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CONSTRUCTION OF DURABLE ROADSROM ROLLED CONCRETE BASED ON BELITE SLAG CEMENT AND BINDERS

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ABSTRACT: Roads for wheeled vehicles are one of the main types of transportation infrastructure required for economic activity. The construction of road pavements with cement concrete requires the use of modern, expensive concrete-laying machines. The complexity of this construction technology can be an impediment to using these materials. The main reason for the complexity of the technology, is the use of traditional Portland cement, with a fast-setting time. This paper presents a study of the strength properties of belite cement. The samples were investigated under normal conditions, at constant low positive and negative temperatures according to the specified curing regimes. The results of the study show that the development of the strength of belite cement can exceed conventional concrete. Concrete based on belite binder at 90 days has similar strength as conventional concrete. While the conventional concrete stopped gaining strength at 30 days, the strength of the slag concrete based on belite cement binder continued to increase for 15 months.

Keywords: Auto Road, Belite cement, Asphalt binders, Construction, Reconstruction, Phosphorus slag

1. INTRODUCTION

Currently, due to changes in the composition of traffic and an increase in the load capacity of motor vehicles, the service life of road surfaces has been sharply reduced. Pavements made of asphalt concrete are considered to last up to 5-6 years and those made of cement concrete can last up to 25 years [1-2]. Also, the low rate of reconstruction and construction of new roads, according to outdated standards, designed for 20 years [3], does not allow for avoiding the annually increasing costs of road repairs. And in turn, the effective functioning and sustainable development of roads in modern conditions become important factors in the transition to economic recovery and improvement of the quality of life [4-5]. Therefore, the search for a solution to building durable roads is an open one.

A review of the literature shows that most of the existing studies have focused on reducing production costs by co-milling clinker and various industrial waste slags that have been heat-treated. For example, the production of belite (C2S) is less energy intensive (25% lower) and emits 10-15% less CO2 compared to alite (C3S) [6].

Other work [7] presented the influence of different curing temperatures on the hydration of belite-calcium sulfoaluminate cement. The hydration kinetics and the hydrated phase assemblages were studied by isothermal calorimetry, X-ray powder diffraction, differential thermal analysis, and thermogravimetric analysis, as well as field emission scanning electron microscopy.

So, the laboratory study [8] investigated the influence of different cooling regimes on the microstructure and consequent reactivity of belite-sulfoaluminate clinkers. Clinker reactivity was studied using isothermal calorimetry and was additionally investigated through compressive strength, which was determined for the cement prepared from the synthesized clinkers.

The authors [9] considered the mechanical properties, phase composition, and microstructure of HBC and quartz sand have been analyzed at high temperatures, to optimize the amount of sand and provide guidelines for further exploring the application of HBC in high-temperature oil and gas well cementing. The experimental results show that the high-temperature mechanical properties of the cement stone mixed with 40% quartz sand are the highest, thus, delaying the decline in the strength to the greatest extent.

Laboratory studies are mainly limited to a set of strengths up to 28 days, while the difference in road construction, where the calculation of loads and strength of the foundation is carried out for 15 years or more, considering the intensity of road transport. It follows from this that the strength of the concrete base should reach its maximum in 15 years [4]. All the time the pavement perceives and is under the dynamic, oscillatory, impact load from the traffic [10]. In contrast to point construction (man-made structures and buildings) where the main load is static and designed to hold the weight. Concretes in road construction as a rule is in the zone of soil freezing and work from +30 to -15 C and standard tests in ideal conditions +20c for strength in the laboratory do not give a complete picture [11-12].

As opposed to Portland cement, during the hydration of slag binders based on granular slag, the main product of hydration of two-calcium hydrosilicate C2S-belite, gel-like calcium hydrosilicates of C-S-H type are formed, and the presence of other crystalline hydrates is insignificant. The structure of mineral stone of slow-hardening binders differs from the structure of cement stone by the fact that in the latter hardening occurs due to the coalescence of crystalline hydrosilicates filled [13] in the gaps with calcium hydrosilicate gel, and in the former, due to consolidation of gel-like calcium hydrosilicates, having in its volume some number of crystalline hydrates [14]. Based on the above data, we can conclude that the hydration of these binders occurs in the following sequence: slag glass → gel-like accumulations →C-S-H [15].

The road binders used for monolithic cement concrete and asphalt concrete must be adjusted to their chemical and mineralogical compositions so that their properties meet the following requirements [16]:

- technological modes, considering the specifics of continuous line-and-line road construction production.
- resistance and self-repairability of roads in conditions of increasing intensive dynamic traffic and seasonal changes in temperature and humidity stress the state of road structures during multiyear operation of roads.

2. RESEARCH SIGNIFICANCE

Technological complexities of road pavement layers are solved by their arrangement from rigid rolling concretes, based on slow-hardening binders. In this work, the preparation of belite cement was carried out by grinding together phosphorus-granulated slag with cement dust. The regularities of the formation of the structure of belite cement at different temperatures have been established. Studies of slow-curing slag binders during long periods of hardening have shown that structure formation is provided by colloidal hardening. These results allow the construction and long-term operation of highways from road concrete on their basis. In this case, high manufacturability during construction including at low temperatures.

3. MATERIALS AND METHODS

Belite cement was prepared by grinding together phosphate granulated slag with cement dust in laboratory ball mills (Fig.1) to a fineness characterized by a residue on the sieve 0.08 mm not more than 15% or to a specific surface not less than 3000 cm^2 / g (Fig.2). Before milling, the phosphate granulated slag was dried to a constant weight at a temperature not exceeding 105° C.

Fig.1 Shelf milling drum

Fig.2 Ground phosphorus slag 0.08 mm

The preparation of samples to determine the strength properties of belite cement was carried out by pressing the binders at optimum moisture content, which more realistically reflects the conditions of formation and hardening when they are used in monolithic rolling road concrete [12].

To dry the material, a laboratory drying cabinet was used for drying, heating, thermosetting, and heat treatment of various materials and products in an air environment.

Then the mixture was transferred into a spherical shutter bowl for further milling of the material. The study of strength and deformation characteristics of belite cement was carried out on samples - beams of size 40x40x160 mm and cylinders with a diameter and height equal to 50 mm. The samples were formed according to the standard method by compaction on the press in metal forms with double-sided inserts under the load of 15 MPa and the time of its application was within 3 minutes. The strength, deformation properties, and frost resistance of road concrete based on slow-hardening belite cement were studied on beam specimens 100x100x400 mm in size and cylinder specimens 100 mm in height and diameter.

The concrete mixture was compacted on a hydraulic press under a load of 20 MPa for 3 min. The number of specimens was at least three, for each type of test, based on the repeatability in measurement, which ensures the reliability of the experiment equal to 0.95 with a relative error equal to 3σ.

The mixture was poured through a funnel into a mold which was placed under the hydraulic press and maintained in compression at a loading of 30 kN for 3 minutes.

The pressed sample was removed from the hydraulic press by unscrewing the hand wheel on the press control and the cylinder sample was placed in the frame to remove the molding support from it.

After removing the sample cylinder from the molding support (matrix) the dimensions of the sample cylinder were checked with a caliper (height, diameter, it should be 50 mm in diameter and 50 mm in height according to the standards) and then the finished weight of the resulting sample-cylinder was weighed. The samples were stored before the test in the baths with a hydraulic seal, conditionally accepted as normal conditions.

According to the normative documents, it is allowed to use cement-strengthened soils at low temperatures of +5 to -100 C, and when strengthened with slag binders only at positive air temperatures. Therefore, the first stage of the study examined the effect of low positive and low negative temperatures (down to -100C, typical for the winter period of the fifth road and climatic zone) on the properties of slag binder during its hardening.Some of the samples were kept under normal conditions, the other samples were kept at constant low positive or negative temperatures according to the specified curing regimes in temperature controlled chambers.

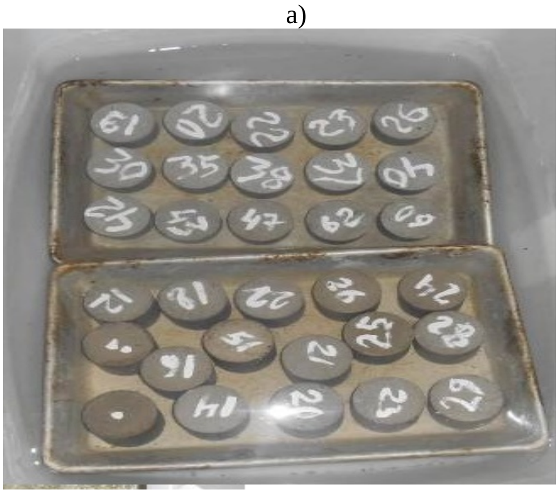
Some samples were placed in cooling chambers immediately after preparation, others, after preliminary incubation at positive temperatures. In addition, one series of samples was kept under conditions of periodic changes in temperature over time, that is, with a gradual decrease from +5 to -10°C, then with an increase from -10 to +5°C, and after this cycle was completed, the samples were placed in baths with a hydraulic shutter.

The duration of the terms of exposure of these samples at certain temperatures was established by averaged data on the occurrence and duration of average daily multiyear air temperatures, typical for areas of Kazakhstan, located in the fifth climatic zone of the road.

The actual duration in a year of low temperatures from 0°C to -10°C is 140-150 days, for laboratory research and convenience of comparison with the control samples (Fig.3) curing under normal conditions, 150 days with an interval of not less than 15 or 30 days were accepted.

When storing the samples in cold storage chambers, they were wrapped in polyethylene film to exclude moisture freezing. Before testing, the samples were thawed for at least 4 hours in wet sand. At first, specimens-beams were tested for bending tension, and specimen halves were tested for compression. Then, under loads of 0.2-0.4 of the bending tensile strength, the elastic deflection value was set on three beams and the elastic modulus of the material was determined.

a)



b)

Fig.3 Samples for testing: a) sample b) samples during the test

To study the physical and chemical processes occurring during the hardening of slag binder, after the strength test, samples were taken from the middle of the samples for petro-, X-ray thermographic, and electron microscopic analyses [17-18]. Immediately after sampling, the samples were ground in an agate mortar and treated with ethyl alcohol and ether to remove free water from the system. Differential thermal analysis (DTA) was performed on a Hungarian derivatograph with a heating rate of 10° per minute at a weight sensitivity of 500 mg and sample weights of 0.5-1.0 g.

The analysis was carried out in platinum crucibles. As a reference sample was used calcined aluminum oxide Al_2O_3. Part of the thermographic research was carried out on a thermographic unit with a heating rate of 100° per minute at a sample weight of 0.01g. The analysis was performed in ceramic crucibles. The mineralogical composition was studied by X-ray phase analysis performed on an X-ray apparatus using a copper anode at an anode current of 10 μA and a tube voltage of 35 kV. The radiographs were recorded on a standard chart tape at a rate of 2 degrees per minute. The sample was placed in a flat cuvette 1.5 mm thick. Literature data on thermography and radiography were used to transcribe the thermographic and radiographic images.

Mineralogical and petrographic studies were carried out with a microscope. The products of hardening were studied in immersion preparations and in transparent thin sections. Due to the strong hygroscopic nature of the material [19], a liquid paste mixed with alcohol was prepared from the binder powders, which was applied with a thin layer to the slide and then dried [20]. Further preparation and viewing of immersion preparations were performed according to the generally accepted technique. Kerosene was used to prepare transparent slides. Counting the content of components was carried out in thin sections under a microscope by the point method. The essence of the method is that in polished thin sections many observation points were evenly distributed under a microscope on a square grid.

At the same time, the number of points on each mineral was counted. According to the theory of probability, these numbers are proportional to the volumes occupied by the corresponding minerals in the thinning. At calculation, the method of fields is accepted. For this purpose, a mesh eyepiece was used, in which the total number of crossings of threads (knots) is equal to 400. In each field, the number of points (knots) falling on a certain mineral was counted.

Viewing of 10 fields in the slate was provided with sufficient reliability of quantification. Within one field of view, the counting of grains was carried out 3 times. The average content of a mineral for the given field was determined. The total number of fields for each thin sheet, on which the volumetric content of the glass phase was determined, was equal to 10. Thus, the average percentage content of the mineral was determined by 30 counts, which increases the accuracy of the conclusion of averages.

4. RESULTS AND DISCUSSION

Tables 1-2 show the test results of several samples number: 5, 6, 7, and 8 in comparison with samples number 2, constantly hardening in normal heat and humidity in the laboratory conditions, in baths with a water trap.

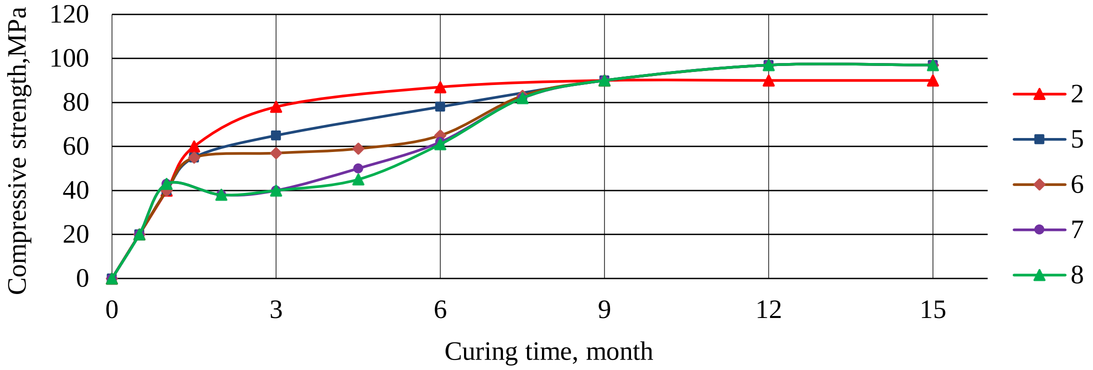
Table 1 Results of testing samples

Specimen samples	Month															
	0.5	Average	1	Average	1.5	Average	3	Average	6	Average	9	Average	12	Average	15	Average
	Compressive strength, MPa															
	17.5		38.9		59.7		77.4		88.1		91.5		90.7		91.8	
No. 2 at normal conditions	19.3	19.4	41.3	40.3	61.8	60.0	75.9	77.9	86.4	86.6	90.2	89.9	91.2	90.7	92.3	92.5
	21.3		40.7		58.6		80.5		85.2		88.1		90.2		93.4	
	18.7		41.9		55.4		66.7		78.6		92.2		97.6		99.1	
No. 5 at +5 °C	20.3	20.4	42.4	41.4	52.3	53.8	65.3	66.4	76.8	78.2	88.5	89.5	98.1	97.4	97.3	98.2
	22.1		39.8		53.7		67.1		79.1		87.9		96.5		98.3	
	19.6		42.1		54.6		56.7		59.6		92.1		97.3		99.1	
No. 6 at 0 °C	21.2	19.8	40.3	40.7	55.8	54.5	60.1	58.7	60.2	60.4	90,7	91.4	98.2	97.3	95.3	97.6
	18.7		39.8		53.2		59.2		61.5		91.3		96.5		98.3	
	20.6		42.6		37.3		39.5		62.2		90.7		97.3		98.5	
No. 7 at -5 °C	21.1	20.0	43.8	43.7	36.6	37.7	41.2	39.8	61.9	61.9	91.2	90.1	98.1	97.4	95.6	97.2
	18.4		44.6		39.1		38.7		61.5		88.4		96.9		97.6	
	19.3		43.3		37.6		40.1		60.3		91.1		98.8		97.4	
No. 8 at -10 °C	20.3	20.6	44.5	43.3	35.8	37.2	39.8	40.7	61.1	60.4	90.3	90.4	97.1	97.4	97.3	97.6
	22.3		42.1		38.3		42.1		59.8		89.9		96.2		98.1	

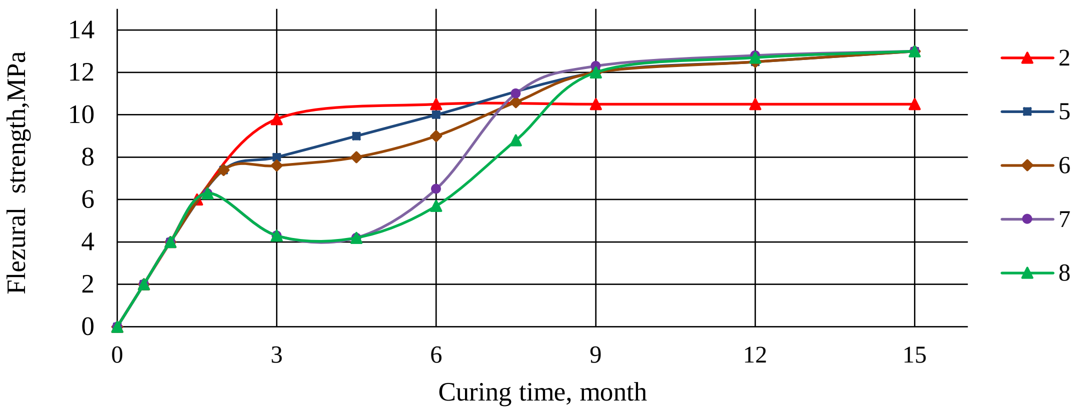
Table 2 Results of tensile strength

Specimen samples	Month: 0.5	Average	1	Average	1.5	Average	3	Average	6	Average	9	Average	12	Average	15	Average
	Tensile strength at bending, MPa															
No. 2 at normal conditions	2.3		4.1		6.1		9.9		10.8		10.6		10.7		10.2	
	1.9	2.1	3.9	4.1	6.5	6.2	10.0	9.8	11.0	10.6	11.0	10.6	10.9	10.6	10.8	10.5
	2.1		4.2		5.9		9.6		10.1		10.2		10.1		10.5	
No. 5 at +5 °C	1.8		4.3		5.7		8.1		9.8		12.0		12.6		12.9	
	2.2	2.0	4.1	4.1	6.4	6.0	8.3	8.1	9.6	9.9	12.2	12.0	12.3	12.6	13.5	13.2
	2.0		3.8		6.0		7.8		10.2		11.8		12.9		13.2	
No. 6 at 0 °C	1.7		3.7		5.9		7.7		9.1		12.1		12.6		13.1	
	1.9	1.9	4.3	4.0	5.7	5.9	7.3	7.6	9.3	9.1	11.9	12.1	12.4	12.4	13.4	13.3
	2.1		4.0		6.1		7.8		8.8		12.2		12.1		13.3	
No. 7 at -5 °C	2.2		4.1		6.2		4.5		6.1		12.3		12.5		13.1	
	2.0	2.0	3.9	3.9	5.8	5.9	4.1	4.3	6.9	6.5	12.5	12.2	11.9	12.2	12.9	13.1
	1.8		3.7		5.6		4.4		6.4		11.9		12.3		13.4	
No. 8 at -10 °C	1.7		4.0		5.5		4.1		5.8		12.1		12.7		13.3	
	1.9	1,9	3.6	3.8	5.9	5.8	4.3	4.3	5.7	5.7	12.0	12.0	11.8	12.2	13.1	13.2
	2.0		3.8		6.1		4.6		5.5		11.8		12.1		13.3	

Note: Sample 2 - continuously in normal conditions; Samples 5,6,7,8 - previously kept 1 month at normal conditions, then 5 months: at +5 ° C; 0 ° C; -5 ° C; -10 ° C; and again, in normal conditions



a)



b)

Fig.4 Kinetics of change in the strength of specimens of belite cement stone in time: a) compressive strength; b) tensile strength at bending

Note: Sample 2 - continuously in normal conditions; Samples 5,6,7,8 - previously kept 1 month at normal conditions, then 5 months: at +5 ° C; 0 ° C; -5 ° C; -10 ° C; and again, in normal conditions.

The data indicate that low positive and negative temperatures slow down the process of hardening cement pre-cured under normal conditions (Fig.4). At the same time, the compressive and flexural strength reaches respectively: more than 100 MPa and 13 MPa, which indicates equal strength of belite cement with high-strength Portland cement

Further keeping of the material in humid conditions provides gel adsorption of moisture, replenishment of binding aqueous films between layers of hydrosilicate lattice, and restoration of material strength (Fig. 4).

Therefore, belite road concretes have the property of self-restoration, regardless of temperature and climatic changes, and dynamic transport loads.

This is also confirmed by the change in the amount of firmly bound water in the cement stone of samples aged at different temperature regimes. The results of changes in the amount of strength-bonded water in the cement stone (Table 3, Fig. 5), established by measuring the mass loss of samples after their ignition at 1000 ° C, pre-conditioned at 105 ° C, confirm the following.

Table 3 Results of testing from 1 to 7 months

Specimen samples	Month													
	1	Ave rage	2	Ave rage	3	Ave rage	4	Ave rage	5	Ave rage	6	Ave rage	7	Ave rage
	Tensile strength at bending, MPa													
No. 2 at normal conditions	2.3		4.1		6.1		9.9		10.8		10.6		10.7	
	1.9	2.1	3.9	4.1	6.5	6.2	10.0	9.8	11.0	10.6	11.0	10.6	10.9	10.6
	2.1		4.2		5.9		9.6		10.1		10.2		10.1	
No. 5 at +5 °C	1.8		4.3		5.7		8.1		9.8		12.0		12.6	
	2.2	2.0	4.1	4.1	6.4	6.0	8.3	8.1	9.6	9.9	12.2	12.0	12.3	12.6
	2.0		3.8		6.0		7.8		10.2		11.8		12.9	
No. 6 at 0 °C	1.7		3.7		5.9		7.7		9.1		12.1		12.6	
	1.9	1.9	4.3	4.0	5.7	5.9	7.3	7.6	9.3	9.1	11.9	12.1	12.4	12.4
	2.1		4.0		6.1		7.8		8.8		12.2		12.1	
No. 7 at -5 °C	2.2		4.1		6.2		4.5		6.1		12.3		12.5	
	2.0	2.0	3.9	3.9	5.8	5.9	4.1	4.3	6.9	6.5	12.5	12.2	11.9	12.2
	1.8		3.7		5.6		4.4		6.4		11.9		12.3	
No. 8 at -10 °C	1.7		4.0		5.5		4.1		5.8		12.1		12.7	
	1.9	1.9	3.6	3.8	5.9	5.8	4.3	4.3	5.7	5.7	12.0	12.0	11.8	12.2
	2.0		3.8		6.1		4.6		5.5		11.8		12.1	

Note: Sample 2 - continuously in normal conditions; Samples 5,6,7,8 - pre-conditioned 1 month in normal conditions, then 5 months respectively at +5 ° C; 0 ° C; -5 ° C, -10 ° C, -15 ° C, then again in normal conditions.

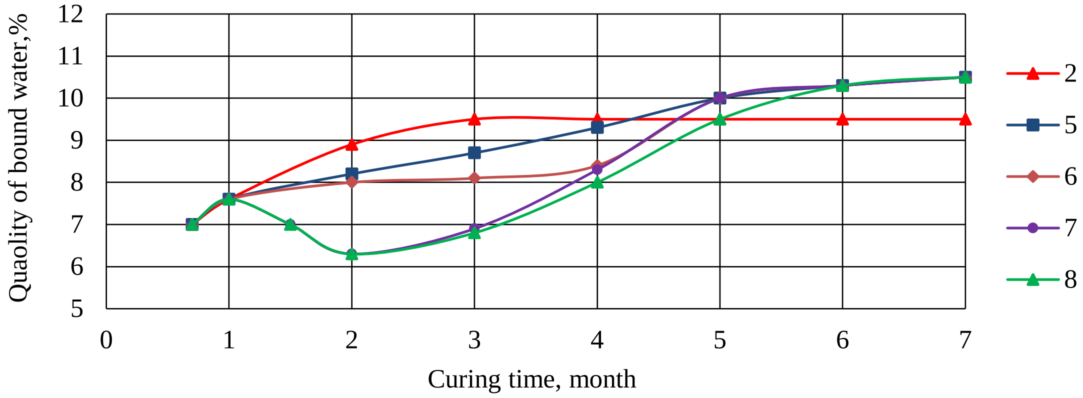


Fig.5 Kinetics of change in the amount of firmly bound water in the belite cement stone during hardening at different temperatures

Note: Sample 2 - continuously in normal conditions; Samples 5,6,7,8 - pre-conditioned 1 month in normal conditions, then 5 months respectively at +5 ° C; 0 ° C; -5 ° C, -10 ° C, -15 ° C, then again in normal conditions.

The kinetics of changes in strength (Fig. 4) and amount of water of cement stone, depending on sample ageing temperature, are similar, which confirms the reliability of theoretical assumptions about self-reinforcing properties of belite cement. When the cement stone is aged at low temperatures (samples №5-8), strength reduction (Fig.4) is accompanied by displacement of strength-bonded water (Fig.5) from fibrous neoplasm in the amount of 10-30% of the weight of available moisture in their capillaries, and at further ageing at normal conditions, their amount and strength of cement stone are restored within one month.

Further aging at normal conditions for three months the strength and amount of strength-bonded water exceeds the samples of normal hardening. This testifies to the deepening of cement grains hydration processes and increasing dispersion of new formations at low curing temperatures, which also increases the strength of cement stone and road concretes (Fig. 4).

When concrete samples were tested (Table 4) for frost resistance at 90 days of age (Fig.6), up to 200 cycles of freezing and thawing were performed. Figure 5 presented a slight decrease in strength due to the squeezing of moisture from the C-S-H capillaries and a decrease in its amount. At further ageing of specimens under normal conditions, the strength of the concretes is completely restored and even exceeds the strength of 90-day specimens, which is confirmed by the test results shown in Figures 4,5.

During the hardening of belite cement, the main structure-forming new formations in concretes are gel-like low basic calcium hydro silicates of nano-size C-S-H [21-22].

Table 4 Results of compressive strength

Samples	Month							
	1	Average	3	Average	6	Average	9	Average
	Compressive strength, MPa							
10wt,%	9.8 10.1 9.7	9.9	14.3 13.9 14.1	14.1	10.3 9.8 10.1	10.1	13.1 13.2 13.0	13.1
12wt,%	12.2 13.1 12.5	12.6	19.8 20.2 20.3	20.1	17.8 18.2 17.7	17.9	19.7 19.1 18.8	19.2
15wt,%	16.1 15.8 15.7	15.9	26.5 27.2 27.0	26.9	20.5 19.5 20.1	20.0	28.8 29.2 29.0	29.0
18wt,%	17.8 18.1 17.6	17.8	34.7 36.0 35.4	35.4	29.8 30.2 30.1	30.0	36.8 37.4 37.1	37.1
20wt,%	19.5 19.1 19.3	19.3	41.9 42.1 42.0	42.0	41.0 39.7 39.9	40.2	43.0 43.4 42.9	43.1

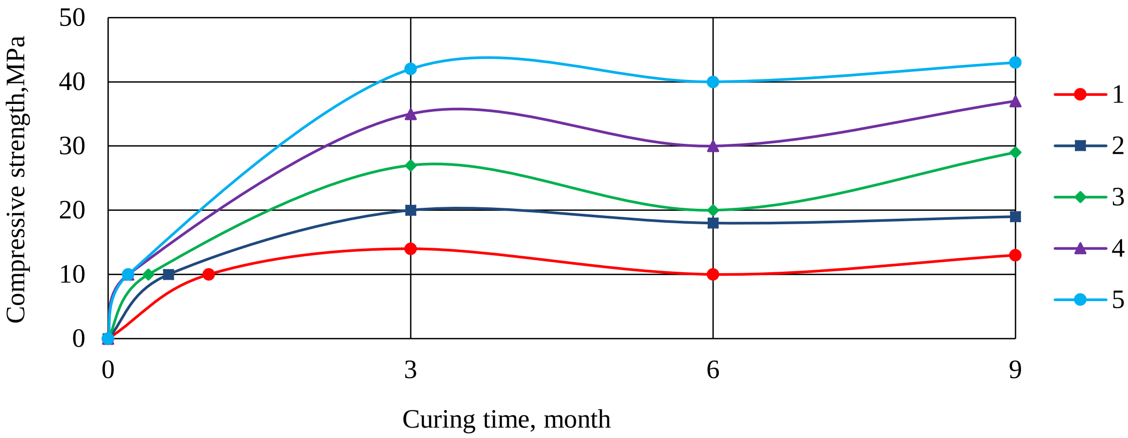


Fig.6 Self-restoring strength of road concrete tested for frost resistance (MRZ-200), depending on the amount of belite cement: 1, 2, 3, 4, 5 correspond to 10, 12, 15, 18, and 20 wt.% in concrete

Based on the results of the selection of compositions was derived a comparative graph of the gain strength of conventional concrete on Portland cement grade M250 and similar characteristics of slag concrete based on belite binder according to Figure 9.

Figure 7 shows that the concrete based on belite binder at 90 days has similar strength as traditional concrete. While the traditional concrete stopped gaining at 30 days, the strength of the slag concrete based on the belite binder increased for 15 months and continues to grow from M150-200 to M 400-500. This can be explained that the nanosized C-H-S are not destroyed, and due to the deepening of the hydration of grains, there is a constant hardening of strength.

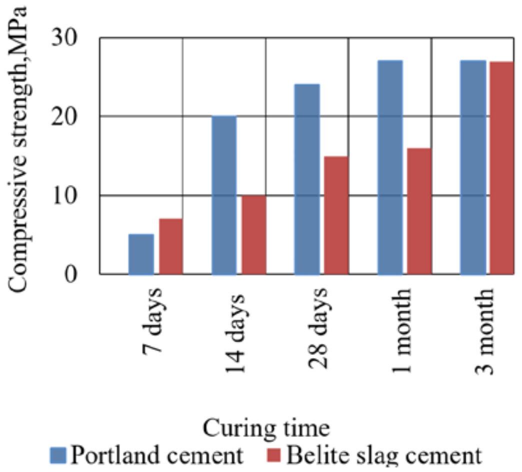


Fig.7 The kinetics of strength gain of traditional concrete on Portland cement M250 and slag concrete with similar characteristics

5 CONCLUSIONS

The predominant content of nanosized C-S-H hydrosilicates in belite cement stone and asphalt binder, gives the road rolling concrete the property of colloidal long-term hardening, exclusively in conditions of multiyear operation of roads.

Road concretes based on belite cement do not require warm conditions to gain critical strength before freezing unlike conventional cement concrete. It is possible to freeze them during any period of hardening, strength, and deformative properties of belite cement and concretes will self-repair and strengthen during the operation of the road. The strength and deformative properties of slag-mineral concrete materials prepared from aggregates of different grain compositions of gravel-sand mixtures vary within a wide range. It is established that the greatest influence on the strength of the material has the quantitative content of the slag binder in its composition. The increase in the quantity of slag binder in the material composition leads to an increase in its strength. The kinetics of strength gain of traditional concrete on Portland cement M250 and slag concrete with similar characteristics presented that belite slag cement builds up the strength set and reached a similar indicator in 90 days. In this case, the extreme value of strength is achieved with a strictly defined grain composition of the gravel-sand mixture.

The use of nanotechnology and nanomaterials has the following advantage the speed is accelerated, the quality of concrete road construction is guaranteed due to the absence of concrete seasoning until it reaches the design strength, the traffic on nano-concretes can be opened immediately after compaction is completed; -road construction of cold and warm asphalt-mineral and road rolling concretes can be performed at low and subzero temperatures up to minus 20° C.

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