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Prospects for 21st- century nanotechnology for creating climate-resistant and environmentally friendly transport infrastructure

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Abstract

This paper presents the results of fundamental laser research, experimental studies, and long-term monitoring of highways constructed using concrete based on belite road cements. Belite cements, containing 50–80% C2S, ensure up to 50 years of pavement durability without major repairs. Laser analysis revealed nanoscale colloidal calcium hydrosilicates (CSH) that enable nearly complete cement hydration and provide unique long-term material behavior: thixotropy (self-healing upon micro-damage) and rheopexy (strengthening under traffic and temperature variations). Monitoring of Kazakhstani concrete roads confirms continuous hardening of belite-cement pavements over 35–46 years of operation, validating V. Michaelis' 19th-century theory on colloidal mineral binders for the first time in practice.

Comparative analysis shows that traditional Portland cement pavements (C3S up to 65%) last only 25–30 years due to partial hydration, leaving up to 40% "Young microconcrete", which later hydrates and disrupts the crystalline structure. The study demonstrates that nanoscale colloidal CSH phases are key to long-term durability. Additionally, a new concept for extending asphalt concrete service life is proposed: protecting bitumen from aging and reinforcing the colloidal structure with belite powder. Kazakhstan's long-term results (12–19 years without repair for nanostructured asphalt concrete) confirm the high potential of 21st-century nanotechnologies for climate-resistant road infrastructure.

Keywords: Highways, fundamental research, colloidal structure, cement belite concrete, asphalt belite concrete, ecology

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XXI ғасыр нанотехнологияларының климатқа төзімді және экологиялық қауіпсіз көлік инфрақұрылымын қалыптастырудағы болашағы

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Түйіндеме
Бұл мақалада белитті жол цементтері негізінде салынған автомобиль жолдарының фундаменталды лазерлік зерттеулері, эксперименттік жұмыстар және ұзақ мерзімді мониторинг нәтижелері ұсынылады. Құрамында 50–80 % C2S бар белит цементтері ірі жөндеусіз 50 жылға дейінгі төсем қызметін қамтамасыз етеді. Лазерлік талдау цемент дәндерінің іс жүзінде толық гидратациясын қамтамасыз ететін наноөлшемді коллоидты кальций гидросиликаттарының (CSH) түзілуін анықтады. Бұл құрылымдардың ерекше ұзақ мерзімді қасиеттері – тиксотропия (микробұзылулардан кейін өзін-өзі қалпына келтіру) және реопексия (көлік және температуралық әсерлер кезінде нығаю) дәлелденді. Қазақстандағы бетон жолдарының 35–46 жылдық пайдалану мониторингі V. Michaelis ұсынған минералды байланыстырғыштардың коллоидтық теориясының алғаш рет практикалық түрде расталғанын көрсетті. Салыстырмалы талдау көрсеткендей, құрамында C3S 65 %-ға дейін болатын дәстүрлі портландцемент негізіндегі жол жамылғылары 25–30 жыл ғана қызмет етеді, себебі толық гидратация жүрмей, 40 %-ға дейін «жас микробетон» қалады, ол кейін гидратацияланып, құрылымның бұзылуына әкеледі. Зерттеу нәтижелері ұзақ мерзімді беріктіліктің негізгі факторы наноөлшемді CSH фазалары екенін көрсетті. Сонымен қатар битумның картаюын баяулатып, белит ұнтағымен коллоидтық құрылымды күшейту арқылы асфальтбетонның қызмет мерзімін арттыру тұжырымдамасы ұсынылды. Қазақстандағы ұзақ мерзімді нәтижелер (наноқұрылымды асфальтбетон үшін 12–19 жыл жөндеусіз) XXI ғасыр нанотехнологияларының климатқа төзімді көлік инфрақұрылымын қалыптастырудағы жоғары әлеуетін дәлелдейді.

Түйін сөздер: автомобиль жолдары, фундаменталды зерттеулер, коллоидтық құрылым, белитті цемент бетон, белитті асфальтбетон, экология.

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Перспективы нанотехнологий XXI века для создания климатоустойчивой и экологически безопасной транспортной инфраструктуры

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Аннотация
В статье представлены результаты фундаментальных лазерных исследований, экспериментальных работ и долгосрочного мониторинга автомобильных дорог, построенных с применением бетонов на основе белитовых дорожных цементов. Цементы, содержащие 50–80 % C2S, обеспечивают долговечность покрытия до 50 лет без капитального ремонта. Лазерный анализ выявил формирование наноразмерных коллоидных гидросиликатов кальция (CSH), обеспечивающих практически полную гидратацию цементных зерен и формирующих уникальные свойства материала: тиксотропию (самовосстановление после микроразрушений) и реопексию (упрочнение под воздействием транспорта и температурных колебаний). Мониторинг казахстанских автомобильных дорог в течение 35–46 лет подтвердил непрерывное упрочнение белитового цементобетона и впервые экспериментально доказал применимость коллоидной теории минералокомпозитов V. Michaelis. Проведенный сравнительный анализ показал, что покрытия на портландцементе (C3S до 65 %) служат лишь 25–30 лет, поскольку неполная гидратация приводит к формированию до 40 % «молодого микробетона», позднее разрушающего кристаллическую структуру. Установлено, что основу долговечности составляют наноразмерные фазы CSH. Кроме того, предложена концепция увеличения срока службы асфальтобетона путем защиты битума от старения и усиления коллоидной структуры белитовым минеральным порошком. Долговременные результаты эксплуатации в Казахстане (12–19 лет без ремонта) подтверждают высокую перспективность нанотехнологий XXI века для создания климатоустойчивой транспортной инфраструктуры.

Ключевые слова: автомобильные дороги, фундаментальные исследования, коллоидная структура, белитовый цементобетон, белитовый асфальтобетон, экология.

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1. Introduction

By the end of the 20th century, an intensification of traffic flows led to a two- to three-fold increase in loads on highway pavement systems, resulting in a significant reduction in their operational lifespan. Traditional cement-concrete pavements demonstrated durability of only 25–30 years, while asphalt-concrete pavements on rigid concrete bases required rehabilitation every 10–12 years, with surface repairs typically performed every 5–6 years. These trends contradicted the strategic global concepts of "eternal roads" (USA) and "long-life pavements" (EU), according to which road infrastructure should remain operational for 50 years or more, ensuring economic feasibility over its lifecycle. To achieve this goal, road structures must exhibit increased bearing capacity from the foundational layers upward, as well as enhanced durability against mechanical and climatic stresses [1].

In response to these challenges, Kazakhstan has developed alternative road construction technologies based on nanostructured asphalt-concrete and belite-cement concrete systems featuring colloidal reinforcement mechanisms. Long-term field observations demonstrate that such pavements are capable of sustaining stable performance for 35–50 years or more, providing significant resource and energy savings.

The widespread implementation of advanced belite cements produced from thermally processed industrial mineral waste presents a promising research direction. Unlike traditional Portland cement systems, belite-based binders possess latent hydraulic activity and contribute to long-term structure formation. Furthermore, recent scientific investigations in asphalt-concrete technology increasingly focus on modifying binders through polymers and bitumen additives. However, it is now well established that the functional binder is not pure bitumen, but rather a composite asphalt binder composed of bitumen and finely dispersed mineral powder. Mineral particles with a specific surface area of up to 3000 cm^2/g form a colloidal medium with bitumen, enabling thixotropic behavior and providing enhanced cohesion.

Colloidal mineral binder systems demonstrate two fundamental rheological properties highly relevant to pavement longevity: thixotropy, ensuring reversible self-healing after structural disturbance, and rheopexy, facilitating progressive strengthening under cyclic traffic and thermal loads. These mechanisms form the scientific foundation for the development of climate-resistant nanostructured road materials capable of ensuring long-term pavement performance under severe continental climatic conditions.

The purpose of this research is to substantiate and experimentally confirm the efficiency of belite nanotechnology-based cement and asphalt-concrete materials for creating climate-resistant, environmentally friendly transport infrastructure with an extended life cycle.

2. Materials and Methods

The research methodology integrates fundamental laser diagnostics, laboratory testing, and long-term monitoring of road pavements constructed with belite-based nanostructured concretes and asphalt-belite composites. A series of experimental studies was carried out to identify the physicochemical mechanisms responsible for long-term strengthening and self-healing properties of colloidal calcium hydrosilicates (C-S-H) in belite cements.

Laser microstructural analysis was used to examine hydration morphology, nanoscale colloidal formations, and the kinetics of C-S-H development within cement stone. X-ray diffraction, differential thermal analysis, and scanning electron microscopy were applied to identify mineral composition, phase transformations, and the evolution of colloidal gel structures under varying temperature-hardening regimes. Cement and composite samples were subjected to normal curing, low-temperature exposure (from +5°C to –10°C), and repeated freeze-thaw cycles to model long-term operational conditions.

Mechanical testing included compressive and flexural strength assessments at different concrete ages (up to 180 days) and after durability cycles. Additional monitoring involved core extraction from road sections aged 12–46 years, with comparative evaluation of strength recovery, thixotropy, rheopexy, and frost resistance (up to MRZ-200). Asphalt-belite mixtures with varying cement and bitumen content were tested under temperature gradients from −10°C to +50°C to determine plasticity, modulus changes, and binder-powder colloidal behavior.

Long-term field monitoring was conducted on highways built between 1976–1984 and 2005–2016, including Astana–Borovoe and regional road sections. The collected data enabled verification of self-healing capacity, year-round construction feasibility, and the potential for extended service life exceeding 35–50 years.

3. Results

The idea of creating a stronger foundation than the coating is not new. The prospects for using industrial man-made mineral waste (hereinafter referred to as IWM) in combination with cement or cement dust, lime and other activators have been repeatedly noted in the works of Kazakh and Russian scientists [2,3]. Below are the main results of road research and testing, confirming the durability of road concretes based on belite cements and their TMO, used in road construction in Kazakhstan, the strengthening of which has been ongoing for more than 35-40 years. (Figure 1).

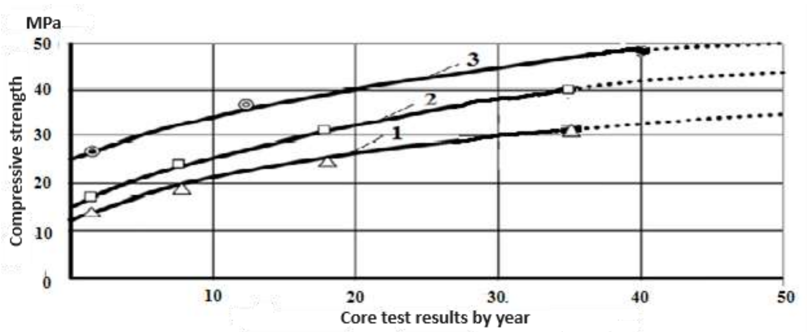

Figure 1. Kinetics of strength gain of self-healing concrete road pavements with a wearing layer made of asphalt concrete on highways built in 1976–1984 : where 1, 2, 3 are respectively on belite cements from TMO: fly ash from thermal power plants, bauxite sludge and granulated slags [own material]

Table 1 shows a comparison of the chemical and mineralogical compositions of traditional Portland cements (hereinafter referred to as alitite cements) and slow-hardening high-tech cements (hereinafter referred to as belite cements).

Table 1. Chemical and mineralogical compositions of alite Portland cements and slow-hardening belite cements cements.

Types cements	**Chemical composition, mass %**			
	CaO	**SiO_2**	**Al_2O_3**	**Fe_2O_3**
Alite	60-67	17-25	3-8	0,2-6
Belit	33-46	39-61	3-10	3-5
	Mineralogical composition, mass %			
	C_3S (Alit)	**C_2S (Belit)**	**C_3A**	**C_4AF**
Alite	40-75	5-25	2-15	5-20
Belit	10-35	60-85	3-5	2-7
Note: Conventional names of cements are given according to the predominant content of minerals: C_3S - alite, C_2S - belite.				

Physicochemical studies have confirmed [4-7] that the mineralogical composition of belite cement stone consists predominantly of colloidal calcium hydrosilicates of the C-S-H type compared to the crystalline neoformations of Portland cement. The formation of the structure of slow-hardening cement stone during its hardening over 8 years is shown for clarity in photographs of fractures of cement beams tested for tensile strength under bending, shown in Figure 2. The nature of the slow decomposition of cement grains and the emergence of neoformations is clearly visible in the photographs (Figure 2).

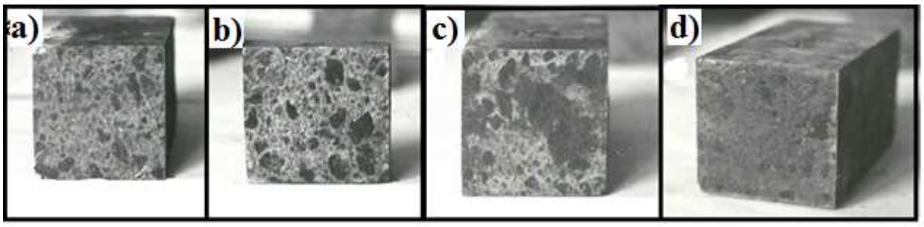

Figure 2. Photographs of fractures of samples hardened under normal conditions and tested after: a) – 1 year; b) – 3 years; c) – 6 years; d) – 8 years [own material]

Figure 2a clearly shows undecomposed cement grains and grains with a formed peripheral shell, which gradually grows (see Figure 2b) and transforms into amorphous gel-like formations (see Figure 2c). The amorphism of these formations is due to the fuzziness and blurriness of their edges and their disordered growth in all directions. Along with amorphites, single C–S–H crystals are observed (see Figure 2b). In immersion, the gel is a colorless isotropic mass with a refractive index of 1.330–1.567. The number of gel-like formations in the samples increases with increasing age. However, even after 8 years of hardening under normal conditions, unhydrated grains are observed in the cement samples, indicating the potential for further hardening of the cement. The radiographs of belite cement stone shown in Figure 3 confirm the obtained data.

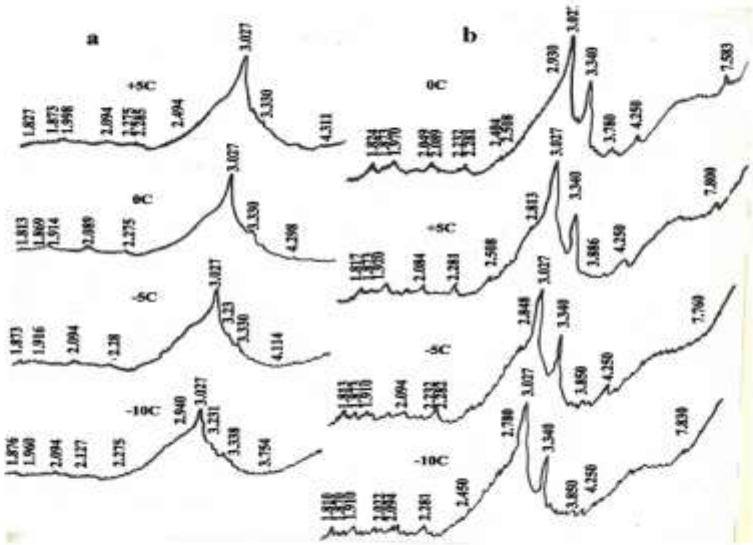

Figure 3. X-ray diffraction patterns of belite cement stone samples hardened for 3 months at temperatures of +5^o C; 0^o C; -5^o C; -10^o C. Where: a) – after 1 month of exposure to normal conditions; b) – without exposure to normal conditions [own material]

Thus, regardless of the temperature conditions of hardening of belite cement stone (within the experimental limits) and the curing period, the phase composition of the new formations does not undergo any significant changes. The slowing down of the cement hydration processes with a decrease in the hardening temperature is evidenced by the decrease in the diffraction line corresponding to an interplanar distance of 3.027 Ǻ, compared to 3.039 Ǻ, during hardening at positive temperatures, described in detail by H.F. Taylor [8].

Figure 4 shows the test results for a number of samples 5, 6, 7, 8 compared to samples that were continuously hardened under normal conditions - 2.

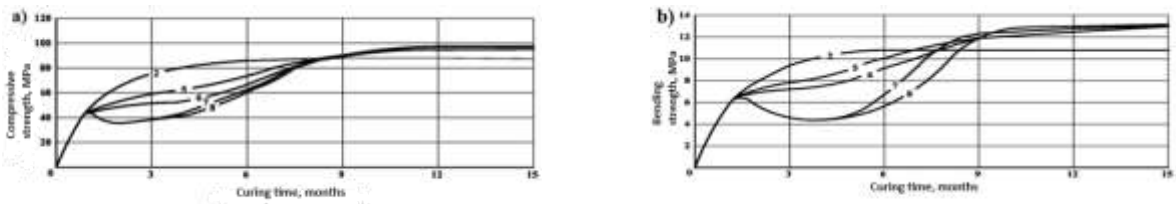

Figure 4. Kinetics of change in the strength of belite cement stone samples over time: 2 – constantly under normal conditions; 5, 6, 7, 8 – pre-aged for 1 month under normal conditions, then respectively at +5°C; 0°C; -5°C, -10°C, then again under normal conditions: a – compressive strength; b – tensile strength in bending [own material]

Data shows that low positive and negative temperatures slow the hardening process of cement previously cured under normal conditions. Moreover, the lower the curing temperature, the slower the strength gain.

The greatest degradation of road concrete occurs during alternating freezing and thawing, with temperatures crossing 0°C. Therefore, the primary requirement for road concrete is its frost resistance during long-term road use.

In July 2016, a survey of test sections of roads constructed using cinder concrete pavements with a cold asphalt wearing course was conducted. The roads were found to be in good technical and operational condition, with no potholes or subsidence, but with expansion cracks occurring at intervals of 12-15 running meters . In some areas, the edge of the asphalt pavement has been damaged. Cinder concrete bases, which have been in service for 39-40 years, show no deformations other than expansion cracks.

Fegolevo-Zhdanovo road were conducted in the spring of 1989, 13 years after construction. A survey conducted in July 2016, 39 years later, showed that the test section is in good operational condition. Longitudinal and transverse cracks are present. The distance between transverse cracks, compared to 1989, has decreased to 12-15 linear meters, with an opening width of 2-1/2-3 mm. In some areas of the asphalt concrete wearing course, there are potholes, but the cinder concrete is in good condition and free of any defects. A core sample was taken, cutting out concrete for beam tensile testing. No repairs have been performed on this road during its 39 years of operation.

Figure 5. Photo – 2016. Testing of beam samples made from cuttings of the bottom layer of cinder concrete pavement for bending strength (the structure of the beam is non-uniform - the filler is a local gravel-sand mixture) [own material]

In the table 2, the results of testing cores drilled in 1989 from the bottom layer of concrete pavement and beams made from concrete cuttings in 2016 of the Fogolevka-Zhdanovo highway, built in December 1977, are presented.

Table 3. Results of testing cores from 1989 and beams from 2005 from the bottom layer of concrete pavement of the Fogolevka–Zhdanovo highway

Name of the measured indicator	Core testing 1989, MPa, (the concrete is 12 years old)	Testing of core beams in 2016, MPa, (the concrete is 39 years old)
Compressive strength	36.4; 36.7; 36.5 Average 36.5 (M 350)	48.6; 49.0; 48.8 Average 48.8 (M 450)
Bending strength	-	8.6; 8.3

The results of a study on the construction technology of cinder concrete pavements with an asphalt concrete wearing course in winter and the monitoring of test road sections constructed in summer and winter are confirmed. This demonstrates that cinder concrete road pavements exhibit self-healing properties and long-term strengthening under constant dynamic vibration loads, including traffic and climatic loads, over many years of road operation. Figure 1 presents the test results of cinder concrete bases on several road sections constructed between 1976 and 1984. Cinder concrete hardening occurs over a period of 30-40 years during road operation.

The results we obtained from petrographic, X-ray structural (Fig. 2), differential thermal analysis and observation using a scanning electron microscope showed that during the hardening of belite cements, the main structure-forming new formations in concrete are colloidal low-basic calcium hydrosilicates of the C–S–H type [6].

4. Discussion

The obtained experimental results allow us to assume that of all the theories of hardening of mineral binders, the colloid-chemical theory of V. Michaelis can be distinguished [6], which will obviously be more justified in explaining the hardening processes of belite cements.

At normal temperatures, C–S–H hydrosilicates form as lamellar colloidal submicrocrystals with an average length of approximately 10,000 Å (1 μm), and width and thickness of 360–560 Å and 20–30 Å, respectively. Due to the very small size of hydrosilicates and their ability to adsorb water on their surface, hydrosilicates exhibit colloidal properties. Water loss or saturation is accompanied by a change in the distance between the layers of the C–S–H hydrosilicate crystal lattice, which leads to changes in the material's strength. Further exposure of the material to humid conditions ensures moisture adsorption by the gel, replenishment of the binding water films between the hydrosilicate lattice layers, and restoration of the material's strength. Therefore, belite road concretes exhibit self-healing properties, regardless of temperature and climate changes and dynamic traffic loads.

The main structure-forming component in belite cement stone is low-basic calcium hydrosilicates C–S–H, which are an amorphous adhesive of nano-sized sizes [6–9], possessing the property of long-term thixotropy. Concrete is the most common building material, a nanostructured multiphase composite that matures over time. It consists of an amorphous phase, crystals ranging in size from nano- to micrometers, and bound water. The properties of concrete, as well as its degradation characteristics, exist across a multiscale range (from nano- to micro- and macro-levels), with the material properties at each level being formed based on the properties of the previous, smaller-sized cell [9-10]. The amorphous phase of calcium silicate hydrate (C–S–H) is the "glue" that binds the components of concrete together [11, 12] and is itself a nanomaterial. Recently, due to interest in the formation of stable concrete structures [9, 13, 14], much attention has been paid to the nanoscale modification of the C–S–H structure to create hybrid, organic, cementitious nanocomposites. The layered structure and the tendency of silicon chains (except tetrahedral) to have structural defects in C–S–H [9,11] open the possibility of introducing a variety of organic molecules into the basic C–S–H structure. Three schemes have been proposed for hybridization or introduction of "guest molecules" into C–S–H. The first scheme interpolates organic molecules into the C–S–H layer [15].

We have investigated the following properties of belite nanocements, as self-healing, with the aim of developing the technology of road construction work at various temperatures for year-round construction and operation of highways.

This is also confirmed by the change in the amount of tightly bound water in the cement stone of samples maintained at different temperature conditions (Figure 6).

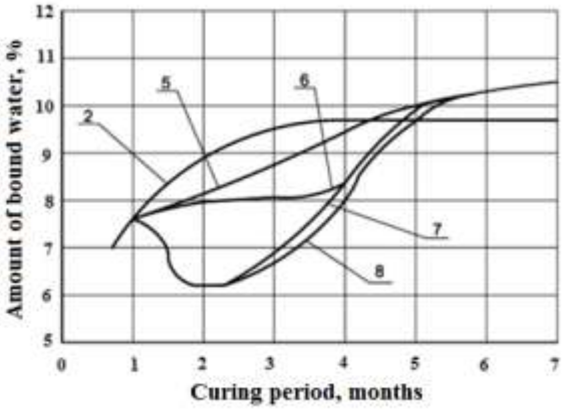

Figure 6. Kinetics of changes in the amount of tightly bound water in belite cement stone during hardening at different temperatures: where 2 is constant under normal conditions, 5, 6, 7 and 8 – initially one month under normal conditions, then three months at temperatures: +5^o C, 0^o C, -5^o C and -10^o C and again three months under normal conditions [own material]

The results of changes in the amount of strongly bound water in the cement stone (Figure 6), established by measuring the mass loss of samples after their calcination at 1000°C, previously kept at 105°C, confirm the following. The kinetics of changes in strength (Figure 3) and the amount of strongly bound water (Figure 6) of the cement stone, depending on the temperature of sample holding, are similar, which confirms the reliability of the theoretical assumptions about the self-healing properties of belite cement. When holding the cement stone at low temperatures (samples 5-8), the decrease in strength (Figure 3) is accompanied by the displacement of strongly bound water (Figure 6) from fibrous new formations in the amount of 10-30% of the mass of moisture present in their capillaries, and with further holding under normal conditions their quantity and the strength of the cement stone are restored within one month. After further curing under normal conditions for three months, the strength and amount of tightly bound water exceed those of normal curing samples. This indicates an intensification of cement grain hydration processes and an increase in the dispersion of new formations at low curing temperatures, which also increases the strength of cement stone and concrete (Figure 3).

Figure 7 shows the results of strength tests of various road concrete compositions depending on the amount of belite cement, which confirm the conclusion about the long-term increase in concrete strength over 2 years.

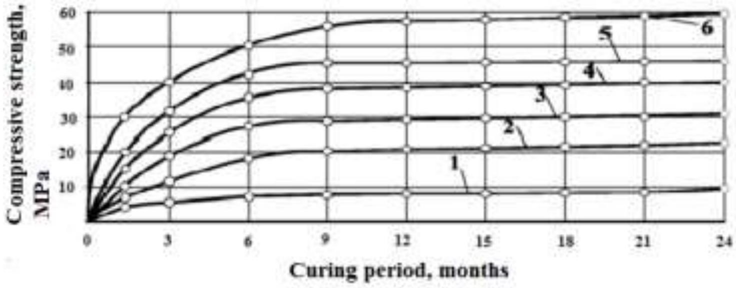

Figure 7. Kinetics of strength gain of road concrete over time depending on the amount of belite cement: *1, 2, 3, 4, 5* – 7, 10, 12, 15 and 18 % by weight of cement, respectively [own material]

When testing 90-day-old concrete samples for frost resistance, up to 200 freeze-thaw cycles were performed. As Figure 13 shows, there is a slight decrease in strength due to moisture being squeezed out of the capillaries and a decrease in its volume. Upon further curing of the samples under normal conditions, the concrete strength is fully restored and even exceeds that of 90-day-old samples (Figure 8).

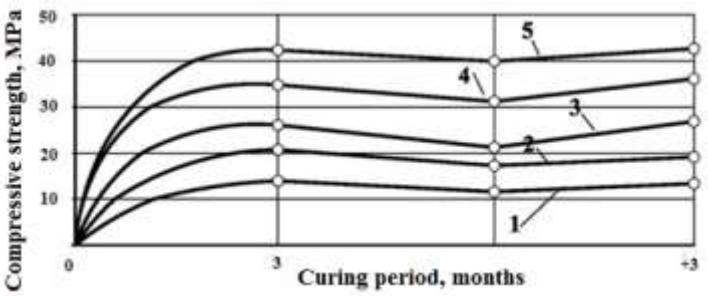

Figure 8. Self-healing strength of road concrete tested for frost resistance (MRZ-200), depending on the amount of belite cement: *1, 2, 3, 4, 5* – 7, 10, 12, 15 and 18 wt.% cement with a C_2S content of 75–80 % [own material]

Belite road concretes harden slowly compared to traditional alite cements, but their strength properties at 180 days are virtually comparable, and the deformation properties of belite concrete even exceed those of alite concrete. Moreover, flexural tensile strength is 31% higher, and the elastic modulus is 5000 MPa lower (Table 4).

Table 4. Comparison of performance indicators: road cement concrete and slow-hardening road concrete on belite cement

Composition of road concrete, wt. %				Ultimate strength at the age of 180 days , MPa (average of 3)			Modulus of elasticity E_y, MPa
Crushed stone fractions, mm:		Sand M_{pr} = 2.5	Cement,%	R_{comp}	R_{bend}	R_{bend}/ R_{comp}	
5-10	10-20						
15	34	29	Belite cement, 15%	30.9	5.9	0.19	30,000
15	34	29	Alite cement, M 400,15%	30.0	4.5	0.15	35,000

The high deformative properties of slowly hardening concrete indicate high dispersion and tensile strength (cohesive bond) of new formations of cement stone of belite cements (Figure 9).

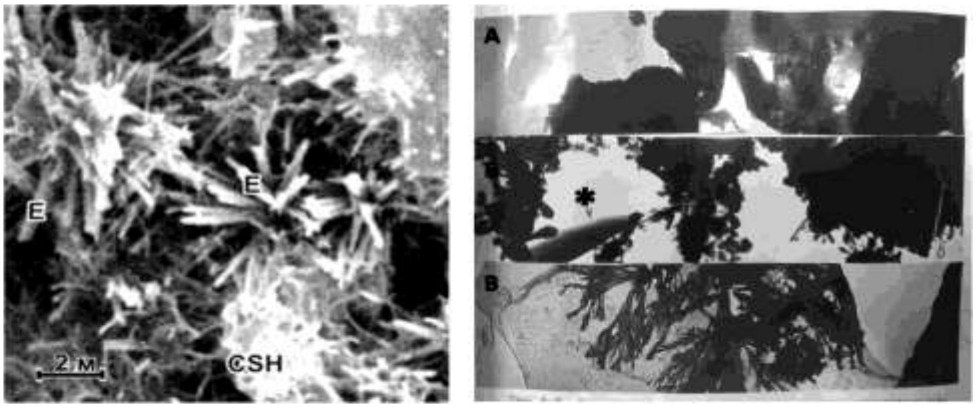

Figure 9. Microstructure of cement stone: on the left – alite cement stone, after 28 days, E – ettringite crystals , CSH – C-S-H fibers [6]; on the right – belite cement stone [7]: a – after 28 days; b – after 90 days, tube (*) CSH; c – after 180 days, C-S-H fibers. Fiber sizes are 0,3-0,5 nanometers. (Electroscope – magnification 25000) [own material]

X-ray diffraction, thermographic (not shown), and electron microscopic studies, shown in the photograph (Figure 9), confirm that in such concretes, the aforementioned technological and operational advantages are primarily due to the gel-like curing structure of belite cements . In contrast, in the structure of traditional alite Portland cement stone, the small amount of gel-like calcium hydrosilicates fills only the free space within the main framework formed by the intergrowth of large crystalline hydrates.

Table 5. Results of selection of asphalt-belite concrete mixtures for the construction of the Astana-Borovoe highway

№ Composition of the mixture	Materials used in the mixture, %						
	Asphalt concrete granules	Crushed blast furnace slag fraction 5-20	Crushed blast furnace slag fraction 20-40	Belit powder	Activator cement M-400	Water	Bitumen
1	40.0	10.0	30.0	20.0	2.0	5.0	2.0
2	40.0	10.0	30.0	20.0	2.0	5.0	0
3	30.0	20.0	30.0	20.0	2.0	5.0	2.0
4	50.0	10.0	25.0	15.0	2.0	4.0	2.0
5	50.0	10.0	25.0	15.0	2.0	4.0	0
6	60.0	10.0	20.0	10.0	2.0	3.0	2.0
7	70.0	10.0	10.0	10.0	2.0	3.0	2.0
8	70.0	10.0	10.0	10.0	2.0	3.0	0

Table 6. Strength of samples of asphalt-mineral concrete cores cut from the base of the Astana-Borovoe highway (of different ages)

Age of the sample	**Compressive strength R_{zh}, MPa at t^0C**			
	20^oC	**50^oC**	**0^oC**	**-10^oC**
7 days	4.81	2.29	7.4	7.9
2 years	9.44	3.32	12.5	18.6
3 years	13.15	4.22	13.8	22.5

The test results presented in Tables 5 and 6 showed that the addition of 2% bitumen is excessive; strength decreases and bitumen separation appears on the road. Therefore, the road was built using composition №8; with a maximum amount of asphalt granulate up to 70%. The strength of asphalt belite concrete, the strength of which is strengthened during the operation of roads up to M15-20 (within the experiment of 3 years) and exceeds the strength of traditional asphalt concrete by 3-5 times, depends on the core test temperature (Table 7). This indicates that the elastic-plastic properties of asphalt concrete are preserved at the microstructure level in asphalt belite concrete and bitumen molecules are embedded in the colloidal structures of calcium hydrosilicates C-S-H, which is confirmed in the works of the USA, Czech Republic and others [8-15].

Nanostructured asphalt concretes and road concretes based on nanostructuring powders and cements meet the requirements of modern concepts of “eternal roads” and “roads with a long service life” in the USA and EU countries, which make it possible to build road structures with a service life of at least 50 years [2,5].

The innovative concept of road construction (road structures) provides for complete resource conservation at all stages of the road's life: during construction, repair, and reconstruction, with the complete recycling of all materials and their reuse.

5. Conclusion

Belite cements, with a predominant content of two calcium silicates (C_2S-belite up to 50-80%), demonstrate high durability of concrete based on them in road construction, potentially up to 50 years or more, compared to alite (C_3S up to 65%) Portland cements, which have a shorter service life of 25-30 years for cement concrete roads.

The uniqueness of belite cements, characterized by the formation of a colloidal structure with nanosized calcium hydrosilicates CSH, ensures almost complete hydration of cement grains, due to which the colloidal structures have the properties of long-term thixotropy (self-healing upon destruction) and long-term rheopexy (strengthening under the influence of transport loads and seasonal temperature changes), which ensures the elimination of premature destruction in concrete, exclusively under the conditions of long-term operation of concrete roads.

Research conducted for the first time in Kazakhstan confirms the effectiveness of the theory put forward by the French scientist V. Michaelis regarding the strengthening of mineral binders with a predominant content of colloidal structures. This theory was proposed 180 years ago, but has not yet found practical application.

Monitoring of roads constructed from belite nanostructured cement concrete and asphalt-belite concrete under real conditions, which continues to strengthen the concrete for 35-46 years, demonstrates their effectiveness and confirms the conclusions of the VI Prague International Forum: "Road layers can be constructed from 100% old asphalt concrete."

Global concerns about environmental pollution can be reduced by producing environmentally friendly belite cements, eliminating the need to fire alite Portland cement clinker , and replacing them with thermally processed by-products from large-scale industrial metallurgical and energy production. Global alite cement production contributes 7-10% of global atmospheric CO^2 emissions.

The transition to environmentally friendly, cold, nanostructured asphalt concrete in road construction, eliminating toxic gases both during construction and during long-term operation from heating of asphalt concrete road surfaces, will ensure protection from air pollution in large cities.

Research suggests that the use of belite cements and asphalt-belite binders in road construction could result in more durable infrastructure, reminiscent of the durability of ancient Roman concrete.

Conflict of interest. The correspondent author declares that there is no conflict of interest.

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