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Asphalt Mixtures and Flexible Pavement Construction Degradation Considering Different Environmental Factors

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Abstract: Water, frost, and road salt are counted as environmental factors. They affect the pavement structure, particularly during the winter or in regions located above sea level. In the article, a literature review related to water, frost, and road salt impacts was performed. The main problem of evaluating asphalt mixture degradation and its influence on pavement fatigue life via environmental factors was stated. Four types of asphalt concrete (AC22) road mixes were prepared for laboratory tests. They differed in production technology and the type of binder applied. One binder content level was tested. To investigate the impact of water, frost, and road salt on mineral-asphalt mixtures utilized in flexible constructions, two proprietary experimental methods were applied. Methods allowed for determining the mixtures' degradation level using the measured stiffness modulus in the 4-PB-PR test. Based on the obtained results, it was found that both interactions cause a significant decrease in the value of the stiffness modulus. In the article, a degradation ratio was proposed. The ratio expressed the impact of water, frost, and road salt on the stiffness mix variability. Its value was considered for pavement fatigue life based on the AASHTO 2004 fatigue criterion. The article demonstrates that the type of binder used influences the mix's resistance to water, frost, or road salt impact. The highest resistance was reached by a mixture with highly modified asphalt (hot technology), and the worst was with asphalt WMA (warm technology). It has also been proven that the impact of water, frost, or road salt on pavement fatigue life is significant. The drop was significant, amounting to a few dozen percent. It was stated that environmental impacts (such as water, frost, or road salt) should be considered in asphalt mixture and pavement construction design.

Keywords: environmental factors; road salt; water and frost; degradation; mineral asphalt mix; pavement fatigue life; stiffness modulus

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1. Introduction

Over the winter, the layers of the pavement structure are exposed to various environmental factors: heavy rainfall, snowfall, and temperature variability (alternating freezing and thawing of rainwater). Unfavorable environmental conditions force road services to take decisive action to ensure the safety of vehicle traffic on the road. To improve the traffic conditions on the road, various chemicals or their mixtures are used. Road salt, sodium chloride (NaCl), is the very effective agent used in winter maintenance [1]. Road salt is an agent used for the removal of snow and ice from roads [2]. It is used commonly due to its effectiveness and price. The first recorded use of salt was on New Hampshire roads (USA) in the winter of 1938. Since then, sodium chloride has become a popular agent to reduce slipperiness all over the world [3]. From the first use of salt to the present day, there has been a significant increase in its usage (20 million tons of salt per year are used on American roads during the winter) [4–6].

In many European countries, including Poland, road salt is commonly used. Road salt is a mixture of sodium chloride (approx. 96% NaCl), calcium chloride (approx. 2.5% $CaCl_2$), and approximately 0.2% anti-caking agent (potassium ferrocyanide, $K_4[Fe(CN)_6]$).

The additive prevents the formation of salt lumps due to improper storage conditions or excessive exposure to moisture.

Road salt for winter road maintenance is mostly used in three different forms: dry material, its solution (brine), or its mixture (wet salt). Dry salt is directly sprinkled on the pavement surface at [g/m^2]. The brine solution should have a strictly defined concentration. Considering the interior regulations of different countries, its value could vary between 20 and 25%. The wet salt for sprinkling should contain 30% brine with a concentration of 20–25% and 70% dry salt. The amount of the agents used, the form, and the concentration of the solution are determined depending on the recorded issue (frost, black ice, or permafrost) and the prevailing temperature [7–10]. The increased salt usage is causing the rapid and effective melting of ice and snow at temperatures even below 10 °C [6,7,10]. However, while applying salt for winter maintenance is effective, it should be remembered that maintenance procedures require cyclical repetition depending on the prevailing conditions. This fact, in turn, results in the accumulation of the applied chemicals in the road lane.

Pavement structure deterioration is a complex problem. In addition to mechanical factors (loads from the vehicle wheels), environmental impacts are also significant: water, frost, and road salt, which could degrade the utilized material. The change from the liquid state of water to a solid could cause the formation of various types of damage, such as cracks. Road salts could cause the same issues. Although road salt improves traffic safety conditions, it may affect the strength properties of the pavement. It may have an impact on the surface course as well as deeper layers.

The impact of road salt on the pavement may be different. It could take place, for example, through a chemical reaction (enthalpy changes), the direct interaction of solution ions on the structure's material over time, or through the freezing and thawing of the reacted solution. It is difficult to indicate which impact interacts with the material the most. Each of them occurs during winter road maintenance. The influence of salt on the strength and durability of asphalt mixtures and pavements is new and deserves a deeper investigation.

Rainwater as well as brine solutions may penetrate the structure in five different ways.

1. As a result of the aerosol dispersion of saltwater droplets in the air by passing vehicles and its deposition on other areas of the road, including those that were not covered with salt.
2. Through surface damage, e.g., fatigue cracks caused by operation (mainly top-down, including imperceptible microcracks), the mixture penetrates the cracks "by gravity" and by pressure injection caused by the movement of the vehicle wheel.
3. The specificity of the region and its climatic conditions. Roads in coastal areas are constantly subjected to the impact of salt on the surface (not just during the winter when maintenance measures are implemented). Salt could enter the inside of a vehicle through tire contact with a damaged surface.
4. Vehicle traffic is permitted on the milled wearing and binder course during the winter pavement reconstruction. Then, the solution penetrates directly into the upper part of the base course, and additionally, as a result of pressure and friction from the wheels of vehicles.
5. As a result of leakiness between the layers, inappropriate road shoulder conditions, or constructing errors.

It is worth mentioning that material degradation caused by the effects of water, frost, and salt may also have an impact on fatigue life. Although these impacts are seasonal, they could accumulate through all years of the construction's use, reducing its durability.

Water and frost impact problems on asphalt mixtures (MMA, or "mineral asphalt mixes") are not a new topic at all. Many publications present the negative influence of this factor. Nevertheless, the influence of water and frost on MMA has not been effectively studied so far to take into account the durability of the designed mixtures and structures.

A similar situation applies to the impact of road salt. On the one hand, road salt degradation is a new topic that has not been explored due to material changes that affect strength and durability. On the other hand, it has been repeatedly proven that salt usage is effective in winter maintenance, while simultaneously signaling that road salt usage might cause some issues.

The negative impact of environmental factors (freeze-thaw or road salt) on MMA and pavement is discussed in the manuscript based on observed issues.

1.1. Water and Frost Impact

The effect of water and frost on mixtures has been studied since the 1930s [11]. Initially, water impact analysis on aggregate and asphalt-coated aggregate was investigated. For this purpose, various experimental studies were made, including the use of the static water bath or bottle method. It was only at the turn of the 1980s that key publications focusing on the impact of water and frost on mineral asphalt mixes appeared.

The first key studies were performed between 1980 and 2004 [12–14] by Lottman, Said, and others. The authors performed laboratory-field tests using the static indirect tensile test (ITT) to evaluate the impact of water and freeze on different MMA types. Most of the tests performed were focused on the comparison between the test method used (ITT vs. Marshall stability), the set of samples (wet and dry), the additives used in the mix composition (rubber), or several freeze-thaw cycles applied. The mixes used in the tests were made from fine aggregate and soft (and very soft) common road asphalt.

Subsequently, between 2004 and 2015, significant studies related to water-frost impact in asphalt mixtures were published [11,15–17]. The authors investigated the effect of various freezing and thawing cycle configurations (for example, ref, after: 6, 12, 18, 24 cycles) on Marshall stability and attempted to compare the results to the ITT test. Furthermore, it was noticed that for the first time, a low-cycle dynamic indirect tensile test (ITFT) was used to assess the water and frost impact on asphalt mixtures. The authors performed research related to method usage, the impact of additives like basalt fibers on MMA water and frost resistance, the influence of adhesive chemicals, and different configurations of freeze-thaw cycles. Most of this research was performed on asphalt mixes consisting of the fine or dense graded mineral mix (AC 25P) and common road asphalt (like 60/80).

Following that, between 2015 and 2020, articles on the freeze-thaw impact on asphalt mixtures were published [18–21]. The authors focused on the effectiveness of the ITT and ITFT tests for water and frost MMA resistance. Asphalt mixtures contained both common road (like 50/70) and modified road (like 45/80-55) asphalt. It was proven that mixtures containing polymer in the asphalt matrix could not be successfully tested by the ITT test [20]. Various combinations of the applied freeze-thaw cycle were also investigated. Moreover, water and frost MMA resistance tests (using the ITT test) were performed on asphalt mixes made in warm mix technology (WMA) and compared with reference mixes in hot technology (HMA) [18]. Furthermore, for the first time, a four-point bending (4-PB) test was applied to investigate the water-frost impact on fine-graded asphalt mixtures (binder and common road asphalt 50/70). The durability decreased by more than twice as much as the reference set [21].

Thereafter, between 2020 and 2022, some key articles [22–24] were published according to the effectiveness of ITT and ITFT test usage (water and frost impact and MMA resistance). Preformed tests were related to asphalt mixtures containing various additives: chemical (e.g., Zycotherm, Evotherm), organic (e.g., Sasobit), on the characteristics of mixes produced in the WMA technology, or other additives inside the hot technology (e.g., steel fibers). It was demonstrated that the use of appropriate additives enabled mixture production in WMA technology, but this significantly reduced the material's resistance to water and frost (even by approximately 68.5%). Moreover, tests were performed using various combinations of freeze-thaw cycles. In the previously mentioned articles, AC13 and AC16 mixes were mostly used.

According to key articles, critical guidelines [25,26] concerning the research and requirements for newly designed asphalt mixtures were published. The full procedure of testing MMA resistance to water and frost using the ITT test and the ISTR ratio was included and described.

Nowadays, these guidelines have become a reference for how to test and determine the required minimum resistance to water and frost impact for designed and utilized asphalt mixtures. Based on these works, the American standard AASHTO T-283 (2021) [27] was created and is being constantly updated, while in European countries such as Poland, independent guidelines have been developed to adjust the water and frost resistance tests to the respective climatic conditions [28,29].

Indirect tensile static testing is still used today to evaluate MMA resistance to water and frost, but unfortunately, there are no articles related to another test method like the four-point bending test (4-PB), which fairly well approximates in-situ pavement working conditions. Furthermore, there is no complex comparison between different asphalt mixes containing various types of asphalt (common road, modified, and highly modified) or production technology. Moreover, already known tests are only applied to the material; they are not directly included in the design formulas, for flexible or semi-flexible pavement using the fatigue criterion, e.g., AASHTO 2004, in terms of their fatigue lives.

1.2. Road Salt Impact

The first studies related to the applicability of road salt for road surfaces date back to the late 1980s [30]. Susan et al. tried to develop a mathematical model describing the defrosting of an ice-covered pavement surface layer according to the location of the agent used, its temperature, and its amount. Based on the analysis, the authors have proven that sodium chloride is a cheap and effective agent for defrosting large areas in a short time compared to comparable calcium chloride.

Since 1987, no one has investigated the effect of salt on road mixtures. Because of the widespread availability and use of road salt, as well as the relatively low negative effects, there was a lack of interest in negative impact. However, after some severe winters, attention was refocused on treatments and agents supporting the improvement of road traffic safety in snowfall, rain, and frost periods.

The first publications related to the impact of road salt on asphalt mixtures were published between 2002 and 2008 [31–33]. The authors concentrated on various freeze-thaw cycle combinations that took into account the use of de-icing agents (road salt), weight loss measurement through the impact of road salt, and separate freeze-thaw. Experimental methods allowing the detection of chlorides and water in the layers of the pavement structure based on wave measurements were also proposed.

Subsequently, between 2008 and 2015, a few key manuscripts dedicated to the impact of road salt on asphalt mixtures were published [34–36]. Most of them tried to evaluate the influence of various combinations of freeze-thaw cycles with various chemicals (including road salt) using Marshall's stability test. The negative effect of various road salt concentrations (e.g., 3%, 5%, 10%, 15%, and 20%) on the asphalt mixture stiffness determined in a static three-point bending test was also investigated. Furthermore, the road salt solubility depending on various temperature levels was also analyzed.

Afterwards, between 2015 and 2020, absorbing articles [37–40] developing subject areas connected with road salt impact on asphalt mixtures were published. Authors have compared the snow melting effect via various de-icing agents (including salt) between asphalt mixtures and concrete. Moreover, the effectiveness of various de-icing salts (ex. calcium chloride II, magnesium chloride II, and sodium chloride I) was also investigated. Furthermore, a few experimental methods based on specimen mass changes or disturbances in the electromagnetic field were proposed. These methods allowed for the evaluation of the impact of road salt on subgrade and subbase pavement layers, but they had some limitations (salt concentration could not be high due to measurement error).

The following important publications [41–45] on the impact of road salt on asphalt mixtures were published between 2020 and 2022.

Gandara et al. [41] investigated the effect of road salt on the properties and parameters of three different types of bituminous mix combinations: 1: mixes were immersed in a salt solution; 2: aggregate was immersed in a salt solution and then used in the mix; 3: a salt additive was directly added to the mixing process. PA-16 porous asphalt and AC-16 asphalt concrete containing common 50/70 road asphalt were used in the tests. Various salt concentrations of 3.5%, 5%, and 10% were taken into account; the soaking time was 3 days, and the test temperature was 20 °C. The 4-PB method was first used to determine stiffness modulus changes. The fatigue level was also assessed. A similar subject area was analyzed by Zamanillo et al. [42]. The authors have applied different soaking conditions (brine concentration of 5%, temperature as in the previous article, 20 °C, soaking time of 2 days). The ITS method was used to test the stiffness, and the 4PB-PR test was used to determine the fatigue life.

Zhou et al. [43] investigated the effect of water and brine (NaCl, 5 and 10% concentrations; Na2SO4, 5% concentrations) on strength loss (modified asphalt (45, 80, and 55) and fine-graded asphalt mixtures were investigated). The main aim was to check strength variability (by ITT test) through various soaking combinations.

Mączka and Mackiewicz [44] investigated the impact of water and road salt on the degradation of five mixtures (AC 16W 50/70, AC 22 WMS Pmb 25/55-60, and 25/55-80 HIMA). The authors proposed an experimental method of soaking the material and testing it using the 4-PB test. Mass changes and stiffness modulus variability considering various soaking times (for 2 days and 21 days) were studied. Moreover, salt-induced degradation and its penetration into the mixture using X-ray imaging were analyzed and presented.

Feng et al. [45] have summarized the state of the art related to research on road salt. The authors presented various methods of analyzing these issues, ranging from mechanical tests (among which the static ITT or dynamic ITFT indirect tensile test were most often used) to microscope or computer tomograph imaging usage. In the review, the importance of mixture degradation caused by road salt was repeatedly emphasized. Moreover, most of the research has been focused on AC 13 or AC 16 mixes based on soft common road asphalt or modified ones, intended for the surface course or the binding course.

Based on the literature review, it was emphasized that water, frost, and road salt significantly affect asphalt mixtures, causing their degradation. Moreover, it contributes to pavement deterioration.

The conducted literature review revealed that existing articles are related to the assessment of material degradation caused primarily by water and frost, and rarely, road salt. Most of them were performed using indirect tensile tests. In these tests, various combinations of freeze-thaw cycles (water and frost) or soaking in a salt solution for several days (mainly NaCl concentrations of 5, 10, and 15%) were considered. So far, the studies have not analyzed the conditions of de-icing agents' impacts for longer (than 7 days) or higher levels of brine concentrations (especially those that may occur in winter after intensive salting of the pavement, ex. 20% or 25%). In addition, there are a few studies listed using other tests than the indirect tensile test to assess degradation, such as 4-PB-PR (which corresponds with pavement layer behavior under load). So far, no other different levels of soaking temperature in brine have been investigated (other than those resulting from the analogy to the MMA test according to resistance to water and frost). Also, no simulations of solution flow during soaking were seen in the articles. Furthermore, the review demonstrated that, thus far, attention has been paid primarily to mixtures intended primarily for the surface course or binding course of the AC 13 or AC 16 type, containing primarily common 50/70 or occasionally modified 45/80-55 asphalt. There have been no studies concerning coarse-grained mixtures, such as AC-22, intended for the base course or binding course (where the degradation caused by water, frost, or salt may also occur). In addition, there are no articles that comprehensively address the topic of asphalt mix degradation caused by environmental factors based on different types of asphalt and technologies (ex. HMA and WMA). Moreover, there is a lack of articles that consider environmental factors' impact on mix and pavement construction durability.

Because of the aforementioned issues, the authors looked into the effects of water, frost, and road salt on the degradation of various mineral-asphalt mixtures. The article's investigation considered the different types of asphalt and production technology. The primary goal was to determine material degradation using the 4-PB test while taking environmental conditions for Polish roads into account. Measured test data was commented on, re-used, and applied to FEM modeling to estimate changes in pavement fatigue life based on fatigue criteria. The proprietary procedure used allowed for the differentiation of which mix and separate construction is more or less resistant to environmental factors.

2. Materials and Methods

Four road mixes, AC 22 asphalt concrete, intended for the binding and base course layers of flexible construction, were designed. The only difference between the mixtures was the type of asphalt applied. The mineral mix curve was identical. The stone material came from the same source. The asphalt binder was selected based on a similar penetration index and usage frequency in road construction. Assumptions applied allowed to analyze, compare, and take into account both variables: the type of binder and the technology of production (hot HMA and warm WMA among mixes). Table 1 shows the material composition for experimental tests involving water, frost, and road salt impacts.

Table 1. Mineral asphalt mix composition.

Mix Type	Mix Destination	Mineral Mix Composition	Binder Type	Binder Content
AC 22	binder course base course	16/22 gabbro grit–31.0% 11/16 gabbro grit–7.0% 8/11 gabbro grit–10.0% 4/8 gabbro grit–10.0% 2/5 gabbro grit–16.0% 0/2 gabbro crushed sand–18.0% 0/1 milled stone extender–8.0%	35/50 WMA (common road asphalt) 35/50 (common road asphalt) 25/55–60 (modified asphalt, polymer SBS) 25/55–80 HIMA (highly modified asphalt, polymer SBS)	1 identical level was analyzed for each binder type: 3.82%

The designed mix recipes' usefulness was checked in accordance with the requirements included in the regulation on Polish roads, taking into account the EN standards [28,29,46–48]. All mixtures met the basic requirements.

Prepared recipes and materials were named according to the following convention, referring to mixture and recipe:

- A4–mix containing 35/50 WMA binder (warm technology),
- B4–mix containing 35/50 binder (hot technology),
- C4–mix containing 25/55–60 binder (hot technology),
- D4–mix containing 25/55–80 HIMA binder (hot technology).

Prismatic beams with dimensions of 65 × 65 × 390 mm were prepared for the tests. Each side of the samples was polished. The prepared mixtures were appropriately selected to create 3 sets of samples per mixture and asphalt level: reference (ref), subjected to the effects of water and frost (f-t), and road salt (rs). Each set was made up of six beams with similar stiffness modulus.

The tests were carried out using the 4-PB-PR stiffness modulus test [49]. The general stiffness modulus test parameters were emphasized in Table 2.

Table 2. General stiffness test conditions.

Test Condition	Property	References
static diagram	4-PB-PR	PN-EN 13108-1:2016-07 [47] PN-EN 13108-20:2016-07 [48] WT-2 [29] Mackiewicz [50]
load diagram	cyclically determined	
load cycle type	oscillatory cycle	
impulsive load shape	sinusoidal	
load condition	controlled displacement	
frequency	constant, 10.0 Hz	
temperature	constant, 10.0 °C	PN-EN 13108-1:2016-07 [47] PN-EN 13108-20:2016-07 [48] WT-2 [29] Sybilski [51] Judycki [52] Pszczoła [53] Leszczyńska [54] Haponiuk [55] Mączka [56]

The tests were performed in a modern, specialized hydraulic strength press dedicated to asphalt mixtures, the "*Dynamic Testing System 130 kN (DTS 130 kN)*", made by Pavetest industry. The device is equipped with a climatic chamber, a mounting frame (4-PB), a digital controller (maintaining the set test parameters in real-time), and appropriate sensors, e.g., displacement, temperature, and force. The machine and a sample on the test stand are presented in Figure 1.

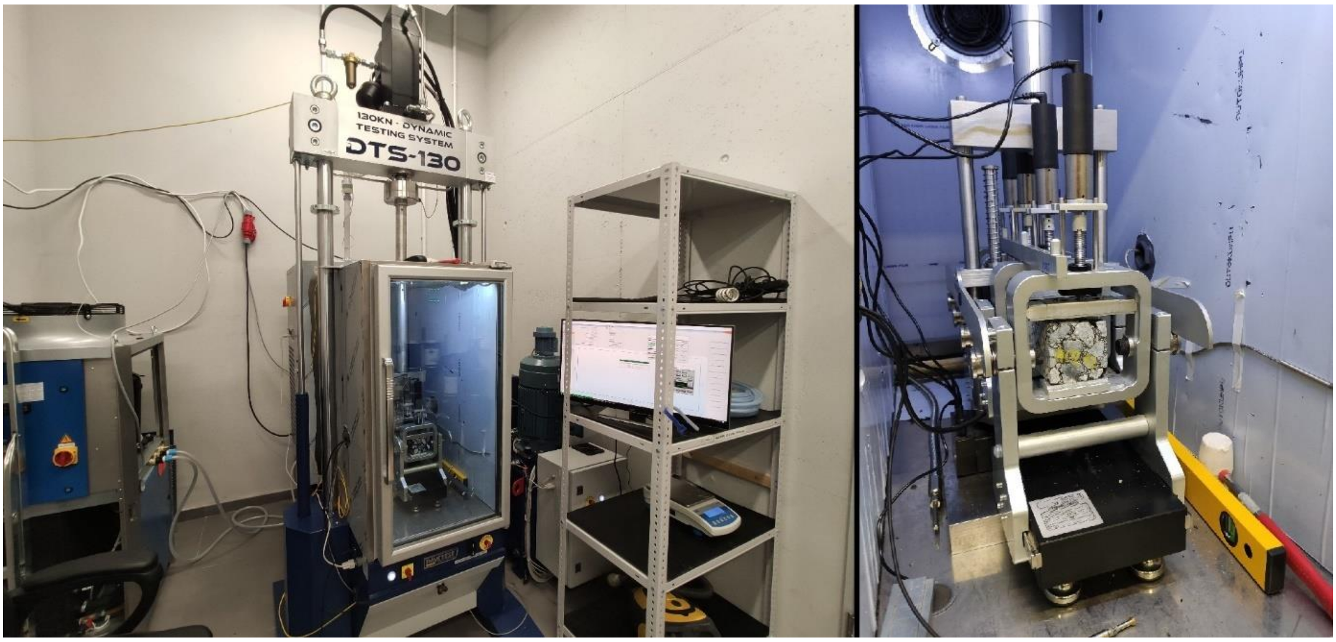


Figure 1. Hydraulic test machine.

To investigate the degradation of mixtures caused by the influence of water, frost, and road salt, environmental variables simulating in-situ conditions were used in the study. The research was carried out using two proprietary experimental research methods.

2.1. Water and Frost Impact–Freeze-Thaw Cycle

The first experimental method was related to water and frost impact. The proprietary method in the test mechanism was applied. It was based on the ITSR described in the Polish standard WT-2 [29] and the American standard AASHTO T-283 2021 [27]. The dynamic 4-PB test was used for testing, instead of the static ITT test. Some test assumptions were also modified. Its appliance made it possible to effectively study water and frost impacts. They include, among others:

- the beams were fully soaked in water; the vacuum suction procedure was skipped. Marshall samples required such treatment due to the external surface and numerous pores,
- the container with water and specimens was located directly in the thermal chamber, which allowed for programming the temperature ramp and full automation of the whole conditioning process. Initially, for 72.0 h, the samples were conditioned at 40.0 °C, and then, for 24.0 h, they were frozen at (−) 18.0 °C, considering the time to reach this temperature,
- the impact was assessed based on changes in the stiffness modulus; its value was examined before and after water and frost treatment,
- the target test temperature was 10.0 °C instead of 25.0 °C,
- due to the polished surfaces of the beams, the method D (geometric measurements) was used to determine the bulk density of the samples; in this case, it was recognized as effective [28],
- after defrosting and reaching the test temperature, the samples were removed from the container, and successively, using a dry microfiber cloth (good absorbency), the top layer of water was partially dried, and finally, the test was carried out (it was assumed that the preparation process did not exceed a minute).

Figure 2 depicts the camber view to water and frost impact tests.

Figure 2. Camber view: water-frost impact.

2.2. Road Salt Impact: Brine Soaking

The second experimental method was related to the study of the impact of road salt on asphalt mixes. There are currently no developed test procedures for evaluating the impact of road salt on MMA and its durability. The subject matter is relatively new.

The mixtures, which formed into prismatic beams, were placed in a closed container with a maximum capacity of 130 L. Inside the container, four independent water pumps were mounted on its walls (resistant to water and salt corrosion), with an average pumping capacity of 7500 L/h, forcing a fixed solution circulation. The application of these devices was aimed at two crucial aspects:

- the brine concentration was constant and well distributed all over the container (no local concentration points),
- forced circulation causes the cyclical solution pressure on the material, an approximate approximation of in-situ conditions where the vehicle wheel forces the brine mixture into the road material under pressure.

Moreover, the temperature sensors were installed in five places near the bottom of the container. It made it possible to track temperature changes via the whole soaking process. The entire set was placed in a thermal chamber. The brine-soaked prismatic samples were immersed to a depth of about 18 cm. The scheme of the experiment and the test stand at the stage of soaking the samples, as presented in Figures 3 and 4.

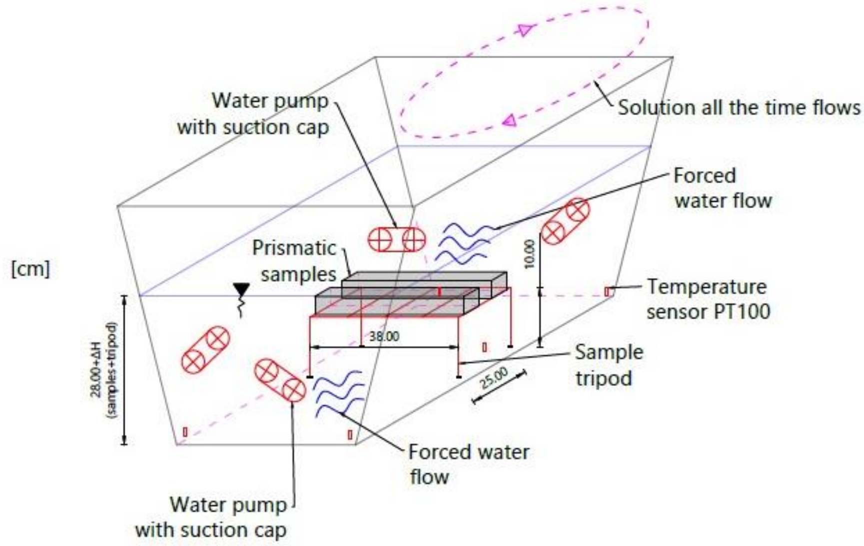


Figure 3. Experimental brine soaking pattern.

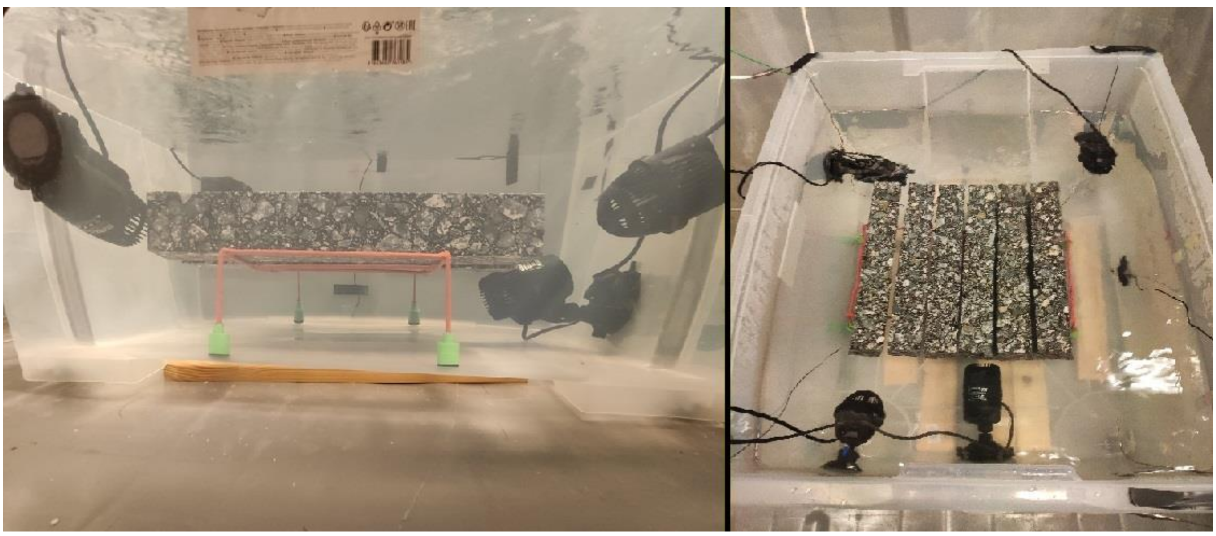


Figure 4. Armed container before the road salt dosage.

Following brine conditioning, commercially available BIO-WAY road salt containing an anti-caking agent was applied. The brine solution concentration was equal to 20.0%. The amount of road salt was estimated based on Formula (1).

$$C_p \to m_s = \frac{C_p \cdot m_w}{100\% - C_p} \quad (1)$$

where:

C_p—percentage concentration [%],

m_s—substance mass [g],

m_w—water mass [g].

The road salt was applied to a container containing prismatic samples and water. A temperature drop amounting to about 2.5 °C was noticed. The final conditioning temperature was 10.0 ± 0.2 degrees Celsius. The prismatic beams selected for the tests were soaked for 2 weeks. After soaking, the samples were partially dried with a microfiber cloth and tested immediately. The brine soaking process was repeated several times because the container was not able to contain all the samples selected for testing at once. The salt applied and the view of the brine system are presented in Figure 5.

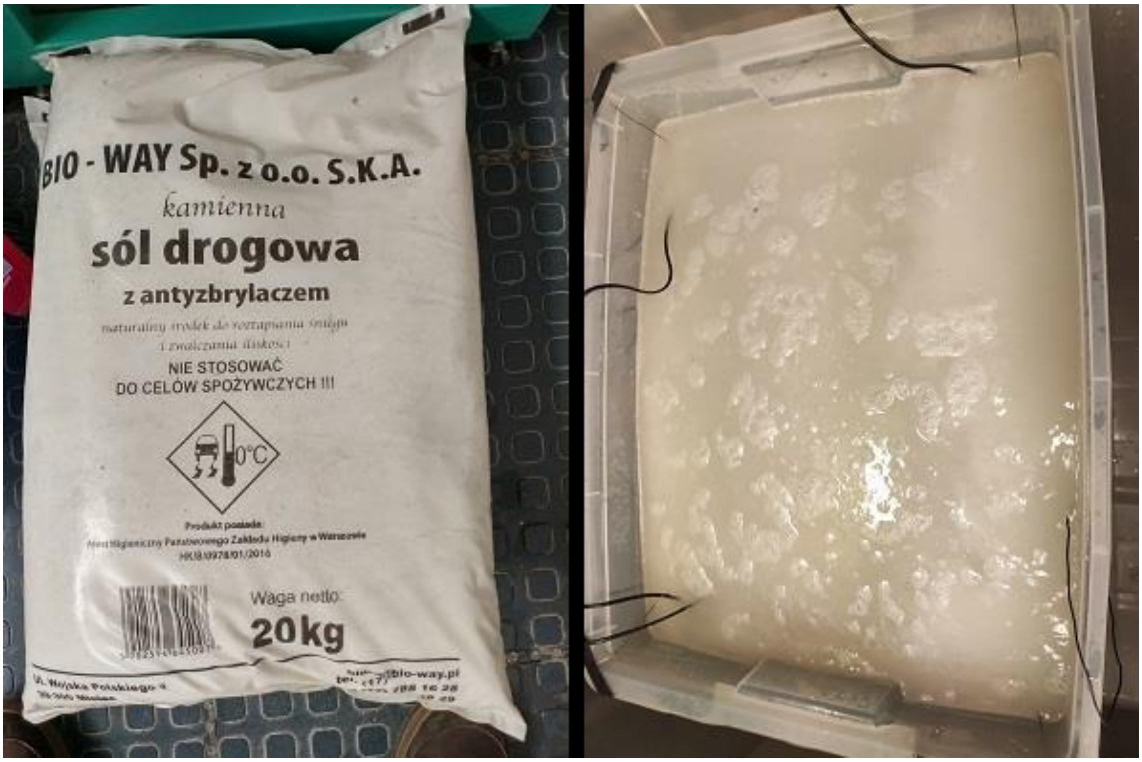


Figure 5. Road salt used in the experiment and brine solution.

The following rules adopted in the research experimental method were established based on the phenomena occurring in winter and the basic test practices applied in European countries like Poland.

A temperature of 10 °C for the brine solution was assumed to determine the road salt impact. It is one of the equivalent temperatures in Poland that can be used in the design of flexible pavement structures [51,52]. Moreover, this temperature level is commonly used in stiffness and fatigue life tests of most mixtures in accordance with Polish national guidelines or PN-EN standards [29,47–49].

The 20% brine concentration is used as a compromise between saturated and unsaturated solutions, which could affect pavement construction. Full saturation or oversaturation of the top layers of the pavement is also possible. This situation would occur with a thin layer of snow or ice and a frequent sprinkling of salt on the surface. It should be mentioned that the road salt impact will be lower for deeper mixes utilized in pavement construction. Moreover, the whole construction is tight, up until the moment when some issues happen (cracking, deterioration observed). The applied concentration should be interpreted as salt accumulation affecting the material over the entire design period, e.g., 20 years (this is an assumption by analogy to single freeze-thaw cycle usage in the ITSR test).

The task of water pumps with a flow of 7500 L/h was to simulate the impact of variable snow-ice-salt environmental conditions related to the interaction of vehicle wheels.

The proposed experimental method successfully determined the effect of road salt on stiffness modulus variability in tested MMA.

It should be clearly emphasized that before the water, frost, and road salt impact implementation on the appropriate sample sets, each of them was previously tested and the stiffness modulus value was determined. Then appropriate conditioning was implemented, and the stiffness modulus value was re-examined. Due to the following methodology, the degradation expressed by changing the stiffness modulus, which is a material parameter, was effectively assessed.

3. Results

3.1. Laboratory Test Results

The stiffness modulus was estimated based on the PN-EN 12697-26:2018-08 test [49], considering the previously described assumptions. The applied strain amplitude was 50 με. The peak-to-peak value was 100 με. The stiffness modulus was established in the 100-test cycle. The results were recorded in real-time using the Testlab software. An exemplary result was presented in Figure 6.

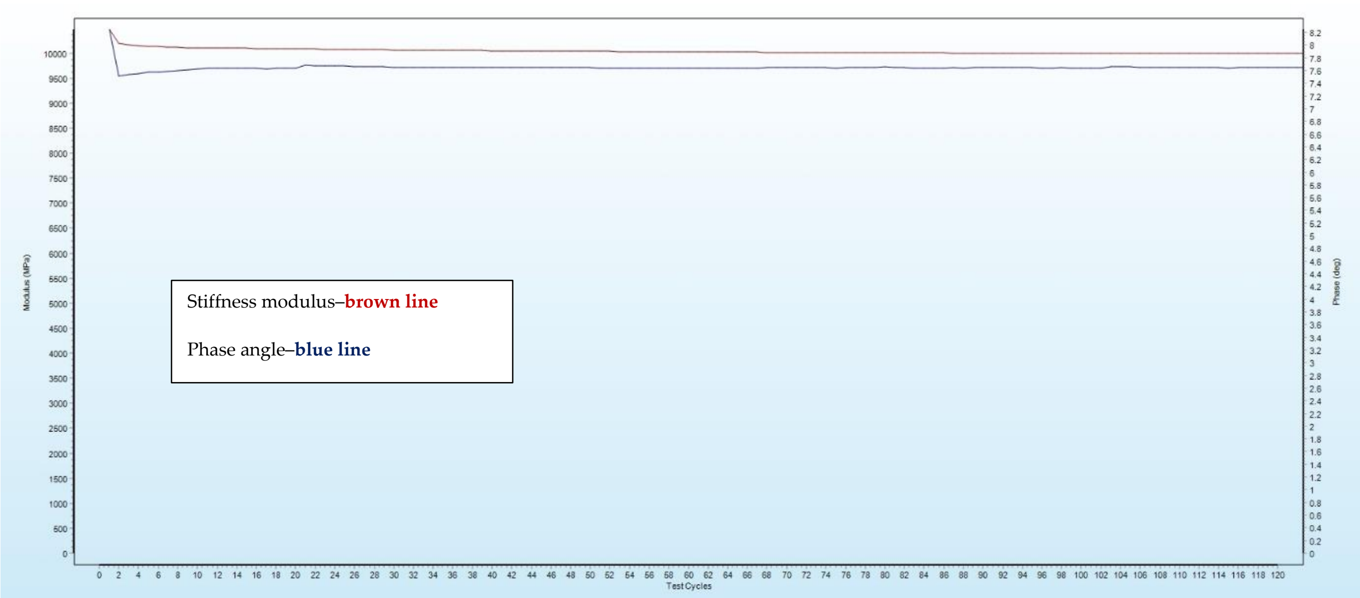


Figure 6. Sample result registered by testlab software.

Based on the test results, a degradation index was developed. It expresses a change in the stiffness modulus caused by an appropriate impact, such as water, frost, or road salt. The ratio made it easier to analyze asphalt mixture degradation caused by water, frost, and road salt impact. The formula was presented in the Equation (2).

$$DI_{(S)} = \left(\frac{E^*_{0,2}}{E^*_{0,1}} - 1 \right) \cdot 100\% \tag{2}$$

where:

$DI_{(S)}$—degradation ratio expressed by the change in the stiffness modulus of the mixture [%],

$E^*_{0,\,1}$ —stiffness modulus value before the corresponding impact (fresh) [MPa],

$E^*_{0,2}$ —stiffness modulus value after the corresponding impact (degradated) [MPa].

Test results due to the excessive data amount are presented and discussed as an average of at least 5 markings (independently tested beams) per each mix recipe. The dispersion of the results (expressed by the classical coefficient of variation), considering the specificity of the method used (the four-point bending test (4-PB)), was very low—it did not exceed 5%. Data was featured in Table 3.

Table 3. Comprehensive test results.

Mix	Binder Type	V_b [%]	V_m [%]	Variant	$E^*_{0,1}$ [MPa]	$E^*_{0,2}$ [MPa]	$DI_{(S)}$ [%]
A4	35/50 WMA	3.82%	6.22%	**ref**	9987	9987	
				f-t	9948	8468	**−14.87%**
				rs	9400	8274	**−11.99%**
B4	35/50	3.82%	5.00%	**ref**	10,136	10,136	
				f-t	10,096	8684	**−13.99%**
				rs	10,614	10,099	**−4.85%**
C4	25/55-60	3.82%	5.59%	**ref**	9927	9927	
				f-t	9016	8137	**−9.74%**
				rs	9535	9007	**−5.54%**
D4	25/55-80 HIMA	3.82%	5.77%	**ref**	9836	9836	
				f-t	10,166	9438	**−7.16%**
				rs	10,141	9720	**−4.15%**

The following symbols are used in Table 3:
ref—reference set,
f-t—set impacted by water and frost,
rs—set impacted by road salt,
V_b—percentage of binder content added to MMA (by weight) [%],
V_m—air void content in MMA [%],
$E^*_{0,1}$—stiffness modulus value before the corresponding impact (fresh) [MPa],
$E^*_{0,2}$—stiffness modulus value after the corresponding impact (degradated) [MPa],
$DI_{(S)}$—degradation ratio expressed by the change in the stiffness modulus of the mixture [%].

Four-point bending (4-PB-PR) test results (Table 3) expose the degradation of various asphalt mixtures caused by freeze-thaw and road salt impact. Only the binder type and production technology differentiated the mixes. At first glance, the material appeared to have a significant environmental impact. Results were discussed in a further part of the manuscript.

3.2. Pavement Fatigue Life under Environmental Conditions

To investigate the impact of water, frost, or road salt on the selected construction fatigue life, FEM modeling was performed considering the degradation index value. Based on the catalog solutions and modeling tips [46], a typical flexible pavement construction for heavy traffic in the KR-5 traffic category was applied. Construction consisted of 3 layers made from MMA and soil subgrade, characterized by the following thicknesses and parameters:

- surface course (thickness: 4.0 cm, stiffness modulus-7300 MPa, Poisson's ratio-0.30),
- binding course (thickness: 8.0 cm, stiffness modulus-10,300 MPa, Poisson's ratio-0.30),
- base course (thickness: 18.0 cm, stiffness modulus-9800 MPa, Poisson's ratio-0.30),
- subgrade (thickness: 2.0 m assumed, secondary module-120 MPa, Poisson's ratio-0.35.

The durability of the pavement structure was determined using the AASHTO 2004 fatigue criterion in accordance with Formula (3). Fatigue damage equal to the occurrence of 5% of alligator cracks was assumed in the calculations.

$$N_f = D_{FC} \cdot 7.3557 \cdot 10^{-6} \cdot C \cdot k' \cdot \left(\frac{1}{\varepsilon_t}\right)^{3.9492} \cdot \left(\frac{1}{E_0^*}\right)^{1.281} \quad (3)$$

where:

D_{FC}–fatigue damage, taking into account asphalt layer thickness and the assumed percentage value of alligator cracks [-],

N_f–number of repetitive loads until fatigue cracks occur [repetitive loads],

C–volumetric properties MMA coefficient [-],

k'–calibration factor, depending on the asphalt layers thickness and the type of the cracks (down-top) [-],

ε_t–critical tensile strain level in pavement asphalt layers [-],

E_0^*–asphalt layer stiffness modulus [MPa].

To determine the durability of the structure using the criterion, modeling was carried out in the Abaqus program using the finite element method (FEM). An elastic model of the layered half-space, commonly used for dimensioning flexible and semi-rigid pavement constructions, was used. General assumptions based on catalog data [46] were made for modeling related to the load level (57.5 kN per wheel and 115 kN per axle (EU standard)), shape and application surface, and layer-to-layer interaction. Assumptions were presented in Table 4. The designed 3D model and the mesh view were presented in Figures 7 and 8.

Table 4. General hints and assumptions used in FEM modeling.

	Value
Force shape	circle
Radius [m]	0.1368
Contact area [m^2]	0.0588
Contact pressure [kPa]	977.5
Layer-to-layer interaction	full

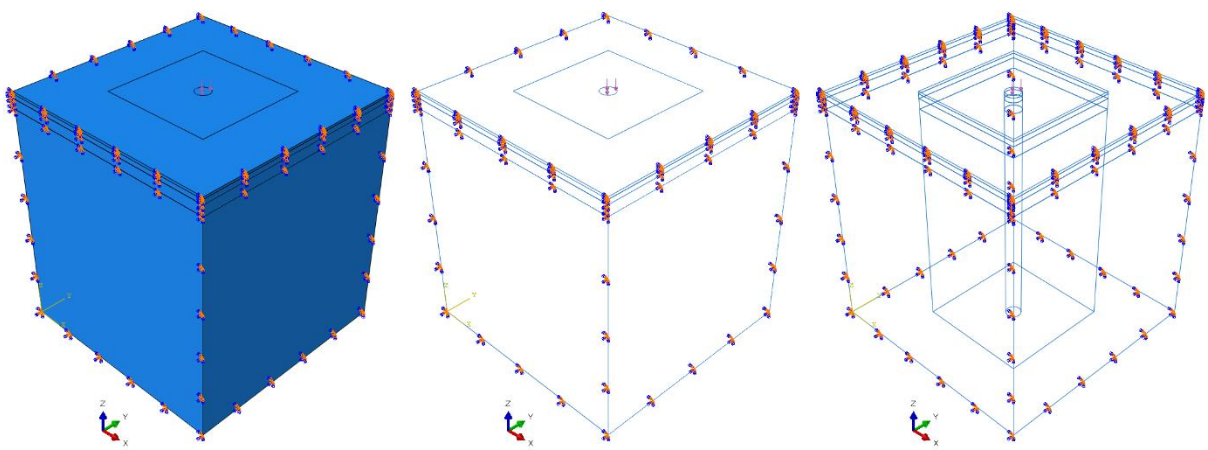


Figure 7. Model 3D in Abaqus.

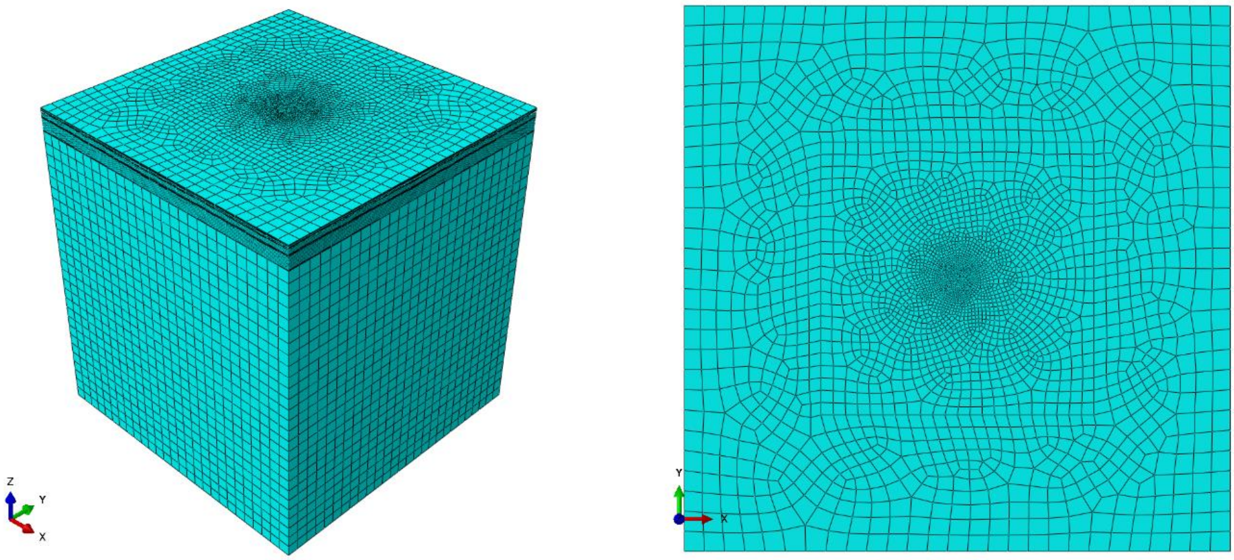


Figure 8. Mesh in designed model.

For pavement fatigue life analysis employing the criterion, 12 models were made in the Abaqus program for 4 mixes differing in the type of asphalt and the impact case (reference model, model considering degradation caused by water, frost, or road salt).

The investigation was carried out on the previously analyzed level of binder content in mixtures A4, B4, C4, and D4 equal to $V_b = 3.82\%$. It is a value that corresponds to the binder level content commonly used in mixtures dedicated to this type of pavement construction (binding and base course layers). For the calculations, the same level of void content in mixtures, equal to $V_m = 6.2\%$, was assumed. In this way, among others: imperfections resulting from compaction on the construction site, the low temperature of the utilized mixes, and the air void content test results of the A4, B4, C4, and D4 mixtures were considered.

Referring to the adopted layer's parameters, in order to take into account the degradation caused by water and frost or road salt, the previously calculated degradation ratio $DI_{(S)}$ was used. It was assumed that the value determined for the tested mixtures would evenly degrade all pavement asphalt layers in the same way. Furthermore, estimated values represent the total degradation result for the entire useful life duration of the pavement. The assumption can also be interpreted as the average value of degradation that will occur in the entire package of asphalt layers, which would be determined by the base course layer mixes. Another reasonable interpretation is that degradation determined on base course mixes with a lower binder content and harder asphalt affects roughly the same as degradation determined on binding and surface course mixes with a higher asphalt content and softer asphalt.

The degradation index was used to convert the adopted layers' stiffness modulus for KR5 flexible pavement construction. To calculate the pavement durability based on the fatigue criterion, the highest tensile strain level value at the bottom of the base course layer was identified. The obtained data were summarized in Table 5.

Table 5. Degradation assumptions and modeling results.

Traffic Category	Mix	Variant	Layer	Thickness [m]	Raw Layer Stiffness Modulus [MPa]	Poisson Coefficient [-]	$DI_{(S)}$[%]	Layer Stiffness after Degradation [MPa]	Max. Micro-Strain Level [-]
KR5	A4	**ref**	surface course	0.04	7300	0.30			**−40.67**
		ref	intermediate course	0.08	10,300	0.30			**6.297**
		ref	base course	0.18	9800	0.30			**59.17**
		ref	subgrade	4.00	120	0.35			**3.161**
		f-t	surface course	0.04	7300	0.30	−14.87%	6214	**−46.38**
		f-t	intermediate course	0.08	10300	0.30	−14.87%	8768	**7.794**
		f-t	base course	0.18	9800	0.30	−14.87%	8342	**67.45**
		f-t	subgrade	4.00	120	0.35			**3.408**
		rs	surface course	0.04	7300	0.30	−11.99%	6425	**−45.14**
		rs	intermediate course	0.08	10300	0.30	−11.99%	9066	**7.459**
		rs	base course	0.18	9800	0.30	−11.99%	8625	**65.65**
		rs	subgrade	4.00	120	0.35			**3.357**
	B4	**ref**	surface course	0.04	7300	0.30			**−40.67**
		ref	intermediate course	0.08	10,300	0.30			**6.297**
		ref	base course	0.18	9800	0.30			**59.17**
		ref	subgrade	4.00	120	0.35			**3.161**
		f-t	surface course	0.04	7300	0.30	−13.99%	6279	**−46.05**
		f-t	intermediate course	0.08	10,300	0.30	−13.99%	8859	**7.688**
		f-t	base course	0.18	9800	0.30	−13.99%	8429	**66.89**
		f-t	subgrade	4.00	120	0.35			**3.393**
		rs	surface course	0.04	7300	0.30	−4.85%	6946	**−42.36**
		rs	intermediate course	0.08	10,300	0.30	−4.85%	9800	**6.728**
		rs	base course	0.18	9800	0.30	−4.85%	9324	**61.62**
		rs	subgrade	4.00	120	0.35			**3.238**
	C4	**ref**	surface course	0.04	7300	0.30			**−40.67**
		ref	intermediate course	0.08	10,300	0.30			**6.297**
		ref	base course	0.18	9800	0.30			**59.17**
		ref	subgrade	4.00	120	0.35			**3.161**
		f-t	surface course	0.04	7300	0.30	−9.74%	6589	**−44.23**
		f-t	intermediate course	0.08	10,300	0.30	−9.74%	9297	**7.214**
		f-t	base course	0.18	9800	0.30	−9.74%	8845	**64.33**
		f-t	subgrade	4.00	120	0.35			**33.19**
		rs	surface course	0.04	7300	0.30	−5.54%	6896	**−42.61**
		rs	intermediate course	0.08	10,300	0.30	−5.54%	9729	**6.791**
		rs	base course	0.18	9800	0.30	−5.54%	9257	**61.99**
		rs	subgrade	4.00	120	0.35			**3.249**
	D4	**ref**	surface course	0.04	7300	0.30			**−40.67**
		ref	intermediate course	0.08	10,300	0.30			**6.297**
		ref	base course	0.18	9800	0.30			**59.17**
		ref	subgrade	4.00	120	0.35			**3.161**

Table 5. *Cont.*

Traffic Category	Mix	Variant	Layer	Thickness [m]	Raw Layer Stiffness Modulus [MPa]	Poisson Coefficient [-]	$DI_{(S)}$[%]	Layer Stiffness after Degradation [MPa]	Max. Micro-Strain Level [-]
		f-t	surface course	0.04	7300	0.30	−7.16%	6777	**−43.22**
		f-t	intermediate course	0.08	10,300	0.30	−7.16%	9562	**6.949**
		f-t	base course	0.18	9800	0.30	−7.16%	9098	**62.87**
		f-t	subgrade	4.00	120	0.35			**3.276**
		rs	surface course	0.04	7300	0.30	−4.15%	6997	**−42.11**
		rs	intermediate course	0.08	10,300	0.30	−4.15%	9872	**6.661**
		rs	base course	0.18	9800	0.30	−4.15%	9393	**61.26**
		rs	subgrade	4.00	120	0.35			**3.227**

The following symbols are used in Table 5:
ref¯reference set,
f-t¯set impacted by water and frost,
rs¯set impacted by road salt,
$DI_{(S)}$¯degradation ratio expressed by the change in the stiffness modulus of the mixture [%].

Pavement structure durability was calculated using the pavement fatigue life criterion, taking into account degradation $DI_{(S)}$ (water and freeze, as well as road salt impact). The results were presented in Table 6.

Table 6. Variability in pavement fatigue life due to water, frost, and road salt degradation.

Mix	Binder Type	$V_{b,vol}$ [%]	$V_{m,vol}$ [%]	Variant	$DI_{(S)}$ [%]	$E^*_{0,3}$ [MPa]	$\mu\varepsilon$ [-]	N_f [mln Rep. Loads]	ΔN_f [mln Rep. Loads]	ΔN_f [%]	DI_r [-]	Fatigue Life Trend Regarding to Reference
AC22	35/50 WMA	9.6%	6.2%	**ref**	**0.0%**	9800	59.17	**17.6**				
				f-t	**−14.9%**	8342	67.45	**12.9**	**−4.7**	**−26.7%**	**1.80**	**decrease**
				rs	**−12.0%**	8625	65.65	**13.8**	**−3.9**	**−21.9%**	**1.83**	**decrease**
	35/50	9.8%	6.2%	**ref**	**0.0%**	9800	59.17	**18.2**				
				f-t	**−14.0%**	8429	66.89	**13.6**	**−4.6**	**−25.3%**	**1.81**	**decrease**
				rs	**−4.9%**	9324	61.62	**16.5**	**−1.7**	**−9.2%**	**1.89**	**decrease**
	25/55-60	9.7%	6.2%	**ref**	**0.0%**	9800	59.17	**18.0**				
				f-t	**−9.7%**	8845	64.33	**14.8**	**−3.3**	**−18.0%**	**1.85**	**decrease**
				rs	**−5.5%**	9257	61.99	**16.1**	**−1.9**	**−10.5%**	**1.89**	**decrease**
	25/55-80 HIMA	9.7%	6.2%	**ref**	**0.0%**	9800	59.17	**18.0**				
				f-t	**−7.2%**	9098	62.87	**15.6**	**−2.4**	**−13.4%**	**1.88**	**decrease**
				rs	**−4.2%**	9393	61.26	**16.6**	**−1.4**	**−7.9%**	**1.91**	**decrease**

The following symbols are used in Table 6:
ref—reference set,
f-t—set impacted by water and frost,
r_s—set impacted by road salt,
$V_{b,vol}$—binder content in the mixture (by volume),
$V_{m,vol}$—air void content in the mixture (by volume),
$DI_{(S)}$—degradation ratio expressed by the change in the stiffness modulus of the mixture [%],
$E^*_{0,3}$ —base course stiffness modulus [MPa],
N_f—pavement fatigue life [million repetitive loads],
ΔN_f—pavement fatigue life variability in relation to the reference [million repetitive loads],
ΔN_f—percentage pavement fatigue life variability in relation to the reference [%],
DI_r—pavement fatigue life variability ratio expressed as a $\frac{\Delta N_f}{DI_{(S)}}$ (material stiffness change comparison with pavement fatigue life) [-].

Modeling results (Table 6) expose the durability decrease of four flexible pavements with traffic category KR-5 caused by environmental degradation. Impacts (road salt and water frost) were investigated separately. Environmental impacts caused a significant decrease in the fatigue life of selected pavements. Results were discussed in a further part of the manuscript.

4. Discussion of the Results

The article focused on the significant problem of the impact of water, frost, and road salt on asphalt mixtures. Two proprietary experimental research methods using the dynamic 4-PB test were presented. The methods used allowed one to effectively determine the material degradation caused by water, frost, or road salt through the stiffness modulus variability. Four types of mixtures, differing only in the type of binder and technology, were prepared for the research. One identical level of binder content was analyzed. Based on the obtained results, a degradation ratio was developed. Its value made it easier to assess and analyze the degradation caused by environmental factors in the mixtures. Moreover, the degradation ratio was applied in the modeling section. Its value was proposed to recalculate the stiffness modulus for each asphalt layer chosen in flexible pavement construction. Considering the degradation ratio for all investigated pavement constructions, the pavement fatigue life was determined. The 2004 AASHTO criterion was used.

According to the results obtained in the previous sections, the Sections 3.1 and 3.2 results discussion part was divided into two sub-sections: asphalt mixture degradation and pavement durability.

4.1. Asphalt Mixture Degradation

According to test results presented in Table 3, eight major observations related to asphalt mixture degradation were listed.

1. Water and frost impact implication reduced the stiffness modulus of all mixes; the material was degraded. The degradation ratio value shown in Figure 9 is relatively high; the decrease in the value of the stiffness modulus was even about 15%. The same observations involved road salt impact, which negatively affected mixture stiffness; the degradation ratio was equal to about 12%. The degradation caused by water, frost, or road salt depends on the type of asphalt used.

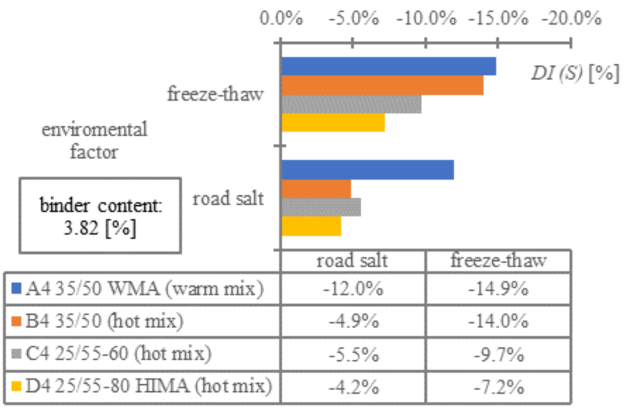


Figure 9. Asphalt mixtures degradation caused by environmental factors.

2. According to Figure 9, the mixture based on highly modified asphalt D4 showed the lowest sensitivity to water and frost impact. Mix is one of the most resistant among all the respondents. Stiffness decreased by 7.2%. The C4 material with modified binder demonstrated comparable resistance, with a 9.7% decrease. In the case of common asphalts, the greater susceptibility of mixtures to degradation caused by water and frost is observed. The B4 mixture performs worse than C4 but better than A4. MMA

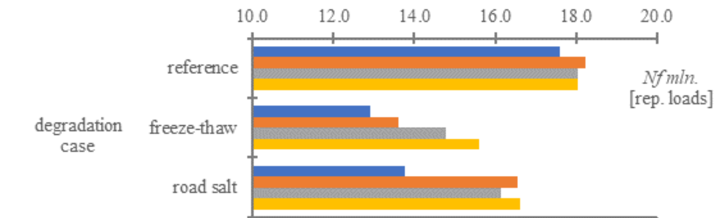
(B4): stiffness decreased by 14.0%, and (A4): stiffness decreased by as much as 14.9%. The A4 mix was the worst. It was found that the mixture of A4 and B4 at lower binder levels might show insufficient resistance to the effects of water and frost in in-situ conditions. The probable consequence of warm mix A4 application is the premature exhaustion of the construction durability, which will result in numerous issues (e.g., cracks or chipping).

3. Comparing the B4-D4 mixtures considering hot technology (Figure 9), due to water and frost impacts, the ones with the matrix modification with the SBS polymer are unmatched. The material degradation ratio $DI_{(S)}$ was approximately two times lower (for D4 with HIMA) compared to MMA based on common road asphalts (B4). The mixtures C4 and D4 were more resistant than B4. The use of SBS polymer to modify the asphalt matrix greatly increases the mixture's resistance to water and frost impact.
4. Comparing the mixtures made in the warm WMA (A4) and hot (B4) technologies (Figure 9), mixture B4 is less sensitive to water and frost impact than A4 by about 6.2%. Hot technology mixes could provide better resistance to water and frost impacts.
5. According to Figure 9, the mixture based on highly modified asphalt D4 marked the lowest sensitivity to road salt and was the most resistant. The stiffness modulus decreased only by 4.15%. The C4 mix based on a modified binder resulted in similar resistance—a decrease of 5.54%. In the case of common road asphalts, a greater decrease in the modulus value is observed. Mixture B4 was even better than C4; the degradation ratio was about 0.6% lower. It was caused by a lower amount of air-void content. Mix B4 is definitely better than A4. MMA (B4): stiffness decreased by 4.85%, and (A4): stiffness decreased by 11.99%. It has been found that mixes of A4 with lower levels of binder content might exhibit insufficient in-situ resistance to road salt impact. The probable consequence of warm mix A4 application is the premature exhaustion of the construction's durability, which will result in numerous issues, such as cracks or chipping. Occurrences will be more severe, especially when two factors (water and frost + road salt) interact.
6. Comparing the B4 and D4 mixtures inside the hot technology (Figure 9), due to the road salt impact, all the mixtures resulted in similar vulnerability; the degradation is about 5%. Still, the D4 mixture with highly modified asphalt is better than C4 and B4.
7. When comparing the mixtures made in the warm WMA (A4) and hot B4 technologies (Figure 9), the hot one is clearly more resistant to road salt, up to 147%. Hot technology mixes could provide better resistance to road salt impact. Furthermore, the additives used for WMA asphalt (which help decrease production temperature) probably contributed to the mixture's increased susceptibility to road salt impact. It is stated that the tested A4 mixture in warm technology is very sensitive to road salt impact. WMA mixes should be avoided in areas where road maintenance will be frequent during the winter. Similarly, it is not recommended to use this type of mixture in coastal regions, where the salt effect is year-round.

4.2. Pavement Durability

Based on the results presented in Table 6, seven of the most important observations were listed.

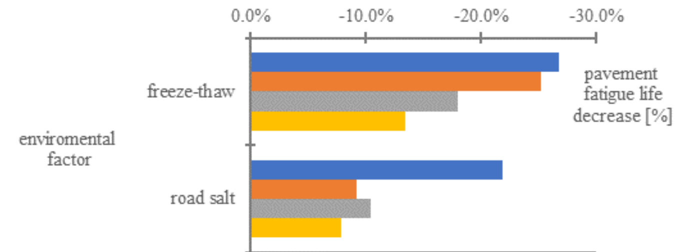
1. Analyzing the pavement fatigue life using the AASHTO criteria could cause a significant underestimation of the results when asphalt mixes are utilized in construction containing polymer asphalts (modified and highly modified). The fatigue life of such mixtures in the laboratory is definitely higher than that of those based on common asphalt [56,57]. Binder usage affects not only the mix but also the entire structure's durability. Modeling results emphasizing the mentioned problem according to tests are presented in Figure 10. Obtained results also confirm that relying only on the stiffness modulus, horizontal tensile strain level, and volumetric parameters of the mixture in its current form is insufficient, and this problem should be examined.



	road salt	freeze-thaw	reference
A - common road asphalts WMA (warm mixes)	13.8	12.9	17.6
B - common road asphalts (hot mixes)	16.5	13.6	18.2
C - modified asphalts (SBS) (hot mixes)	16.1	14.8	18.0
D - highly modified asphalts (SBS) (hot mixes)	16.6	15.6	18.0

Figure 10. KR5 typical flexible pavement fatigue life variability caused by water, frost, or road salt.

2. All pavement constructions' fatigue lives were decreased by water and frost and, in turn, by the independent road salt impact (implemented value). Moreover, water and frost impacts caused a higher decrease in fatigue life than road salt, regardless of the type of binder used in construction. The degradation level (fatigue life reduction) was presented in Figure 11.

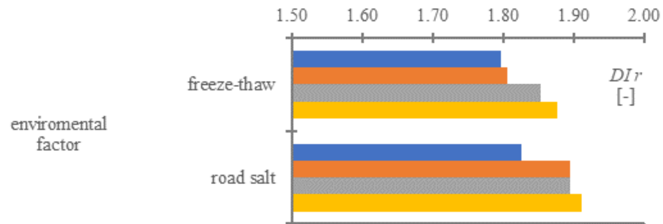


	road salt	freeze-thaw
A - common road asphalts WMA (warm mixes)	-21.9%	-26.7%
B - common road asphalts (hot mixes)	-9.2%	-25.3%
C - modified asphalts (SBS) (hot mixes)	-10.5%	-18.0%
D - highly modified asphalts (SBS) (hot mixes)	-7.9%	-13.4%

Figure 11. The impact of road salt, water, and frost on pavement reduces its fatigue life.

3. The degradation caused by road salt impact caused a smaller (from 18 to 63%) decrease in the pavement fatigue life than water and frost impact (Figure 11). The changes depended on the type of binder and air void content in the designed mixture.
4. The pavement construction degradation caused by water, frost, or salt is significant and should be considered in the mix design and pavement fatigue criteria. The decrease in the fatigue life of the structure ranged from 7.9% to as much as 26.7% (Figure 11).
5. The pavement consisting of highly modified asphalt (25/55-80 HIMA) turned out to be up to 2.00 times more resistant to water and frost impact and 2.77 times more resistant to road salt impact than pavement with common road asphalt in warm technology (35/50 WMA) (Figure 11). It is stated that mixtures based on polymer-modified bitumen ensure higher durability (environmental resilience) and should be used in constructions subjected to difficult environmental and traffic conditions.
6. Pavement mixes made with warm technology can be up to 2.38 times less resistant to environmental factors such as road salt than those made with hot technology. The effect of the discussed susceptibility might be more frequent damage occurrences (Figure 11) to the structure and its shorter durability. It is not recommended to use mixtures in warm technology, e.g., for roads built in coastal regions, where the impact of salt on the pavement structure occurs throughout the year.
7. The pavement fatigue life decrease ratio (DI_r), referring to the tested mixes' degradation, is at a similar level, regardless of the impact (water and frost as well as road

salt) and the type of binder. Its values were exposed in Figure 12. Values fluctuated between 1.80 and 1.91. This could mean that the stiffness modulus mixture decrease causes an almost two-fold decrease in the fatigue life of the pavement structure. It is stated that the value of this index might help to perform durability analysis of similar pavement constructions in a simplified way (the entire pavement construction durability decrease ΔN_f is equal to ~1.85 $\Delta DI_{(S)}$ for the analyzed environmental factors.



	road salt	freeze-thaw
A - common road asphalts WMA (warm mixes)	1.83	1.80
B - common road asphalts (hot mixes)	1.89	1.81
C - modified asphalts (SBS) (hot mixes)	1.89	1.85
D - highly modified asphalts (SBS) (hot mixes)	1.91	1.88

Figure 12. Degradation ratio (DI r) considering stiffness changes in the mix.

5. Conclusions and Recommendations

In the article, it was proven that degradation caused by environmental impacts is significant and should be considered in asphalt mixture durability. In addition, it was proven that the decrease in pavement fatigue life caused by the action of water and frost, or road salt, is also significant and could even be several dozen percent.

It is worth emphasizing that environmental factors affecting pavement fatigue life (based on fatigue criteria) have not been taken into account so far. The authors proposed some solutions and assumptions about how these environmental impacts could be considered. It is a noteworthy achievement regarding the actual state of knowledge.

Eleven more important conclusions were drawn from the discussed results, which took into account asphalt mixtures and pavement construction modeling separately.

1. Water and frost or road salt impacts caused significant (up to 15%) material degradation. Environmental factors should be considered in asphalt mixture laboratory test procedures (especially fatigue life).
2. The degradation of mixtures caused by environmental factors (water and freeze, road salt) depends on the type of binder used in the mixture and the impact considered.
3. The mixtures containing highly modified 25/55/80 HIMA asphalt, demonstrated the highest (up to 2.88 times higher) resistance to water, frost, and road salt. Modifying the asphalt matrix by adding SBS polymer increases mixture resistance to environmental factors.
4. The presence of temperature-lowering additives (special waxes or chemicals-WMA production technology) in the asphalt matrix increased the mixes' susceptibility to environmental factors.
5. The use of proprietary methods allows for a more comprehensive and straightforward study of the asphalt mixtures considering the environmental impacts–material could be reused for further tests, e.g., fatigue.
6. Increasing SBS polymer content in the asphalt matrix (25/55-60 (C4) vs. 25/55-80 HIMA (D4)) allowed for increasing mix resistance to water, frost, and road salt by up to 36%.
7. Applying the hot technology (in comparison to warm) enabled to increase in mix resistance (up to 2.47 times–B4 vs. A4) to analyzed environmental factors.
8. The developed degradation ratio $DI_{(S)}$ based on stiffness modulus changes in the 4-PB test enables effective analysis of mixture degradation caused by water, frost, and road salt.

9. All the discussed pavement constructions revealed a significant decrease (up to 26%) in durability caused by environmental impacts. Water, frost, or road salt should be also considered in pavement durability.
10. Road salt impact is less destructive (from 18 to 63%) than water and frost impact considering pavement durability.
11. The pavement consisting of highly modified asphalt (25/55-80 HIMA) turned out to be up to 2.00 times more resistant to water and frost impact and up to 2.77 times more resistant to road salt impact. Mixtures based on polymer-modified bitumen should be used in constructions subjected to difficult environmental and traffic conditions.
12. The pavement consisting of WMA asphalt (35/50 WMA) could be up to 2.38 times less resistant to environmental factors than asphalts mixtures made in hot technology. It is not recommended to use mixtures produced in warm technology in areas where road salt usage is frequent or in roads built-in coastal regions where the impact of salt occurs throughout the year.

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