Use of self-recovering slowly-hardening concrete to ensure the longevity of highways

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Abstract. At the beginning of this century, the new requirements for the durability of highways are made according to the modern concepts of the US and EU. The article describes the main results of theoretical, experimental studies and long-term monitoring of highways’ sections, built using the self-recovering road concretes that meet the new requirements. The durability of road concretes substantiates the results of physical and chemical studies, physical and mechanical tests of various compositions of belite cements, concrete and concrete cores. It was shown that the strength of the concrete continues to increase for more than 39 years of roads’ maintenance. It is assumed that the path to durable «Roman concrete» is found.

Keywords: concept, durability, highways, road concrete, belite cement, research, physical-chemical properties, physical and mechanical tests, strength.

1. Introduction
Currently, due to changes in traffic and increase of the load capacity of vehicles up to 12–13 tons per axle, the service life of road pavements of the highways declined sharply: the durability of asphalt concrete coatings in Russia and Kazakhstan decreased to 5–6 years [1–5], and of the cement concrete, including abroad – to 20–25 years [6–11]. The current critical situation, in reducing the service life of road pavements, is caused by mismatch of the technical state of the road structures and the actual composition, intensity and dynamic traffic flow. The effectiveness of the highways’ construction is justified at the service life of at least 50 years [6–11]. At the beginning of this century, this was the impetus for the development of new concepts: 1) concept of the «road pavements with a long life» on the European terminology; 2) concept of the «eternal road pavements» in accordance with the terminology adopted in the USA [6, 11]. In connection with these concepts, the Technical Committee С 4.3 «Road pavements» of the World Road Association (PIARC-AIPCR) has developed a Program and Methods of examination of the road pavements, created an Expert Committee on the questionnaire survey of the durability of the roads sections. Experts from 10 countries (for 100 road sections) established the basic principles and conditions to ensure the longevity/durability of roads based on concepts of the US and EU in order of their importance:
• ensuring the comfort and safety of traffic on the roads;
• stability of roads under the influence of transportations and climate changes;
• increasing bearing capacity of pavement layers from bottom to top;
• increased strength of the coatings’ materials for compression to perceive heavy loads from the top.

Under the terms of the roads’ durability, on the modern concepts of the US and the EU, to extend the life of roads up to 50 years or more it is necessary to ensure that the bearing capacity of the
pavement layers increases from bottom to top. This condition is completely contrary to the methods of designing the road pavements, adopted in Russia and Kazakhstan, on which the strength of the layers, conversely, decreases downwards. The main conditions to achieve the durability of the highways on the new concepts are increasing the bearing capacity of the lower layers of road pavements, subject to compliance with economic and technical efficiency of road construction. The idea of creating a more solid foundation, than the actual covering, is not new [14]. For example, during construction of a long-lasting road structure on the road with very heavy traffic (USA, California), the bottom layer contained more binding agent than the other layers. The same idea was expressed in the 1970–80s in the works of A.O. Salle, A.E. Merzlikin and B.S. Radovsky and was realized in Russia by A.E. Merzlikin on the Ring Road’s section in the city of Kazan during construction of the layered foundation of the cement-modified soil [6]. The implementation of such structural changes in the design of road pavements, using traditional materials and techniques, certainly, results in a significant increase in the cost of road construction.

The authors of this work have conducted a many years research and have developed new alternative efficient self-recovering road concretes, which allow significantly enhance the durability of the highways’ bases with the disposal of industrial technological wastes of Kazakhstan [15–19]. Durability of the proposed concretes is ensured by a radical change in the structure of the road concrete, by moving from a crystalline structure to a thixotropic one of the cement stone. For the scientific justification of the concrete durability, the authors carried out studies of the properties of new belite cements and road concretes on their basis in a year-round operation of highways in the sharply continental climatic conditions of Kazakhstan [24–31].

2. Methods of studying the physical and mechanical properties of belite cements based on phosphoric granulated slag.

Preparation of belite cement was carried out by joint grinding of granulated phosphorus slag with cement dust in the laboratory ball mills (MBL type) to the fineness, characterized by the residue on a sieve of 0.08 mm (not more than 15 %) or to a specific surface of at least 3000 cm²/g.

Before grinding, granulated phosphorus slag had been dried to a constant weight at a temperature not exceeding 200 °C. Samples preparation for the determination of the strength properties of belite cement was performed by compression of binding agents in the optimum moisture. This, in our opinion, most realistically reflects the conditions of formation and hardening at their use in road concrete.

The study of strength and deformation characteristics of belite cement was carried out on the following samples: test beams with a size of 40x40x160 mm and the cylinders with diameter and height of 50 mm. Forming of the samples was performed by standard methods – by compacting on a press in metal molds with bilateral liners under a load of 15 MPa and within 3 minutes.

Strength, deformation properties and frost resistance of the road concrete on the basis of slowly-hardening belite cements was studied on the samples – test beams with a size of 100x100x400 mm and the cylinders with diameter and height of 100 mm. The concrete mix was compacted in a hydraulic press under a load of 20 MPa for 3 minutes. The number of samples was at least three based on repeatability when measuring that ensures the reliability of the experience equal to 0.95 with a relative error of 3σ.

Storage of test samples was carried out in the water-sealed baths; in the future, these conditions of hardening will be called as normal. Currently, the existing normative documents allow construction of basements of soils reinforced with cement at lower temperatures (from +5 to −10 °C), and at strengthening with slag binding agents – only at positive air temperatures. Therefore, on the first phase of the study, we have studied the impact of low positive and small negative temperatures (up to −10 °C, typical for the winter periods of fifth road climatic zone) on the properties of the slag binding agent during its hardening.

Some of the samples were kept under normal conditions (series 2), the others – at constant low positive and negative temperatures at a given mode of hardening in cold rooms. Some samples were
placed in cold storage immediately after preparation, others – after the preliminary storage at positive temperatures. Moreover, one series of samples was kept in a periodic variation of temperature within time (series 13), i.e. with a gradual decrease from +5 to –10 °C, and then with an increase from –10 to +5 °C, and after the end of this cycle, the samples were placed in the water-sealed baths. Duration of holding samples of a series 13 (under certain temperatures) was set at the averaged data of the onset and duration of multiyear average daily air temperatures, typical for the regions of Kazakhstan, located in the fifth road-climatic zone. The actual length of low temperatures (in the year) from 0 to –10 °C is 140 days; for laboratory tests and ease of comparison with control samples, hardened under normal conditions, we used 150 days with intervals of no less than 15 or 30 days. For storing the samples in refrigeration chambers, they were wrapped in a polyethylene film. Before the test, the samples were thawed for at least 4 hours in moist sand. Initially, the samples were tested for bending tension, and the halves of samples – for compression. Then, with loads of 0.2–0.4 of tensile strength in bending, on 3 beams, we set the amount of elastic deflection and measured the elastic modulus of the material.

3. Methods of physical and chemical research of slag binding agent

To study the physical and chemical processes occurring at hardening of slag binding agent, after durability test, from the middle of the samples we selected the samples for petrographic, X-ray, thermographic and electron-microscopic analysis. Immediately after the sampling, samples have been crushed in an agate mortar and treated with ethanol and ether to remove free water from the system.

Differential thermal analysis (DTA) has been performed on a Hungarian derivatograph of the system "R. Paulik, I. Paulik, D. Erdei" at a heating rate of 10° per minute, at the sensitivity of the weight of 500 mg and with the sample weight of 0.5–1.0 g. Analysis was performed in platinum crucibles. As the reference sample we used calcined aluminum oxide (Al₂O₃). Some thermographic investigations have been carried out on the thermographic device TU-IM at a heating rate of 100° per minute and with the sample weight of 0.01g. Analysis was performed in ceramic crucibles.

The mineralogical composition was studied at X-ray diffraction data, performed on the X-ray machine URS-50 IM with an attachment PK-2 and applying a copper anode, at the anode current of 10uA and a tube voltage of 35 kV. Recording of radiographs was performed on a standard chart tape at 2 degrees per minute. The sample was placed in a flat cell of 1.5 mm thickness. To decrypt thermal- and radiographs, we used the published data from thermography and radiography.

Mineralogical and petrographic studies were performed on the microscope (brand MIN-8). Study of hardening products has been performed in immersion preparations and transparent sections. Because of the strong hygroscopic properties of the material, from powders of the binding agents we were preparing a liquid paste in admixture with an alcohol, which was applied by a thin layer on a glass slide, and then dried. Further preparation and review of the immersion preparations was carried out by the usual method. When preparing transparent thin sections, kerosene was used. Counting of components was performed in thin sections under the microscope by a point method. The essence of the method is that in the polished sections we evenly distributed a large number of observation points under the microscope on a square grid. At the same time, we counted the number of points got on each mineral. According to the theory of probability, these amounts are proportional to the volumes, occupied by the relevant minerals in thin section. When counting, method of fields has been applied. For this purpose we used the net eyepiece, wherein the total number of strand intersections (nodes) was 400. In each field, we counted the number of points (nodes), attributable to certain mineral. View of 10 fields in thin section ensured sufficient reliability of quantifying. Within one field of view, counting was performed 3 times. We have determined the average mineral content for the field. The total number of fields for each of the section, where we determined the volume content of the glass phase, was 10. Thus, the average percentage of the mineral was determined by 30 estimates, that increases the accuracy of the result for average values.

Electron microscopic studies have been performed on the microscope UEMB-100.
4. Main part (Results and Discussion)
In Kazakhstan to confirm the idea of building strong and durable roads, a number of experienced road sections with monolithic bases of slowly-hardening high-strength road concrete, coated with hot and cold asphalt concrete, were built in 80–90s [15]. Calculation of road constructions was carried out according to the traditional method of nonrigid road clothes; in calculation the indices of slowly-hardening reinforced materials of 90-days samples with a compressive strength of not more than М60 (RoK ST 973) were taken into account. Here further strengthening of concrete for more than twice (during the years of operation) was not taken into account. By the way, method of calculation of road pavements/cloths with long-term strengthening concretes, called below as «self-recovering road concrete», is still not developed. The longevity of these road constructions is confirmed by the works [15], and below we will give justification for this effect.

To improve the durability of roads, the Ministry of Transport and Communications of Kazakhstan in 2006 made a decision on designing and construction of roads of international importance (under the traffic load of not less than 13 tons per axle) with cement-concrete and asphalt stone mastic coatings. Construction of cement concrete pavements on new technologies required the study of foreign experience in Germany and the US for the joint development of Kazakhstan's regulatory and technical documents [16,17].

Currently, in the Republic of Kazakhstan there are more than 600 kilometers of roads with cement concrete pavements. International highway "Western Europe – Western China" (2900 km) as well as the highway "Astana-Karaganda" (more than 220 km) is under construction. During the construction of cement concrete pavements, there used a technology of laying rigid concrete mixtures with sliding formwork, using high energy compaction of high-performance road concreting machines. The cost of roads’ construction has increased significantly, since the regulations [16, 17] recommended to use expensive high-strength Portland cement and high-quality stone aggregates, that requires substantial financial and material costs. This is further amplified by the annual increase in the deficit of traditional road-construction materials (bitumen, cement, road mastic, rubble, mineral powder) and an increase in the cost of land acquisition.

Professor V.A. Zolotarev [18] confirms that «Today in the world road construction there are three main priorities. The first priority is durability of roads, which is generalized by the concept of "eternal roads" (USA) or «roads with a high life expectancy» (EC) with renewal of the upper layer every 6–7 years. The second and third priorities are interrelated: energy saving, environmentally friendly technologies, with re-use of old asphalt concrete, which is 100 % processed material [18]. Resource Saving with re-use of all materials of the reconstructed roads is not less important for high material-intensive road construction [19–22]. Besides that, Kazakhstan accumulated in the dumps huge amounts of technogenic mineral waste (hereinafter – TMW), suitable for road construction. Ministry of Environment Protection (RoK MEP) accounted 775 facilities of TMW, which have accumulated about 34 billion of tons; at the same time there is a trend of their annual growth for 700–800 mln tons. For these priority directions, as a result of years of research, the authors developed and tested long-life monolithic bases, using the secondary road-building materials and industrial technogenic mineral wastes (TMW) [15–17, 19]. Evidences of the effectiveness of using TMW and monolithic bases of road clothes (in terms of their durability) are Roman roads, some parts of which are preserved in the state suitable for traffic nowadays [23]. During construction of roads in Italy, the volcanic ash from the town of Pozzuoli (near the city of Naples) [23]) and volcanic tuff from the banks of the Rhine have been used as the binding agents. Subsequently, all these additives have been named “pozzolanic”, as they had the same property – ability to solidify in the presence of lime and water. Coryphaeus of road science – Prof. V.F. Babkov – gave examples of road structures on the Roman roads, which had monolithic bases and preserved until today. It was found [15] that Kazakh TMW, in particular, blast furnace / phosphorous slags, bauxite sludges, fly ash, phosphogypsum etc., being heat-treated, similar to volcanic ash and tuff, have the same durable cemented properties. To build long-lasting monolithic bases, Kazakhstan first developed compositions of slowly-hardening belite cement [24] and mastered the use of long-lasting «self-recovering road concretes» [25], including, by using the subgrade «Zhertas», for which there is a patent in the Republic of Kazakhstan [18].
Kazakh scientists [19–21] repeatedly noted the prospects of using TMW in combination with cement. Many foreign studies have found [22–25] that there are potential opportunities to increase the durability of cement concrete pavements when using such mixtures. In 2002 for the construction of airport taxiways (United States, Texas), cement (50 %) in combination with ground granulated slag (25 %) and fly ash (25 %) have been used. Concrete was tested in 2008 and it was approved that the service life of cement concrete pavement was at least 120 years [32].

The results of years of research and monitoring on the experimental sections of roads in Kazakhstan, being in operation for the past 31–39 years, confirm the accuracy of the performed theoretical and experimental studies. Below are only the main results of research and testing of the roads confirming the durability and self-recovery of road concrete, used in road construction in Kazakhstan since 1976. The use of new slowly-hardening road concrete allows significantly improving the durability of concrete roads. This effect is substantiated by a radical change in the macro- and microstructure of road concrete, by moving from a crystalline to a thixotropic structure of the cement stone.

It is well known [39] that technological modes of construction of concrete roads are caused by the setting time of Portland cements and the hydration rate of four main clinker minerals: \( \text{CaSO}_4; \text{CaSO}_3; \text{CaA} \) and \( \text{C}_4\text{AF} \) (see Table 1). The prevailing content in Portland cement clinker of the following materials: highly basic tricalcium silicate \( \text{C}_3\text{S} – \text{Alite} \), tricalcium aluminate \( \text{C}_3\text{A} \) and tetracalcium aluminoferrita \( \text{C}_4\text{AF} \), the degree of hydration of which is 100 % in 28 days, causes rapid setting and hardening of road Portland cement and concrete with formation of a cement stone, basically, of a crystal structure. In the same time, the hydration degree of tricalcium silicate \( \text{C}_2\text{S} – \text{Belite} \) only after 180 days barely reaches 50 %, with amorphous formations of a thixotropic structure. Therefore, to provide slow solidification of the new cements, the content of slowly-hardening low-basic dicalcium silicate \( \text{C}_2\text{S} – \text{Belite} \) is increased in their compositions up to 60–85 %; and the number of fast-setting materials (highly-basic silicates \( \text{C}_3\text{S} \), aluminates \( \text{C}_3\text{A} \) and aluminoferrita \( \text{C}_4\text{AF} \)) is minimized. Table 1 compares the chemical and mineralogical compositions of traditional Portland cements (hereinafter – alite cements) and slowly hardening cements (hereinafter – belite cements).

| Cement type | Chemical composition, mass. % | Mineralogical composition, mass. % |
|-------------|-------------------------------|----------------------------------|
|              | \( \text{CaO} \) | \( \text{SiO}_2 \) | \( \text{Al}_2\text{O}_3 \) | \( \text{Fe}_2\text{O}_3 \) |
| Alite*       | 60–67                         | 17–25                           | 3–8                             | 0.2–6                         |
| Belite*      | 33–46                         | 39–61                           | 3–10                            | 3–5                           |

|             | \( \text{C}_3\text{S} \) (alite) | \( \text{C}_3\text{S} \) (belite) | \( \text{C}_3\text{A} \) | \( \text{C}_4\text{AF} \) |
|-------------|----------------------------------|---------------------------------|-----------------|-----------------|
| Alite*      | 40–75                            | 5–25                           | 2–15            | 5–20            |
| Belite*     | 10–35                            | 60–85                          | 3–5             | 2–7             |

Notes* – code names of cements according to the predominant content of minerals: \( \text{C}_3\text{S} – \text{Alite}, \text{C}_2\text{S} – \text{Belite} \).

Phosphorus and blast furnace slags, bauxite sludges and ash of TPP (thermal power plant) are the main components of belite cements [24] and self-recovering road concretes [3].

Physico-chemical studies [24, 25] confirmed that according to the mineralogical composition, belite cement stone is mainly represented by the slow-hardening low-basic silicate \( \text{C}_3\text{S} \) (Belite). Formation of the structure of a slowly hardening cement stone, during its hardening within 8 years, is shown in the photos of fractures of cement beams, tested for tensile bending (Fig. 1).

Thus, the nature of the slow decomposition of the cement grains and the occurrence of formations can be clearly traced in Fig. 1, a–d. Fig. 1, a shows undecomposed cement grains; then, over time, there are grains with formed peripheral shell, which gradually grows (Fig. 1, b) and then amorphous formations with a gelly-like structure appeared (Fig. 1, c).
Figure 1. Photos of fractures of the samples, hardened under normal conditions and tested after 1 year (a), 3 years (b), 6 years (c) and 8 years (d)

Amorphism of these formations is caused by fuzziness and diffuseness of their edges and chaotic growth in all directions. Along with amorphites, there are single crystals of C-S-H (Fig. 1b). In immersion gel is presented as a colorless isotropic mass with an index of refraction 1.330–1.567.

The number of gelly formations in samples raises with increasing age of the samples. But even after 8 years of hardening under normal conditions, belite cement samples have unhydrated grains, indicating the potential possibility of the cement for further hardening.

Radiographs of belite cement stone, shown in Figure 2, confirm the data obtained. Radiographs of the cement stone samples, previously stored under normal conditions and then hardened at the temperatures of +5, 0, –5 and –10 °C within three months (Fig. 2, a), as well as the samples, hardened without preincubation at normal conditions (Fig. 2, b), are almost similar.

Diffraction lines, typical of hydrosilicates of tobermorite group, are combined with the lines of calcite, that somewhat complicates their decryption. So, interplanar distances of 1.875; 1.913; 2.095; 2.283 Å correspond to interplanar distances of calcite. Lines 1.814; 2.88; 3.03 Å match interplanar distances of silicate C-S-H. Radiographs of all samples contain lines with a maximum of 3.34 Å and the lines close to the values of 2.82; 1.980; 1.817 Å, relevant to interplanar characteristics of the quartz.

Thus, regardless of the temperature conditions of hardening of the belite cement stone (within experiment) and timing of incubation, the phase composition of formations has not changed significantly. Retardation of hydration processes for belite cement (with decreasing temperature of hardening) is confirmed by the decrease in diffraction line, corresponding to the interplanar distance 3.027 Å, compared with the line 3.039 Å, obtained in the process of hardening at positive temperatures.

A number of studies noted that construction of roads with slowly hardening road mixtures should be carried out in early summer or at least two months before the first frost, in order to give them the opportunity to harden before winter. In order to test this hypothesis, we examined the effect of hardening temperature for further growth of the strength of the belite cement stone samples, previously stored (within 30 days) under normal conditions (Fig. 3, a, b).

Figure 3 shows the results of tested samples in the series 5–8, which after the preliminary storage for 1 month (30 days) under normal conditions, have been hardened for 5 months at the temperatures of +5, 0, –5, –10 °C, and then – under normal conditions. The test results of the samples (series 5–8) were compared with the samples of series 2, being permanently hardened under normal conditions.

The data obtained indicate that low positive and negative temperatures slow down the process of hardening of belite cement stone, previously stored under normal conditions. Moreover, the higher the temperature of hardening, the slower the curing and hardening.

So the strength of the samples of months of age (at normal hardening), after three months of their storage at a temperature of +5 °C (series 5) increased in compression by 33 %, when bending – by 38 %, and at 0 °C (series 6) – by 22 % (in compression) and 20 % (when bending) respectively. At the temperatures of –5 °C (series 7) and –10 °C (series 8), strength growth is practically not observed (its decrease is even marked). Upon further storage in normal conditions, strength of all samples of
series 5–8 raises (compression – up to 10 %, tensile bending – up to 18 %), compared with the strength of samples (series 2), which were constantly kept at normal conditions. Increased bending strength indicates an increase in dispersion of formations, which leads to improved deformation properties of the cement stone structure.

Figure 2. Radiographs of samples of belite cement stone, being hardened for 3 months at the temperatures of +5, 0, –5, –10 °C: a – after 1 month of storage under normal conditions; b – without aging under normal conditions

When keeping/storing the samples at positive temperatures in the water-sealed baths or under normal conditions, cement stone is gaining strength within 2–3 years and further strength is stabilized. The compressive strength reaches 130 MPa and tensile bending – up to 10.7–12 MPa, indicating high-strength and deformation properties of belite cement.

Test of cores of self-recovering road concrete on the basis of belite cements, drilled from the monolithic bases of experimental road sections has shown that in a sharply-continental climatic conditions of Kazakhstan, increase in the strength of concrete occurs during the period of long-term operation of roads.
Figure 3. The kinetics of change in strength of samples of belite cement stone over time (series 2, series 5, 6, 7, 8), preliminary stored for 1 month under normal conditions: а – compressive strength; б – tensile strength in bending

Compositions of concrete mixes for experienced road sections were selected from the rubble-sand and gravel-sand aggregates: aggregates – 80–90%; belite cement (C₂S up to 80%) – 10–15%; (C₂S up to 70%) – 10–18%; (C₂S from 60%) – 10–20%. The water-cement ratio is chosen within 0.35–0.45.

Compressive strength of concrete, tested in vitro, was: at the age of 90 days – 10–20 MPa, after 2 years – 20–30 MPa.

Table 2 shows the results of the test of cores, drilled from the concrete base of the road «Fogolevka-Zhdanovo» PK 54-74, built in December 1977, and PK 74-90, built in November 1978.

| Name of the indicator measured | Test of cores in 1989, MPa (Concrete age – 12 years) | Test of cores in 2005, MPa (Concrete age – 28 years) |
|-------------------------------|---------------------------------------------------|---------------------------------------------------|
| Compressive strength          | 36.4, 36.7, 36.5                                  | 48.6, 49.0, 48.8                                   |
|                               | Average 36.5 (M 350)                              | Average 48.8 (M 450)                               |
| Bending strength              | –                                                 | 8.6, 8.3                                          |

At design marks of road concrete, chosen for construction of experimental roads, their strength at the age of 90 days is M100–M200; the actual strength of concrete at the age of 28–39 years of operation reached M250–M450, i.e. increased more than 2 times (Fig. 4).
This indicates that belite road concretes have the property of self-recovering and prolonged hardening in conditions of constant dynamic vibration transport and climatic loads. To explain the effect, the authors have conducted detailed physico-chemical studies. The results of petrographic, X-ray, differential-thermal analysis and monitoring with a scanning electron microscope have shown that at hardening of belite cements, basic structure-forming formations in concrete are gelled low-basic hydrosilicates of calcium (type C-S-H).

The obtained experimental results suggest that from all theories of hardening of mineral binding agents, it is possible to highlight a colloid-chemical theory of V. Michaelis, which obviously will be more reasonable to explain the process of hardening of belite cements.

At normal temperature hydrosilicates C-S-H are formed as plate submicro-crystals, the average length of which is close to 10000 Å (1 micron), and the width and the thickness are 360–560 Å and 20–30 Å. Due to the very small sizes of hydrosilicates, as well as their ability to adsorb water, hydrosilicates have properties of colloids. These calcium hydrosilicates have bonds, different from the rigid crystallization bonds. The structure, formed by amorphous products, takes precedence over crystallization bonds, because it does not cause significant crystallization pressure and contacts are thermodynamically stable. Hydrosilicates of the type C-S-H have similarities with layered minerals of swelling clays. This similarity is shown in the ability to give some of the water (between the layers of the crystal lattice) reversibly. Loss or saturation of water is accompanied by a change of the distance between the layers of the crystal lattice of hydrosilicate C-S-H, which leads to changes in the material strength. Further maintaining of the material under wet conditions provides adsorption of moisture with gel, replenishment of bonding water films between the layers of the hydrosilicate lattice and restoring the strength of the material (Fig. 3–7). Therefore belite road concretes have the ability of self-recovering depending on the temperature and climatic changes and dynamic traffic loads. This is also confirmed by the change in the number of firmly bound water in the cement stone (Fig. 5).

The kinetics of change in strength over time (Fig. 3) and the kinetics of changing the number of firmly bound water (Fig. 5) in belite cement stone, depending on the temperature of samples, are similar, that confirms the validity of theoretical assumptions about the self-recovering properties of the belite cement.

When keeping the cement stone at low temperatures (samples of series 5–8), decrease in strength is accompanied by the displacement of firmly bound water from the fibrous formations in an amount of 10–30 % by weight of moisture, available in their capillaries. When storing samples (series 5–8) under

Figure 4. Kinetics of concrete strength of self-recovering concrete road bases of experimental roads, built in 1976–1984. The content of belite (C_2S) in belite cement: 1 – 60; 2 – 70; 3 – 80 %
normal conditions, a number of firmly bound water and the strength of the cement stone are restored within a month. Further keeping samples (series 5–8) under normal conditions within three months leads to increased strength and amount of tightly bound water unlike samples (series 2), hardened under normal conditions. This indicates a deepening of the hydration processes of the cement grains and increasing dispersion of formations at low storing temperatures, that also increases the strength of the cement stone (Fig. 3, 4).

Figure 5. Kinetics of changes in the number of firmly bound water in the belite cement stone during hardening at different temperatures

When testing concrete samples at the age of 90 days to frost resistance, there were performed up to 200 cycles of freezing and thawing. As it can be seen from Fig.6, there is a slight decrease in strength due to squeezing of moisture out of the capillaries and reducing of its amount. With further exposure of the samples under standard conditions, concrete strength is fully restored and even exceeds the strength of 90-days concrete samples, shown in Fig. 3.

Figure 6. Self-recovering of strength of the road concrete, tested for frost resistance (MP3-200), depending on the amount of belite cement: 1 – 15; 2 – 20; 3 – 25; 4 – 30; mas. % of the cement with the content of CaS 60–65 %
Road belite concretes have a slow hardening compared to traditional alite cements, but the strength characteristics of concretes at the age of 180 days are almost equal; the deformative indices of belite concrete even exceed the indexes of alite one. Moreover the tensile strength in bending is 31% higher, and elastic modulus is below for 5000 MPa (Table 3).

| Fractions of rubble, mm | Sand M₄₀=2.5 | Cement, % | Tensile strength at the age of 180 days, MPa (average value) | Elastic modulus Е₀ |
|------------------------|-------------|-----------|------------------------------------------------------------|-------------------|
| 5–10                   | 10–20       |           |                                                             |                   |
| 15                     | 34          | 29        | Belite cement, 15 %                                        | 30.9              |
|                        |             |           |                                                             | 5.9               |
|                        |             |           |                                                             | 0.19              |
|                        |             |           |                                                             | 30000             |
| 15                     | 34          | 29        | Alite cement, M40 0.15 %                                   | 30.0              |
|                        |             |           |                                                             | 4.5               |
|                        |             |           |                                                             | 0.15              |
|                        |             |           |                                                             | 35000             |

High deformation properties of slowly hardening concrete evidence of a high dispersion and tensile strength (cohesive bond) of the new-formations of belite cements stone.

Presented X-ray diffraction, thermographic and electron microscopic studies confirm that in the slowly hardening road concretes, technological and operational advantages are provided by gelly structure of hardening of belite cements. Road concretes preserve their «self-recovering» properties due to water permeability of fibrous formations and continuing increase of hydration of the cement stone with an increase in strength during the years of roads’ operation. In the structure of the traditional alite Portland-stone, contrary, low content of gelly dicalcium hydrosilicates fills only the free space inside the main frame, formed due to accretion of large crystalline hydrates. The basis of the frame is highly basic hydrosilicates of calcium, hydroaluminates, hydroaluminoferrites, hydroaluminoferrates and calcium hydroxides. These crystal hydrates are hard leakproof, that prevents the penetration of moisture to the non-hydrated cement grains (microconcrete Jung is more than 40%), and therefore does not have the property of self-recovery after fracture. The service life of concrete covers is not more than 25–30 years at their operation in the sharply continental conditions.

It was found that formation of mostly rigid crystallization bonds predetermines the limited terms of existence of thixotropic properties in the cement stone of the traditional Portland cements. This, in turn, reduces the productivity of complex road concreting machines, because it requires strict adherence to all technological operations and conditions in the linear-in-line road building.

5. Conclusions
The presented results of years of research and practical experience of monitoring the behavior of different road structures, built on the basis of the proposed innovative materials and technologies, as well as requirements to ensure the longevity of roads in accordance with modern concepts of the US and EU, allow us to make the following conclusions.

1) To improve the durability of roads up to 50 years or more, in accordance with modern concepts of the US and EU, it is advisable to use «self-recovering road concretes» on the basis of belite cements for the construction of the «support road bases with a high life expectancy». At this, updating the upper layer of the coating (made of various high-strength asphalt concretes) should be carried out every 5–7 years.

2) Do not exclude ways to improve the durability of cement concrete pavements by adjusting the mineralogical compositions of traditional Portland cements and increasing the number of hydrosilicates C₂S, which will require changes to the requirements for road Portland cements and concretes on their basis.

3) The use of road constructions with increasing strength «upwards», in accordance with the new concepts, will require changes in design techniques and calculation of road pavements (non-rigid and rigid types).

4) The widespread use in the construction and reconstruction of roads of hydraulically active
technogenic wastes (fly ash from TPPs, phosphorus and blast furnace slags, bauxite sludges, phosphogypsum) and re-use of recycled road construction materials and soils will improve the quality of construction, reduce costs, improve the quality of the environment and ensure the environmental safety of road construction.

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