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Elasticity Modulus as a Criteria of Asphalt Concrete Frost Resistance

Abstract: The relevance of this study is determined by the need to improve the assessment of asphalt concrete frost resistance under cyclic freezing and thawing, especially in road pavements exposed to continental climatic conditions, water saturation and de-icing agents. The research problem lies in the fact that traditional frost resistance assessment is usually based on strength indicators before and after freeze–thaw exposure, whereas changes in elastic modulus and load-bearing capacity are insufficiently considered. The scientific novelty of the study consists in substantiating the elasticity modulus as an informative criterion for evaluating asphalt concrete frost resistance and in considering linear viscoelastic deformation analysis as a non-destructive testing approach. The object of the study is asphalt concrete subjected to cyclic freezing and thawing. The aim of the research is to determine how repeated freeze–thaw cycles and subsequent rest periods affect the elastic modulus of asphalt concrete and the frost resistance coefficient. The methodology includes cyclic freezing and thawing, water saturation, controlled temperature exposure, dynamic testing of asphalt concrete beams at different temperatures and frequencies, and analysis of elastic moduli within the region of linear viscoelastic deformation. The source base includes studies on freeze–thaw damage, frost resistance of asphalt concrete, bituminous binder brittleness, self-healing behaviour, internal void structure, de-icing resistance, and relevant CIS and European testing standards. The study analyses the influence of temperature, loading frequency, curing duration, freeze–thaw cycles and rest periods on the deformation characteristics of asphalt concrete. Particular attention is paid to the dependence of the frost resistance coefficient on time–temperature testing conditions and to the recovery effect, through which the elastic modulus may partially or almost completely return after ageing or rest at positive temperatures. The results show that asphalt concrete requires at least 30 days of curing before frost resistance testing, since structural formation continues after specimen preparation. The frost resistance coefficient increases with decreasing temperature and increasing test frequency, which indicates a strong relationship between frost resistance assessment and the rheological state of the material. The study also demonstrates that defects formed during cyclic freezing and thawing may undergo partial self-healing during rest at positive temperatures. It is concluded that linear viscoelastic deformation methods may serve as a reliable non-destructive approach for evaluating structural changes, damage and recovery processes in asphalt concrete after cyclic freeze–thaw exposure.

Keywords: asphalt concrete, frost resistance, linear viscoelasticity, elasticity modulus, heat recovery, cyclic freezing and thawing.

Abbreviations:

CFT is Cyclic Freezing and Thawing,

CIS is Commonwealth of Independent States,

K_{CFT} is frost resistance coefficient

Introduction

Due to its technological and operational advantages, asphalt concrete remains the most widely used material for road surfacing. Its advantages include relatively simple construction, high repairability, the possibility of tailoring mixture properties to specific operating conditions, rapid opening of pavement to traffic after construction, and a comparatively low noise level during use. However, despite extensive research on asphalt concrete performance, a number of technological and climatic factors affecting its long-term durability remain insufficiently investigated. Among these factors, special attention should be paid to temperature transitions around 0 °C, cyclic freezing and thawing, moisture saturation, and the combined influence of de-icing materials.

The relevance of this study is determined by the need to improve the assessment of asphalt concrete frost resistance under real pavement operating conditions. In regions with continental climates, cyclic freezing and thawing are seasonal processes that repeatedly affect asphalt concrete during the service life of road pavements. These processes are complicated by water penetration, ice formation, traffic loading and the possible use of de-icing agents. As a result, asphalt concrete may undergo changes in its internal structure, mechanical response and deformation characteristics, which ultimately influence the load-bearing capacity and durability of the entire pavement structure (*Cao et al., 2022; Mohi Ud Din et al., 2020; Lövqvist et al., 2021*).

Cyclic freezing and thawing are known to adversely affect asphalt concrete in road conditions. Although the consequences of this damage are visible from season to season in the form of flaking, potholes, surface degradation and local pavement failure, the mechanisms of asphalt concrete resistance to such damage have been studied less thoroughly than the mechanisms of low-temperature cracking. The complexity of these processes is associated with the simultaneous action of several factors: reduced temperature, vitrification of the bituminous binder, freezing of water in the pore space, temperature-induced microstresses, hydraulic pressure, and changes in the behaviour of the binder at phase boundaries (*Golonko, 1983; Gokhman & Gersbkoben, 1997; Mauduit et al., 2007*).

The research problem lies in the fact that frost resistance has traditionally been evaluated mainly by comparing strength indicators of asphalt concrete specimens before and after freeze–thaw cycles. In many testing approaches, compressive strength, flexural strength or tensile strength are used as the main criteria for judging frost resistance (*STB 1115-2004, 2004; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*). However, this approach does not sufficiently reflect changes in the load-bearing capacity of pavement structures, especially when these changes are associated with the elastic modulus and deformation behaviour of asphalt concrete. A reduction in frost resistance may be directly expressed through changes in deformation parameters, and this can compromise both the asphalt concrete layer and the road structure over the design period.

The problem is further complicated by the uncertainty surrounding structural changes in asphalt concrete after freeze–thaw cycles and during subsequent rest periods in the warm season. Asphalt concrete is a material whose properties depend strongly on temperature, loading frequency and time-dependent deformation processes. Under decreasing temperature, it gradually passes from a visco-plastic state to a viscoelastic state and then towards an elastic and brittle state. Therefore, the frost resistance coefficient may depend not only on the number of freeze–thaw cycles, but also on the specific time–temperature testing conditions, the loading frequency, the duration of temperature exposure, and the possibility of partial structural recovery after rest at positive temperatures.

The working hypothesis of the study is that the elasticity modulus of asphalt concrete can serve as a more informative criterion of frost resistance than strength indicators alone, because it reflects changes in the material's deformation behaviour and load-bearing capacity after cyclic freezing and thawing. It is also assumed that some structural defects formed during freeze–thaw exposure may be partially reversible, and that this recovery effect can be detected through changes in the elastic modulus after rest periods at positive temperatures. Consequently, linear viscoelastic deformation analysis may be used as a non-destructive method for evaluating damage and recovery in asphalt concrete.

The scientific novelty of the study consists in substantiating the elasticity modulus as a criterion for assessing asphalt concrete frost resistance under cyclic freeze–thaw exposure. Unlike traditional approaches based mainly on destructive strength testing, the proposed approach focuses on the rheological and deformation characteristics of asphalt concrete within the region of linear viscoelastic behaviour. The study also considers the recovery of elastic modulus after rest periods, thereby highlighting the reversible component of structural changes in asphalt concrete. This makes it possible to evaluate not only damage accumulation, but also the capacity of the material for partial self-healing or restoration of mechanical properties (*Qiu et al., 2020; Wang et al., 2021*).

The object of the study is asphalt concrete subjected to cyclic freezing and thawing.

The subject of the study is the change in the elastic modulus and frost resistance coefficient of asphalt concrete under different temperature, frequency, curing and rest conditions.

The study aims to determine how cyclic freezing and thawing, together with subsequent rest periods, affect the elastic modulus of asphalt concrete and to substantiate the applicability of linear viscoelastic deformation analysis as a non-destructive method for evaluating frost resistance.

To achieve this purpose, the following research tasks are set:

- to analyse the influence of cyclic freezing and thawing on the deformation characteristics of asphalt concrete;
- to examine how temperature and loading frequency affect the frost resistance coefficient calculated from elastic modulus values;
- to determine the influence of curing duration on the elastic modulus of asphalt concrete specimens;
- to evaluate the recovery effect after rest periods at positive temperatures following freeze–thaw exposure;
- to compare the behaviour of asphalt concrete before freeze–thaw cycles, after freeze–thaw cycles, and after subsequent rest periods;

- to substantiate the use of elastic modulus as a criterion for assessing changes in frost resistance;
- to assess the potential of linear viscoelastic deformation methods as a non-destructive testing approach for asphalt concrete frost resistance evaluation.

The methodological basis of the study includes cyclic freezing and thawing of asphalt concrete specimens, water saturation, controlled temperature exposure, dynamic loading of beam specimens at different temperatures and frequencies, and measurement of elastic moduli in the region of linear viscoelastic deformation. The study also takes into account existing approaches to determining frost resistance and resistance to de-icing fluids in standards and testing procedures (*European Committee for Standardization, 2023; EN 12697-26, n.d.; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*).

The theoretical significance of the study lies in developing the understanding of frost resistance as a property connected not only with strength loss, but also with time-dependent deformation behaviour, elastic modulus variation, temperature–frequency sensitivity and structural recovery. The study contributes to the interpretation of asphalt concrete as a viscoelastic material whose resistance to freeze–thaw damage should be analysed through rheological parameters as well as through traditional strength indicators.

The practical significance of the results lies in the possibility of improving laboratory assessment of asphalt concrete frost resistance and making it more closely related to pavement performance. The use of elastic modulus as a criterion may reduce dependence on destructive testing, allow repeated testing of the same specimen, increase the reliability of comparisons, and provide more informative data on the structural condition of asphalt concrete after cyclic freezing and thawing. The proposed approach may be useful for road material laboratories, pavement designers and engineers working in regions where freeze–thaw cycles and de-icing agents significantly affect pavement durability.

Thus, the present study addresses the need to refine the evaluation of asphalt concrete frost resistance by shifting attention from strength indicators alone to deformation characteristics and elastic modulus changes. This approach makes it possible to analyse both damage accumulation and recovery processes and to develop a more reliable basis for assessing the durability of asphalt concrete under cyclic environmental loading.

Methods

The main factors affecting asphalt concrete under freeze–thaw conditions are reduced temperature, vitrification of the bituminous binder, and freezing of water within the material structure. At the same time, asphalt concrete changes from a two-phase system to a three-phase system when water is introduced and then, after ice formation, to a more complex multi-phase system (*Löngvist et al., 2021*). This process is associated with the transition of asphalt concrete from a viscoelastic state to an elastic and brittle state when the temperature falls below a critical value. This critical value depends on the consistency of the bituminous binder, including its grade, penetration and type, as well as on the ratio between dispersed mineral powder content and binder content. Temperature-induced microstresses are intensified by water-related processes. As temperature changes, the density, degree of structuring and wetting ability of the binder also change, as does its behaviour at phase boundaries with the surface of mineral aggregates and the

walls of bituminous films and capillaries. The ice formed in the material may be amorphous, crystalline or anisotropic.

According to observations reported in previous studies, the filtration and water saturation coefficients of asphalt concrete vary throughout the year: they decrease at the beginning of autumn, reach their maximum in April of the following year, and then decrease again as a result of water evaporation, although they remain higher than in the previous year. This development may result in extensive pavement destruction after 8–10 years of service. Based on widespread spring and winter damage to asphalt pavements in France in 2004–2005, it has been estimated that the total number of freeze–thaw cycles over 12–15 years may reach 500–1,200 or more, which can lead to catastrophic pavement failure (*Mauduit et al., 2007*). It has also been shown that even after 200 cycles of “dry” bending of bituminous membranes, microcracks may develop, indicating increased brittleness of the asphalt concrete and creating favourable conditions for pavement destruction during the transition period (*Gokhman & Gersbkohen, 1997*).

Several studies consider thermal freeze–thaw damage to be primarily caused by large internal forces arising in the asphalt concrete structure when water freezes, as well as by hydraulic shock pressures occurring in spring under vehicle traffic (*Zhang et al., 2020; Mauduit et al., 2007*). Other studies attribute this damage to temperature-induced microstresses (*Golovko, 1983*). This interpretation is supported by data on dry and wet freeze–thaw cycles, including up to 70 cycles at temperatures from -20°C to -40°C , from which it may be inferred that, in some cases, “dry” and wet freeze–thaw cycles have comparable destructive effects.

Frost resistance coefficients are generally used to compare the strength values of asphalt concrete specimens before and after freeze–thaw cycles, similarly to the assessment of stone materials and cement concrete. Requirements for the frost resistance coefficient of asphalt concrete, (K_{CFT}), are included in the standards of various CIS countries (*STB 1115-2004, 2004; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*). As a rule, these requirements are similar to those established for long-term water resistance. At the same time, a decrease in asphalt concrete frost resistance is reflected in its deformation parameters and may reduce the load-bearing capacity of both the asphalt concrete pavement layer and the entire road structure during the design service period. Therefore, the relationship between cyclic freezing and thawing and deformation characteristics should be evaluated in order to estimate this reduction more objectively. The present study is primarily aimed at examining the influence of cyclic freezing and thawing on the rheological properties of asphalt concrete.

The research methods selected by different scholars at different times have generally not been aligned in terms of either the duration of exposure or the temperature regimes applied to test specimens. Golovko (*1983*) studied freezing under different conditions, including temperatures of -20°C and below -40°C , with the number of freeze–thaw cycles varying up to 70. According to one standard method, specimens are saturated with a 5% sodium chloride solution, frozen at -18°C , thawed for two hours in the same solution, and then subjected to compressive strength testing (*STB 1115-2004, 2004*). In GOST 12801-98, a four-hour freeze–thaw cycle at -18°C and $+18^{\circ}\text{C}$, respectively, is recommended, with the number of freeze–thaw cycles set at 5, 10, 15, 25 or 50 (*GOST 12801-98, 1999*). The Ukrainian reference standard indicates freezing at -25°C for four hours and thawing at 20°C for four hours, with the minimum number of freeze–thaw cycles

set at 25; in this case, the frost resistance coefficient is determined by the ratio of compressive strength to tensile strength along the cross-section (*SOU 42.1-37641918-110:2014, 2014*).

European standards define a method for determining the resistance of asphalt concrete to de-icing fluids, but they do not provide a full analysis of frost resistance mechanisms as such (*European Committee for Standardization, 2023*). None of the above methods makes it possible to reveal the nature of changes in asphalt concrete properties under freeze–thaw cycles. Their function is mainly to record the effect of exposure rather than to explain the mechanisms of structural change.

The research approaches described in other studies differ from the methods mentioned above. In particular, values of (K_{CFT}) calculated from the ratio of stiffness moduli under bending and from indirect tensile loading associated with cyclic loading have been reported (*Zhang et al., 2020; Yu et al., 2022*). The approach proposed by Yu et al. (2022) is non-traditional because it involves freezing for 24 hours at -18°C and thermostating at 60°C for 24 hours. After ten cycles under these conditions, the frost–heat resistance coefficient may decrease to approximately 0.3. However, the regime proposed by Liang (2008) may be considered insufficiently representative of actual asphalt concrete operating conditions in pavement because it combines two processes: freezing and water exposure. Moreover, water exposure may dominate the frost effect, since high temperatures cause rapid degradation of adhesion and water resistance in asphalt concrete (*Kodirov, 2022*).

Nevertheless, the results reported by Yu et al. (2022) are original and methodologically significant. In addition, the European standard for determining the modulus of elasticity under indirect tensile loading may be considered a non-destructive testing method, because the same specimen can be tested before and after exposure to water. The present study follows a similar logic by using a classical European test rig for determining elastic moduli under cantilever bending and for investigating resistance to frost-induced stress (*EN 12697-26, n.d.*).

To determine the elastic moduli at different temperatures and loading frequencies, a HADI vibration test rig was used (*Wang et al., 2021*). It was necessary to determine the elastic moduli within the region of linear deformation, which is limited by critical stresses and strains; beyond these limits, asphalt concrete enters the region of non-linear deformation (*Figure 1*).

The frost resistance tests were carried out as follows. On the second day, asphalt concrete specimens were placed under vacuum at 10–15 mm Hg, sealed, immersed in water at a temperature of $19\text{--}22^{\circ}\text{C}$, and then kept in air for two hours at room temperature, also within the range of $19\text{--}22^{\circ}\text{C}$. On the third day, the specimens were placed in a freezer pre-cooled to $-20 \pm 1^{\circ}\text{C}$. After freezing, the specimens were removed from the freezer and kept in water for four hours, after which they were frozen again for four hours. During overnight periods, from 8 p.m. to 8 a.m., the specimens were kept in water at a temperature of $19\text{--}21^{\circ}\text{C}$. In the studies dealing with property recovery, the required rest periods were provided in air at temperatures of 21°C and 30°C .

It should be noted that, because the effect of water content on the elastic modulus has been insufficiently studied, and in order to improve measurement accuracy, homogeneous sand-based asphalt concrete of type “G” was selected. The mixture was composed of separate fractions so that the particle size distribution curve occupied an average position between the boundary curves of dense mixtures. The content of mineral powder particles smaller than 0.071 mm was 11%. The content of bitumen of refinery grade BND 70/100 was 6%. The physical properties of the bitumen were as follows: penetration at 25°C — 82×0.1 mm; softening point— 50.5°C ; brittleness point— -17°C ; elongation at 25°C —94 cm.

A complete cycle of testing involved a number of technical difficulties. Therefore, during unavoidable interruptions, the test specimens were stored in a water bath at 21°C.

The standard stress–relative strain relationships shown in Figure 1 demonstrate that, at a given strain level, approximately corresponding to that experienced in road pavement, namely 0.2×10^{-3} , the critical stress before 50 freeze–thaw cycles is considerably higher than after 50 cycles. The difference is approximately 1.76 times. This indicates a change in the structural condition of asphalt concrete and a reduction in its load-bearing capacity, under which traffic loads may generate stresses exceeding the limits of linear deformation.

Literature Review

The main factors are: a drop in temperature, the bituminous binder undergoing vitrification, and water freezing. In this process, the asphalt concrete transitions from a two-phase system to a three-phase system, as water is added, and subsequently, following ice formation, to a four-phase system (Lövqvist *et al.*, 2021). This is accompanied by its transition from a viscoelastic state to an elastic state, and subsequently to a brittle state as the temperature drops below a critical value, which, in turn, depends on the consistency, grade, penetration and type of the bituminous binder and the ratio between the content of dispersed mineral powder and the binder. Temperature-induced microstresses are compounded by processes associated with the influence of water. As the temperature decreases, the density, degree of structuring, wetting ability and behaviour at the phase boundaries with the surface of stone materials and the walls of bituminous surfaces and capillaries change. The ice formed can be amorphous, crystalline and anisotropic.

A.S. Barankovsky (1980), based on observations of 11 sites on the streets of Moscow, stated that the filtration and water saturation coefficients of asphalt concrete fluctuate throughout the year: they decrease at the start of autumn, reach a maximum by April of the following year due to the central heating system, and thereafter, due to water evaporation, they decrease but remain higher than in the previous year (Zhang *et al.*, 2020). According to Cao *et al.* (2022), after 8–10 years of such development, widespread destruction occurs. Based on widespread spring and winter damage in France in 2004–2005, French researchers concluded that the total number of cycles over 12–15 years can reach 500–1,200, after which the pavement undergoes catastrophic failure (Mauduit *et al.*, 2007).

Gokhman and Gershkohen (1997) show that even after 200 cycles of ‘dry’ bending of bituminous membranes, microcracks form on them, indicating greater brittleness of the asphalt concrete and creating favourable conditions for the destruction of the asphalt concrete pavement during the transition period. Zhang *et al.* (2020) and Mauduit *et al.* (2007) consider the main causes of thermal-freeze-thaw damage to be the enormous forces affecting the structure of asphalt concrete when water freezes, and hydraulic shock pressures in spring during vehicle traffic. In Golovko (1983), the damage is explained by temperature-induced microstresses. In support of this, data on dry and wet freeze-thaw cycles, at temperatures of minus 20°C and minus 40°C based on up to 70 cycles, are presented, from which it follows that in some cases ‘dry’ and wet freeze-thaw cycles are comparable in terms of their destructive effect.

To assess frost resistance, coefficients are typically used which define the ratio of the strength values of asphalt concrete specimens before and after freeze-thaw cycles, in a similar manner to that used for stone materials and cement concrete. Requirements for the frost resistance

coefficient, (K_{CFT}), of asphalt concrete are included in the standards of various CIS countries (*STB 1115-2004, 2004; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*). As a rule, they are similar to the requirements for long-term water resistance specified in the same standards.

At the same time, a reduction in the frost resistance of asphalt concrete is directly reflected in its deformation characteristics, impairing the load-bearing capacity of the asphalt concrete pavement and the entire road structure over the design period. The extent of this reduction can only be assessed by evaluating the effect of cyclic freezing and thawing on the deformation characteristics themselves. This study is devoted to investigating the effect of cyclic freezing and thawing on the rheological characteristics of asphalt concrete.

Results

The frequency-dependent characteristics of the elastic moduli determined under these conditions across a frequency spectrum from 0.01 Hz to 10 Hz (three orders of magnitude) and at various temperatures (-10°C , 0°C , 20°C , 35°C) closely align with power-law relationships. At lower temperatures and higher frequencies, the elasticity modulus reaches up to 24,000 MPa, akin to grade 300 cement concrete levels. Conversely, under elevated temperatures (35°C) and reduced frequencies (0.01 Hz), this modulus declines dramatically to 400 MPa—a six-fold decrease. The temperature dependence of the elastic moduli across different frequencies illustrates an ongoing transition of asphalt concrete during its service life on road surfaces—from visco-plastic to visco-elastic states and ultimately toward brittleness (*Wang et al., 2021*). Even at sub-zero temperatures, asphalt concrete typically approaches a brittle state. It is this brittle material that encounters cyclic stresses and strains while also being affected by water action, which cools it down and can lead it into a frozen state; this sequence reduces both the strength and elastic moduli of the asphalt concrete.

Table 1 represents data from investigations involving beams prepared through different methods. One beam underwent dynamic loading just one day post-manufacturing, whereas another was pre-cured for a duration of 90 days at a temperature of 21°C . It is well-established that structural formation within asphalt concrete continues after production, concluding typically between 25–35 days. The findings displayed in the Appendix (*Table 1*) support this notion: across all tested frequencies and temperatures, pre-curing enhanced resistance against dynamic loading in the specimens. This discrepancy raises initial concerns regarding the methodological rigor applied in preparing specimens for evaluating other mechanical properties.

The data presented in Table 1 illustrates specific attributes of the K_{CFT} response under tested conditions, for which prior evidence is lacking. The K_{CFT} values across all temperatures exhibit an upward trend with increasing measurement frequency. This trend parallels the rise in elastic moduli and tensile strength values as test speeds increase, as noted by N.N. Ivanov and A.V. Rudensky. It can be inferred that at elevated deformation frequencies, the damping effect of significant structural defects does not have sufficient time to influence elastic moduli, similar to how long-term relaxation processes do not occur during rapid deformation.

Considering the principle of temperature-time superposition within viscoelastic systems, one can comprehend the rise in K_{CFT} values as temperature decreases across all frequencies. Consequently, the lowest K_{CFT} values are observed at higher temperatures and lower frequencies, while the highest are recorded at lower temperatures and higher frequencies. In the former

scenario, asphalt concrete behaves like a viscoelastic material; in the latter, it exhibits brittle characteristics. This raises a pertinent question: which combination of time (frequencies) and temperature presents a more accurate basis for investigation? It is suggested that this combination should align with the climatic conditions experienced by the asphalt concrete.

If we accept that frost resistance defines asphalt concrete's capacity to remain intact within pavement structures, whereas crack resistance pertains to its ability to preserve continuity along its length, it is essential to recognize that these mechanisms are fundamentally different. In terms of frost resistance, various microstructural failures arise due to water and frost exposure predominately affecting performance. Conversely, transverse cracks emerge from stresses within the pavement that exceed asphalt concrete's strength or from insufficient deformability relative to thermal linear contraction occurring along the pavement strip.

These disparate failure mechanisms can yield varying consequences throughout their respective life cycles. Cracks induced by temperature-related shrinkage typically do not self-heal and may only receive temporary repairs through sealing methods. In contrast, defects originating from thermal shrinkage may indeed recover under ambient temperature influences coupled with tire compaction effects. Generally, wheel tracks exhibit minimal flaking or spalling incidents, with potholes being infrequent occurrences.

To substantiate these hypotheses, heating tests were conducted on 50 samples of asphalt concrete that underwent pre-heating for 12 days at 21°C followed by an additional 10 days at 30°C. The results obtained (*Table 2*) demonstrate a notable increase in moduli during the initial stage: at 20°C—between 27% and 28%; at 30°C—up to 40%. Furthermore, prolonged ageing at 30°C results in a diminished rate of increase; this reduction becomes more pronounced as both test temperature and frequency decrease.

These findings corroborate a recent discovery that has been supported by numerous scientists, while others, including one of the authors of this study, have raised objections (Qiu et al., 2020). Consequently, it can be inferred that the defects produced during the CFT process possess the ability to self-repair, and efforts should be made to activate this healing mechanism. The increase in critical stress values at a relative strain of 2×10^{-4} , as illustrated in Figure 1, reinforces the proposed mechanisms of damage and recovery. It would also be beneficial to validate these observed phenomena through physico-chemical methods. Ultrasonic testing may lack sufficient sensitivity for these processes; however, scanning gamma-densitometry and electro-densitometry—techniques suggested by French researchers—might effectively identify internal defects (*Fauchard et al., 2016*).

The patterns discerned throughout this research and systematic control measurements regarding the reproducibility of initial test data suggest that the linear deformation method can indeed be recognized as a non-destructive approach for evaluating the frost resistance of asphalt concrete. In broader terms, this entails conditioning moulded specimens at temperatures between 18°C and 22°C for a duration of 30 days before assessing their modulus of elasticity at temperatures of 0°C, 10°C, and 20°C. The research findings indicate that employing higher temperatures is inadvisable due to potential self-healing of defects during tests lasting between 4 to 8 hours. Subsequently, samples undergo an appropriate number of CFT stages tailored to the specific climatic conditions of the region. After each stage, the modulus of elasticity is measured; utilizing known values from samples not subjected to CFT allows for determining corresponding K_{CFT}

values. A significant advantage of this proposed methodology lies in its enhanced reliability since it eliminates reliance on results from heterogeneous samples while also reducing the total number tested.

The intricate nature of changes in elastic moduli during the initial testing phase is depicted in Table 3. The beam was evaluated on day six post-manufacturing. Following a period of exposure to air at 20°C for 32 days, elastic moduli values exhibited an increase by a factor of 1.5. At a testing temperature of 10°C, there was approximately a 1.3-fold increase in elastic moduli; however, this increment diminished to between 1.1 and 1.2 times at temperatures ranging from 0°C to –10°C. An additional aging period of eighteen days at these lower temperatures had minimal impact on elastic moduli values. Furthermore, subjecting samples to ten freeze-thaw cycles resulted in decreased elastic moduli values alongside reductions in K_{CFT} : at temperatures of 20°C they fell to between 0.78–0.97; at 10°C they ranged from 0.82–1.03; at 0°C they were recorded between 0.74–0.92; and, finally, at –10°C they varied from 0.83–1.00.

As observed in prior instances, the CFT values exhibited an increase with frequency and a decrease in temperature. This particular case illustrates that, for an individual sample, there is an observable rise in modulus during the air-curing phase, which is subsequently followed by a decline after undergoing cyclic freeze-thaw testing.

Discussion

The results of the study demonstrate that the frost resistance of asphalt concrete cannot be adequately assessed only through conventional strength indicators measured before and after cyclic freezing and thawing. Although compressive, tensile or flexural strength values remain useful for standardised comparison, they do not fully reflect the changes that occur in the deformation behaviour and load-bearing capacity of asphalt concrete during environmental cycling. The elastic modulus appears to be a more sensitive and informative parameter because it reflects the internal structural state of the material, its rheological response, and its transition between viscoelastic, elastic and brittle behaviour under different temperature–frequency conditions.

The obtained results confirm that asphalt concrete is strongly dependent on both temperature and loading frequency. At lower temperatures and higher frequencies, the elastic modulus increases significantly, indicating that the material approaches a more rigid and brittle state. Conversely, at higher temperatures and lower frequencies, the elastic modulus decreases sharply, reflecting the dominance of viscoelastic and viscoplastic deformation mechanisms. This behaviour is consistent with the general theory of bituminous materials as temperature- and time-dependent systems. It also confirms the importance of the temperature–time superposition principle for interpreting frost resistance, because the same material may demonstrate substantially different mechanical responses depending on the selected testing temperature and loading frequency.

This dependence has direct implications for the interpretation of the frost resistance coefficient, (K_{CFT}). The study shows that (K_{CFT}) tends to increase as the testing temperature decreases and the loading frequency increases. This means that the coefficient is not a fixed material constant, but a parameter determined by the testing regime. Therefore, the selection of temperature and frequency conditions becomes a methodological issue of central importance. If the testing regime does not correspond to actual pavement operating conditions, the obtained frost resistance coefficient may either overestimate or underestimate the real durability of asphalt concrete under

cyclic environmental loading.

The observed reduction in elastic modulus after freeze–thaw cycles indicates that cyclic freezing and thawing causes structural degradation in asphalt concrete. This degradation may be associated with several mechanisms: water penetration into pores and microcracks, ice formation, hydraulic pressure, temperature-induced microstresses, weakening of bitumen–aggregate adhesion, and increased brittleness of the bituminous binder. These mechanisms are consistent with previous studies that describe freeze–thaw damage as a complex process involving water, low temperature, internal pressure and microstructural change (Cao *et al.*, 2022; Lövqvist *et al.*, 2021; Mauduit *et al.*, 2007). The reduction in critical stress after 50 cycles also indicates that the material becomes less capable of maintaining linear deformation under traffic loads.

A significant finding of the study is the recovery effect observed after rest periods at positive temperatures. The increase in elastic modulus after ageing or rest at 21°C and 30°C suggests that some defects formed during cyclic freezing and thawing are at least partially reversible. This effect may be connected with relaxation processes in the bituminous binder, redistribution of internal stresses, partial restoration of adhesive bonds, closure of microdefects, and self-healing of bituminous films. Such behaviour corresponds to the broader concept of self-healing in asphalt materials, according to which bituminous binders may restore part of their mechanical integrity under favourable thermal and temporal conditions (Qin *et al.*, 2020).

At the same time, the recovery effect should not be interpreted as complete restoration of asphalt concrete durability in all cases. The degree of recovery depends on temperature, duration of rest, initial structural condition, number of freeze–thaw cycles, binder properties, air void structure, water saturation and previous ageing of the material. The results indicate that recovery is more pronounced at positive temperatures and may be more limited at lower testing temperatures. This suggests that frost damage in asphalt concrete includes both reversible and irreversible components. Reversible changes may be associated with relaxation and self-healing processes, whereas irreversible changes may include permanent microcracking, loss of adhesion and structural weakening of the mineral–bitumen matrix.

The findings also highlight the importance of specimen curing before testing. The increase in elastic modulus during the initial curing period confirms that structural formation in asphalt concrete continues after specimen preparation. This means that insufficiently cured specimens may produce distorted results in frost resistance testing. The conclusion that asphalt concrete should be cured for at least 30 days before testing is therefore methodologically significant. It reduces the risk of confusing the effects of structural formation with the effects of freeze–thaw damage and allows a more objective evaluation of material behaviour.

The comparison between specimens tested shortly after preparation and those subjected to longer curing demonstrates that the initial structural state of asphalt concrete plays a decisive role in its response to cyclic freezing and thawing. A specimen that has not completed its structural formation may show lower resistance to dynamic loading and may respond differently to moisture and temperature cycling. This observation is important for laboratory practice because reproducibility and comparability of frost resistance results depend not only on the freezing–thawing regime, but also on specimen preparation, curing history and storage conditions before testing.

The results also question the adequacy of traditional frost resistance standards based mainly

on destructive strength testing. Existing standards in CIS countries generally calculate frost resistance through ratios of strength values before and after freeze–thaw exposure (*STB 1115-2004, 2004; GOST 12801-98, 1999; SOU 42.1-37641918-110:2014, 2014*). Such methods can indicate that damage has occurred, but they do not reveal the nature of the structural changes or their influence on the deformation behaviour of pavement. By contrast, elastic modulus measurement in the linear viscoelastic range allows the same specimen to be tested repeatedly, making it possible to trace the evolution of damage and recovery over time.

The use of linear viscoelastic deformation analysis as a non-destructive testing approach is one of the most important methodological implications of the study. Since the same specimen can be measured before freeze–thaw exposure, after selected numbers of cycles, and after rest periods, this method reduces the influence of specimen heterogeneity. It also improves the reliability of comparisons because changes are assessed within the same material sample rather than between different specimens. This is particularly important for asphalt concrete, whose composition, air void content, aggregate structure and binder distribution may vary even within a single laboratory batch.

The proposed approach also provides a more pavement-oriented understanding of frost resistance. In actual road structures, asphalt concrete is subjected not only to low temperature and moisture, but also to repeated traffic loading. Therefore, changes in deformation characteristics are directly relevant to pavement performance. A reduction in elastic modulus and critical stress may indicate a decrease in the load-bearing capacity of the pavement layer, increased susceptibility to deformation, and a higher risk of crack development or surface distress. Thus, the elasticity modulus is not only a laboratory parameter, but also a performance-related indicator.

The study also supports the need to distinguish between frost resistance and low-temperature crack resistance. These two phenomena are connected with low temperatures, but their mechanisms are different. Frost resistance concerns the ability of asphalt concrete to withstand damage caused by water, freezing, thawing and repeated environmental cycling. Low-temperature crack resistance, by contrast, is associated primarily with thermal stresses and insufficient deformability under contraction. The results show that freeze–thaw damage may include microstructural failures that can partially recover, whereas transverse thermal cracks usually do not heal spontaneously and often require repair. This distinction is important for both material testing and pavement design.

From a theoretical perspective, the study contributes to the understanding of asphalt concrete as a complex viscoelastic material whose frost resistance should be considered in relation to rheological state, loading frequency, temperature and structural evolution. The elastic modulus reflects the internal balance between stiffness, relaxation capacity and damage accumulation. Therefore, frost resistance should not be reduced to a single strength ratio. It should be interpreted as a dynamic property that changes under cyclic environmental loading and may partially recover under favourable thermal conditions.

From a practical perspective, the findings may be used to improve laboratory procedures for evaluating asphalt concrete in regions exposed to repeated freeze–thaw cycles. The proposed method can support more informative frost resistance testing by including elastic modulus measurements at selected temperatures and frequencies. It may also help pavement engineers select asphalt concrete compositions that maintain sufficient stiffness and linear deformation capacity

after environmental cycling. In addition, the method may be useful for comparing binders, aggregate structures, air void contents and mixture designs in terms of their resistance to frost-induced degradation.

The study also has implications for pavement construction timing. The recommendation that pavement installation should be limited by ambient temperature and seasonal conditions is justified by the continuing structural formation of asphalt concrete after placement. If asphalt concrete does not have sufficient time and favourable thermal conditions to develop its structural integrity, it may enter the cold season with lower resistance to freeze–thaw damage. This is especially important in spring and autumn, when temperature fluctuations around 0°C are frequent and moisture conditions are unfavourable.

However, several limitations should be acknowledged. First, the study focuses on one asphalt concrete type and one bitumen grade, which limits the generalisability of the results to other mixture compositions, binders, aggregate structures and air void contents. Secondly, the testing programme involves specific freezing, thawing, rest and loading regimes; other climatic regions may require different combinations of temperature, duration and number of cycles. Thirdly, although the recovery effect is clearly observed through elastic modulus changes, its physicochemical mechanisms require further confirmation using additional methods. Fourthly, the study does not fully separate the influence of water saturation, freeze–thaw action, binder ageing and thermal relaxation, although all of these factors may contribute to the observed response.

Future research should therefore include a broader range of asphalt concrete mixtures, binder grades, polymer-modified binders, air void contents and aggregate gradations. It would also be useful to compare dry and wet freeze–thaw regimes, as well as the influence of de-icing agents, under controlled laboratory conditions. Additional physicochemical and microstructural methods may help confirm the mechanisms of damage and recovery. Scanning gamma-densitometry, electro-densitometry, X-ray computed tomography, acoustic emission, digital image correlation and microscopic analysis may be particularly useful for detecting internal defects and monitoring their evolution.

Further research should also aim to develop a unified testing framework that connects elastic modulus changes with pavement design parameters. Such a framework could include recommendations for specimen curing, temperature–frequency testing conditions, number of freeze–thaw cycles, rest periods and interpretation of recovery effects. This would make it possible to move from empirical frost resistance coefficients towards a more mechanistic and performance-related assessment of asphalt concrete durability.

Overall, the discussion confirms that the elasticity modulus is a valuable criterion for assessing the frost resistance of asphalt concrete. It reflects damage accumulation, structural weakening, rheological state and recovery potential more comprehensively than traditional strength-based indicators alone. The use of linear viscoelastic deformation analysis enables non-destructive monitoring of the same specimen over successive stages of testing and provides a more reliable basis for evaluating the durability of asphalt concrete under cyclic freezing and thawing. Therefore, the proposed approach may contribute to improving both laboratory assessment and practical pavement design in cold and variable climates.

Conclusion

The study confirms that the assessment of asphalt concrete frost resistance should take into account not only conventional strength indicators, but also changes in the elastic modulus, since this parameter reflects the deformation behaviour and load-bearing capacity of the material after cyclic freezing and thawing. The results show that asphalt concrete continues to undergo structural formation after specimen preparation; therefore, a curing period of at least 30 days should be provided before testing the modulus of elasticity and frost resistance indicators. This requirement is important for obtaining reliable and comparable results, because insufficiently cured specimens may demonstrate unstable mechanical behaviour that does not objectively represent the material's resistance to freeze–thaw damage.

The findings also indicate that the frost resistance coefficient is strongly dependent on testing conditions. It increases as the temperature decreases and as the loading frequency rises, which corresponds to the relaxation behaviour of asphalt concrete and the temperature–frequency dependence of its elastic modulus. This confirms that the frost resistance coefficient cannot be treated as an absolute material constant without reference to the selected testing regime. Consequently, the choice of test temperature and loading frequency must be scientifically justified and correlated with the actual climatic and operational conditions of the pavement.

A further important result is the observed ability of asphalt concrete to partially restore frost resistance after rest or ageing at positive temperatures. This recovery effect becomes more pronounced at elevated positive temperatures, indicating that some structural changes caused by cyclic freezing and thawing may be reversible. The restoration of elastic modulus after rest periods suggests the presence of relaxation and self-healing processes within the asphalt concrete structure. At the same time, this recovery should be understood as partial, since freeze–thaw exposure may also produce irreversible defects that accumulate during pavement service life.

The results have practical implications for both laboratory testing and road construction practice. Since structural formation and recovery processes are temperature-dependent, pavement construction should be limited by ambient air temperature and seasonal conditions. In particular, asphalt concrete pavement installation should not be carried out at temperatures below 5°C in spring and below 10°C in autumn, similarly to the restrictions applied to pavement layers made with cold asphalt concrete mixtures. These limits are necessary to ensure proper structural formation before the pavement is exposed to intensive freeze–thaw action.

The study substantiates the use of linear viscoelastic deformation methods as a non-destructive approach for analysing the structure, damage and recovery of asphalt concrete after cyclic freezing and thawing. This method makes it possible to test the same specimen at different stages of exposure, thereby reducing the influence of specimen heterogeneity and improving the reliability of frost resistance assessment. Overall, the elasticity modulus can be considered an informative criterion for evaluating asphalt concrete frost resistance, while linear viscoelastic deformation analysis provides a promising methodological basis for more accurate and performance-oriented testing of asphalt concrete in cold and variable climatic conditions.

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Conflict of Interest

The author declares that there is no conflict of interest.

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Appendix

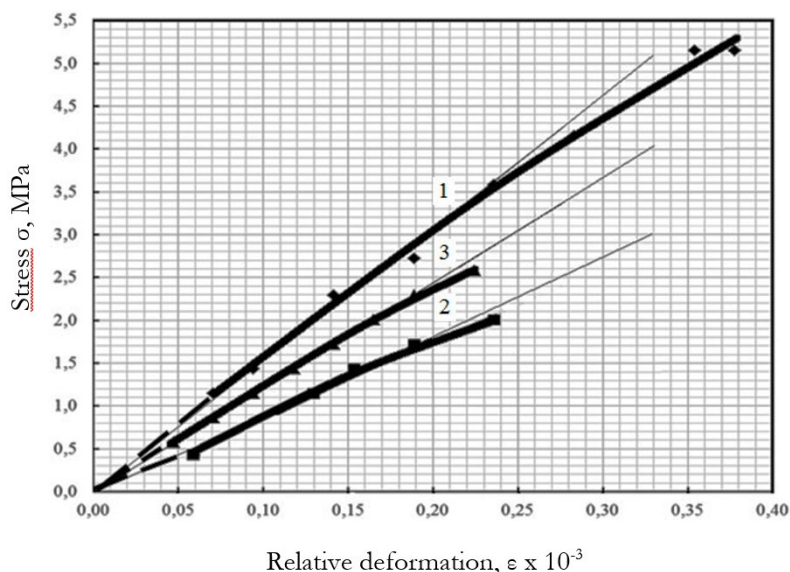


Figure 1. Differences between deformation and stress in asphalt concrete at 0.5 Hz: 1—Before 50 cycles; 2—After 50 cycles; 3—After 50 cycles and 12 days of curing at 21°C

Table 1. Dependence of the frost resistance coefficients of asphalt concrete after 21 cycles of freezing and thawing, 17 days of immersion in water and 29 cycles of freezing and thawing on temperature and frequency

Frequency, Hz	Frost resistance coefficients at temperatures, °C				
	35	20	15	0	-10
0,01	0,63 / -	0,53 / 0,27	0,53 / 0,35	0,63 / 0,63	0,85 / 0,91
0,1	-	0,54 / 0,33	0,56 / 0,30	0,78 / -	- / -
0,5	-	0,58 / 0,33	0,63 / 0,40	0,85 / -	- / -
1,0	-	0,61 / 0,38	0,63 / 0,45	0,63 / 0,71	- / -
5,0	0,85 / -	0,64 / 0,38	0,77 / 0,44	- / -	1,0 / 0,95

Note: In the numerator—a beam that was left to stand for 90 days at a temperature of +21°C prior to the load test; in the denominator—a beam that was formed prior to the load test.

Table 2. The effect of dormancy on frost resistance

Temperature, °C	Frequency, Hz	Increase in frost resistance coefficients after curing			
		Modulus relative to the reference value, MPa	K _{CFT} after 50 CFT's	K _{CFT} after 12 days of ageing (21°C)	K _{CFT} after 12 days of rest (21°C) and 10 days of rest (30°C)
20	0,01	2344	0,27	0,56	0,78
	0,1	3467	0,33	0,61	0,79
	0,5	4786	0,33	0,62	0,78
	1,0	5248	0,38	0,67	0,76
	5,0	6918	0,38	0,65	0,72
15	0,01	3019	0,35	0,66	0,74

	0,1	6025	0,30	0,52	0,62
	0,5	6310	0,40	0,60	0,72
	1,0	6920	0,45	0,72	0,76
0	0,01	6606	0,63	1,0	0,98
	0,1	9332	0,68	1,0	0,98
	0,5	11430	0,69	1,0	0,98
	1,0	13180	0,68	1,09	0,92
	5,0	14790	0,71	1,12	0,83

Table 3. The effect of the CFT regime and rest periods on frost resistance indicators

Temperature, °C	Frequency, Hz	Complex elasticity moduli $E^* \times 10^{-3}$, MPa					Ratio of modules and K_{CFT} 's		
		Test mode							
		After CFT (for 6 days)	Rest (for 32 hours)	Rest (for 50 hours)	10 CFT's	50 CFT's	E_3/E_1	K_{CFT} E_4/E_3	K_{CFT} E_5/E_3
		E_1	E_2	E_3	E_4	E_5			
20	0,01	1,03	1,56	1,55	1,21	1,13	1,51	0,78	0,73
	0,5	2,13	3,34	3,87	3,38	3,38	1,80	0,87	0,87
	10	3,5	5,43	5,57	5,43	5,43	1,59	0,97	0,97
10	0,01	3,1	4,06	3,53	2,89	2,70	1,31	0,82	0,76
	0,5	6,0	7,67	6,8	6,79	6,79	1,28	1,00	0,99
	10	7,99	9,60	9,63	10,05	8,51	1,20	1,03	0,88
0	0,01	6,54	8,72	8,82	6,55	7,25	1,33	0,75	0,82
	0,5	11,05	14,75	13,6	10,88	10,9	1,33	0,82	0,80
	10	11,68	15,88	14,80	13,7	13,6	1,36	0,92	0,91
-10	0,01	12,16	13,27	12,50	10,41	10,15	1,09	0,83	0,81
	0,5	16,34	17,70	16,34	16,34	15,64	1,08	1,00	0,96
	10	17,47	21,80	20,33	18,31	17,45	1,16	0,90	0,86