Asphalt mixture performance and testing

Evaluation of Asphalt Mixture Frost-Resistance based upon its Stiffness

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Abstract

A number of freezing-thawing cycles for French climate were estimated to stay in a range from 500 to 1200 in 12-15 years of service life. In this regards pavements in Eastern Europe could experience even larger detrimental effect from the frost damage. As a consequence, this may potentially lead to a decreased load carrying capacity of the whole pavement. For the freezing-thawing effect on the asphalt mixture to be assessed, the stiffness modulus of the asphalt mixture was determined. The specimen under consideration was subjected to 50 freezing-thawing cycles at temperatures ranging from -10 ºC to 20 ºC and strain rates from 0.01 Hz to 5 Hz. To exclude any uncertainties arising from the non-linear behaviour, an effective stiffness modulus was defined, which was taken within a linear visco-elastic region of the bituminous mix before and after the freezing-thawing exposure. The method used was therefore of a non-destructive type. Based upon the results derived, frost resistance coefficients were quantified and a set of relationships between the stiffness and these coefficients was possible to be established. It was found that the frost-resistance coefficient increases as the strain rate increases and as the temperature drops. A considerable effect on the frost-resistant ability was also observed to occur immediately after the application of the first freezing-thawing cycle during the rest phase. It was noticed that as both duration of the rest phase and an ambient temperature become larger the material is more resistant to the frost damage. This indicated that the frost-related damage in the asphalt mixture might be partly healed. The variaiton in the stiffness modulus and the frost-resistance coefficient identified from the experiments is depended on the settings adopted in the test and should be explained by taking real conditions the pavement is exposed to into account.

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INTRODUCTION

Demolition of asphalt concrete layers through peeling, crumbling, pothole formation, and delamination from the lower layer is to a significant degree caused by the influence of freeze–thaw cycles (FTC). Under a FTC, bitumen, mineral components, and asphalt concrete experience temperature change; bitumen passes many times from a viscoelastic state to a vitreous state, and its volume changes cause internal stress. Water in asphalt concrete becomes ice that is accompanied by the alteration of pressure in intergranular space. Water that has accumulated under a bituminous film in autumn causes a peeling effect. These types of FTC influence are particularly considered in [1–3].

In accordance with observations published in [4], water filtration into asphalt concrete varies over a year. Filtration slows down by autumn and reaches its maximum by mid-spring. At the same time, in spite of the evaporation of water during warm seasons, the water content of coating layers becomes higher by early autumn from year to year. Thus, the influence of the FTC increases with the water content. Researchers [3] concluded that the total amount of FTCs could be up to 500–1200 over a time span of 12–15 years. This is followed by avalanche deterioration. These processes are aggravated by traffic loadings, especially by hydraulic impact pressure and this is also accompanied by fatigue failure. According to [5], cyclic fatigue tests demonstrate that the 30-day operating life of water-saturated samples is 2.6 times shorter after one FTC, 3.2 times shorter after 50 cycles, and 10.5 times shorter after 200 cycles. The topicality of the problem of asphalt concrete frost resistance is highlighted in [6].

1. CURRENT METHODS TO ASSESS FROST RESISTANCE

In order to take into account the destructive effect of the FTC on asphalt concrete during composition design and operating life, it is necessary to apply research methods that are well-grounded and able to detect this effect. One of the most common parameters of asphalt concrete frost resistance is a freeze-proof factor, which is the ratio of asphalt concrete strength after a certain amount of FTCs to ‘dry’ sample strength. This parameter is similar to one proposed in 1962 by M. Duriez [7] to assess asphalt concrete water resistance which refers to the last phase of asphalt concrete life – its demolition. Irrespective of the type of asphalt concrete load (compression, tension, bend), this parameter fails to assess the asphalt concrete state of strain or understand the essence of the changes to its properties during an FTC. The European standard of asphalt concrete resistance to de-icing fluids [8] focuses on the choice of more effective de-icing fluids to decrease asphalt concrete deterioration and improve environmental safety rather than the measurement of strain–strength characteristics.

The method used in the USA [9] is a complex assessment of freezing for 24 hours at -18ºC with the further thermostating of asphalt concrete in water for over 24 hours at 60ºC. This is an extremely difficult method [10] that enables us to obtain a complex frost and water resistance parameter of about 0.3 for 10 days. It is hardly expedient to unite these two controversial factors in a frost resistance test because this combination of impacts is not applicable in practice. At the same time, temperature changes all day long: a high temperature does not follow a cold period; hot water expedites the separation of bituminous films from stone surfaces [11] in such a way that it can doubly decrease asphalt concrete strength during transition from 20ºC to 70ºC over a time span that is 112 times shorter. This is illustrated in [12], using results that were obtained in Bangladesh where annual precipitation reaches 3000 mm and the average summer temperature is 40ºC.

A new approach in [9, 13] is the use of a coefficient, which is the ratio of asphalt concrete elastic moduli before and after an FTC, as a criterion of frost resistance assessment. The results of this assessment can be used to forecast road coating maintainability at an estimated time period in various climatic conditions and regions.

Research into asphalt concrete viscoelastic deformation, which was initiated by Ch. Huet [14], demonstrates that deformation remains linear up to a specific level of loading until the stress and strain relation is proportional. Linear viscoelastic limits depend on temperature, deformation rate, and frequency, as well as asphalt concrete composition. To obtain correct data about the impact of an FTC on reliable asphalt concrete operation in road coatings, it is necessary to determine the freeze-proof factor based on elastic modulus values that are within a linear region of deformation.

The aim of this paper is to investigate the impact of test conditions on complex asphalt concrete elastic moduli before and after an FTC and to develop a method to determine the freeze-proof factor.

2. EXPERIMENTAL RESEARCH RESULTS

2.1. Test method

Finding the values of the complex elastic modulus relation before and after a specific amount of FTCs is necessary to achieve the goal of the research. In the Ukraine, the amount of FTCs is 50, which is close to the number of times the environmental temperature passes zero; the greatest severity in this respect occurs in the north-east and the Carpathian highlands. The equation $K_F = \frac{E^*_{after}}{E^*_{before}}$ was determined to find a frost resistance coefficient, where E^*_{before} is a complex elastic modulus before FTC, and E^*_{after} is the one after FTC. The method is based on the main principle of defining values of E^*_{before} and E^*_{after} in the linear strain area. The complex elastic modulus (E*) was determined using a cantilever bending scheme on a rectangular beam in accordance with EN 12697-26 [15].

The test specimen sizes were 40 x 40 x 250 mm. The dynamic research modes were frequencies of 0.01, 0.05, 0.1, 0.5, 1.0, 5, and 10 Hz and temperatures of 35, 20, 10, 0, and -10ºC. The strain–stress values were in linearity limits at all frequency–temperature combinations. These were provided by short loading cycles with a linearity deviation of no more than 8–10%. The use of the same sample for the tests before and after FTC is a specific feature of this method. In the first phase the specimens were tested in age of 3 days in air medium. The complex moduli before FTC were obtained at the temperatures and frequencies given above.

During the second phase, test specimens with embedded plates were saturated with water in a vacuum (10–15 mm Hg) for 60 minutes and kept in water for another 60 minutes at atmospheric pressure. Then, they were placed in the freezer at -20±1ºC for 4 hours. After that they were kept in water at 19–21ºC for another 4 hours and the freezing phase was repeated. From 20:00 until 08:00, the samples were in water at a temperature of 19–21ºC. In this way, 50 FTCs were simulated over 25 days.

Having completed a given number of FTCs, the samples were placed in a vibrostand test chamber, and then the time–temperature dependences of their complex moduli were determined.

2.2. Materials

This research primarily used sandy asphalt concrete because it is largely homogenous in comparison with crushed rock asphalt concrete. In sandy asphalt concrete, 2.5–5 mm sized grains make up 24.0%, 0.14–2.5 mm grains constitute 60.0%, 0.071–0.14 mm grains constitute 5.0%, mineral powder (grains smaller than 0.071 mm) constitute 11%, and bitumen accounts for 6%.

The specimens were prepared by hot asphalt mix compaction at a pressure of 30 MPa in steel formworks. The binder extraction method was used to check the identity of the asphalt mixture composition before and after compaction. The asphalt concrete indicators were: air voids at 4.9%, compressive strength was 4.5 MPa at 20°C and a rate of 3mm/min, compressive strength at 50°C was 1.7 MPa, and water resistance coefficient was 0.85 (specimens after saturation with water in vacuum at 10–15 mm Hg for 60 minutes were placed in water for 14 days at a temperature of 20(±1)ºC).

Binders with a penetration of 72 dmm and 115 dmm, and bitumen modified by 6% SBS-type polymer, were used in this study. The properties of the binders are shown in Table 1.

Table 1. Properties of bituminous binders

Property parameters	Parameter		
	BND 60/90	**BND 90/130**	**BND 60/90 + 6% SBS**
Needle penetration depth 25°C, dmm	72	115	47
Softening temperature for ring and ball, °C	50.5	45.7	84.3
Elasticity at 25°C, %	-	-	92.1
Adhesion to glass, %	36	23	96.6
Brittle temperature, °C	-17	-20	-21.0
Penetration index	-0.17	-0.12	+4.72
Cohesion at 25ºC, MPa	0.12	0.074	0.298

Note: The methods to determine adhesion are outlined in [11] and cohesion are outlined in [16].

2.3. Dependence of frost resistance on test conditions.

The characteristic stress–strain dependence before and after an FTC is shown in Figure 1. It shows that stress linearly decreases 1.7 times at a frequency of 0.5 Hz after 50 FTCs. Linear strain that is determined within 10% deviation is less susceptible to the FTC than stress.

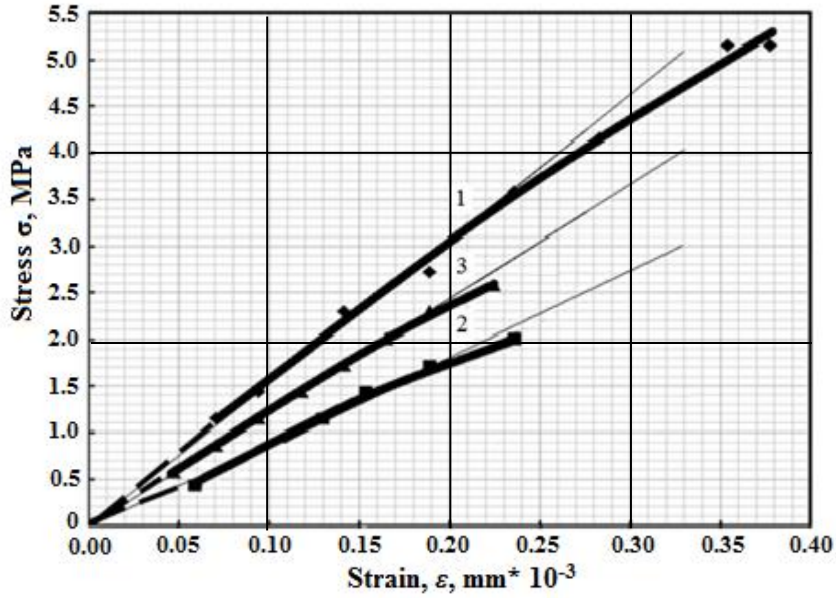

Figure 1: Asphalt concrete strain–stress dependence at frequency 0.5 Hz:
1- before FTC; 2- after 50 FTCs; 3- after 50 FTCs and rest at 21°C for 12 days

The first tests to determine the freeze-proof factor discovered effects which were not detected during common tests to determine the temperature–frequency dependence of elastic moduli. This is clear from Table 2 where freeze-proof factor values are shown at five frequencies and five temperatures. In Table 2 the numerator is the freeze-proof factor of asphalt concrete which was aged for 90 days in air at 21ºC before an FTC. The denominator is the freeze-proof factor of asphalt concrete aged for 6 days before an FTC. Long-term storage samples have far higher freeze-proof factor values compared with short-term storage samples. The difference between the freeze-proof factors of the pairs tested at a temperature of 20ºC and frequencies of 0.01–5 Hz is 0.24–0.26. If a test temperature decreases from 20ºC to 0ºC, the difference is considerably lower and there is practically no difference at a temperature of -10ºC. The higher values of the freeze-proof factors of preliminary air-aged samples are probably due to structural connections that have been formed in asphalt concrete over time due to absorption processes at the boundary of phase division (i.e., mineral material and bitumen). This agrees with asphalt concrete fatigue assessment results after 1, 15, 27, and 51 months in paving applications [17]. This time series corresponds to the following service life (in deformation cycles): $0.6{\cdot}10^5$; $1.1{\cdot}10^5$; $1.8{\cdot}10^5$. The evolution of fatigue parameters enables us to state that asphalt concrete placement in late autumn can decrease asphalt concrete freeze–thaw stability in a transitional spring period [1].

The freeze-proof factor, measured at 35ºC and an accepted frequency range, has a higher value than 15ºC and 20ºC, as shown in Table 2. This can be linked with a feature of the preparation of samples for tests. The sample which was tested at previous temperatures was kept in air at 35ºC for 3 hours. It can be assumed that the accelerated curing of defects, which affect bitumen during an FTC [2], and the recovery of the adhesive relationship between bitumen and a rock material surface take place in these conditions. Thus, the freeze-proof factor is higher at 35ºC rather than at 20ºC. Therefore, the determination of the freeze-proof factor at a high temperature using the elastic modulus has no practical meaning.

Table 2. Dependence of an asphalt concrete freeze-proof factor and temperature and frequency

Frequency, Hz	**Freeze-proof factor at a temperature of 35, 20, 15, 0, -10ºC**				
	35	**20**	**15**	**0**	**-10**
0.01	0.63 / –	0.53 / 0.27	0.54 / 0.35	0.63 / 0.60	0.85 / 0.80
0.1	0.70 / –	0.56 / 0.30	0.59 / 0.39	0.75 / 0.63	0.89 / 0.86
0.5	0.76 / –	0.58 / 0.35	0.63 / 0.41	0.85 / 0.66	0.92 / 0.89
1.0	0.80 / –	0.61 / 0.38	0.65 / 0.43	0.89 / 0.70	0.94 / 0.92
5.0	0.85 / –	0.64 / 0.40	0.68 / 0.45	– / –	1.0 / 0.95

Note: the numerator is the freeze-proof factor of the sample kept in air at 21ºC for 90 days; the denominator is the freeze-proof factor of the sample tested 6 days after its production.

If the temperature is below 20ºC, the values of the freeze-proof factor increase for all deformation frequencies. When the temperature goes down, the tendency to increase the freeze-proof value is common. Below zero, the values of the freeze-proof factor become so high that it is impossible to evaluate a destructive effect of an FTC because asphalt concrete becomes brittle. Therefore, it is necessary to choose the optimal intermediate temperatures to determine the freeze-proof factor.

Temperatures of 18–20ºC are usually the basic temperatures used to compare asphalt concrete mechanical properties in various countries [7, 18, 19]. The results of this research indicate that the range 0–20ºC [2] is optimal. Hence, we can suppose that a more objective temperature is the spring temperature, which is used for the calculation of road structures [3]. Temperature can change depending on a climatic region. The problem is whether this range is optimal for all bituminous consistencies. To determine the freeze-proof factor temperature, it is necessary to collect data for various types of asphalt concrete.

As per the data in Table 2, the frequency and temperature dependences of the freeze-proof factor are identical. When a deformation frequency within a given temperature range increases, freeze-proof factor values go up in a way that agrees with the equivalence principle of the effects of deformation frequency and temperature [20]. Close values of the freeze-proof factor can be obtained at low or high temperatures and frequencies. For example, at a temperature of 0ºC and frequency of 0.01 Hz, on the one hand, and a temperature of 20ºC and frequency of 5 Hz, on the other, the freeze-proof factors are identical (0.63 and 0.64). They are also equal to 0.35 at 15ºC and 0.01 Hz and at 20ºC and 0.5 Hz. This correspondence might be true in the transitional section of the generalised time–temperature dependence of moduli where the effects of temperature and frequency are maximal. Naturally, this is less obvious in gently sloping sections of the generalised dependence of elastic moduli at the lowest temperature and the highest frequency [14, 21]. According to [3], the recommended frequency to determine fatigue and an elastic modulus has to be sufficiently low. Table 2 illustrates this tendency.

An FTC and rest directly influence linear asphalt concrete behaviour. The linear stress limit (Figure 1) reduces after 50 FTCs and rises after rest. However, it remains lower than the initial value. This agrees with the conclusion in [4] about the accumulation of defects each season after FTCs. According to [10], a critical amount of FTCs worsens indirect tension strength by more than 50%. This happens after several hundred FTCs. A critical amount of FTCs depends on the characteristics of cycles, and asphalt concrete composition, structure, and properties.

If frost resistance characterizes asphalt concrete damageability, according to [1, 2, 3] the factors of damage can be adhesion disturbance, cohesion deterioration due to reverse emulsification, or microdisturbances of bitumen film integrity due to mechanic and hydraulic impact. Such defects can be cured at ambient temperature.

Accordingly, additional tests were done to age the asphalt concrete which had preliminarily undergone 50 FTCs at 21ºC for 12 days and then at 30ºC for 10 days. The results (Table 3) indicate considerable growth of the freeze-proof factor as duration and temperature increase with ageing. After the first ageing (12 days), the freeze-proof factor, which is measured at 20ºC, increases by 1.7–2.1 and the freeze-proof factor, which is measured at 0ºC, increases by 1.25–1.33. After additional rest for 10 days at 30ºC, they again increased by 1.18–1.28 times at 20ºC. The freeze-proof factor increases if temperature reduces at a certain frequency and if a deformation frequency increases at given temperatures. The increase of moduli can level out after rest when a frequency rises and temperature decreases.

Table 3. Impact of rest duration and temperature on the freeze-proof factor

Test temperature, ºC	Deformation frequency, Hz	Values of elastic modulus and freeze-proof factor			
		Elastic modulus before FTC, MPa	Freeze-proof factor after 50 FTCs	Freeze-proof factor after a 12-day rest at 21ºC	Freeze-proof factor after a 12-day rest at 21ºC and a 10-day rest at 30ºC
20	0.01	2340	0.27	0.56	0.72
	0.1	3470	0.30	0.58	0.76
	0.5	4790	0.35	0.62	0.78
	1.0	5250	0.38	0.67	0.80
	5.0	6920	0.40	0.68	0.80
0	0.01	6600	0.60	0.76	0.80
	0.1	9330	0.63	0.80	0.83
	0.5	11430	0.66	0.84	0.87
	1.0	13180	0.70	0.88	0.92
	5.0	14790	0.72	0.90	0.92

2.4. Impact of binder consistency on asphalt concrete frost resistance

Asphalt concrete robustness is considerably influenced by the contact zone of the adhesive type and the binder film integrity on the surface of rock materials which differ in nature and size. Therefore, asphalt concrete frost resistance is determined by the set of binder properties: consistency, adhesion and cohesion, elasticity and wetting ability at technological temperatures. That is why the investigations primarily considered bitumen consistency. Bitumen with penetrations of 72 dmm and 115 dmm was used (Table 1).

The elastic moduli values of asphalt concrete that has more elastic bitumen (P_{25} =72 dmm) in the given temperature range 0–20ºC and frequencies 0.01–5 Hz are 1.3–1.9 times higher than those of asphalt concrete that has elastic bitumen (P_{25} =115 dmm) (Table 4).

Table 4. Freeze-proof factors of asphalt concrete for different consistencies of bitumen

Frequency, Hz	Freeze-proof factors at temperatures, ºC		
	20	10	0
0.01	0.73 / 0.37	0.76 / 0.45	0.78 / 0.50
0.05	0.78 / 0.40	0.83 / 0.50	0.80 / 0.54
0.1	0.8 / 0.43	0.85 / 0.53	0.85 / 0.56
0.5	0.86 / 0.47	0.88 / 0.57	0.91 / 0.60
1	0.88 / 0.50	0.94 / 0.59	0.91 / 0.63
5	0.95 / 0.52	0.98 / 0.64	0.98 / 0.66

Note: the numerator is the freeze-proof factor of asphalt concrete with bitumen of P_{25} =72 dmm; the denominator – P_{25} = 115 dmm.

The freeze-proof factor, as in previous cases, increases depending on frequency and temperature. The difference between the freeze-proof factors of asphalt concrete containing these two bitumen samples slightly decreases as temperature decreases. The frequency has less influence on it (Table 4).

The ratio of the elastic moduli of asphalt concrete containing different consistencies of bitumen is lower before an FTC than after it. The ratio of the freeze-proof factors of asphalt concrete containing different consistencies of bitumen at 20ºC is 1.8–2.0, at 10ºC is 1.5–1.7, and at 0ºC is 1.4–1.6; i.e., it goes down as temperature decreases and frequency increases. This confirms the idea of the expediency of slow loading during testing at temperatures when winter is over, as mentioned in [3]. The data in Table 4 also confirm the expediency of the application of extra hard asphalt concrete to increase frost resistance.

2.5. Impact of modified bitumen on asphalt concrete frost resistance

To assess the impact of polymer-modified bitumen, a binder, made by introducing 6% polymer into the bitumen with a penetration of 72 dmm, was used (Table 1). As a result, the elastic moduli values at 20ºC double at a frequency of 0.1 Hz and increase 1.45 times at a frequency of 5 Hz. At a temperature of 10ºC these ratios are 1.3 and 1.5, respectively. At a temperature of 0ºC the elastic moduli are practically identical.

The tendency to level the elastic moduli of the asphalt concrete containing basic bitumen and a binder that is modified by a large amount of polymer is shown in [22]. The tendency is less obvious if the basic bitumen is more viscous.

The freeze-proof factors of the asphalt concrete with either a basic binder or a polymer-modified binder follow the tendency mentioned; i.e., they increase if temperature goes down and frequency goes up (Table 5). A difference in the freeze-proof factors of the two types of asphalt concrete is lower than a difference in the penetration of the binders per se. A considerable advantage of polymer-modified asphalt concrete is evident at a minimum frequency.

Table 5. Freeze-proof factors of asphalt concrete containing either basic bitumen or polymer modified bitumen

Frequency, Hz	Freeze-proof factor at a temperature of, ºC		
	20	10	0
0.01	0.73 / 0.80	0.76 / 0.83	0.78 / 0.84
0.05	0.78 / 0.83	0.83 / 0.86	0.80 / 0.90
0.1	0.80 / 0.86	0.85 / 0.89	0.85 / 0.93
0.5	0.86 / 0.87	0.88 / 0.92	0.91 / 0.97
1	0.88 / 0.89	0.94 / 0.95	0.91 / 0.98
5	0.95 / 0.91	0.97 / 0.95	0.98 / 0.99

Note: the numerator is the freeze-proof factor of asphalt concrete on basic bitumen; the denominator is one of asphalt concrete on bitumen containing a 6% polymer.

The data in Table 5 can be considered as a data of a search experiment. If a large amount of polymer is used, the optimum content of polymer-modified bitumen in the mixture is higher in comparison with pure bitumen, and mixing and compaction temperatures are higher. We can assume that the effectiveness of polymer is more obvious if a basic binder consists of bitumen with a lower consistency (higher penetration).

CONCLUSIONS

1. A non-destructive method to determine the asphalt concrete freeze-proof factor is proposed based on the temperature–frequency dependence of complex moduli that correspond to the linear region of viscoelastic asphalt concrete behaviour. This method enables us to determine the freeze-proof factors of the same sample and excludes bias caused by heterogeneity of different samples.

2. Freeze-proof factor values, which are determined using temperature–frequency dependence, increase if deformation frequencies rise and temperature decreases. The same is true for elastic moduli.

3. The asphalt concrete freeze-proof factor depends on test conditions. Its value increases as the time span between the completion of test sample moulding and the start of the freeze–thaw test increases. The freeze-proof factor can increase after the previous test if the time span before the previous and following tests increases and ambient temperature contributes to curing the defects which came into existence in the course of previous FTCs. The results of this research show that a temperature of 10–20ºC or estimated spring temperature in a region can be used to assess frost resistance. The same is true about normalisation of FTCs.

4. The increase in the freeze-proof factor over time after producing asphalt concrete in laboratory conditions enables us to assume that the placement and consolidation of an asphalt concrete coating should not be made during autumn or winter. In addition, if road coatings are designed, it is expedient to use a coefficient that takes into consideration the decrease of asphalt concrete bearing resistance due to the damaging effect of the FTC.

5. Tests of asphalt concrete containing various consistencies of bitumen and bitumen–polymer binders indicate that more solid bitumen and polymer-modified bitumen considerably improve asphalt bitumen frost resistance.

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