 2017, the samples were subjected to uniaxial compression of 50–60% of the destructive load and were unloaded then. Special instrumentation recorded continuously deformation during loading–unloading. The longitudinal and transverse deformation was measured by potentiometric linear displacement (measurement accuracy 1 μm).

The dynamic method uses measurement of P- and S-wave velocities in the test samples in the range of ultrasonic frequencies. The measured values of the waves help calculate Poisson' ratio and the dynamic elasticity modulus E_d:

$$\mu = \frac{0.5-\chi^2}{1-\chi^2}, \quad E_d = \frac{C_p^2\rho(1+\mu)(1-2\mu)}{1-\mu},$$

where $\chi = C_s / C_p$; C_p and C_s are the P- and S-wave velocities, respectively, m/s; ρ is the cemented backfill density, kg/m^3.

The P- and S-wave velocities were measured using ultrasound system UK10P (impulse frequency 200 kHz). Alongside with the elasticity estimation from the standard procedures, the density ρ, moisture W and the uniaxial compression strength σ_s were determined in all test samples.

Table 3. Physical and mechanical, and deformation and elasticity properties of experimental backfill composition in static and dynamic tests

Mixture no.	Physical and mechanical properties			Deformation and elasticity properties					
				Static testing		Dynamic testing			
	W, %	ρ, kg/m^3	σ_s, MPa	E_s, GPa	μ	C_p, m/s	C_s, m/s	μ	E_d, GPa
Grade M40									
1	20.7	1920	8.00	2.9	0.31	2670	1414	0.31	10.0
2	20.9	1920	8.07	2.9	0.32	2822	1475	0.31	11.0
3	20.7	1930	8.85	3.0	0.35	3083	1445	0.36	11.0
Grade M100									
4	20.1	1870	10.20	3.1	0.35	3070	1416	0.36	10.2
5	20.9	1880	10.40	3.1	0.35	2879	1385	0.35	9.7
6	20.2	1870	10.23	3.1	0.35	2927	1418	0.35	10.1

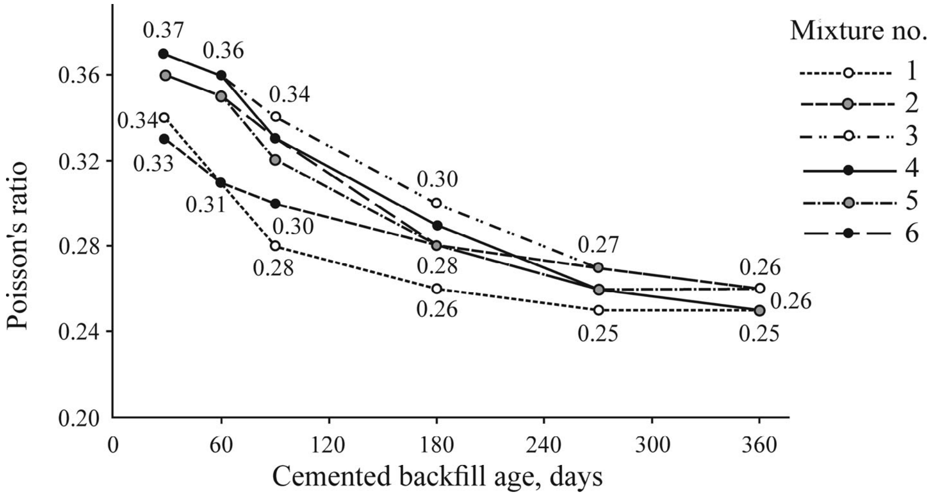

Fig. 1. Poisson's ratios for experimental backfill compositions at different times of strength development.

For correlating the deformation and strength indices from the dynamic and static tests, the linear regression analysis was performed by the method of static research in Microsoft Excel.

The tests of all experimental compositions produced the data on the strength, elasticity and deformation characteristics of the test backfill samples at different ages of strength development (28, 60, 90, 180 and 360 days of normal curing). Table 3 gives the test data of the backfill samples at the age of 60 days.

The test data processing and analysis results are:

- all samples during testing have humidity of ~20%;
- the samples have unaltered density at all testing stages;
- the P-wave velocity increases with the increasing uniaxial compression strength of the samples;
- the S-wave velocity is lower than the P-wave velocity but the ratio C_s / C_p from 0.50 in the samples at the age of 28 days to 0.57 in the samples at the age of one year;
- Poisson's ratios in the static and dynamic tests are mostly equal in the samples but reduce in the older samples and with the increase in the strength σ_s. Figure 1 depicts Poisson's ratios in experimental compositions at different ages;
- the elasticity modulus in the dynamic tests is much higher than this modulus in the static tests but both follow a certain trend in all tested compositions of backfill.

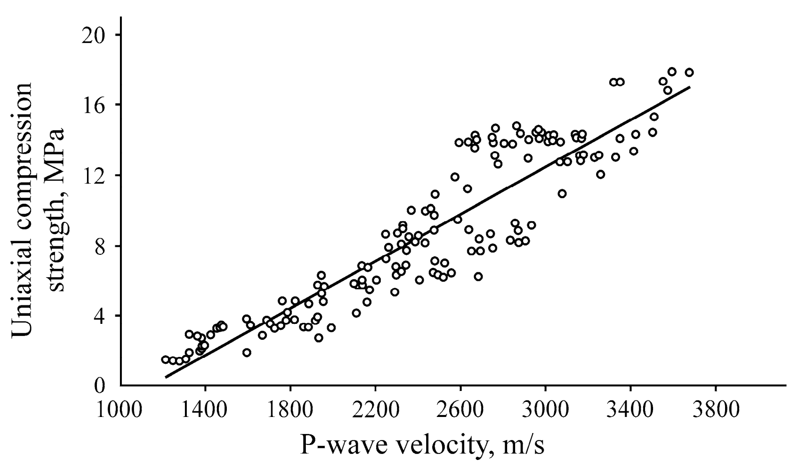

Fig. 2. Uniaxial compression strength versus P-wave velocity in experimental compositions of cemented backfill.

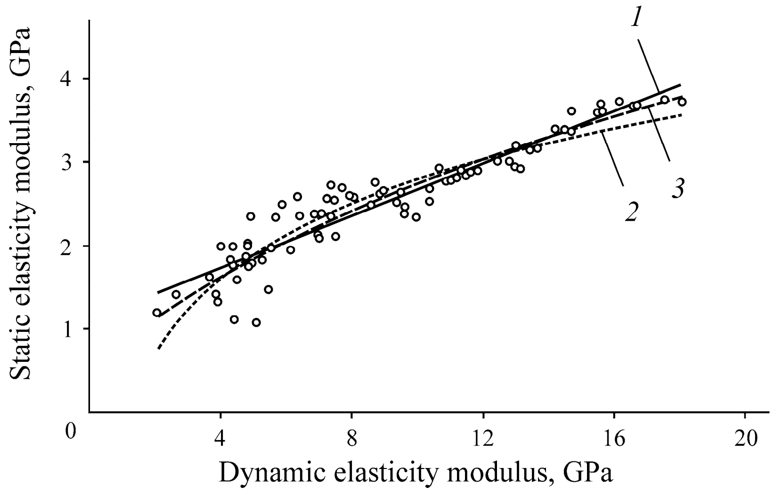

Fig. 3. Static versus dynamic elasticity moduli for experimental compositions of cemented backfill: *1*—linear curve; *2*—logarithmic curve; *3*—exponential curve.

The research findings include some relations below:

—the equation of the linear dependence of uniaxial compression strength on the P-wave velocity in the test samples, where $\sigma_s = 0.0067C_p - 7.75$ and the regression $R^2 = 0.85$ (Fig. 2);

—the equations of the linear, logarithmic and exponential dependence of the static elasticity E_s and dynamic elasticity E_d (curves *1*, *2* and *3* in Fig. 3, respectively):

$$E_s = 0.157E_d - 1.1 \quad (R^2 = 0.88),$$

$$E_s = 1.3\ln(E_d) - 0.2 \quad (R^2 = 0.87),$$

$$E_s = 0.76E_d^{0.55} \quad (R^2 = 0.83).$$

CONCLUSIONS

The strength, elasticity and deformation of the same grade backfill samples depend on their density and humidity. There is a consistent pattern between the strength, elasticity and deformation properties determined in the static and dynamic tests of the same humidity samples. As a result, simple linear dependences have been obtained at a high correlation factor. The application of the dependences can improve the speed and reduce the labor content of the strength, elasticity and deformation testing of backfill at any stage of its undermining. However, these dependences need being adapted to different humidity of backfill, which calls for additional research.

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