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Behavioral Characteristics of Cement Concrete Pavements in South Kazakhstan: Climatic Changes and Optimal Construction Method

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Abstract. The present paper describes experiments and research outcomes concerning the construction of cement concrete pavements in South Kazakhstan, taking into account significant climate changes. The study has identified potential problems in the construction of cement concrete pavements in the region, where there was no experience of their construction until the mid-2000s. In order to develop an optimal solution, the technical factors that characterize the process of arranging these coatings using sliding molds are analyzed and quantitatively normalized. These factors include the optimal amount of mortar for curing concrete, the optimal joint cutting time, the interval and effective width of expansion joints to prevent the formation of cracks in concrete at an early age. The effectiveness of the use of polyethylene film to prevent the formation of contraction cracks and maintain the required mode of hardening of the cement concrete pavement is shown. The main cause of damage to the expansion joints along the length of the day coverage of coatings in the conditions of South Kazakhstan has been established. Recommendations have been developed for the installation of cement-concrete pavement and expansion joints during the construction of roads in this region. The accumulated data on climatic factors and methods of work with the use of polyethylene film have made it possible to create an optimal method for the construction of cement concrete pavements, which will improve the quality of roads in South Kazakhstan.

Keywords: cement concrete pavement, cutting time, curing mode, polyethylene film, mock-up test, climatic factors, South Kazakhstan, joint cutting

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Поведенческие характеристики цементобетонных покрытий в Южном Казахстане: климатические изменения и оптимальный метод строительства

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Реферат. В статье изложены результаты исследований цементобетонных дорожных покрытий в Южном Казахстане, для которого характерны значительные изменения климата. Выявлены потенциальные проблемы устройства

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цементобетонных дорожных покрытий в регионе, где не было опыта их строительства вплоть до середины 2000 гг. С целью выработки оптимального решения проанализированы и количественно нормированы технические факторы, характеризующие процесс устройства данных покрытий с использованием скользящих форм. К таким факторам отнесены оптимальное количество раствора для отверждения бетона, оптимальное время нарезки шва, интервал и эффективная ширина деформационных швов для предотвращения образования трещин в бетоне в раннем возрасте. Показана эффективность применения полиэтиленовой пленки для предупреждения образования усадочных трещин и поддержания требуемого режима твердения цементобетонного покрытия. Установлена основная причина повреждения швов расширения на длине дневной захватки и разработаны рекомендации по устройству цементобетонных покрытий и швов расширения при строительстве автомобильных дорог в регионе. Накопленные данные о климатических факторах и методах производства работ с использованием полиэтиленовой пленки позволят оптимизировать строительство цементобетонных дорожных покрытий в Южном Казахстане.

Ключевые слова: цементобетонное покрытие, время резки, режим твердения, полиэтиленовая пленка, пробный макет, климатические факторы, Южный Казахстан, совместная резка

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Introduction

In general, construction techniques are developed through trial and error for cement concrete pavement construction in areas without a history of road construction. According to a preliminary survey, research on the development of construction techniques for South Kazakhstan reflecting the region's climatic and material characteristics is still in an early stage. Conversely, a rich body of research outcomes exists for countries with a large coverage of concrete pavement including the US and South Korea, which started many decades ago. Recent studies present models for curing durability and performance assessment [1–3], as well as for joint behavior, cracks, and temperature stress [4–6]. As such, the present paper aims to analyze and reassess a number of experiment and construction data and other related data accumulated from the cement concrete pavement construction project, which has been ongoing since 2011 at the study site, which is characterized by climatic changes.

Study objective and method

Many existing studies demonstrated that construction methods and early-stage quality management significantly affect the endurance and lifespan of cement concrete pavement [1, 7, 8]. Considering climate variables, various experiments were conducted to determine concrete pavement construction methods to overcome changing climatic conditions. These included investigating road length for daily pavement work, effective curing and temperature control methods to prevent initial cracks, optimal spraying amount and method to maximize the effect of the curing-membrane, determining the most suitable installation interval and effective width of expansion joints, and optimal joint cutting period and depth. In particular, the target site experienced a number of days with strong winds, and it was judged that surface defects are highly likely because of rapid water evaporation from the concrete pavement surface during the construction process [9]. Therefore, polyethylene film (PE-film) was used as a measure to prevent this problem. Thus, this study also investigated the effect of the initial curing method, in which entire concrete slabs were covered.

Characteristics of the climate of South Kazakhstan

The target site for this study is situated in South Kazakhstan, 100 km from Shymkent in the direction of Turkestan. The Western Europe – Western China Road Project is currently in progress, and the region is marked by a highly varying diurnal temperature range, which is relatively large compared to other areas of the country. Fig. 1 shows the measured temperature pattern during the summer from August to September.

The temperature at the study site during the summer season was measured for analysis. Tab. 1 provides the maximum temperature range. The maximum temperature recorded was 48 ^{o}C when direct sunlight directly affected the area. The temperature dropped to between (–15) and (–25) ^{o}C in the winter. The highest temperature was recorded at around 3 to 4 pm, and the minimum at 5 to 6 am.

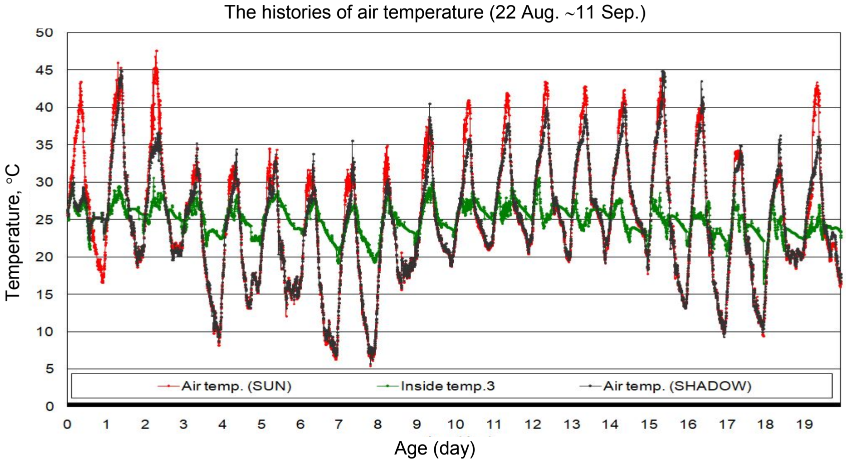


Fig. 1. Measured temperature (August to September in South Kazakhstan)

Table 1

Characteristics of summer season climatic changes in South Kazakhstan

Category	Range of indicators	Range of concrete temperature change
Highest temperature, °C	40–44	43–48
Lowest temperature, °C	15–25	20–30
Diurnal temperature range, °C	19–25	18–23
Humidity, %	15–65	–
Wind speed, m/s	4–10	–

The humidity of the study site ranged between 15 and 65 %. This relatively low humidity range is explained by the low probability and amount of rainfall during the summer. Although the rainfall probability increases from late September to May the next year, the rainfall amount is only as high as a few dozen mm. Wind speed was measured using a wind speed meter, ranging from 1–2 m/s, 4–5 m/s, and reaching a maximum of more than 10–20 m/s on days with strong winds.

Concrete mock-up test

• Production of experimental concrete slab and test results

The concrete mix design used for the mock-up test is shown in Tab. 2. Materials meeting the standards and regulations were used for the cement, aggregates, water, and admixture.

The amount of concrete curing compound, curing method, and changes in slab surface and concrete strength development according to the climate were analyzed, as shown in Fig. 2. The change in concrete strength in the slab surface induced by the changing climate was analyzed, and the optimum joint cutting period was determined. The results are provided in Tab. 3.

The surface was finished upon pouring the concrete. Then, 0.50 and 0.75 l/m^2 of the concrete curing compound tested in experiment were sprayed on two test slabs, and the curing process was observed as shown in Fig. 3, 4.

Table 2

Mix design of concrete, kg/m^3

Slump, cm	Water	Cement	Sand	Gravel (5–20 mm)	Gravel (20–40 mm)	Admixture
0–4	147	405	696	598	489	3.0

Fig. 2. Process of experiment (spraying the concrete curing compound and cutting joints)

Table 3

Experiment results of concrete curing compound and cutting joints

<table>
<tr><td>Concrete temperature</td><td>28 °C</td><td>Slump</td><td>4 cm</td><td>Air content</td><td>4,5 %</td><td>Humidity</td><td>20–40 %</td></tr>
<tr><td>State of changing air temperature during the experiment (condition)</td><td colspan="3">(Condition 1) 20 °C → when the temperature rises
(Condition 2) 50 °C → when the temperature drops</td><td colspan="2">Range of curing temperature</td><td colspan="2">20–50 °C</td></tr>
<tr><td rowspan="2">Results of curing experiment
(occurrence of cracks)</td><td colspan="3">(Condition 1) concrete curing compound sprayed (0.5 l/m^2) and not sprayed</td><td colspan="4">Period of small cracks observed on the slab surface
Concrete curing compound not applied: 1 h
Concrete curing compound applied: 2 h</td></tr>
<tr><td colspan="3">(Condition 2) concrete curing compound sprayed (0.5 l/m^2)</td><td colspan="4">No cracks occurred</td></tr>
<tr><td rowspan="2">Results of joint cutting experiment</td><td colspan="3">(Condition 1) concrete curing compound sprayed (0.5 l/m^2) and not sprayed</td><td colspan="4">No damage was observed on joints from after 6 h
The air temperature rose to 50 °C
The hydration reaction of concrete became faster</td></tr>
<tr><td colspan="3">(Condition 2) concrete curing compound sprayed (0.5 l/m^2)</td><td colspan="4">No damage was observed on joints from after 8 h
The air temperature dropped to 20 °C
The hydration reaction of concrete was delayed</td></tr>
</table>

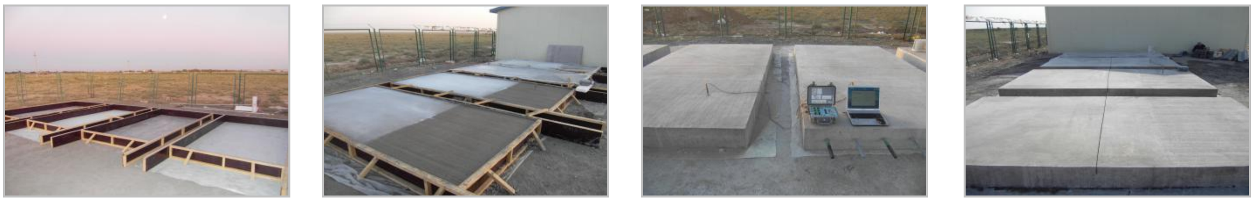


Fig. 3. Process of concrete slab mock-up test

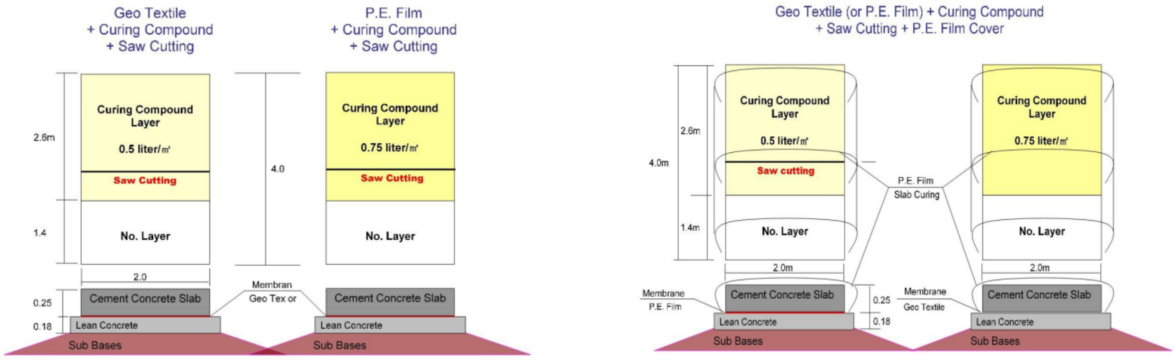
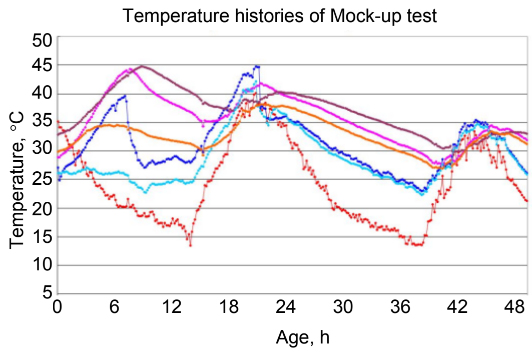


Fig. 4. Curing and joint cutting in concrete slab mock-up test

The two test slabs were cured under the same climatic conditions as at the study site without additional curing intervention. The surfaces of the other two concrete slabs were covered with PE-film, and the curing process and strength development according to the temperature were measured in real time. The temperature of the test slabs was measured at the top surface, the central core, and at bottom surface every 10 min. The results of the mock-up test are provided below.

1. Two to three hairline cracks were observed in the test slab sprayed with a concrete curing compound without a PE-film during the initial curing process. On the other hand, no defects were observed on the surface of the slab covered with the PE-film.

2. The internal temperature change of the concrete slabs was analyzed. As shown in Fig. 5, the maximum temperature of the core area of the air-cured slab was approximately 35 ^{o}C, and the air temperature determined the surface temperature. On the other hand, the internal temperature of the test slab cured using PE-film increased to 45 ^{o}C. The surface temperature increased along with the changing internal temperature. Therefore, the curing method using PE-film is highly effective as a temperature and strength control method to handle the climatic changes of the region.



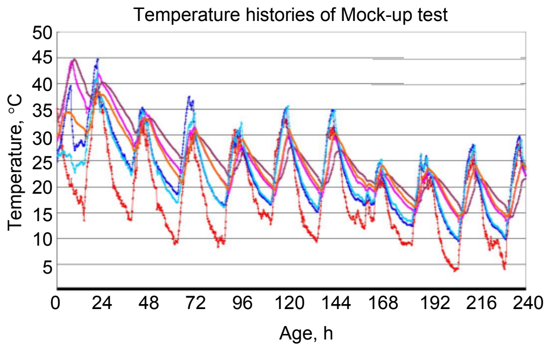


Fig. 5. Temperature pattern of the concrete slabs (2nd and 10th days):
– Air temperature; – Top surface (#3); – Core (#3); – Bottom (#3);
– Top surface (#2); – Core (#2);

3. All slab temperature changes maintained a slight temperature difference after 16 to 20 h after pouring the concrete. At this point, the slab temperature increased if the air temperature was high, and decreased when the air temperature was low.

4. In regions with a relatively large diurnal temperature range caused by the changing temperature, the contraction and expansion rate of slabs increases. Cracks are highly likely in areas affected by the base confinement caused by friction, as the difference in stress also increases [8, 10].

5. To prevent initial cracks in concrete slabs, it is critical to determine an optimal cutting period to reduce the section of contracted joints before random cracks occur. These are caused by stress imposed on the concrete during the initial hardening period [11].

• Results of the curing test

A test was conducted using the existing curing method of spraying concrete curing compound commonly used for cement concrete pavement and the new alternative method of PE-film application [8, 12, 13]. The general operation speed of the curing compound spraying equipment is approximately 20 m/min for concrete pavement work, and 0.5 l/m^2 of material is sprayed. The equipment was operated at varying speeds. It was found that operating the equipment at 10 m/min, which is half the general operation speed, produced a positive result for forming curing membrane on the slab surface. Noteworthy is that a spraying operation at an extremely slow speed causes curing material flow across the slab surface.

The curing performance of PE-film was highly effective in preventing various defects caused by dramatic drying and temperature changes, as shown in Fig. 6. This new curing method induces the early development of concrete strength and shortens the time required for contraction joint cutting.

• Early behavior assessment of concrete pavement joints and cutting test

According to the field survey and experiment, joints were identified as areas of unreinforced cement concrete pavement where defects most frequently occur. The most important factor in joint work is the time point of covered slab cutting, as shown in Fig. 7. When joints are cut too late, cracks are not induced in the intended way, but irregularly occur in unwanted areas. In contrast, as shown in Fig. 8, cutting the joints too early may cause defects and damage the joints [14–16].

Fig. 6. Process of the curing test using polyethylene film

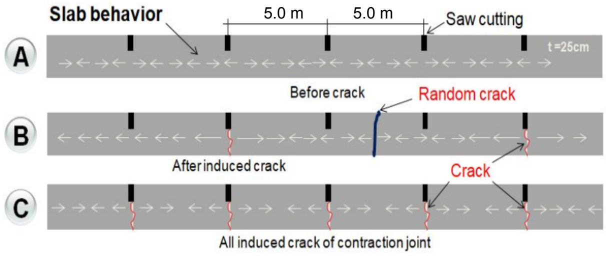


Fig. 7. Behavior of concrete slab with joints

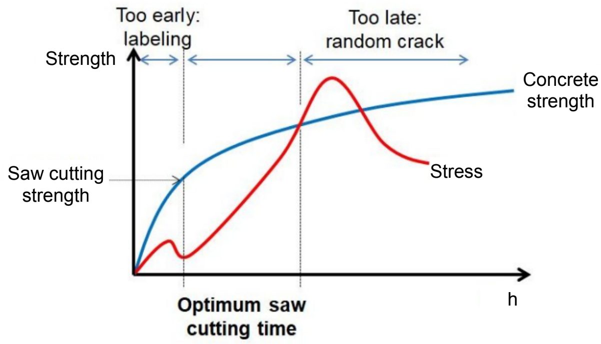


Fig. 8. Stress change in slab and joint cutting period

Crack induction test in horizontal contraction joint. Concrete slab behavior after completing the placement work is closely associated with the occurrence of initial cracks. The major causes are environmental load including temperature and humidity, not traffic load [10, 17]. Cracks started to occur on the slabs 15 to 24 h after completing the concrete pouring. The survey and experiment demonstrated that slab volume decreases as its temperature drops when the air temperature falls. This causes friction on the lower part of the structure, which produces cracks [8, 17].

The results of the assessment of cracks induced in the contraction joints are provided in Tab. 4. In total, 27–85 % of the total joints were normally induced as intended between the second and seventh day of curing. More joints were induced when the road length for daily pavement work was longer than when shorter, and more cracks occurred on the inside than on the outside. Fig. 9 shows the joint cut appearing in the concrete slabs and form of induced cracks. The survey of induced cracks indicated that the crack gap ranged about 0.3 to 0.5 mm around the two ends of the slabs, and a maximum of 2.5 mm in the center. These gaps are closely associated with the friction caused by the degree of slab contraction and base confinement. This indicates that the climatic conditions on the day of the pavement pouring and temperature change in the paved slab are associated with the process of crack induction in contraction joints.

Table 4

Overview of crack induction in contraction joints

Road length per day, m	Number of installed contraction joints, number of places	Measurement date, day	Number of induced cracks, number of places	Rate, %
335	67	2	26	38.8
55	11	3	3	27.3
205	41	5	30	73.2
90	18	7	15	83.3

Fig. 9. Form of crack in contraction joints of concrete pavement

Tab. 5 shows the optimal joint cutting time for concrete slabs, which is closely associated with temperature, wind, diurnal temperature range, and concrete pouring time. Considering climatic changes in the South Kazakhstan region, 4 am to 3 pm is the most appropriate time for pouring concrete when the temperature ranges between 20 and 40 °C for slab temperature and strength management. It is easy to induce contraction joint cracks if joint cutting is completed late the same night.

Table 5

Optimal joint cutting time for concrete pouring (temperature range 20–40 °C)

Category	Optimal joint cutting time according to concrete pouring time				
Concrete pavement time	4:00–9:00	9:00–11:00	11:00–15:00	15:00–21:00	21:00–01:00
Optimal time for joint cutting, h	6	5	4	8	10

Horizontal expansion joints and construction joints. The expansion and contraction of concrete slabs are caused by various factors including types of coarse aggregates; concrete contraction coefficient [18, 19]; texture of separation membrane; climatic changes such as temperature, humidity, and wind; diurnal temperature range; concrete pouring temperature; curing method; and cutting period. In this study, the actual slab behavior and deformation were measured. The measurement results were analyzed to establish a maximum construction length per day and detailed construction plan to design a new technique that prevents slab cracks. Fig. 10 shows the behavior of horizontal expansion joints and the process to measure expansion.

Fig. 10. Measurement of the behavior and length of expansion of horizontally expanded joints

Fig. 11 shows the forms of damage to the expansion and contraction joints caused by the slab behavior when the concrete expands. Fig. 12 shows the behavior of horizontal expansion joints and the measured expansion in a graph.

According to the experiment and measurements, the requirements for setting the interval of expansion joints installed in the daily paving length are as follows:

1) the expansion joint should be installed at the end of daily work. The installation should be performed with great precision;

2) the total expansion of a slab reduces if cracks are caused in many contraction joints within 24 h after completion of the concrete pavement;

3) the concrete slab during early curing should be stronger than the internal stress;

4) the cumulative expansion of a slab exposed to a high temperature has a greater effect than contraction, and this is the major cause of damage to expansion joints;

5) therefore, the daily paving length for a cement concrete pavement and width of expansion joints can be controlled, as shown in Tab. 6. This causes noise for running vehicles and damage to the joints when the width of the expansion joints is greater than 30 mm. Thus, the width should be less than 30 mm.

Fig. 11. Contraction joints and expansion joints damaged by slab behavior

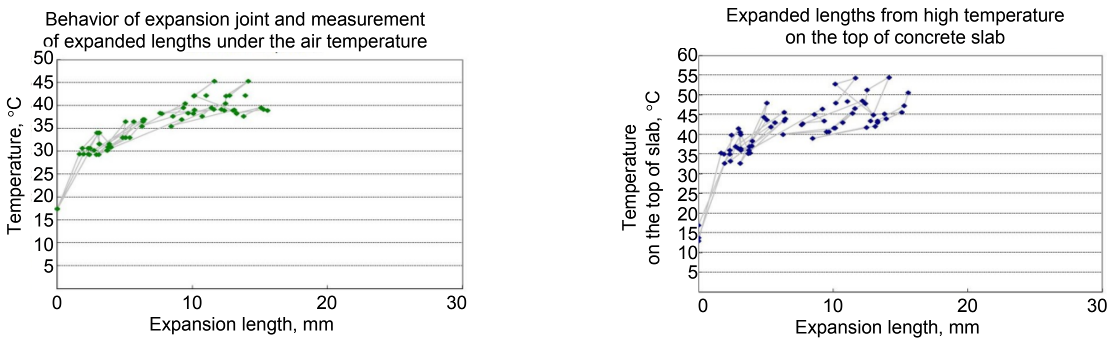


Fig. 12. Measurement of changes in horizontally expanded joints caused by slab behaviors

Table 6

Number of joints to be installed and effective width according to the length of concrete paving per day

Length of concrete paving per day, m	200	300	400	500	600
Width (mm) × number of joints for installation	20×1	30×1	20×2	25×2	30×2

CONCLUSIONS

1. Various defects in cement concrete pavement are determined by the climatic environment and conditions of the target construction site (including temperature, humidity and wind speed). However, it was difficult to identify the real causes, as the areas with defects were not assessed and no data were collected from the damaged areas.

2. It is necessary to establish a construction technique that considers climatic changes variables for cement concrete-paved road construction in this area. It is recommended to survey and analyze the initial behaviors of concrete pavement produced reflecting the material properties and environmental conditions to enhance the quality of the product.

3. It was necessary to first perform a mock-up test and field construction test, and then to investigate the thermal and mechanical properties of concrete slabs in the same climatic conditions as those at the real study site. This study surveyed the behavioral characteristics of the test slabs to prevent damage to the joints, which are the vulnerable part of a cement concrete pavement. The study suggests the location and width of expansion joints reflecting the optimal joint cutting period and suitable road length for daily pavement work in the given climatic conditions.

4. Finally, standards for the optimal amount of concrete curing compound and optimal operation speed of spraying equipment were suggested to help prevent cracks caused by drying and contraction, which may occur on the paved road surface during the summer season. In addition, the application of polyethylene film was suggested for the effective curing control of concrete slabs. It was confirmed that this method prevents cracks caused by dry surfaces and contraction, and provides the effect of humid curing to the surface.

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