



Section: Roads and Railways

Properties of the recycled base course with respect to the road binder type

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Abstract

This paper presents the results from the tests performed on the recycled base mixes manufactured in cold deep recycling technology with bitumen emulsion and different types of binding agent. Portland cement denoted as CEM I 32.5, lime and the blends of both were used. The mineral mix design was based on the recycled material derived from the local road renovation. The material consisted of recycled bituminous layers and base unbound aggregate. For the purpose of evaluating an influence of the binding agents, the tests were to determine indirect tensile strength (ITS), indirect tensile modulus (S_m) at specific temperatures of 0 °C, 10 °C and 20 °C and water and frost resistance of the recycled base mixes. The results obtained from the tests indicated that the impact of the tested binders on the properties of recycled base varies. In addition, a beneficial influence was observed of a little amount of lime in binder blends on water and frost resistance of the recycled base. The paper provides a preliminary assessment of the amounts recommended for application.

Keywords: Deep cold recycling; binding agents; wather resistance; bitumen emulsion; cement and lime.

Nomenclature

MCE	mineral cement-emulsion mix
V_m	air void content (%)
n_w	absorption
ITS_{DRY}	indirect tensile strength under air-dry conditions at 25 °C
ITS_{WET}	indirect tensile strength after soaking in water at 25 °C
$ITS_{40^\circ C}$	indirect tensile strength at 40 °C
TSR	water resistance indicator (tensile strength ratio)
<i>Greek symbols</i>	
α	significance level
ρ_{dB}	Proctor maximum density of the mineral matrix (Mg/m^3)
ρ_b	volume density of a cement-emulsion mineral mix (Mg/m^3)
ρ_m	density of a cement-emulsion mineral mix (Mg/m^3)

1. Introduction

The technology of cold recycling with bitumen emulsion is used for road rehabilitation and strengthening of the load-carrying capacity of modernised roads. In the process of reconstruction, the damaged structural layers of the pavement are transformed into load-carrying base courses [1], [2]. The advantage of this technology lies in the possible use of lower quality materials provided that the requirements laid down in [3] are met. One of the requirements is that the highest quality Portland cement 325R(N) or 42.5R(N) must be applied with no additions. The performance of different class cements and quicklime with respect to emulsified bitumen recycling has been analysed by many researchers [3–9].

Accordingly, the properties of the recycled base with bitumen emulsion have to be determined in terms of the binders used. Also, the potential they have as a replacement for a high quality Portland cement has to be studied.

2. Subject of the study

The subject of the study was the effect of different binders and their blends (cement, lime and fly ash) on the properties of the mineral cement-emulsion mix MCE, manufactured in the cold recycling technology [3]. The recycled base mix was designed for the fatigue life of 5 500 000 ESAL standard 100kN axle load applications/20 years or to KR4 category (medium/heavy traffic) according to the Polish standard [10]. One mixture was prepared and the binder at varying contents was added (MIX-1 to MIX-7).

2.1. Mineral mix design

The base course mix design assumed using the existing subgrade soil (fine sand 0/2 with 8.6% silt clay fraction), aggregate with continuous grading of 0/32 and reclaimed asphalt. This combination allowed a simulation of the deep cold in-situ recycling process. The sand used corresponded to the soil subbase with a CBR>10% and the aggregate 0/32 corresponded to the aggregate base. The reclaimed asphalt was derived from the damaged bituminous structural layers. The mineral cement-emulsion mix contained 3% cationic slow setting bitumen emulsion C60B10 ZM/R. The type of the emulsion was chosen to the Annex to the Polish standard [11]. Table 1 summarizes the basic physical parameters of the bitumen emulsion.

Table 1. Physical properties of asphalt emulsions

Properties	Units	Emulsion C60B10 ZM/R
Binder content	% (m/m)	60
Mixing stability with cement	g	1.0
0.5 mm sieve residue	% (m/m)	0.04
Efflux time Ø 2 mm at 40OC	s	32
Adhesion to aggregate	%	85
Recycled asphalt penetration	0.1 mm	107
Recycled asphalt softening temperature	OC	45

The road binders in the recycled base were added at a 2.5% level. Table 2 shows percentages of mineral components used. The grading curve for the designed mix is presented in Fig. 1.

Table 2. Mineral mix components

Component	Content (%)
Reclaimed asphalt	48.5
Aggregate 0/32	25.2
Sand 0/2	20.8
Emulsion C60B10ZM/R	3.0
Binder (1-7)	2.5

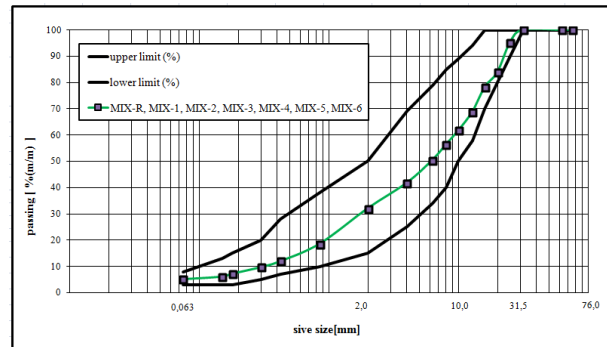


Fig. 1. Design grading curve

The mineral mix was optimized in such a way that the grading curve lies the central part of the good grading range, in between given limits, providing the correct mineral matrix. Obtaining a greater silt clay fraction (less than 0.063 mm) was an additional condition to meet. Its content obtained in the design process was 6.1%.

2.2. Binders

The binders were chosen from among the most common binding agents used in road and building construction (lime, cement) and a mixture of those agents in different proportions with or without an addition of dusts from lime and cement kilns. To determine the impact of hydraulic binders on the properties of the recycled mix, seven different road binders were used, as in Table 3.

Table 3. Binders used in the recycled base

Binder symbol	Description	Mix denotation	Specific surface area – Blaine value (cm ² /g)
"R"	100% CEM I 32.5R	MIX-1	3490
"1"	100% CEM II/B-V 32.5R	MIX-2	4570
"2"	50% CEM I 32.5R + 50% dusts from lime kilns	MIX-3	4210
"3"	50% CEM I 42.5R + 50% dusts from cement kilns (CKD)	MIX-4	5120
"4"	25% CEM I 32.5R + 75% quicklime CaO	MIX-5	6420
"5"	50% CEM I 32.5R + 50% quicklime CaO	MIX-6	5760
"6"	100% quicklime CaO	MIX-7	6510

The choice of the binders was dictated by their availability and common use. Technical requirements [3] forced the use of Portland cement CEM I 32.5R. The mineral cement-emulsion mix prepared to [3] is denoted as reference mix, MIX-R. Multi-component Portland cement with an addition of 21-355 fly ash [12] was used due to its availability and a high demand. All Polish cement plants produce this type of cement (CEM II/B-V 32.5R).

Quicklime was used to ensure coagulation and ion exchange. When the mineral material contains clay parts, quicklime will reduce their negative influence on the properties of the recycled base. The deep cold recycling technique allows using mineral materials with lower parameters [3], [13], [14] and clay parts. Therefore it is necessary to determine the impact of this binder type on the properties of the base course in the cold recycling technique with bitumen emulsion.

Dusts that derive from the cement (CKD) and limekilns are a waste product of cement or lime production. Their utilization is a challenging issue, addressed by many researchers [15–19] dealing with sewage sludge stabilisation. Due to 30–40% CaO content [18], [19], sewage sludge is highly reactive. Too much CaO in the composition of the binder may delay hydration, cause volume change, and ultimately damage the hardened mix [20].

3. Methodology, results and analysis

The aim of this study was to evaluate the impact of hydraulic binders on changes in physical and mechanical properties of the recycled base mix manufactured in the deep cold technique with bitumen emulsion, and to determine its resistance to water (TSR) [3], [13], [21].

To evaluate the impact of the binders on the properties of the mixes, determining the compaction level and air void content (Marshall test) was necessary. The compaction ratio should be $\geq 98\%$ [3], [13] and the air void content should be in the range 5–12% [3]. Ensuring the same level of the air void content in all the recycled base mixes allows obtaining the results that are not burdened with the impact of this parameter variation.

The density of the mineral cement emulsion mix was found with the Proctor method [22], determining the maximum mineral matrix density ρ_{dB} . To find the air void content V_m , first the density of the mix ρ_m was determined [23] and then the void free bulk density ρ_b was established for the mineral mix with different types of binder [24]. The results of determining the compaction ratio and the air void content are summarized in Table 4.

Table 4. Compaction ratio values

Mix number	Proctor density ρ_{dB} (Mg/m ³)	Void free bulk density ρ_b (Mg/m ³)	Density ρ_m (Mg/m ³)	Compaction ratio (%)	Air void content V_m (%)
MIX-R	2.315	2.302	2.548	99.4	9.7
MIX-1	2.312	2.301	2.548	99.5	9.7
MIX-2	2.305	2.295	2.548	99.6	9.9
MIX-3	2.32	2.318	2.548	99.9	9.0
MIX-4	2.282	2.263	2.535	99.2	10.7
MIX-5	2.299	2.282	2.540	99.3	10.1
MIX-6	2.293	2.284	2.529	99.6	9.7

Analysis of the results suggests that similar values of the compaction ratio and the air void content obtained for all the mixes confirm the same level of compression of the mineral constituents in the mixes. The resulting structure allows comparing the air void values and excluding the impact of the reduced load bearing capacity of the air voids. It has to be noted that all the mixes under consideration obtained the values lying within the limits defined by the requirements [3], [13] with respect to the air void content and the compaction ratio.

To confirm the lack of significant differences between the obtained results from the air void content (V_m) tests, a one-way analysis of variance was conducted. The assumed level of significance was $\alpha = 0.1$ [1]. The results of the analysis are shown in Table 5.

Table 5. Impact significance evaluation of mixes (MIX) on V_m of the recycled base

Analysis of Variance	
Variable	Marked effects are significant at $p < .10000$
P-value	
Air void content (V_m)	0.999911

Analysis the significance evaluation implies that from the statistical point of view, in the group of mixes studied there are no significant differences between the means of air void content (V_m). In addition, the p -value=0.999911 is close to 1.0, which means that there are no differences for the studied attribute.

The test program, defining the effect of the hydraulic binder type on the basic parameters of the cold recycled base mix with bitumen emulsion, was designed to determine:

- Absorption
- Indirect tensile strength ITS_{DRY} at 25 °C
- Indirect tensile strength $ITS_{40\text{ °C}}$ at 40 °C
- Indirect tensile strength ITS_{WET} at 25 °C
- Resistance to water TSR
- Indirect tensile stiffness modulus IT-CY at 2 °C, 10 °C and 20 °C

A one-way analysis of variance was used to evaluate the results. Owing to the fact that one of the necessary conditions for using the traditional one-way analysis of variance was not met due to a lack of normal distribution, a non-parametric method was employed, the Kruskal-Wallis one-way analysis of variance [25].

3.1. Absorption

The aim of the study was to evaluate the water absorption of the recycled base with bitumen emulsion. Absorption is a physical property defining the ability of a material to absorb water under standardized conditions. This parameter allows specifying the tightness of a given layer. Higher absorption reduces the migration of water into the recycled base structure. The results of the study are shown in Fig. 2.

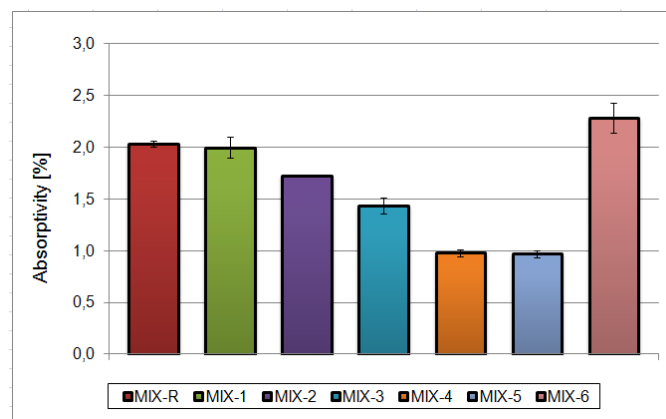


Fig. 2. Absorption of the recycled mixes (error bars denote the standard deviation values)

Analysis of the results leads to the conclusion that the mineral cement emulsion mixes are characterized by homogeneous susceptibility to water. The values obtained lie within the range from 1.0% in the case of MIX-4 and MIX-5 to 2.3% for MIX-6. All the mixes with the cement based binder have lower water susceptibility values than the mix with quicklime. An addition of cement to the binder enhances the hydration process in the water-binder environment and creates the structure that is compact enough to hinder the penetration of water. The mixes with the blend of cement and quicklime (MIX-4 and MIX-5) had the lowest means of susceptibility to water, i.e., 1.0%. The combination of both binders may cause the coagulation of clay particles on the part of quicklime as their water absorption levels are high [26] and it may build a compact internal structure due to cement used.

Relative to the recommended mix, MIX-R, for making of which cement CEM I 32.5R was used, the absorption of mixes MIX-4 and MIX-5 was approximately 1.0% lower. The mix with the quicklime (CaO) had this parameter higher by approximately 0.3%.

The Kruskal-Wallis one-way analysis of variance [25] was used to evaluate the impact of the binder type on the change in the absorption values. The results from the analysis are presented in Table 6.

Table 6. Impact significance evaluation of mixes (MIX) on n_w of the recycled base in the Kruskal-Wallis test

	Multiple Comparisons p values (2-tailed); Nw
Depend.:	Independent (grouping) variable: Type
	Kruskal-Wallis test
	P-value
Absorption (n_w)	0.2488

The non-parametric Kruskal-Wallis test results [25] with p -value = 0.2488 show that there is no evidence of significant differences among the mixes MIX-1 to MIX-7 at the assumed significance level of $\alpha = 0.1$. The results of post-hoc analyses lead to the conclusion that no disparities among the absorption means can be suspected. At a slightly increased probability, 25%, of rejecting the null hypothesis, there are differences within the group of the investigated mixes with respect to water absorption.

3.2. Indirect tensile strength ITS

The indirect tensile strength test is used to define the tensile stresses that occur in the recycled base. The test was performed on the Marshall samples with dimensions and diameters in accordance with PN-EN 12697-23:2004. Non-homogeneous surface of the samples due to unmolding does not affect the results, as proven by [27]. This test was run on three series of samples subjected to different conditioning processes. The first group contained the samples for indirect tensile strength testing at 25 °C. The samples in the second group were cured for 60 minutes at a temperature of 40 °C. The temperature was used as a reference to the maximum temperature existing in the produced base course MCE [1]. The samples in the third group were cured in water for 24 hours at a temperature of 25 °C. The tests complied with the technical requirements laid down in [28]. The test results are summarised in Fig. 3.

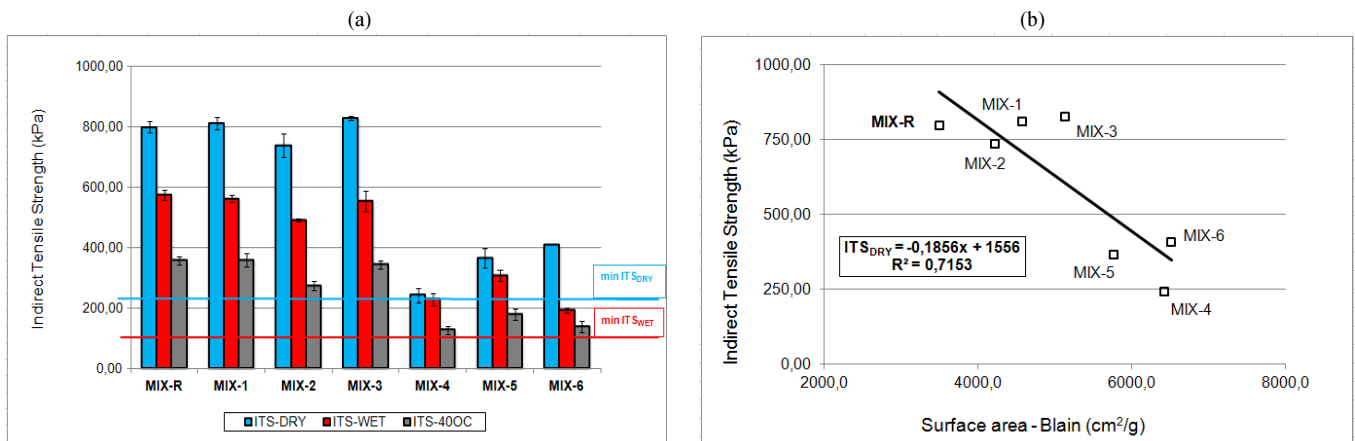


Fig. 3. Indirect tensile strength ITS (a) in relation to binder types (error bars denote the standard deviation) (b) in relation to the specific surface areas of binders

The highest ITS values were obtained for the mixes cured for seven days at a temperature of 25 °C. The tests reported in [7], [21], [29] led to the same conclusion. The guidelines [3], [13] require that the recycled base should have the parameters higher than the minimum parameters of $ITD_{DRY} \geq 225$ kPa and $ITS_{WET} \geq 100$ kPa.

The evaluation of the results indicates that all the mixes MCE met the minimum indirect tensile strength criterion under air-dry conditions, ITS_{DRY} . The maximum value was obtained by MIX-3 (828.95 kPa) with the binder composed on 50% CEM I 42.5R and 50% cement kiln dust (CKD). The high-class cement 42.5R ensures high strength at the initial phase of the test. But it has to be noted that in the case of the recycled base with cement, the behaviour of this layer should be characterised by flexibility. Otherwise, the layer being too stiff may cause damage in the form of reflected cracking.

The evaluation of the indirect tensile strength ITS_{WET} following the curing in water shows that all the samples investigated reached the minimum required strength [13]. The mix with the lowest value of strength was MIX-6 (192.76 kPa), containing quicklime as a binder. With regard to other binders, an addition of cement has a positive effect when the recycled base is subjected to an action of water. This phenomenon may be associated with cement hydration [12] in water during the curing process for the ITS_{WET} test.

The indirect tensile strength test at an increased temperature of 40 °C was carried out to determine the ultimate strengths at maximum temperatures [1] inside the recycled base MCE. The reference criterion for the evaluation of the strength at increased temperature was $ITR_{40OC} \geq 100$ kPa, in accordance with [13]. Based on this criterion, we have to conclude that all the mixes reached the required minimum indirect tensile strength value. The mixes MIX-R (CEM I 32.5R) and MIX-1

(CEM II/B-V 32.5R) had the highest values of $ITR_{40^{\circ}C}$, 360 kPa, containing the cement from a cement production plant. Similar result, 345.06 kPa, was recorded for MIX-3. This result suggests that an addition of 50% cement kiln dust (CKD) with the high-class Portland cement 42.5R does not reduce the strength at elevated temperatures.

Analysis of the indirect tensile strengths ITS_{DRY} and the specific surface area – Blaine presented in Fig. 3b leads to the conclusion that the indirect tensile strength decreases with the increasing specific surface area – Blaine. Fluctuation in test results is 71.5% ($R^2=0.7153$).

To evaluate the significance of impact of the binder type on the variation in the indirect tensile strengths (ITS_{DRY} , ITS_{WET} and $ITS_{40^{\circ}C}$), the one-way analysis of variance Kruskal-Wallis test was used [25]. The results of the tests are shown in Table 7.

Table 7. Impact significance evaluation of the mixes (MIX) on (ITS_{DRY} , ITS_{WET} and $ITS_{40^{\circ}C}$) of the recycled base – Kruskal-Wallis test

Depend.	Multiple Comparisons p values (2-tailed); Nw
	Independent (grouping) variable: Type Kruskal-Wallis test
P-value	
Indirect tensile strength (ITS_{DRY})	0.2046
Indirect tensile strength (ITS_{WET})	0.3207
Indirect tensile strength ($ITS_{40^{\circ}C}$)	0.2694

Based on the results of the non-parametric analysis of variance, we can conclude that at the assumed level of significance $\alpha = 0.1$, there are no statistically significant differences among the mixes MIX-1 to MIX-7. The post-hocs testing of ITS_{DRY} parameters showed that between MIX-5 and MIX-6 the variation is greater than that among other mixes.

3.3. Resistance to water TSR

Water resistance testing was carried out in accordance with the guidelines specified in [28] and previously conducted by [7], [29]. The tests involved determining the decrease in the indirect tensile strength values after the process of curing the recycled base by soaking in water. The tensile strength retained (TSR = Tensile Strength Ratio) is the indirect tensile strength ratio between the soaked and dry samples. The results of the water resistance tests for the samples of recycled base manufactured in deep cold recycling technique with bitumen emulsion in relation to the binder used are shown in Fig. 4.

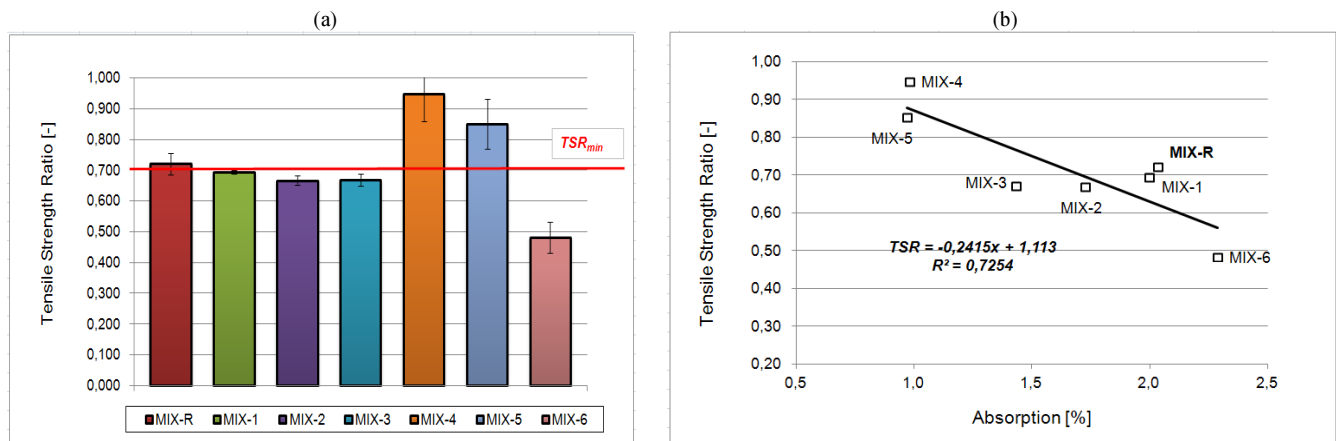


Fig. 4. Water resistance TSR (a) in relation to binder types (error bars denote the standard deviation) (b) in relation to absorption level (n_w)

Analysis of the results from the water resistance tests carried out on the recycled base MCE in terms of the binder type, presented in fig. 6(a) showed that regardless of the proportion used of the individual constituents, the mixes with cement and lime mixture based binders were resistant to the action of water, as required in [13]. The values of TSR for MIX-4 and MIX-5 were 0.95 and 0.85, respectively. The reference mix MIX-R with the recommended in [3] cement CEM I 32.5R obtained the value which although satisfactory is lower than that of the lab-produced binder no. “5” and no. “6” (Table 3).

The lowest resistance to water was recorded for MIX-6 (TSR=0.48), with quicklime used as a binder. The lack of a proper amount of the silt clay part [26] prevented the proper bond between the lime and the mineral components.

Based on the results from the Kruskal-Wallis test [25], for the p-value = 0.3508 and at the assumed level of significance of $\alpha = 0.1$, we found that there is a likelihood that there is no difference between mixes from MIX-1 to MIX-6. The post-hocs tests [25] revealed differences between MIX-4 and MIX-6 at the level of 0.595991.

To illustrate the relationship between the resistance to water and the absorption, Fig. 5 shows a correlation/interdependence of these two characteristics.

Pearson linear correlation results, as presented in fig. 6(b) [30], indicate the water resistance (TSR) relationship with absorption (n_w) defined using a linear function. The variability in the characteristic interdependence results is 72.5% ($R^2 = 0.7254$).

3.4. Stiffness modulus

To evaluate the sensitivity of the recycled base with bitumen emulsion MCE against the binder type used, the IT-CY indirect tensile stiffness modulus method was used, as described in [31]. The tests were carried out at 2 °C, 10 °C and 20 °C. The temperatures were chosen to relate to the base course performance in different seasons [32]. The stiffness modulus means obtained are presented in 6.

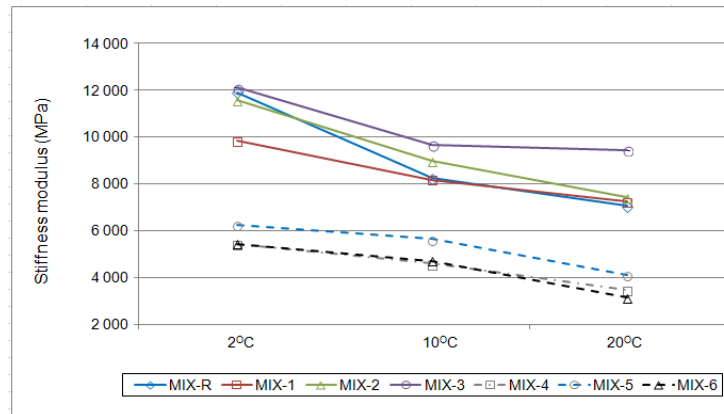


Fig. 6. Dependence of stiffness modulus on the recycled base temperature and binder types used

The spread of the test results shown in Fig. 6 is characteristic. Dashed lines denote the binders containing lime; the solid lines denote the cement based binders. There is an apparent boundary between the mixes. The minimum modulus value at 20 °C for binders with cement is twice as large as the one for the binders with lime. The transfer of the values obtained to real conditions of the recycling technology will prevent the layer made with the mix containing the binder with quicklime from shrinkage cracking while setting. According to the requirements [28] for the recycled mixes (a blend of reclaimed asphalt and crushed stone aggregate), the stiffness modulus at 25 °C should fit the range from 2500MPa to 4000 MPa.

Thus the recycled base courses with binders based on cement have stiffness values much higher than those specified in the requirements.

To evaluate the test results considering the binder types used in the recycled base mix with binder emulsion MCE, the one-way analysis of variance ANOVA [25] was used. Table 8 illustrates the result of the analysis 8.

Table 8. Impact significance evaluation of the mixes (MIX) on V_m of the recycled base.

Variable	Analysis of Variance
	Marked effects are significant at $p < 0,10000$
	P-value
Stiffness modulus (S_m) w + 20°C	0.09529
Stiffness modulus (S_m) w + 10°C	0.04104
Stiffness modulus (S_m) w + 2°C	0.09854

The p-values obtained in the tests for the types of binders used in relation to the recycled base characteristics ($S_{m+20°C}$, $S_{m+10°C}$ and $S_{m+2°C}$) lead to the conclusion that there are at least two groups that vary in a statistically significant way assuming the significance level to be $\alpha = 0.1$, which provides evidence for disparities in the impact of the binder used on the stiffness modulus values obtained.

4. Conclusions

The following conclusions can be drawn from the present study of the recycled base with bitumen emulsion considered in terms the binder type:

- The type of the binder used in the recycled base mineral cement emulsion mix at 2.5% has no effect on the air void content V_m ;
- Mixes produced with the blends of 25% cement and 75% lime as well as those with 50% cement and 50% lime have lower absorption values compared with the reference mix;

- The results obtained from the indirect tensile strength tests, regardless of the method used, indicate that the mineral cement emulsion mixes with cement based binders (MIX-R, MIX-1 and MIX-2) have strength values two times higher than the mixes whose composition contains a blend of cement and lime (MIX-4 do MIX-5) and 100% quicklime MIX-6;
- From the water resistance tests it follows that only MIX-R, MIX-4 and MIX-5 are resistant to water;
- Correlation of absorption (n_w) of the recycled base MCE as well as the decrease in water resistance (TSR) has been explained in 72.5% using a linear function;
- Mixes with cement base binders (MIX-R to MIX-3) have too high stiffness modulus values;
- An increase in the specific surface area – Blaine causes a decrease in the indirect tensile strength;
- The mixes that contain binders resulting from the combination of cement and quicklime have better parameters compared with the reference mix with the recommended cement type CEM I 32.5R.

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