БУДІВЕЛЬНІ МАТЕРІАЛИ ТА ВИРОБИ

UDC: 666.972.16

DOI: 10.31649/2311-1429-2026-1-41-46

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THE EFFECT OF SPECIAL MODIFYING ADDITIVES ON THE PERFORMANCE PROPERTIES OF ROAD CEMENT CONCRETE UNDER CURRENT LOGISTICAL CHALLENGES

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Prospects are outlined for the development of intelligent road pavements with the integration of sensor systems, self-healing materials, and energy-generating technologies. The proposed approach forms the basis for the creation of a modern, resilient, and high-technology transport infrastructure.

Experimental studies verified the high synergy of a "triad" of modifiers: 0.8% PCE MasterGlenium ACE, 0.05% AEA MasterAir, and 0.9 kg/m³ polypropylene microfibers. At W/C=0.34, this complex increases compressive strength from 45.2 to 61.4 MPa and flexural strength from 4.4 to 5.4 MPa.

The resulting low-capillary matrix with pore-dampers reduces abrasion to 0.40 g/cm² and raises salt-frost resistance above F300+, neutralizing "shear impacts" during heavy vehicle braking.

Early hydration kinetics show the modified concrete reaches 68% strength (35.4 MPa) on the 3rd day, whereas the control mix gains only 28% (12.6 MPa). This dynamic shortens traffic closure periods fourfold (opening routes in 3–7 days), allows timely joint cutting, and ensures optimal compatibility with slipform pavers.

Life Cycle Cost (LCC) analysis under ISO 15686-5 proves that a 1–1.2% initial mix cost increase (210,000 UAH/km) extends the maintenance-free interval to 18 years. Integral NPV of the life cycle drops by 24%, reducing maintenance costs by 40% and yielding 3% fuel savings due to prolonged IRI stability.

Keywords: *motor roads, road concretes, performance properties of road pavement, standard static load, road design, polymer fibre, polycarboxylate ethers, air-entraining modifiers.*

Стаття надійшла до редакції / Received 19.03.2026
Прийнята до друку / Accepted 14.04.2026
Опубліковано / Published 29.05.2026

Introduction

The stable operation of Ukraine’s transport corridors under the conditions of martial law depends directly on the technical condition of the road pavement. The sharp increase in the intensity of heavy-duty vehicle traffic and the reconfiguration of logistics routes demand a revision of approaches to pavement design. Today a motor road is regarded not simply as an engineering structure but as a critical element of the logistics chain that must ensure uninterrupted transportation regardless of weather conditions and the weight parameters of vehicles [1].

The issue of increasing concrete strength through the introduction of additives has been actively researched in the works of domestic and foreign scholars. However, in the context of modern logistics, where axle loads often exceed regulatory norms, traditional methods of modification require adjustment. The use of the latest generation of polycarboxylate ethers makes it possible to obtain concrete with ultra-low capillary absorption, which is decisive for resistance to the dynamic impacts of heavy-tonnage road trains [2, 3]. Studies [4, 5] indicate that complex additives with an air-entraining effect create a “damper” structure that absorbs the internal stresses arising from the rapid movement of heavy machinery.

The aim of the article. Substantiation of the effectiveness and parameters of application of specific modifiers for the creation of road cement concrete capable of ensuring the reliability of logistics connections under complex operational conditions, based on original experimental research and life-cycle cost calculations.

Analytical research

Modern logistics in Ukraine is characterised by a shift of freight flows onto motor roads, which leads to systematic overloads. Unlike asphalt concrete, which under the weight of road trains is prone to plastic deformations (rutting), cement-concrete pavement operates as an elastic slab on a semi-rigid base [6].

However, the critical factor is not only static weight but also the dynamic force vectors arising during the braking and acceleration of heavy-duty transport. In the tyre-to-concrete contact zone significant tangential stresses occur. Under the sudden braking of road trains (with a mass of 40 tonnes and more) the "shear impact" effect arises, which provokes the opening of microcracks in the upper layer of the pavement (to a depth of 3–5 cm). If the concrete does not possess sufficient viscosity and adhesion between the cement stone and the aggregate, these microcracks become channels for the penetration of water and salts, leading to rapid surface scaling.

Taking into account the nature of tangential stresses described above, it becomes evident that traditional concrete mixtures require a qualitative transition to multi-component modification.

For the experimental studies, the base composition of road concrete class C30/35 was adopted (per 1 m^3 of mix): Portland cement PC I-500R-N — 420 kg; quartz sand (M_k = 2.2) — 710 kg; granite aggregate fractions 5–10 mm and 10–20 mm (ratio 1:3) — 1,150 kg; water — 143 l. To modify the mixture, a "triad" of additives was used in the following dosages by cement mass:

1. Polycarboxylate ether (PCE) of the MasterGlenium ACE brand at a dosage of 0.8 %;
2. Air-entraining modifier (AEM) of the MasterAir (Sika) brand at a dosage of 0.05%;
3. Polypropylene fibre 12 mm in length (fibre diameter 22 μm) at a dosage of 0.9 kg/m^3 (approximately 0.2% by volume).

Mixtures were prepared in a forced-action laboratory mixer with a mixing time of 3 minutes (fibre was introduced at the dry-mixing stage of the aggregates). The preparation, curing, and testing of cube specimens (150×150×150 mm) and beam specimens (150×150×600 mm) were carried out in accordance with the requirements of DSTU EN 12390-3 (compressive strength) and DSTU EN 12390-5 (flexural tensile strength). Frost resistance was determined in a 5% NaCl solution using an accelerated method in accordance with DSTU B V.2.7-49-96.

The introduction of the comprehensive modification described provides a polyfunctional character of influence of the components:

1. Polycarboxylate ethers (PCE): They create an effect of "electrostatic repulsion" of cement particles at the nanoscale. Unlike traditional additives, PCEs operate on the principle of steric repulsion of cement particles. This makes it possible to reduce the water demand of the mixture by 25–30%, achieving a value of W/C = 0.34, forming an ultra-dense structure with a minimal number of capillaries. This accordingly leads to an increase in compressive strength to class C30/35 and above and enhances the ability of the surface to withstand abrasive wear from the tyres of wheeled vehicles and special machinery.
2. Air-entraining modifiers (AEMs): They create in the concrete a large number of microscopic closed pores (with a diameter of 10–100 μm) with a spacing factor between pores of no more than 0.2 mm. These pores function as "microdampers". During the passage of heavy road vehicles (HRVs) they partially absorb the energy of elastic deformation, preventing the brittle destruction of the concrete matrix and compensating for ice pressure during the freezing of water in saline solutions.
3. Polymer fibre (dispersed reinforcement): The addition of fibre transforms concrete into a composite material. When a microcrack arises from a "shear impact" during braking, the transverse fibre strands within the crack restrain its further opening. This is critically important for preserving slab integrity in customs-inspection zones, weighing complexes, and on the ascents of highways, where the torque on the wheels is at its maximum.

The mechanics of "wheel–pavement" interaction and the role of additives. When analysing the performance of cement-concrete pavement under the influence of HRVs, it should be taken into account that destruction begins not with visible cracks but with the accumulation of microdefects in the structure of the cement stone. In logistics chains dominated by road trains with axle loads exceeding 11.5 tonnes, a "material fatigue" effect arises. This is particularly noticeable on sections with intensive braking and manoeuvring. During the braking of motor vehicles, a horizontal force arises that seeks to "tear off" the upper layer of concrete. It is precisely here that the synergetic effect of the special additives manifests itself.

For a visual comparison of the influence of modification on the key parameters ensuring resistance to such loads, the performance results obtained are summarised in Table 1.

As can be seen from the data in Table 1, the application of modifiers allows the flexural strength to be increased by almost 50%. This is critically important, since flexural tension is the principal cause of the fracture of concrete slabs under the weight of HRVs, especially those of particularly high load capacity. Moreover, the accelerated strength gain makes it possible to open traffic on a section significantly earlier, which is a key efficiency indicator of the logistics network.

Table 1

Comparative characteristics of the performance indicators of road concrete

Indicator (characteristic)	Base composition (without additives)	Modified composition (PCE + AEM + Fibre)
Flexural tensile strength, MPa	4,4	5,4
Compressive strength, MPa	45,2	61,4
Abrasion coefficient, g/cm²	0,6	0,4
Frost resistance (in salts), cycles	F150	F300
Rate of strength gain, days	14	3

In order to achieve the target durability indicators of the pavement structure presented in Table 1, the authors propose a comprehensive technological solution based on the synergetic interaction of three types of special additives: polycarboxylate ethers, air-entraining modifiers, and polymer fibre.

Turning from the composition of the concrete to the timing of its introduction into service, it should be noted that traditional concrete requires 28 days to reach its design parameters. However, under the conditions of intensive logistics such a term is excessively long.

The combination we propose "polycarboxylate ethers + air-entraining modifiers + polymer fibre" fundamentally alters the strength-gain schedule. Owing to the low water-cement ratio and the comprehensive action of the modifiers, cement hydration proceeds more intensively and more evenly. The kinetics of strength gain of road concrete using modifying additives are presented in Figure 1.

The numerical data of the graph (Fig. 1) are based on specimen tests at intermediate hardening intervals. The base composition demonstrated the following compressive strength values as a percentage of design strength (45 MPa): day 1 — 12% (5.4 MPa); day 3 — 28% (12.6 MPa); day 7 — 55% (24.7 MPa); day 28 — 100% (45.2 MPa). The modified composition (our formulation, class C30/35 with a design compressive strength of 52 MPa) showed accelerated kinetics: day 1 — 42% (21.8 MPa); day 3 — 68% (35.4 MPa); day 7 — 85% (44.2 MPa); day 28 — 118% (61.4 MPa).

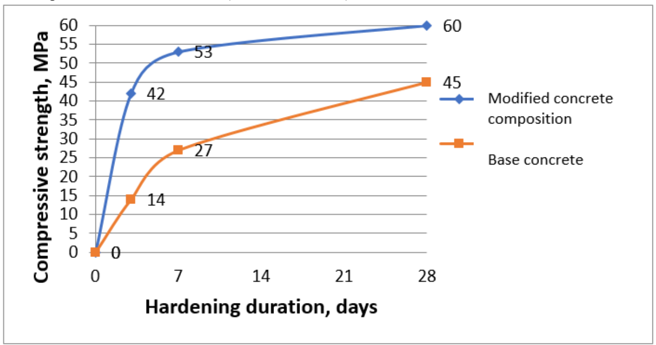

Figure 1 – Comparative kinetics of strength gain of road concrete with the use of comprehensive modification

On the strength graph (Fig. 1) of the dependence of strength on time, two curves are clearly distinguished. The base composition (without additives): demonstrates a slow increase in strength; after 3 days the value amounts to only 14% of the design strength. This makes the movement of heavy machinery impossible for 14 days. However, the modified composition: owing to the accelerated crystallisation of the minerals of the cement clinker, attains 70% of its grade strength as early as day 3.

Such a rapid gain of strength at the initial stage of hardening of the concrete road makes it possible to cut expansion joints significantly earlier, preventing the formation of random temperature cracks. For the motor-transport sector this means the possibility of opening technological traffic for HRVs as early as day 3 (upon reaching 70% strength) after placement, which reduces the blocking time of the logistics route by a factor of four, and also reduces the costs of concrete curing operations.

Rapid strength gain is a matter not only of time but also of the quality of the "road mirror". The rapid formation of the concrete stone minimises prolonged exposure to wind, sunlight, and precipitation. This prevents the washing-out of the cementitious binder and precludes the appearance of surface microcracks — the principal factors that impair the physico-mechanical properties and durability of the pavement.

The effectiveness of the proposed chemical modification cannot be realised in full without the use of precision equipment, in particular slipform pavers, which ensure slab monolithicity. The effectiveness of our proposed modified concrete compositions is fully revealed with the use of high-productivity slipform pavers. This equipment simultaneously performs the distribution of concrete, its vibratory consolidation, the reinforcement of joints with steel bars, and the finish texturing of the surface.

The mechanism of "mixture–machine" interaction: the use of polycarboxylate ethers makes it possible to obtain a mixture with unique rheological characteristics: it is exceptionally mobile under the action of the machine's vibrators but instantly acquires structural strength after exiting the extruder. Such technology makes it possible to lay up to 1.5–2 km of ready highway per day. By comparison, the use of outdated methods with movable formwork required 6 weeks for the same section.

Thus, the synergy of "modified concrete + slipform" creates a monolithic slab. This guarantees the ideal evenness of the road surface (IRI coefficient), which is the key to low operational costs for hauliers. One of the principal barriers to the implementation of modified concretes is often said to be the rise in the estimated cost of the mixture. However, a life-cycle analysis of the pavement refutes this assertion.

To assess economic effectiveness, the standard Life Cycle Cost (LCC) analysis methodology in accordance with ISO 15686-5 was applied. Calculation of the net present value (NPV_{LCC}) was performed using the formula:

$$NPV_{LCC} = C_{inv} + \sum_{t=1}^{T} \frac{C_{m,t} + C_{op,t}}{(1+r)^t} \quad (2)$$

where the summation is taken for each year t from 1 to T. Here C_{inv} — initial investment in pavement construction; $C_{m,t}$ — costs of routine maintenance and upkeep in year t; $C_{op,t}$ — operational costs for users (fuel savings); r — real discount rate (taken at 5%); T — the design service period (30 years).

Input data for calculation per 1 km of a two-lane highway:

- Base composition: C_{inv} = UAH 18.5 million; major repairs (C_m) at years 10, 18, and 25 of service life with a total cost of UAH 11.2 million.
- Modified composition: The introduction of the comprehensive "triad" of additives increases the cost of 1 m^3 of concrete mixture by 1–1.2%, raising the initial investment C_{inv} by UAH 210,000 (to UAH 18.71 million). However, the projected maintenance-free period extends to 18 years. Maintenance and upkeep costs over 30 years amount to only UAH 3.1 million.

The modelling results showed that despite the initial increase in mixture cost of 1–1.2%, the integral NPV_{LCC} for the modified concrete is 24% lower than for the base option, owing to the following factors:

- Reduction of capital repair costs: Owing to the absence of rutting and cracks during the first 18 years, expenditures on pothole repair and joint sealing are reduced by 40 %;
- Logistical synergy: The reduction of rolling resistance and the absence of pavement defects allow hauliers to save up to 3% of fuel.

Thus, every 1% invested in special additives allows the road sector to obtain up to 40% savings on repair works during operation over the first years of the service life cycle.

The proposed concept of road-concrete modification is a first step on the path to creating durable and resilient transport corridors. The further development of this topic involves research into the influence of new-generation PCEs on the rheology of concretes when Portland cement is partially replaced with mechanically activated industrial by-products based on blast-furnace slag or fly ash and the study of the influence of long-term cyclic loads on the fundamental properties of the cement matrix modified with PCE and microfibre.

Conclusions

Based on laboratory testing, the positive effect of the additive complex has been confirmed, comprising 0.8% PCE MasterGlenium ACE, 0.05% AEM MasterAir, and 0.9 kg/m^3 polypropylene microfibres. Owing to the steric repulsion effect of the binder particles, the water demand of the mixture was reduced to values of W/C = 0.34. This provided an increase in compressive strength from 45.2 to 61.4 MPa, and in flexural tensile strength from 4.4 to 5.4 MPa. In turn, the capillary-free matrix formed with energy-absorbing pore-dampers made it possible to reduce the abrasion coefficient to 0.40 g/cm^2 and to raise the salt-frost resistance indicator above the level of F300+, neutralising the destructive effect of "shear impacts" during the braking of heavy machinery.

The regularities of the kinetics of structure formation have been established and the process parameters have been optimised. A sharp acceleration of early hydration of clinker minerals has been identified: the modified cement concrete attains 68% of its design strength (equivalent to 35.4 MPa) as early as the 3rd day of hardening, whereas the control composition without additives attains only 28% (12.6 MPa) by this point. Such dynamics allow the blocking time of logistics routes to be shortened by a factor of four.

The overall NPV_{LCC} for the modified option is 24% lower compared to the base option. This provides a reduction in road-sector expenditures on routine repairs and upkeep of 40.

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ВПЛИВ СПЕЦІАЛЬНИХ МОДИФІКУЮЧИХ ДОБАВОК НА ЕКСПЛУАТАЦІЙНІ ХАРАКТЕРИСТИКИ ДОРІЖНОГО ЦЕМЕНТНОГО БЕТОНУ В УМОВАХ СУЧАСНИХ ЛОГІСТИЧНИХ ВИКЛИКІВ

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У науковій статті теоретично обґрунтовано та експериментально підтверджено ефективність застосування комплекса модифікуючих добавок для підвищення експлуатаційних властивостей дорожнього цементобетону в умовах інтенсифікації логістичних навантажень. Актуальність дослідження зумовлена правовим режимом воєнного стану в Україні, який спричинив перебудову транспортних маршрутів та збільшення руху надважких автопоїздів. Доведено, що традиційні асфальтобетонні покриття за таких умов швидко пошкоджуються через накопичення пластичних деформацій та утворення колійності. Надійною альтернативою, здатною гарантувати безперебійний транзит вантажів, визначено монолітні цементобетонні плити, що функціонують як пружні розподільчі елементи дорожнього одягу жорсткого типу та забезпечують стабільний 30-річний життєвий цикл магістралей.

Основну увагу зосереджено на розробці та лабораторній верифікації рецептури цементного композиту з полікомпонентним модифікуванням. Авторами доведено синергетичний ефект «тріади» добавок, що включає 0,8 % полікарбоксилатного ефіру MasterGlenium ACE, 0,05 % повітровтягувального модифікатора MasterAir та 0,9 кг/м³ поліпропіленової мікрофібри для дисперсного армування. Завдяки механізму стеричного відштовхування частинок в'яжучого на нанорівні досягнуто зниження водопотреби суміші до значень В/Ц = 0,34. Фізико-механічними випробуваннями зафіксовано приріст міцності на стиск із 45,2 до 61,4 МПа, а міцності на розтяг при згині — з 4,4 до 5,4 МПа. Сформована надщільна матриця з амортизуючими пор-демпферами дозволила знизити коефіцієнт стираності до 0,40 г/см² та підвищети солеморозостійкість до F 300, нейтралізуючи руйнівну дію «зсувних ударів» при гальмуванні важкої техніки масою понад 40 тонн.

Важливим технологічним результатом є встановлення закономірностей ранньої кінетики структуроутворення. Модифікований бетон досягає 68 % від проектної міцності (35,4 МПа) вже на 3-тю добу твердіння, що у 4 рази скорочує термін блокування логістичних маршрутів та оптимізує терміни нарізання деформаційних швів.

Економічну доцільність складів підтверджено шляхом моделювання вартості життєвого циклу (LCC) за ISO 15686-5. Стартове підвищення інвестицій на 210 тис. грн на 1 км магістралі через введення добавок (1–1,2 % від вартості суміші) повністю нівелюється зниженням інтегрального значення чистої теперішньої вартості (NPV) на 24 %. Це зменшує витрати на ремонти на 40 % протягом перших 18 років експлуатації та забезпечує 3 % економії пального для перевізників.

Ключові слова: *автомобільні дороги, дорожні бетони, експлуатаційні властивості дорожнього покриття, нормативне статичне навантаження, проектування автодоріг, полімерна фібра. полікарбоксилатні ефіри, повітровтягувальні модифікатори*

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