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Composite cement materials for structures foundation strengthening

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Abstract. There was a development of composite cements (CC), that include aluminosilicates (AS), obtained by enrichment of ash-to-slag mixture (up to 65 wt. %), cement clinker, and gypsum. Based on the developed CC, wide range of injection mortars, including crushed granite, was created. Injection mortars are capable of effectively fixing of underground structures foundations soils, providing high strength (25.6 MPa) with deformation modulus 10.1 GPa. These materials have percentage of water separation from 22.5 % at W/B=1 to 36.5 % at W/B=2. Viscosity indicators of these materials indicate high penetrating ability, since time for mortars to flow through Marsh viscometer is 39 and 33 seconds at W/B=1.5 and W/B=2, respectively. Effect of increasing density of injection mortars at 28 days was maximum at AS dosage of 45 wt. %, then it decreased with aluminosilicate content increase. There are high ratios of strength values on second day to those in grade age: for compressive strength 0.24 (0.20–0.22 for additive-free clinker compositions), for flexural strength 0.16 (0.15 for additive-free compositions; with AS content increase above 45 %, this ratio decreases to 0.14). High early strength makes it possible to effectively use injection mortars for urgent fixing of soils during the repair of underground structures.

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1. Introduction

As a result of the analysis of literature data and our own surveys, the emergency state of many underground structures was established [1–4]. There is an obvious importance of restoring the functional suitability of these facilities, including for the possibility of dual-use operation, which requires a set of repair measures using new building materials (including for fixing soils). It has been established that only the strengthening of load-bearing walls while maintaining weak foundation soils is not effective. Injection fixing of soils with cementing compounds can significantly improve the technical characteristics of the foundations, which will contribute to the comprehensive repair of underground structures.

Strengthening of soils containing an underground object (plugging) consists in the formation of an injected volume that can effectively withstand external pressure [5, 6]. The dimensions of this volume are calculated taking into account the current bearing capacity of the structures of the underground facility and the type of injection mortars used [7, 8].

Harcenko et al. [7], Svintsov et al. [8], Salamanova et al. [9] were engaged in the development of materials and improvement of soil strengthening technologies. The classification of soil strengthening methods is shown in Fig. 1.

Constructive methods for strengthening soils are quite complex and time-consuming [10]. Injection solutions based on various composite binders [11–13] are very promising for consolidating soils. Soil reinforcement is carried out by introducing special reinforcing elements into the soil in the form of tapes or solid mats made of geotextiles (less often, metal reinforcement) [14]. Sheet piling is a solid wall composed of identical elements connected to each other. In this regard, big data is important in predicting the climate resistance of building materials, especially for air temperature and humidity [15]. The construction of embankments (lateral surcharges) is carried out, as a rule, from coarse-grained or sandy soils [16]. Gavrilov and Kolesnikov [17] studied evolving crack influence on the strength of frozen sand soils.

Mechanical methods of fixing soils are divided into surface and deep ones [18]. Deep compaction of soils by drilling holes (soil piles) consists in the fact that holes are pierced in the compacted massif with an impact projectile, with the soil displaced to the sides and the creation of compacted zones around them [19, 20]. Drilling wells with explosions allows for a higher degree of soil compaction, but at the same time, labor intensity and danger increase [21]. Deep vibration compaction (hydrovibrocompaction) is used for compaction of loose sandy soils of natural occurrence, as well as when laying bulk non-cohesive soils, backfilling, etc. [22]. Soil compaction by preliminary soaking and soaking with deep explosions is carried out in a pit with a depth of 0.8 m and a width equal to the thickness of the subsidence soil layer, but not less than 20 m [23, 24].

Physical methods of soil strengthening involve the use of complex and scarce equipment. Thermal fixing of the soil is a transformation of structural bonds in the soil under the influence of high temperatures [25]. Electrochemical fixation is based on the phenomenon of electroosmosis, which means that when a direct current is passed through clay soil, the latter loses cohesive water, which moves (migration) towards the negative electrode (cathode) [26]. The soaking method has limited application and is used only for loess bases [27, 28]. Preliminary soaking of loess bases destroys the loess structure and causes it to sag under its own weight, i.e. the compaction process takes place. Dewatering provides a decrease in the level of groundwater below the bottom of the future excavation [29].

Soil freezing is used in heavily water-saturated soils [30]. To fix dispersed soils with a filtration coefficient kf = 0.01–0.1 m/day, the electrosilication method is used [31–33].

The most effective way to fix soils is injection cementing compositions, which can significantly improve the technical characteristics of the bases. Unlike compaction methods and complex physical methods, injection fixing of soils does not significantly affect their structure. With injection fixing, the introduced compositions form strong structural bonds in the soil massif. As a result of this, an increase in the strength of soils, a decrease in their compressibility, a decrease in water permeability and sensitivity to changes in the external environment, especially humidity, are provided.

The aim of the work is the development of injection mortars and their study for fixing subsiding soils. To achieve this aim, the following tasks were solved:

1. Conduct a sedimentation analysis of mortars to determine the percentage of water separation and viscosity indicators.
2. Determine the effect of increasing the density of the injection solutions on composite cement.
3. Study the early strength of the injection mortars.
4. Determine the potential for consolidating the foundation soils of underground structures with the developed injection mortars.

2. Materials and Methods

2.1. Raw materials characterization

Portland cement clinker (Spasskcement, Spassk-Dalniy, Russia) served as the basis for composite cement (Fig. 2a, Table 1). As a component of composite cement (CS), aluminosilicates (AS) were used, extracted from ash and slag mixtures (ASM) of the Primorskaya Thermal Power Plant by enrichment by flotation and magnetic separation (Fig. 2b). To regulate the setting time, ground gypsum stone (gypsum dihydrate) was added in an amount of 5 % by weight of the clinker (Fig. 2c).

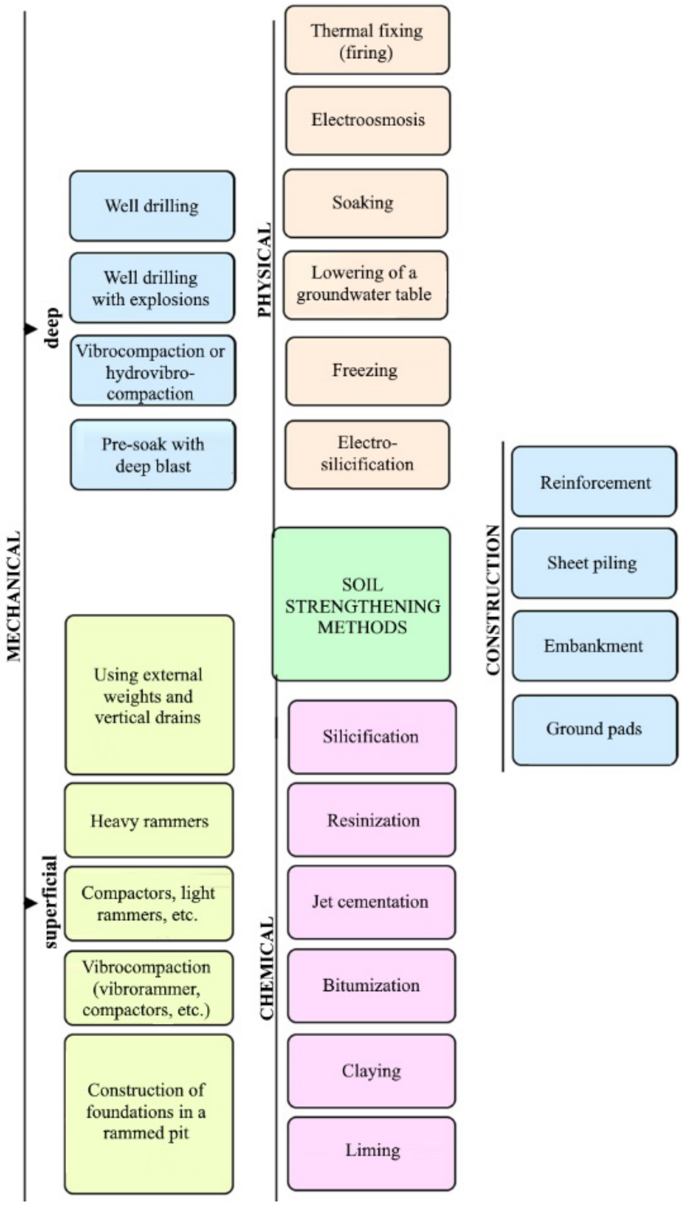
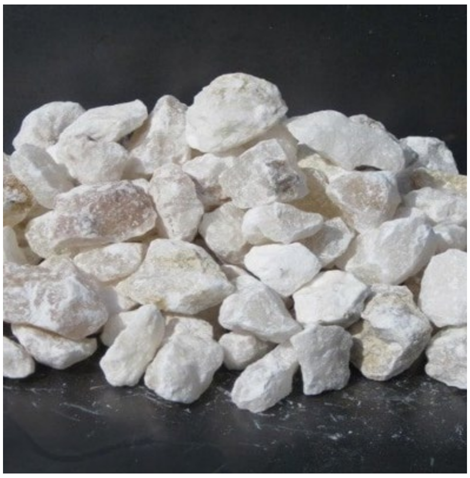


Figure 1. Soil strengthening methods.

a) 

b) 



c)

Figure 2. CC components: a) Portland cement clinker, b) aluminosilicates, c) dihydrate gypsum.

Table 1. Composition of the clinker, % wt.

Chemical content						Mineral content			
CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO_{free}	C_3S	C_2S	C_4AF	C_3A
64.5	22.6	6.4	3.8	1.8	0.9	57.5	23.6	16.8	2.1

The fine aggregate was used from screenings of crushed granite (GCS) (Vostokcement, Spassk-Dalniy, Russia) with fineness module 0.7 (Fig. 3).

Figure 3. Appearance of granite crushing screening.

Polycarboxylate superplasticizer (SP) used to reduce water-cement ratio.

Thus, the materials selected for research are local and often waste products, which is economically and environmentally promising.

2.2. Mix design

At the first stage, from the selected components listed in Fig. 1, a line of composite cements was created, obtained by joint grinding in a vibratory mill to a specific surface area of 450 m^2/kg (Table 2).

Table 2. Compositions and activity of composite cements.

Miz ID	Content				Activity, MPa 28 days	Increase in activity in relation to control, %
	Binder base, wt. %		Gypsum, % by weight of clinker	SP, % of CC wt.		
	Clinker	AS				
C1	100	–	5	–	45.9	–
C2	100	–	5	–	55.,2	17
CC-15*	85	15	5	0.25	56.7	24
CC-25	75	25	5	0.5	59.2	29
CC-35	**65**	**35**	**5**	**0.75**	**67.7**	**47**
CC-45	55	45	5	1	61.2	33
CC-55	45	55	5	1.25	56.1	22
CC-65	35	65	5	1.5	51.6	12

From the developed composite cements, a wide range of injection mortars from composite cements ground to a specific surface area of 450 m^2/kg was developed (Table 3). As a fine aggregate, polyfractional granite screenings with a fineness modulus of 0.7 were used. The level of replacement of clinker by the aluminosilicate component varied from 45 to 65 wt. %. The water-binder (W/B) ratio varied within 1.0–2.0. The ratio “binder : filler” was 1 : 3.

Table 3. The injection mortars.

Mix ID	Consumption, kg/m^3					W/B
	Clinker	AS	Gypsum	Water	GCS	
IM1(C2)	450	–	22,5	472.5	1350	1.0
IM2(C2)	450	–	22,5	708.8	1350	1.5
IM3(C2)	450	–	22,5	945	1350	2.0
IM4(CC-45)	247.5	202.5	12,4	464.4	1350	1.0
IM5(CC-45)	247.5	202.5	12,4	696.6	1350	1.5
IM6(CC-45)	247.5	202.5	12,4	928.8	1350	2.0
IM7(CC-55)	202.5	247.5	10.1	460.1	1350	1.0
IM8(CC-55)	202.5	247.5	10.1	690.1	1350	1.5
IM9(CC-55)	202.5	247.5	10.1	920.2	1350	2.0
IM10(CC-65)	157.5	292.5	7.9	457.9	1350	1.0
IM11(CC-65)	157.5	292.5	7.9	686.8	1350	1.5
IM12(CC-65)	157.5	292.5	7.9	915.8	1350	2.0

2.3. Equipment and methods

2.3.1. Materials morphology

To study the Portland cement mineral composition, a D8 Advance AXS X-ray powder diffractometer (Bruker, Billerick, USA) was used (wavelength λ = 1.5418 Å) using Rietveld refinement. The percentage of oxides and minerals in the Portland cement was determined by the standard method of X-ray fluorescence analysis.

2.3.2. Granulometry

The specific surface of bulk raw materials was studied using a PSH-11 device (Khodakov Devices, Moscow, Russia). The granulometry of the particles of the raw materials was evaluated using a laser analyzer Analysette 22 (Fritsch, Idar-Oberstein, Germany).

2.3.3. Fresh properties

The slump of the concrete mix is determined by laying a metal ruler with an edge on the top of the cone and measuring the distance from the lower edge of the ruler to the top of the concrete mixture with an error of up to 0.5 cm. The slump flow of the concrete mix is determined by measuring the diameter of the spread paste with a metal ruler in two mutually perpendicular directions with an error of not more than 0.5 cm. The viscosity was determined by the flow time of the mortar through a Marsh viscometer.

2.3.4. Physical and mechanical properties

The value of the average density of the samples was calculated by dividing the mass by the volume. The compressive strength was determined according to the standard method of the Russian standard on cubes with an edge of 70 mm. The flexural strength was determined by the three-point method on specimens of prismatic shape 40 × 40 × 160 mm.

2.3.5. Study of soil concrete

The mechanical properties of soil concrete (compressive strength and modulus of deformation) were evaluated on cylinder samples of soil concrete (sandy hard loam) with a diameter of 200 mm and a height of 400 mm with an artificial structure.

3. Results and Discussion

3.1. Fresh properties

Due to the high water-binding ratio, cast mortars were obtained, which are effective for the convenience of injection fixing of soils (Table 4).

Table 4. Indicators of viscosity and sedimentation of injection mortars.

Mix ID	Viscosity, s	Sedimentation over time in minutes, %							
		15	30	45	60	75	90	120	150
IM1	37	0	0.5	8.5	16.5	19.5	27.5	29.5	34.5
IM2	35	0.5	1.5	9.5	17.5	18.5	26.5	28.5	33.5
IM3	32	1	2	10	18	19	27	29	34
IM4	40	0.5	1	9.5	15.5	18.5	21.5	20.5	22.5
IM5	39	0	1.5	2	5.5	10.5	15.5	18.5	24.5
IM6	33	1	1.5	10.5	16	18.5	26.5	27.5	30.5
IM7	37	1	2	10	18	19	27	29	34
IM8	36	2	3	11	17	18	26	28	33
IM9	35	2.5	3.5	9.5	17.5	18.5	26.5	28.5	33.5
IM10	35	2.5	3.5	11.5	19.5	20.5	28	30	33
IM11	34	3	4	12	20	21	29	31	36
IM12	32	3.5	4.5	12.5	20.5	21.5	29.5	31.5	36.5

According to the sedimentation analysis of the mortars, it can be seen that these materials have a percentage of water separation from 22.5 % at W/B = 1 to 36.5 % at W/B = 2. At the same time, the viscosity indicators of these materials indicate a high penetrating ability, since the time of the expiration of solutions through the Marsh viscometer for mortars IM5 and IM6 is 39 and 40 seconds at W/B = 1.5 and W/B = 2, respectively.

An increase in the density of the mixed mixture with an increase in the content of the aluminosilicate component in the composite cement was established (Table 5). This picture is explained by the filling of voids formed in the process of volume reduction during hydration with finely dispersed particles of finely ground CC.

Table 5. Development of the injection mortars density.

Mix ID	Fresh mix average density, kg/m^3	Average density at 28 days, kg/m^3
IM1	2048	2062
IM2	2050 (+ 0.1 %)	2064 (+ 0.1 %)
IM3	2052 (+ 0.2 %)	2066 (+ 0.2 %)
IM4	2112 (+ 3.1 %)	2190 (+ 6.2 %)
IM5	2113 (+ 3.1 %)	2192 (+ 6.3 %)
IM6	2116 (+ 3.2 %)	2196 (+ 6.5 %)
IM7	2128 (+ 3.9 %)	2138 (+ 3.7 %)
IM8	2132 (+ 4.1 %)	2126 (+ 3.1 %)
IM9	2136 (+ 4.3 %)	2132 (+ 3.4 %)
IM10	2149 (+ 4.9 %)	2072 (+ 0.5 %)
IM11	2154 (+ 5.1 %)	2074 (+ 0.5 %)
IM12	2159 (+ 5.3 %)	2070 (+ 0.4 %)

The consequences of an increase in the density of injection mortars based on composite cement at the age of 28 days were maximum at a dosage of AS of 45 % by weight, then it decrease with an increase in the content of the aluminosilicate in the mixes.

3.2. Compressive and flexural strength

The effect of increase in compressive strength of injection mortars based on composite cement was maximum at an AS dosage of 45 % by weight, and at the same time it was the maximum effect for assessing early strength, in particular, at the age of 2 days, an increase in strength indicators during compression compared to the composition without additives was 25 %, and with a bend of 50 %. This also realizes high ratios of strength properties on the second day to comparable indicators at grade age: for compressive strength 0.24 (0.20–0.22 for clinker compositions without additives), for flexural strength 0.16 (0.15 in non-additive clinker compositions). High early strength allows to quickly apply injection mortars for urgent fixing of soils in the process of repairing underground structures (Table 6).

By day 7, the growth rate of strength properties stabilizes to some extent, however, it remains in comparison with the control composition: 6 % and 8 % for compressive and flexural strength. At the same time, the ratio of flexural and compressive strength at this age (0.12) corresponds to a similar characteristic of additive-free compositions, despite the replacement of Portland cement clinker up to 65 wt. %. The ratio of flexural and compressive strengths at different ages can characterize the development of the material's crack resistance. For a rationally developed composition of IM5, it is: on the second day 0.16; in sevenths 0.12; at a grade age of 0.13, which is not only not lower than these characteristics for traditional Portland cement concretes but even exceeds them for some of the obtained materials.

As it was found, the strength development of cement materials based on composite cements is carried out more intensively than that of non-additive compositions due to the positive effect of the superplasticizer and polymineral components, helping to reduce water demand and intensify the hydration of clinker minerals and heat generation. Compaction of the microstructure leads to a decrease in capillary porosity and, accordingly, the permeability of the material for liquids and gases. In turn, this leads to an increase in the entire range of performance and durability.

Thus, the developed injection mortars are able to provide the necessary degree of strengthening of subsiding soils.

3.3. Strengthening of load-bearing structures with developed mixes

The main strength and deformation characteristics of the injection-fixed soils of the foundations of buildings and structures are the compressive strength and the deformation modulus.

To determine these characteristics, at first the properties of soil concretes obtained by injecting solutions into soil cylinder samples (sandy solid loams) with an artificial structure were to be determined. This is explained by the fact that when fixing soils, physical and chemical processes occur mainly in the microaggregate part of the soil. Moreover, the strength characteristics of soil-concrete specimens with natural and artificial structures are practically the same and comparable. It should be noted that it is easy and simple to manufacture samples with an artificial structure in any size and in large quantities, and it is also possible to model soil bases of various configurations, taking into account the requirements of the standard for testing artificial materials (Table 7).

Table 6. Mechanical properties of the developed shotcrete.

Properties	IM1	IM2	IM3	IM4	IM5	IM6	IM7	IM8	IM9	IM10	IM11	IM12
Compressive strength, MPa												
2 days	17.9	17.3 (– 3%)	17.0 (– 5 %)	21.5 (+ 20%)	22.4 (+ 25 %)	19.3 (+ 8 %)	22.1 (+ 23 %)	21.5 (+ 20 %)	21.2 (+ 18 %)	21.9 (+ 22 %)	20.8 (+ 16 %)	19.7 (+ 10 %)
7 days	31.7	30.8 (– 3 %)	30.6 (– 3 %)	32.4 (+ 2 %)	33.7 (+ 6 %)	31.5 (–1 %)	33.5 (+ 6 %)	32.8 (+ 3 %)	32.1 (+ 1 %)	32.3 (+ 2 %)	31.6 (– 1 %)	31.2 (– 2 %)
28 days	54.1	5.,8 (– 1 %)	55.0 (– 2 %)	61.2 (+ 13 %)	68.1 (+ 26 %)	63.3 (+ 17 %)	67.0 (+ 24 %)	67.4 (+ 25 %)	69.1 (+ 28 %)	61.3 (+ 13 %)	67.3 (+ 25 %)	65.2 (+ 20 %)
R^{2}_{com}/ R^{28}_{fl}	0.33	0,32	0.31	0.35	0.33	0.30	0.33	0.32	0.31	0.36	0.31	0.30
Flexural strength, MPa												
2 days	1.8	1.7 (– 6 %)	1,6 (– 12 %)	2.6 (+ 44 %)	2.7 (+ 50 %)	1.9 (+ 6 %)	2.2 (+ 22 %)	2.2 (+ 22 %)	2.2 (+ 22 %)	2.2 (+ 22 %)	2.1 (+ 17 %)	1.9 (+ 6 %)
7 days	3.8	3.7 (– 1 %)	3,7 (– 1 %)	3.9 (+ 1 %)	4.1 (+ 8 %)	3.8	4.0 (+ 5 %)	3.9 (+ 1 %)	3,.9 (+ 1 %)	3.9 (+ 1 %)	3.8	3.7 (– 1 %)
28 days	7.0	7.0	7,1 (+ 1 %)	8.0 (+ 14 %)	8.6 (+ 23 %)	7.6 (+ 9 %)	8.0 (+ 14 %)	8.1 (+ 16 %)	8.3 (+ 19 %)	8.0 (+ 14 %)	7.8 (+ 11 %)	7.3 (+ 4 %)
$R_{fl.}/R_{com.}$, 2 days	0.10	0.10	0.09	0.12	0.12	0.10	0.10	0.10	0.10	0.10	0.10	0.10
R^{2}_{fl}/ R^{28}_{fl}	0.26	0.24	0.23	0.27	0.32	0.25	0.28	0.27	0.26	0.28	0.27	0.26
$R_{fl.}/R_{com..}$, 7 days	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
$R_{fl.}/R_{com..}$, 28 days	0.13	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.12	0.12

Table 7. Strength and deformation properties of soil concrete.

Mix ID	Compressive strength, MPa	Deformation modulus, MPa
IM1	10.1	2100
IM2	11.3	3200
IM3	12.4	3700
IM4	22.3	9300
IM5	25.6	10100
IM6	24.3	9700
IM7	19.1	7600
IM8	20.6	8100
IM9	18.7	7100
IM10	14.2	5800
IM11	15.3	6200
IM12	13.1	4200

Dependence of the deformation modulus on the strength of soil concretes of two different types (sandy hard loams and semi-solid loams fixed with the developed injection mortars) is shown in Fig. 4. The graph shows that the greater the strength index of soil concrete is, the higher its modulus of deformation is. At the same time, it should be noted that the most important factor influencing the strength and deformation properties of soil concrete is the percentage of AS and W/B of the mortars with which these soils are fixed.

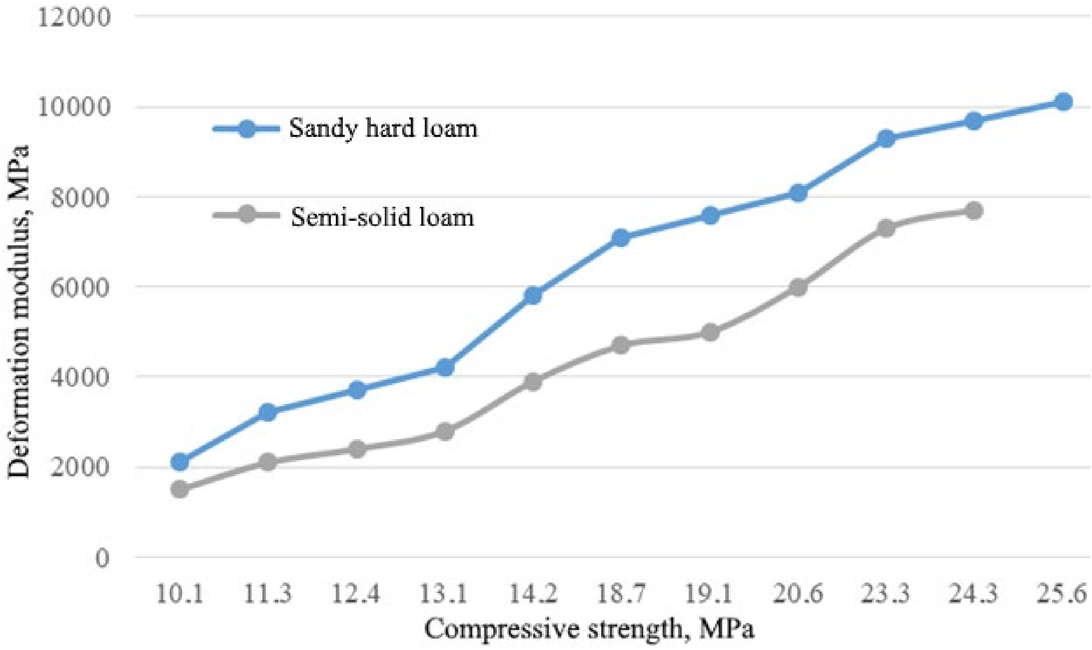


Figure 4. Dependence of the deformation modulus on the strength of soil concrete.

The mechanism of structure formation of fixed soils, which consists in the elimination of reversible transitional contacts that can quickly collapse in the process of wetting, with the formation of stronger phase contacts of the cementation type, leading to an increase in structural strength, has been studied.

Thus, the developed injection mortars are able to effectively fix the soils of the bases of underground structures, providing the strength of the soil-concrete mass up to 25.6 MPa with a deformation modulus of 10.1 GPa.

4. Conclusions

Consolidation of subsidence soils is an important practical scientific and technical task, which makes it possible to carry out construction and repair work on weak (subsidence) base soils. Injection mortars were developed and their research was carried out to strengthen underground structures, as a result of which the following conclusions were obtained:

1. According to the sedimentation analysis of mortars, it can be seen that these materials have a percentage of water separation from 22.5 % at W/B = 1 to 36.5 % at W/B = 2. At the same time, the viscosity indicators of these materials prove a high penetrating ability, since the time of the expiration of mortars through the Marsh viscometer for mortars IM5 and IM6 is 39 and 33 seconds at W/B = 1.5 and W/B = 2, respectively.
2. The effect of increasing the density of injection mortars on composite cement at the age of 28 days was maximum at an AS dosage of 45 % by weight, then it decreased with an increase in the content of the aluminosilicate component.
3. There are high ratios of the values of strength properties on the second day to those in the grade age: for compressive strength 0.24 (0.20–0.22 for additive-free clinker compositions), for bending strength 0.16 (0.15 for additive-free clinker compositions; at the same time, with an increase in the AS content above 45 %, this ratio decreases to 0.14). High early strength makes it possible to effectively use injection solutions for urgent fixing of soils during the repair of underground structures.

The developed injection mortars are capable of effectively fixing the foundation soils of underground structures, providing the strength of the soil-concrete mass up to 25.6 MPa with a deformation modulus of 10.1 GPa.

The developed injection solutions showed improved characteristics (by 15–35 %) in terms of percentage of water separation, viscosity, penetrating ability, density, strength, and deformation modulus compared to modern results of world-class authors [27–31].

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