Case Study Of The Dynamics Of Thermal Expansion Of Concrete In Pavements of South Kazakhstan

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ABSTRACT

This article explores the behaviour of concrete samples from road sections that have experienced warping due to temperature fluctuations. Warping refers to the curling of concrete slabs. The paper presents a novel approach to tracking the expansion and contraction of concrete joints over time. It analyses how the size and shape of concrete samples from cement-concrete (hereafter referred to as concrete) roads change under varying temperatures. Additionally, this study investigates the impact of temperature on concrete deformation. It was assumed that as the concrete's density and compressive strength increased, the linear expansion coefficient also increased. Furthermore, research has shown that this coefficient can vary along different axes within the concrete volume. This article describes the mechanism behind the deformations observed during the thermal expansion of concrete slabs and identifies the key factors influencing the buckling of concrete slabs as the air temperature rises. The temperature expansion may vary depending on the material's structure, as well as the constant polymorphic transformations of cement minerals within the concrete. These transformations are influenced by ambient temperature, humidity, and the presence of free lime. The factors affecting temperature expansion were determined to be the mineralogical composition of the cement, the concrete's strength class, and the cement content within the concrete.

1. Introduction

Kazakhstan has encountered numerous challenges in improving the country's infrastructure as part of its economic development [1–4]. While creating favourable conditions for trade turnover is essential for economic growth, Kazakhstan's highways are ranked 93rd out of 138 countries in terms of quality according to the international road quality ratings, which limits the country's transport potential [5–7].

Leading global technologies have been implemented to enhance the country's logistics capacity, including the construction of cement-concrete highways [8–13]. Experience has shown that the life cycle of concrete pavements is at least three times longer and more durable than that of asphalt pavements [13–18]. Initially, the construction cost of concrete pavements was estimated to be 15–20 % higher than that of asphalt pavements. However, a detailed financial analysis reveals that over their life cycle (approximately 25 years), the costs associated with the repair and maintenance of asphalt pavements make the construction and upkeep of concrete pavements approximately 40–50 % cheaper [19, 20]. Cement-concrete pavements, in particular, are advantageous under conditions of high traffic volume and/or heavy road transport loads [21–25].

The United States leads the world in the number of cement-concrete roads, with over 100,000 km of concrete roads currently in operation, more than half of which serve as high-volume freeway routes. A great deal of experience in road construction and design solutions, especially in the development of cement-concrete roads, has been gained from the 19th century to the present day [26]. During this period, the optimum thickness of concrete roads, pavement composition, expansion and contraction joint construction, and the design and optimal spacing of contraction joints have been determined [3].

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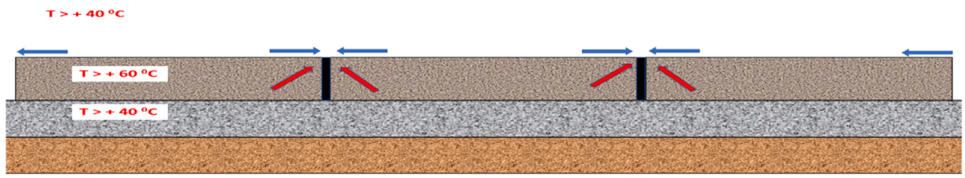


Fig. 1. Scheme of temperature stresses of deformation in concrete slabs.

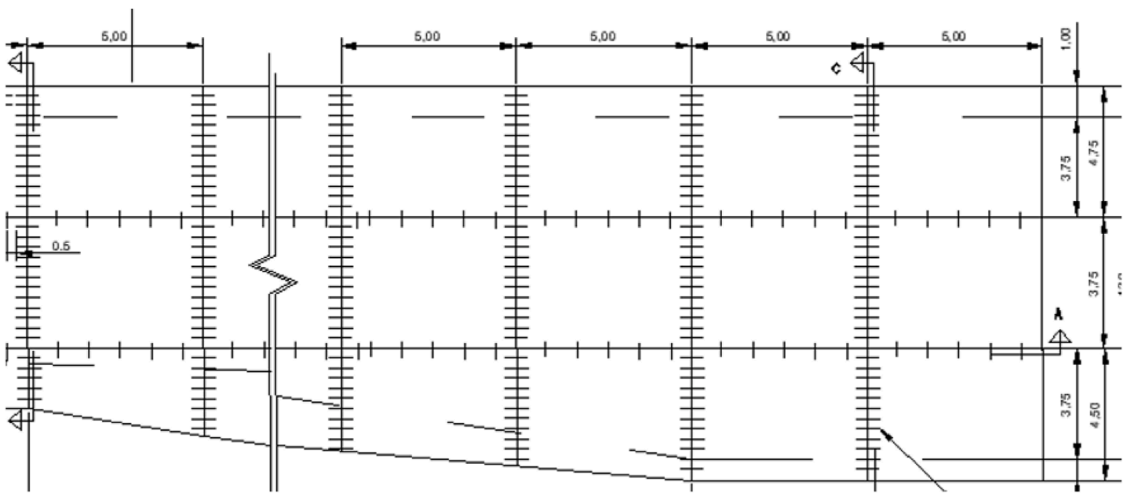


Fig. 2. Scheme of the investigated road.

Since 2007, Kazakhstan has constructed and utilized over 1600 km of concrete roads within its national network. Despite the obvious advantages of concrete pavements over asphalt, a number of issues related to climatic conditions and operational characteristics in the southern regions of Kazakhstan have emerged (with summer temperatures exceeding 45 °C) [27,28].

In the first year of operation, rapid temperature-induced expansion of the concrete led to frequent warping of the concrete slabs. To mitigate these issues, compensating joints, such as compression joints and expansion joints, were employed. However, improper maintenance of concrete slabs and a lack of control over the mineral composition of Portland cement were key factors contributing to the warping of the concrete slabs, with the number of warping cases increasing annually [29–33]. This paper presents the results of laboratory tests conducted on concrete samples obtained from cores, revealing expansion coefficients exceeding the regulatory limits. Monitoring of beacons installed at joints along the highways showed the anisotropic expansion and contraction of concrete slabs.

The aim of this study was to monitor the dynamics of road slab movement depending on temperature expansion. The main objectives of our research are the following questions:

- development of monitoring beacon designs to measure the maximum compression of concrete road slabs and determine how to install them;
- installation of monitoring beacons at transverse expansion joints and false joints;
- taking full-scale measurements from monitoring beacons in the autumn period to determine the compression of concrete road slabs and analysing the data obtained.

2. Materials and methods

The thermal expansion of concrete can cause significant stress in the concrete structure, leading to cracking, chipping, and warping of concrete slabs. When concrete is exposed to high temperatures, tension and compression stresses are created in the concrete mass, and a moment of force from the bottom to the top is created in the plate (Fig. 1).

Fig. 3. Dynamics of defect formation in concrete slabs caused by thermal expansion of the ‘Shymkent-Taraz’ 902 km concrete road (Left: the start of deformations; Middle and right: the end result).

Similar stresses will also occur in the adjacent concrete slab. Initially, these stresses will accumulate until the internal forces exceed the concrete’s strength. The process of destruction begins with cracking at the ends of the slabs. The dynamics of temperature fluctuations, or their amplitudes, play a crucial role in this process.

When there is a sharp rise in temperature during the day followed by a sharp decline at night, these temperature fluctuations create relatively short pulses, which, in turn, generate stresses in the concrete. This creates conditions for the formation of cracks, potholes, and ledges. Fig. 2 shows the layout of the road, while Fig. 3 illustrates sections of the ‘Shymkent-Taraz’ concrete road where defects caused by temperature expansion have been recorded.

Under conditions where temperature fluctuations during the day and night are nearly the same, the temperature amplitude increases, leading to higher stresses. As a result, deformations in the concrete occur more

Fig. 4. Warping* of concrete road slabs (blow up)
* A protective layer of bitumen-based microsurfacing was applied to the concrete slab below.

intensively, causing the slab to crack and virtually blow apart (Fig. 4).

Fig. 3 illustrates the result of concrete slabs "blowing up" or "whipping up" in hot weather at locations of transverse joints that are not wide enough to allow the slabs to expand. The figure shows a section of the Shymkent-Taraz concrete road, where a protective layer of microsurfacing (a mixture of mineral powder and bituminous emulsion) was applied over the concrete. Corrosion occurred at a temperature of 45 °C, with the black colour significantly accelerating the corrosion process.

To determine the buckling of concrete roads, a method for monitoring the maximum temperature expansion in joints was established. Beacons were installed on the false and expansion joints in the same plane (Fig. 5).

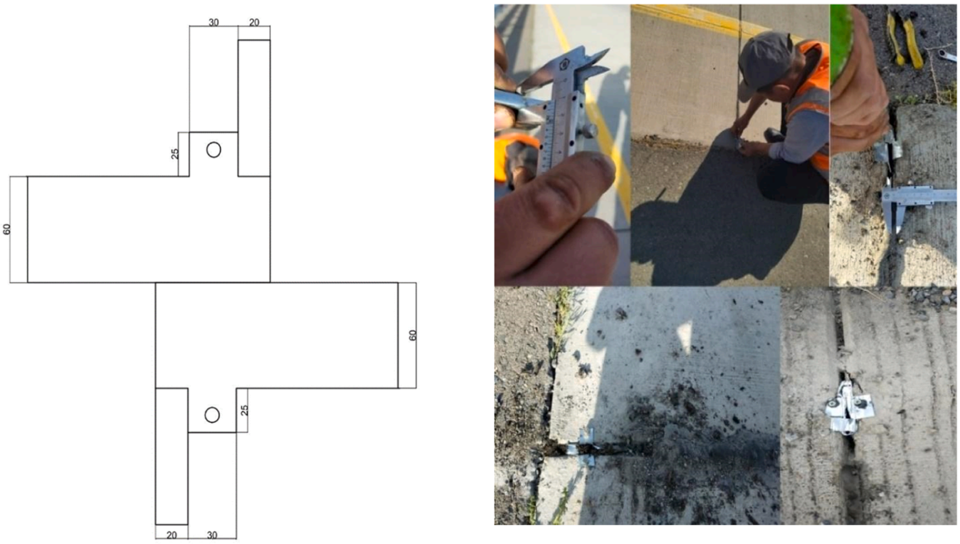
The objects of this study were concrete roads located in the south of Kazakhstan (Shymkent city), where the maximum air temperature in the summer exceeds 45 °C. Analysis of data from the last three years has shown that warping occurs during periods when the air temperature reaches 45 °C during the day and 35 °C at night for three consecutive days. This increase in stress contributed to the formation of cracks and ledges in the transverse joints of the concrete slabs, and in some cases, resulted in significant warping (blow-up) of the slabs.

Beacons were installed at each deformation joint along a 300-meter stretch of the road. The beacons consist of an aluminium tube with a diameter of 16 mm, a wall thickness of 0.8 mm, a length of 40 mm, and an installation envelope, as shown in Fig. 4. The aluminium tube was placed in the envelope, then installed in the deformation joint and fixed to an anchor. A total of 60 beacons were installed.

The main factor in the installation of the beacons is the ambient air temperature, which should not exceed 30 °C. During the installation process, the air temperature was 25 °C. The removal of the beacons was planned for the autumn period, when the air temperature did not exceed 15 °C. During removal, the air temperature was 12 °C.

Measurements were taken using callipers, and the widths of the joints and the installed beacons were recorded during both the installation and removal processes. With temperature fluctuations, the joints expand or contract, and by knowing the initial width of the installed beacon, it is possible to monitor the dynamics of the joints.

Three concrete core samples were taken from road sections where warping had previously been recorded, indicating that the deformation properties of the concrete depend on temperature. The concrete samples were measured in three directions and placed in a freezing chamber and a drying cabinet (−30 °C and +70 °C). Fig. 6 shows the method used to



a) installation envelope for mounting, mm *b) Beacon installation process*

Fig. 5. Beacons for monitoring the temperature expansion of concrete slabs.

Fig. 6. Measurement of geometric parameters of concrete samples taken from road sections with concrete coating after heating and cooling.

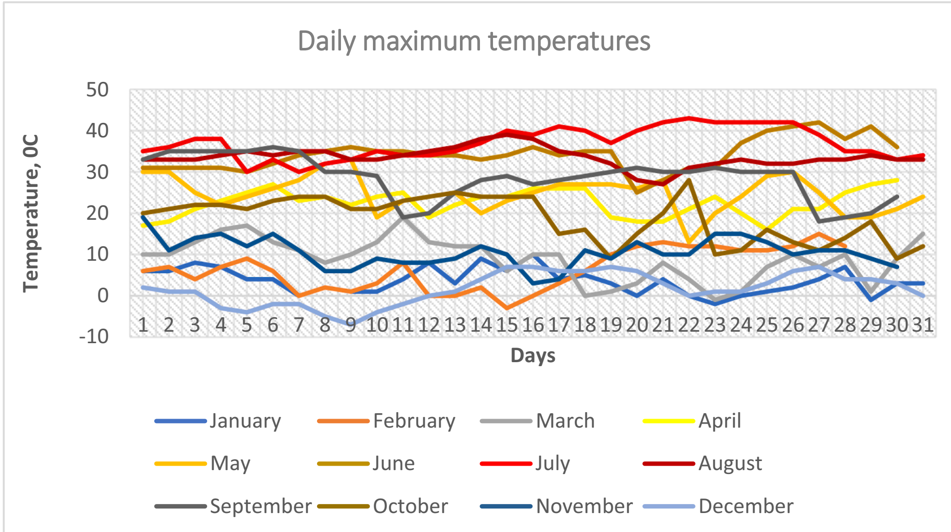


Fig. 7. Maximum daily temperature during the year.

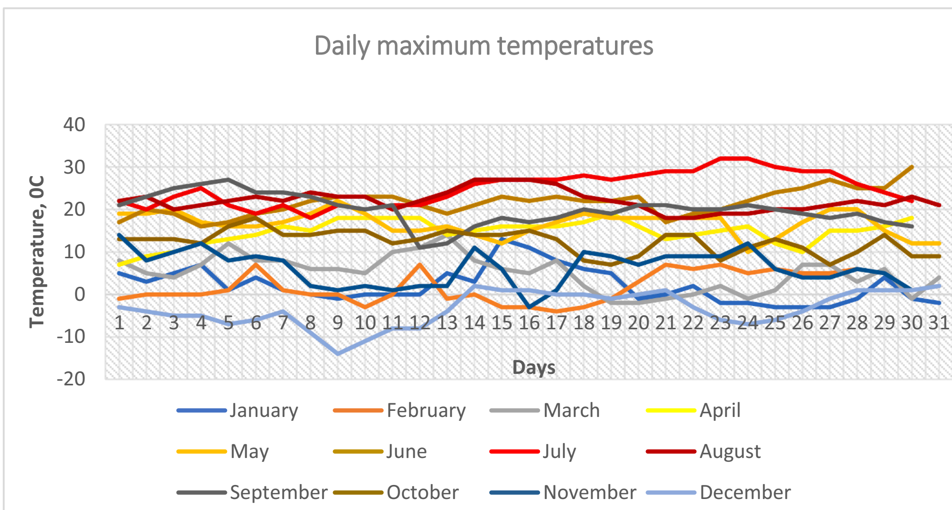


Fig. 8. Minimum daily temperature during the year.

measure the geometric parameters of the concrete samples after heating and cooling in two planes.

The results of the measurements of the geometric parameters of concrete samples taken from road sections with cement-concrete pavements, where warping had previously occurred, confirm the dependence of the deformative properties of concrete on temperature. For this, the concrete samples were measured in three directions and placed in both a freezer and a drying cabinet (−30 °C and +70 °C). Fig. 5 shows the method by which the geometric measurements of the concrete samples were made after heating and cooling in two planes.

3. Results

Climate data were also obtained during monitoring surveys. The average daily and monthly temperatures were determined for the three summer months. The data were obtained from the National Hydrometeorological Service of Kazakhstan. The climatological data are presented in the form of graphs in Fig. 7.

Minimum daily temperature during the summer months are presented in Fig. 8.

The next step involved measuring the expansion and contraction of concrete road joints. This was achieved by utilising a newly developed technique for monitoring joint dynamics, which likely involved displacement sensors placed strategically across the joints. As a result of the monitoring, the dynamics of the changes in the beacons of the joints were revealed, as listed in Table 1.

According to the results presented in Table 1, we observed that in some joints there was an absolute absence of dynamics in the broadening and narrowing of the plates. In the cases of beacons 4, 8, 10, 13, and 32, there was widening of the joint, but no narrowing occurred.

After analysing the results obtained from the width measurements of the beacons, it can be seen that the difference between the two measurements ranged from 0.2 to 2 mm, with percentage differences ranging from 5 % to 25 %. The results of the joint measurements showed that the joint openings ranged from 0 to 2.5 mm, corresponding to a percentage range of 0 % to 25 %.

Based on the data obtained, the dynamics of joint narrowing and widening are observed, though not consistently. This variation can be explained by the presence of inert materials in the joint, which affect their performance. The overall change in dimensions can reach 4.5–5 mm, which is a significant variation. In the studied 300-meter interval, the total deviation of the linear dimensions of the plates due to

Table 1
Beacon installation log.

Beacon number	Installation site (km)	Slab number	In installing		After removing	
			Joint width (mm)	Beacon width (mm)	Joint width (mm)	Beacon width (mm
1	Km 181 + 05m	1	15.0	12.0	17.5	11.0
2	Km 181 + 10m	2	10.0	10.0	10.5	10.0
3	Km 181 + 15m	3	12.0	12.0	12.4	11.0
4	Km 181 + 20m	4	9.0	9.0	11.0	9.0
5	Km 181 + 25m	5	9.0	9.0	9.5	8.5
6	Km 181 + 30m	6	11.0	11.0	11.2	9.0
7	Km 181 + 35m	7	8.0	8.0	9.1	7.5
8	Km 181 + 40m	8	8.0	8.0	9.5	8.0
9	Km 181 + 45m	9	9.0	9.0	9.0	8.4
10	Km 181 + 50m	10	8.0	8.0	9.8	8.0
11	Km 181 + 55m	11	8.0	8.0	8.5	7.9
12	Km 181 + 60m	12	9.0	9.0	10.5	8.9
13	Km 181 + 65m	13	10.0	10.0	10.0	9.8
14	Km 181 + 70m	14	9.0	9.0	9.5	8.4
15	Km 181 + 75m	15	8.0	8.0	10.0	7.0
16	Km 181 + 80m	16	8.0	8.0	10.0	7.5
17	Km 181 + 85m	17	10.0	10.0	10.2	9.1
18	Km 181 + 90m	18	8.0	8.0	9.0	7.0
19	Km 181 + 95m	19	9.0	9.0	10.5	8.8
20	Km 181 + 100m	20	8.0	8.0	8.5	7.2
21	Km 181 + 105m	21	8.0	8.0	8.9	7.1
22	Km 181 + 110m	22	9.0	9.0	10.5	8.9
23	Km 181 + 115m	23	9.0	9.0	9.9	8.0
24	Km 181 + 120m	24	9.0	9.0	9.8	7.5
25	Km 181 + 125m	25	9.0	9.0	9.5	8.2
26	Km 181 + 130m	26	11.5	11.5	11.5	10.4
27	Km 181 + 135m	27	9.0	9.0	9.5	7.9
28	Km 181 + 140m	28	10.0	10.0	10.0	8.8
29	Km 181 + 145m	29	9.0	9.0	9.0	8.0
30	Km 181 + 150m	30	8.0	8.0	10.0	7.8
31	Km 181 + 165m	31	8.0	8.0	8.0	6.5
32	Km 181 + 170m	32	8.0	8.0	9.5	8.0
33	Km 181 + 175m	33	8.0	8.0	9.0	7.3
34	Km 181 + 180m	34	8.0	8.0	9.5	7.1
35	Km 181 + 185m	35	8.0	8.0	9.8	7.5
36	Km 181 + 190m	36	8.0	8.0	9.2	7.5
37	Km 181 + 195m	37	9.0	9.0	10.0	8.5
38	Km 181 + 200m	38	9.0	9.0	9.5	8.8
39	Km 181 + 205m	39	8.0	8.0	8.9	6.0
40	Km 181 + 00m	40	9.0	9.0	10.6	8.0
41	Km 181 + 210m	41	8.0	8.0	9.5	7.5
42	Km 181 + 215m	42	9.0	9.0	10.8	7.5
43	Km 181 + 220m	43	9.0	9.0	10.0	7.7
44	Km 181 + 225m	44	9.0	9.0	10.5	8.0
45	Km 181 + 230m	45	8.0	8.0	9.5	6.9
46	Km 181 + 235m	46	8.0	8.0	9.5	6.4
47	Km 181 + 240m	47	9.0	9.0	10.0	7.5
48	Km 181 + 245m	48	8.0	8.0	9.5	7.5
49	Km 181 + 250m	49	9.0	9.0	10.5	7.2
50	Km 181 + 255m	50	8.0	8.0	9.1	6.9
51	Km 181 + 260m	51	9.0	9.0	10.1	8.0
52	Km 181 + 265m	52	8.0	8.0	9.1	7.5
53	Km 181 + 270m	53	8.0	8.0	9.0	7.1
54	Km 181 + 275m	54	9.0	9.0	10.1	8.0
55	Km 181 + 280m	55	8.0	8.0	9.5	6.5
56	Km 181 + 285m	56	9.0	9.0	10.0	7.3
57	Km 181 + 290m	57	9.0	9.0	9.6	7.1
58	Km 181 + 295m	58	9.0	9.0	10.5	7.5

temperature fluctuations reached approximately 120 mm (with narrowing totalling 51.9 mm and widening totalling 64.1 mm). Data on the dynamics of narrowing and widening of the joints are presented in Figures 9-12.

The results of the measurements of the geometric dimensions of concrete after cooling and heating are summarized in Table 2. When the temperature increased from +22 °C to +70 °C, the absolute elongation of concrete samples in the longitudinal direction was 0.12 mm. When the temperature changed from +70 °C to −30 °C, the elongation was 0.17 mm. The relative elongation of the concrete samples, taking into account the scaling factor, was 1.2 mm/m within the specified temperature range. In the transverse direction, when the temperature increased from +70 °C to −30 °C, the absolute elongation of the concrete samples ranged from 0.055 mm to 0.059 mm, while the relative elongation, considering the scaling factor, was 0.38–0.41 mm/m. Based on the data obtained, the coefficient of linear expansion for the concrete from the cement-concrete pavement of the highway was calculated to be 0.000012 C^{-1}.

Fig. 9. Results by beacon width during installation (blue-initial, red- final).

Fig. 10. Results by seams width after removal (blue-initial, red- final).

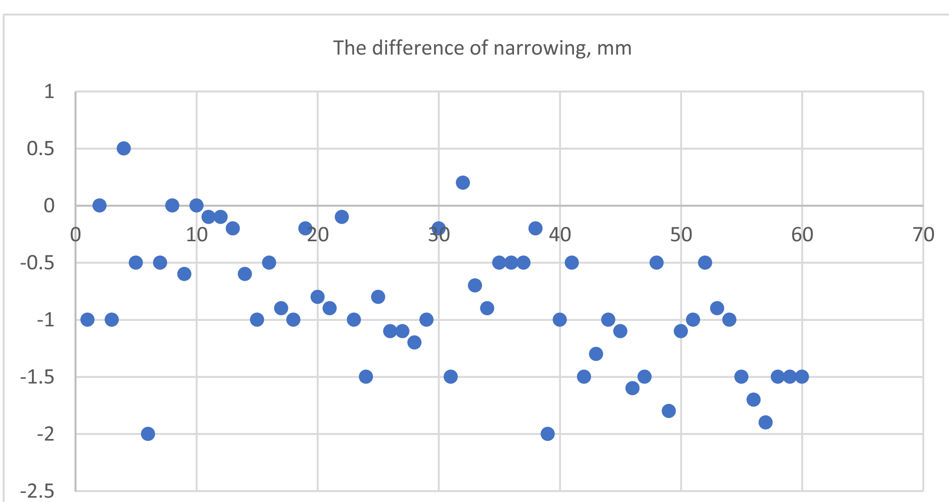


Fig. 11. Difference of narrowing by the measurements of the seams

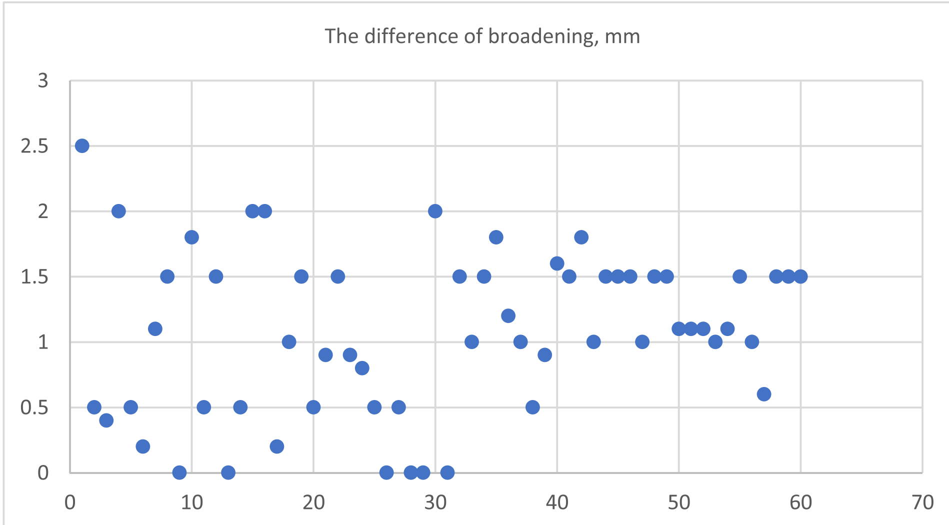


Fig. 12. Difference of expansion by the dimensions of the seams.

Table 2
Geometric parameters of concrete samples from road sections with concrete coating.

№	The length of the concrete sample at a temperature of +22 ° C, mm	Concrete elongation, mm		Absolute elongation Δ, mm	Relative elongation ∂, mm/m
		+70 °C	– 30 °C		
1	143.0	0.12012 (143.12)	−0.05148 (142.949)	0.171	1.2
2	47.2	0.039648 (47.24)	−0.01699 (47.183)	0.056	0.39
3	143.7	0.120708 (143.821)	−0.05173 (143.648)	0.172	1.2
4	45.7	0.038388 (45.738)	−0.01645 (45.684)	0.055	0.38
5	148.5	0.12474 (148.625)	−0.05346 (148.447)	0.178	1.24
6	49.4	0.041496 (49.441)	−0.01778 (49.382)	0.0592	0.41

4. Discussion

Having studied the dynamics of compression and broadening of false seams and expansion seams, we can attempt to describe the causes of concrete slab buckling. The primary cause of warping in concrete slabs is linked to their thermal expansion and the operability of the seams. Data from the monitoring beacons showed that there is a "reserve" in the concrete slabs for expansion and contraction. At low temperatures, the seams shrink by 2 mm, while at high temperatures, they expand by 1 mm, meaning the total deviation in each seam reaches 3 mm over 5 m. This creates potential for a false seam. Therefore, clogging of the false seams contributes to excessive stress in the slabs. Another contributing factor to warping is the insufficiency of the expansion joints, which do not extend through the full thickness of the concrete slab, with a seam thickness no greater than 30 mm. According to several sources, the coefficient of thermal expansion of concrete is 0.00001 $^{\circ}C^{-1}$. Using this coefficient, it was calculated that for a road with a concrete coating, expansion joints should be placed every 75 m. However, expansion joints were not implemented in the studied section of the highway during construction. These factors led to the formation of warped concrete slabs. Thus, the numerical values of the linear expansion coefficient vary, indicating anisotropy in the concrete structure (expansion differs along different axes). As a result, significant stresses occur at the boundaries of the cement stone grains, which affect the deformative properties of the concrete. When critical stress values are exceeded, microcracks form, accumulate over time, and ultimately lead to material destruction and warping. Thermal expansion is a structurally sensitive property, reacting to changes in the material's structure—specifically, polymorphic transformations of cement minerals in concrete, which occur based on temperature, humidity, and free lime migration.

To further investigate the cause of the anomalous linear expansion coefficient, concrete samples from the highway pavements will be tested in the future to determine their physical and mechanical properties, such as strength, density, and frost resistance, according to standard methods. We hypothesize that the abnormal increase in strength indicators is related to the higher content of free lime and the aluminate phase in the cement structure. During its operation, the concrete coating is subjected to extreme conditions (high heat in summer, moisture saturation in spring and autumn, and frost in winter), which promotes ongoing hydration, crystallization, and recrystallization processes in the cement stone structure. In support of these points, we will also conduct a phase composition study of the cement stone structure from the concrete samples using X-ray diffraction analysis. The results of this study will be published in future articles.

5. Conclusions

Based on studies of the temperature expansion of concrete samples from road sections where cases of warping were previously recorded, the dependence of the deformative properties of concrete on temperature was revealed. Monitoring the dynamics of joint expansion and compression, as well as measuring the geometric parameters of concrete samples taken from these road sections, confirmed this dependence. Concrete samples with increased density and compressive strength demonstrated a 20 % higher coefficient of linear expansion (0.000012 $^{\circ}C^{-1}$). It was established that the linear expansion coefficient varies along different axes within the volume of concrete. The anisotropy of the cement stone grain structure determines the direction of deformations in concrete. Temperature expansions are not uniform in volume, and significant stresses arise in the horizontal planes. As a result, microcracks form, accumulate over time, and lead to material destruction and warping. Thermal expansion is a structurally sensitive property that reacts to changes in the material's structure. In our case, polymorphic transformations of cement minerals may occur in concrete, depending on factors such as ambient temperature, humidity, migration of free lime, and more. The determining factors include the mineralogical composition of the cement, the concrete strength class, and the amount of cement in the mix. The research results are of practical significance, and the knowledge gained can be used to develop concrete solutions aimed at reducing deformations and damage to roads with concrete pavements.

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CRediT authorship contribution statement

Zh.A. Shakhmov: Investigation. **K.K. Mukhambetkaliev:** Writing – original draft. **R.E. Lukpanov:** Methodology. **D.S. Dyussembinov:** Conceptualization. **A.A. Zhumagulova:** Formal analysis. **D.O. Bazarbayev:** Formal analysis. **A.E. Jexembayeva:** Funding acquisition, Resources.

Declaration of competing interest

The authors declare no conflicts of interest. The funders had no role in the study design; collection, analyses, or interpretation of data; writing of the manuscript; or decision to publish the results.

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Data availability

Data will be made available on request.

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