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Research paper

Stiffness modulus prediction against basic physical and mechanical characteristics of recycled base course with foamed bitumen and emulsified bitumen

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Abstract: The paper's objective was to present the results of predicting the stiffness modulus of a recycled mix containing a blended road binder with foamed bitumen and emulsified bitumen. The S_m (acc. to IT-CY) indirect tensile test was used at temperatures of −10°C, +5°C, +13°C and +25°C. Prediction of the stiffness modulus accounted for the effect of temperature, the type of road binders, the sampling location and the type of technology selected. All effects, except temperature, were included in the model by entangling their effects through recycled base course physical and mechanical characteristics, such as indirect tensile strength, compressive strength, creep rate, air void content and moisture resistance. As a result, it was possible to determine a regression model based on multiple regression with a coefficient of determination $R^2 = 0.78$. Temperature and compressive strength were found to have the strongest effect on the variability of stiffness modulus. However, indirect tensile strength also significantly affected the Sm characteristic. In addition, FB-RCM (foamed bitumen) recycled mixtures proved to be more favourable than EB-RCM (emulsified bitumen) mixtures as they exhibited a lower deformation rate while retaining limited stiffness.

Keywords: deep recycling technology, foamed bitumen, multiple regression modelling, stiffness modulus, blended binder, trial section

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1. Introduction

Recycled mixtures are a commonly used material for base and sub-base layers in both reconstruction and new road construction. They can be made using foamed bitumen or emulsified bitumen. Note that using waste or recycled material qualifies this technology as an environmentally friendly solution [1]. It is important to remember a vital role played by the proper hydraulic binder in recycled base courses. Its presence is required for proper cohesion of the recycled mix [2], eliminating the risk of exceeding the limit state. According to researchers [3, 4], hydrated lime or cement in recycled mixtures, particularly those made with foamed bitumen, improved the permanent deformation resistance of a service road section in the early stage of service and increased its stiffness. Applying a road binder containing 100% cement is the most widely used way of increasing the cohesion of recycled mixtures. According to Halles et al. [5], cement addition improves the mechanical characteristics of the recycled mix in terms of stiffness or indirect tensile strength (ITS). Other authors [5] successfully applied both cement and cement kiln dust CKD [6] to increase ITS and stiffness modulus, using fly ash as a fine filler. Another important product is hydrated lime. In the studies of Ramanujam et al. [4], hydrated lime was found to increase the resistance to permanent deformation of recycled mixtures, particularly those produced with foamed bitumen, in the early phase of road service. In this case, the strong effect of high CaO content effectively dispersed the binder, resulting in a strong structuring of the bitumen as occurs in the mastic [7, 8]. However, the lack of a correctly performed process of optimizing the cement content can lead to excessive stiffness of the recycled mixture and hence, cracking [9, 10]. When used with other binders or active dust, hydraulic binders will contribute to cement savings, improved tightness of the recycled mix, and its resistance to permanent deformation without losing its elasticity [11, 12].

Despite the many benefits of recycling, limitations are still encountered in its application and popularization. The main reason is the lack of comprehensive knowledge of the recycled mixture's internal structure and the rheological effects prevailing in it, leading to frequent failures of heavily trafficked roads constructed on recycled mixture base courses [10, 13]. In Poland, this was one of the reasons for limiting the use of this technology on roads with traffic volumes above ESAL100 kN > 7.3 million axles. The lack of comprehensive research is also reflected in the number of methods available for predicting the stiffness modulus. In Polish conditions, its value is set at a conventional level of 1500 MPa [14]. Correct representation of the stiffness modulus guarantees the correct estimation of the strain state of the pavement structure [15]. There are few valuable studies on the recycled mix modulus variation [16–18], but they consider conditions limited to single construction technology. Therefore, the authors of the present paper undertook the task of predicting the change in the recycled mix modulus of stiffness, expanding their work over the recycling technology, type of binder and phenomena that may occur during the execution of the experimental section.

2. Materials

2.1. Experimental design

The subject of the study was a cold recycled mix (RCM) composed of two types of binding agent, i.e., foamed bitumen and emulsified bitumen, as well as Portland cement

(CEM I 32.5R) and a dedicated hydraulic binder (designated 5C). The effects of the binder type on the properties of the cold recycled mix were evaluated. Both the bitumen foam and emulsion were prepared from paving grade bitumen 70/100. The recycled mixture was made under industrial conditions using "in situ" technology. The base course layer was designed for traffic volume KR3-4 ($0.50 < \text{ESAL100} \leq 7.30$ million standard axles 100 kN) [19]. The target experimental section constructed using two recycling technologies with the dedicated hydraulic binder was located at an open-pit mine site in the Świętokrzyskie Province, Poland. The experimental section was divided into four subsections of 300 m^2 each. The schematic and division of the section are shown in Fig. 1.

Fig. 1. Test section and subsections [20]

A monitoring system for environmental factors such as temperature and moisture content in the layers was installed. It also monitored the strain state of the base course and subgrade in FB-RCM_5C/EB-RCM_5C sections containing dedicated road hydraulic binder (5C). More detailed results from the monitoring system analysis can be found in the paper [21].

2.2. Dedicated road hydraulic binder

The composition of the 5C blended binder recommended for use in the test section was determined based on the multi-criteria optimization. The experimental domain resulted from the mixture design. The initial design was modified so that the content of each component varied from 20% to 80%. For that purpose, seven different compositions of the universal binder were prepared and randomized [22]. The binder compositions are shown in Table 1.

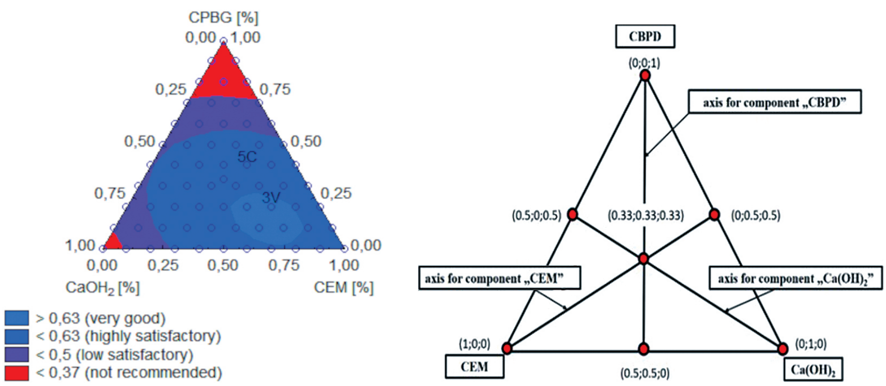
The sum of the mixture's components should not be greater than 100%. Detailed information about the effects of the three-component binder on the properties of standard mortar and the chemical composition of the binder is given by [23, 24]. The extensive data set allowed other optimal solutions for the given criteria and conditions of the binder's

Table 1. Amount of the universal binder components based on the constrained mixture design

Designation of the components combination	Percentage share content of each binder component		
	Hydrated Lime ($CaOH_2$)	Cement (CEM)	Cement By-pass Dust (CBPD)
7 C(2)	33%	33%	33%
6 C(1)	40%	40%	20%
5 C(1)	40%	20%	40%
1 V	20%	20%	60%
4 C(1)	20%	40%	40%
3 V	20%	60%	20%
2 V	60%	20%	20%

use. Therefore, as part of the study, the authors developed a computer program with VBA. As a result of the optimization of the binder composition for the desired characteristics of the recycled mix, the most optimal solution for maximum fatigue life, high stiffness at high temperatures and the lowest possible stiffness at low temperatures was determined within the TECHMATSTRATEG project [20] with foamed bitumen. The evaluation of the effect of blended binder composition on the mixture properties was based on the simplex-centroid design [25]. The optimal solution was projected onto the mix design (Fig. 2a). The simplex experiment plan allows to read out modelled relation between at least three factors projected on 2D surface (experiment domain) by means of some mathematical manipulation. In detail, Fig. 2b gives the data reading methodology.

The binder with a composition corresponding to code designation 5C was used to make a recycled cold mix with foamed bitumen and emulsified bitumen (Fig. 2). The proportion



(a) (b)

Fig. 2. The simplex experiment plan: a) hydraulic binder optimization result [20]; b) simplex-centroid mixture design scheme

of binder components was 40% cement (CEM), 20% hydrated lime ($CaOH_2$) and 40% dust from the cement dust collection system (CPBD). The resulting solution was highly satisfactory [22] and met the premise of maximum utilization of the CPBD component. In addition, the 5C solution was close in quality to the solution where 100% cement was used. The best solution was obtained for the area in which the 3V binder predominated (Table 1). Nevertheless, the CPBD content in the composition of the binder would account for only 20%, which would reduce the efficiency of the optimal solution from the viewpoint of the level of CPBD utilization.

2.3. Mineral mixture design

The design of the cold recycled mineral mixture composition was developed so that the gradation curve would simultaneously meet the particle size requirements for EB-RCM and FB-RCM [26]. The mineral mixture consisted of 3.0% bitumen binder (foamed bitumen/emulsified bitumen), 3.0% hydraulic binder (Portland cement/dedicated hydraulic binder), 37.6% (m/m) reclaimed asphalt pavement, and 56.4% (m/m) 0/31.5 mm aggregate. The designed gradation curve is shown in Fig. 3.

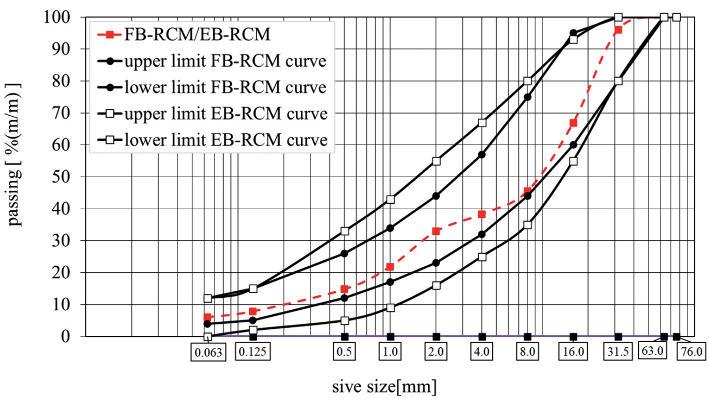


Fig. 3. Designed gradation curves for FB-RCM and EB-RCM

The 70/100 bitumen-based binders were used in the composition of the recycled mix. The bitumen foam characterized by two parameters such as: Expansion ratio value was determined as 14 (times) at corresponding half-time value of 10 sec. The optimal water content in foaming process was 2.7%.

The produced mixture was sampled and compacted under laboratory conditions following EN 12697-30 [27] using the Marshall method with 2×75 blows per side. The samples were compacted in perforated Marshall molds according to the recommendation [28]. The samples prepared from the recycled mixture under “in situ” conditions were designated as (trial). For comparison purposes, mineral components were extracted from the experimental section and mixed under laboratory conditions in the same proportions as in the experimental section. The samples thus produced were designated as (lab.).

3. Methods

The test methods adopted to evaluate the properties of recycled mixtures were selected based on the review of domestic and foreign literature [26, 29–31]. The testing programme for the FB-RCM and EB-RCM mixes involved determining basic physical and mechanical properties by the methods presented in Table 2.

Table 2. Test methods used for EB_RCM/FB_RCM mix evaluation

No.	Property	Standard
1.	Air void content (V_a)	EN 12697-8 [32]
2.	Unconfined compression strength (UCS)	EN 13286-41 [33]
3.	Indirect tensile strength (ITS)	EN 12697-23 [34]
4.	Resistance to water damage (TSR)	Wirtgen [26, 31]
5.	Stiffness modulus (S_m) acc. to IT-CY	EN 12697-26 [35]
6.	Creep rate under compression with lateral confinement (f_c)	EN 12697-25 [36]

4. Data set characterization

4.1. Data structure

All types of variables are characterized by specific variability. An essential element of any analysis in the initial stage of this study was to determine the average level and dispersion of the values. The results of the calculated basic statistics required for parametric tests are presented in Table 3.

Table 3. Descriptive statistics of the data set

Variable	Undivided into groups								
	Mean	Median	Minimum	Maximum	Lower quartile	Upper quartile	SD*	Skew.	Kurtosis
V_a [%]	13.1	13.5	9.5	15.3	12.2	14.1	1.6	–0.460	–0.216
UCS [MPa]	3	3	2	4	2	3	0	–0.405	–0.777
ITS [kPa]	635	647	404	849	478	793	165	–0.111	–1.655
TSR [%]	80	80	68	88	77	83	5	–0.646	1.096
S_m – 10°C [MPa]	14578	14008	8187	19223	11495	17655	3466	–0.175	–1.458
S_m + 5°C [MPa]	10295	10511	6432	13497	8348	11456	2107	–0.148	–1.017
S_m + 13°C [MPa]	9400	8643	5857	14544	7742	10349	2451	1.040	0.304
S_m + 25°C [MPa]	6905	6453	4511	11009	4852	8377	2098	0.634	–0.782
Creep rate (f_c) με/cycle	0.073	0.068	0.031	0.126	0.043	0.099	0.034	0.352	–1.171

*SD – standard deviation, Skew. – Skewness.

Note the high skewness result of the stiffness modulus S_m at +13°C. The shape of the probability density function of the probability distribution for the entire S_m set is expected to deviate from the normal distribution, as confirmed by a significant difference between measures of central tendency, namely the mean and median. The second variable that raises some doubts is the TSR result. A significant value of the skewness parameter and a high > 1.0 kurtosis was observed. This suggests some asymmetry in the distribution of the results that are within a narrow range of variability. Therefore, before building the model, the shape of the result probability distribution should be verified.

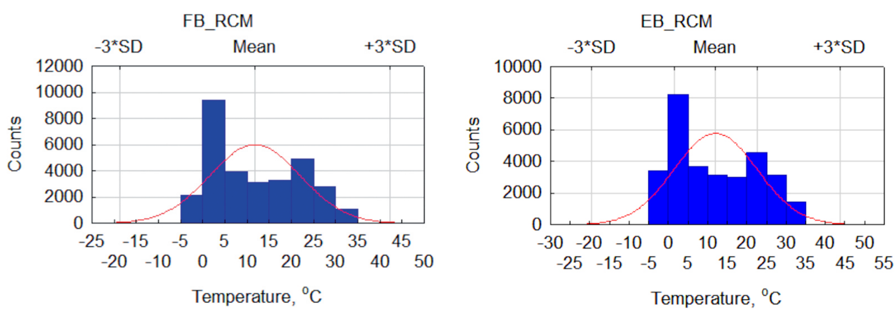
The development of the regression model required using a certain data structure. The approach used was that of machine learning [37]. The principle input set consisted of $\sum N = 204$ determinations containing 2–3 replications of the results. Before the essential data analysis, the data set was divided into a training set and a test set. The test set contained 12 random cases of complete records including S_m determined at +13°C. The remaining cases were classified into the training set. The model also had to account for the presence of several factors (effects):

- Sampling location: in the laboratory (Lab.) and on the experimental section (Trial).
- Type of road binder: samples containing 100% cement (Ref.) and 5C blended binder.
- Type of technology: deep cold recycling with foamed bitumen (FB-RCM) and with emulsion (FB-RCM).

It should be added that all samples that were not marked “Ref.” were prepared with the blended binder 5C.

4.2. Temperature effect on stiffness modulus

The stiffness modulus of recycled mixtures is affected by temperature in the same way as that of bituminous mixtures. This is related to the presence of bitumen binders in their composition [38, 39]. The temperature range adopted for the analysis was derived from the acquired partial monitoring data (Fig. 1) of environmental characteristics covering precisely one year (2020–2021). The histogram of the temperature distribution for the EB-RCM and FB-RCM layers is shown in Fig. 4.



(a) (b)

Fig. 4. Histogram of temperature changes recorded in the layers by the monitoring system (2020–2021): a) FB-RCM; b) EB-RCM

The temperature distribution did not follow the normal distribution, so the median was used to evaluate the average value. The median, indicated by a vertical line, was $Me(T_{EB-RCM}) = 9.18°C$ and $Me(T_{FB-RCM}) = 9.65°C$, respectively. The graphs in Figs. 4a and 4b indicate that the most probable temperatures were those between two modes, i.e., between ranges 0–5°C and 20–25°C. Therefore, the available S_m determinations at −10°C and +25°C were used to predict the stiffness modulus. The stiffness modulus variation is shown in Fig. 5.

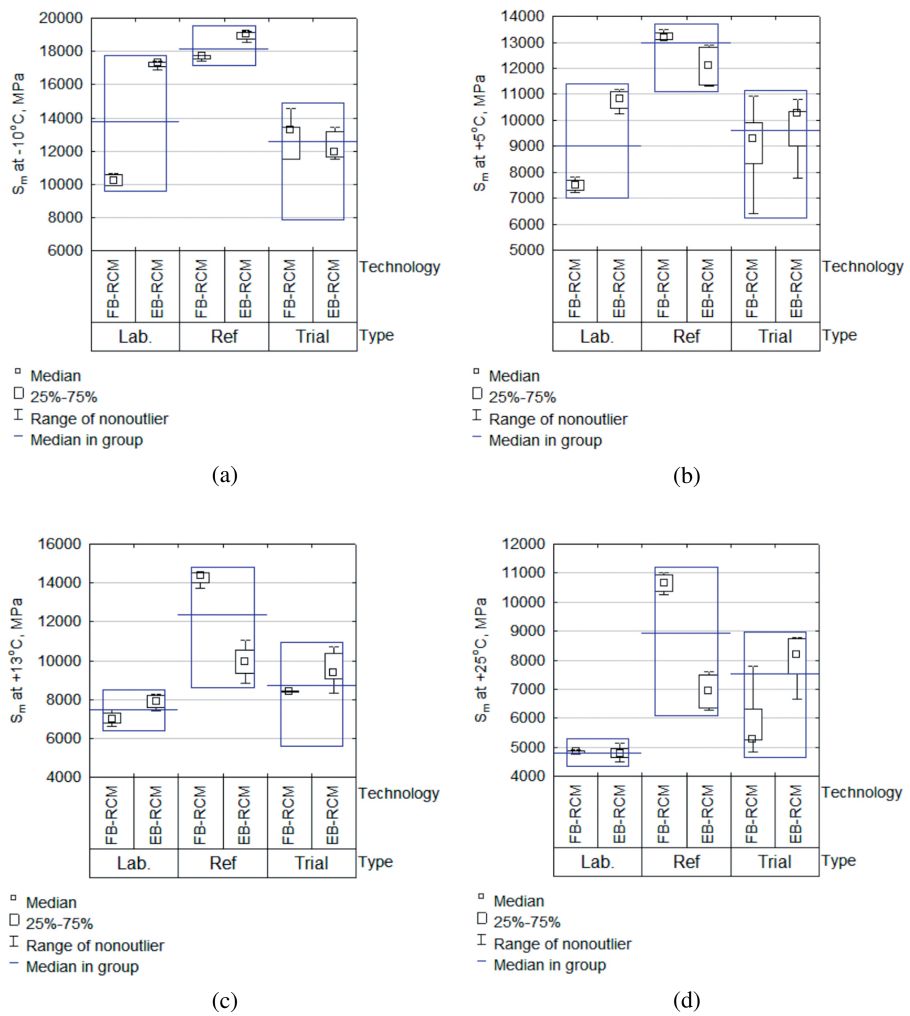


Fig. 5. Stiffness modulus IT-CY determined at: a) −10°C; b) +5°C; c) +13°C; d) +25°C

The modulus results indicate that the modulus values in the reference section (100% cement in binder) reached the highest value. In those sections, recycled mixtures with

FB-RCM had higher stiffness moduli than EB-RCM. An opposite relationship was observed when the 5C binder was used, regardless of the sampling location (Lab., Trial). This decrease can be explained by a different interaction between binder 5C and foamed bitumen or emulsion. Samples from the experimental section obtained a higher average stiffness modulus than samples prepared in the laboratory, regardless of the deep recycling technology. It is noteworthy that in the group of samples in which hydraulic road binder (5C) was used, the modulus value significantly decreased in almost all cases compared to cases where 100% cement was used in the binder. This was especially significant at −10°C. For example, samples in the experimental section (where 5C binder was used), regardless of the type of technology, obtained a lower S_m value at −10°C equal to 12630 MPa (median) compared to the variant where 100% cement was used (at −10°C S_m = 18080 MPa). Note that reducing the recycled mix's stiffness is important in terms of counteracting low-temperature cracking. It should also be noted that regardless of temperature, the relationship between stiffness modulus values is of the same nature. This is possible based on the assumption that the FB-RCM/EB-RCM recycled base course, just as bituminous mixtures, can be considered a thermo-rheological simple body and their value at different temperatures can be functionally related [40, 41]. Therefore, the effect of temperature was added to the prediction of stiffness modulus values in the regression model. However, temperature alone does not completely exhaust the explanation of S_m variability, so the effect of binder type, technology type and recycled mix sampling location were also included in the prediction.

4.3. Linear relations between the recycled mix characteristics

An important step during the construction of the regression model was to determine whether there was collinearity in the structure of the variables, expressed as a high level of cross correlation between the variables. Excessive collinearity between independent variables changes the level of explanation of the dependent variable variance, which is revealed by a very high value of the R^2 coefficient [22] in multivariate regression. Consequently, the suitability of such a model decreases, as does its ability to extrapolate results. The correlations between the characteristics are compiled in the correlation table (Table 4).

The highlighted values suggest a high level of significant correlation between the characteristics. A strong correlation was observed among the results of the stiffness modulus determined at different temperatures. In Table 5, the expected variable S_m at +13°C is correlated with the stiffness modulus value at +5°C. In contrast, S_m at 25°C correlated with S_m determined at +13°C and +5°C. This confirms that the well-known principle of time-temperature superposition was in place [42]. Thus, the stiffness modulus values increased proportionally with a decrease in temperature.

A high correlation of static creep fc results with those for V_a, UCS and ITS was also observed. The deformation rate increased with rising V_a and UCS values but decreased with the increasing cohesion of the recycled mixture, expressed by the ITS value. The compressive strength (UCS) increased with increasing V_a. Probably the level of internal friction angle correlated with V_a played a significant role in the increase of the UCS value.

Table 4. Correlations between physico-mechanical characteristics

Variable	Correlation table								
	V_a [%]	UCS [MPa]	ITS [kPa]	TSR [%]	S_m at −10°C	S_m at +5°C	S_m at +13°C	S_m at +25°C	creep ratio (f_c)
V_a [%]	1.00	**0.67**	**–0.63**	–0.31	0.35	0.28	0.20	0.13	**0.67**
UCS [MPa]	–	1.00	**–0.61**	–0.52	**0.72**	**0.66**	0.47	0.45	**0.59**
ITS [kPa]	–	–	1.00	0.27	–0.41	–0.13	0.30	0.38	**–0.70**
TSR [%]	–	–	–	1.00	–0.37	–0.16	0.02	–0.03	0.02
IT-CY −10°C	–	–	–	–	1.00	**0.92**	0.54	0.38	0.33
IT-CY +5°C	–	–	–	–	–	1.00	**0.80**	**0.67**	0.27
IT-CY +13°C	–	–	–	–	–	–	1.00	**0.96**	0.10
IT-CY +25°C	–	–	–	–	–	–	–	1.00	0.06
creep ratio (f_c)	–	–	–	–	–	–	–	–	1.00

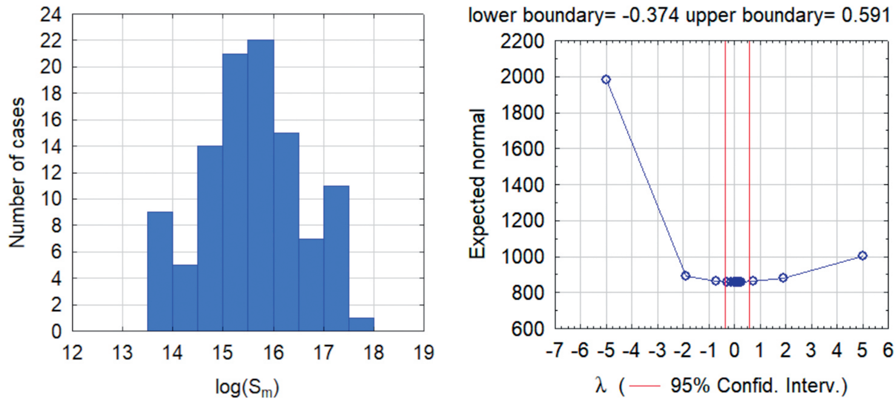
The relationship between V_a and ITS confirmed a well-known trend, i.e., a decrease in the air void content correlates with an increase in the cohesion of the recycled mixture.

Before constructing a regression model to predict the change in the modulus of stiffness S_m, the characteristics V_a, TSR, UCS, and ITS were mapped against S_m. The representative stiffness modulus value at +13°C was selected for the analysis as it corresponded to the temperature accepted as equivalent in Poland [19]. The S_m results were from the test set whose reliability was verified during the construction of the regression model. Observing results in table 5 none of the given characteristics sufficiently explained the variability of S_m +13°C. However, their partial correlation with the S_m variable and low correlation with one another makes it possible to believe that a reliable regression model can be built to allow fast calculation of the elasticity modulus relative to the other basic characteristics.

5. Stiffness modulus prediction

5.1. Constructing a regression model

One of the necessary elements when building regression models is the conformity of the probability distribution of results to a normal distribution. Therefore, before the principal analysis, all variables were subjected to normality tests. Two tests were used: the Kolmogorov–Smirnov (K–S) test and the Shapiro–Wilk (W) test. The largest deviation from normality was registered for the S_m parameter. Particular mathematical formalism was required in this case. It consisted of using a transformation function to bring the distribution of the S_m variable to a normal distribution. Omitting this step of the analysis would have caused the estimator of the central measure (arithmetic mean) of S_m in the model to be inefficient and biased, affecting the final quality of the model's prediction. For this purpose, the Box–Cox transformation algorithm (Box & Cox, 1964) was used. The key to the performance of Box–Cox algorithms was the iterative determination of the fitting parameter λ. The results of estimating the parameter λ are shown in Fig. 6.



(a) (b)

Fig. 6. Transformation of the S_m variable: a) histogram after transformation; b) search for λ

The confidence interval suggested that the value of the λ parameter could be 0 at 95% probability (Fig. 6b). So, using some simplifications, it was assumed that logarithmic was the best transformation function that represented the λ parameter. As a result of using this function, the distribution of results obtained a shape that converged to a normal distribution (Fig. 6a). Next, a multiple regression model was adopted to search for relationships between variables. Its form, which is an objective function of the object of study, was as follows (5.1):

$$y = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_i x_i + \varepsilon \tag{5.1}$$

where: β_i – parameters of the model describing the effect of an i-th variable, ε – random component.

One of the main assumptions that a multiple regression model must meet is the lack of interrelated variables and an adequate sample size n+1 larger than the number of estimated parameters. Once the sample size condition was met, the effect of cross-correlation of independent variables was noticeable, especially in the case of the f_c characteristic (Table 2). The cross-correlation of predictors falsifies the coefficient of determination causing it to have a very high value. Therefore, in order to obtain a reliable model, the backward elimination algorithm was used [22]. This method assesses the redundancy of variables resulting from the relationships between them in the set. In each iterative step, a given variable is evaluated for its maximum correlation with the S_m characteristic and minimum correlation with other variables. As a result, after discarding redundant factors, the final set of variables participating in the multiple regression model was obtained (Table 5).

As a result, variables such as V_a, TSR and fc were eliminated from the model due to the high redundancy they introduced into the model. The result of the partial correlation,

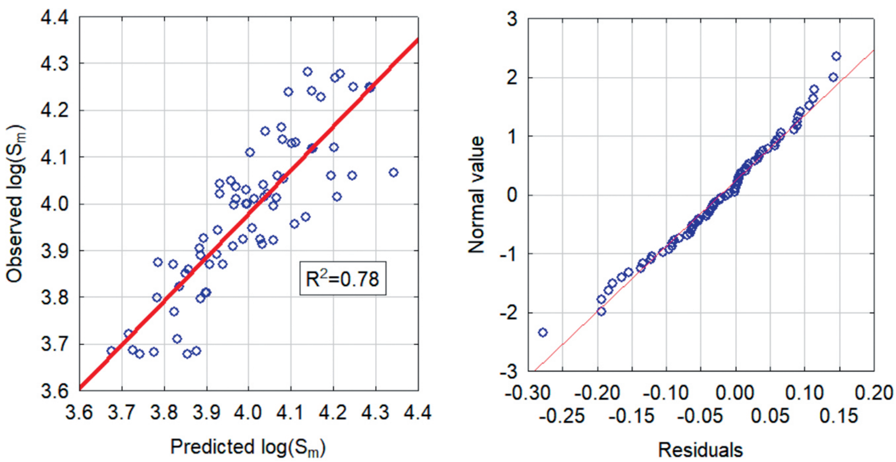
Table 5. Results of multiple regression

	Summary of regression of dependent variable: $\log(S_m) R^2 = 0.78$; Estimation error of $\log(S_m)$ 0.08 MPa			
	bi	SD(b)	Partial correlation	p-value
Intercept	3.062960	0.137229	–	0.000000
UCS [MPa]	0.270403	0.034875	0.759865	0.000000
ITS [kPa]	0.000444	0.000094	0.580463	0.000024
Temp	–0.009038	0.000907	–0.832489	0.000000

shown in Table 5, represented the contribution of the variable in question to explaining S_m variability. Accordingly, the impact of the characteristics: Temp (–0.83) and UCS (0.76) on S_m values was the strongest. The influence of ITS was about 30% smaller but still had a significant impact on S_m variability (0.58). Despite the large effect of temperature (partial correlation = -0.83), failure to account for the presence of effects related to the technology type and sampling method would have made the model too general and insufficient. Therefore, the effects above were entangled in the variability attributed to UCS and ITS. After transformations, the final form of the significant regression model (p-value < 0.05) predicting the S_m characteristic was characterized by formula (5.2):

$$S_m = 10^{3.063+0.27\cdot\mathrm{UCS}+0.0004\cdot\mathrm{ITS}-0.009\cdot\mathrm{Temp}} \pm 835\ \mathrm{MPa} \tag{5.2}$$

Figure 7 shows mapping experimental results against model (2).



(a) (b)

Fig. 7. Fitting the multiple regression model: a) goodness of fit of the predicted results; b) residual randomness evaluation

Figure 7a shows high agreement between the experimental results and those predicted by formula (5.2), which was represented by the coefficient of determination of the multiple regression model $R^2 = 0.78$. The average estimation error was 835 MPa. Another important issue was to maintain the randomness of residuals. Their distribution along the line (Fig. 7b) suggested conformity to a normal distribution. Thus, one of the conditions for obtaining a reliable regression model with the ability to extrapolate results beyond the experimental domain was met. As mentioned earlier, in Poland, a temperature of +13°C is taken as the equivalent temperature for pavement design based on the mechanistic method. Accordingly, an attempt was made for the model to represent the stiffness modulus for this temperature for a set of samples excluded from the model (the test set established at the beginning). The simulated result for the stiffness modulus at +13°C using the test set is shown in Fig. 8.

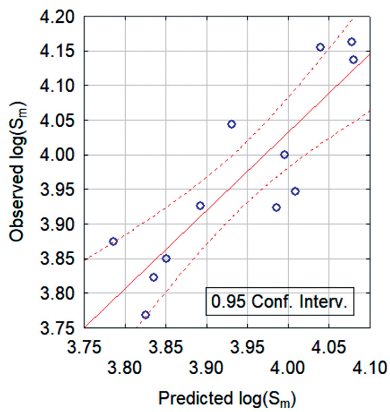


Fig. 8. S_m values at +13°C from the model using the test set

The results shown in Fig. 8 should be considered satisfactory. Nearly all the results were within the 95% confidence interval. This result is significant as all the defined effects, i.e., technology, sampling location, and type of binder, were included in the model. However, some limitations of the model should also be noted. This model applies to mixtures prepared by one of the two technologies with a hydraulic binder that has binding properties similar to cement and ITS and USC values from the ranges provided in Table 1. As a result, this model can be used as support for forecasting the stiffness modulus of recycled mixtures in the absence of other detailed studies. Nevertheless, it should be emphasized that its effectiveness will be higher in the case of forecasting a recycled mixture made in a similar technology.

6. Conclusions

The article presents the results of the study of the stiffness modulus of recycled mixes made in two technologies and for two types of binder. To ensure that the model is adequate, a validation step was also used in accordance with the machine learning methodology including variability regarded to manufacturing process. It should be noted that the model is subject to continuous verification and its effectiveness is constantly increased by taking into account other factors. The next step will be to use the SVM (support vector machines) and MARS (Multivariate adaptive regression spline) algorithms for modeling, which is a generalization of the multiple regression model used in analyses. The following conclusions were formulated based on the study results and analysis performed:

1. Modeling in the form of machine learning is a very good approach in finding relationships between the variables under study. Owing to this the linear model of multiple regression satisfactorily explained the variability of the Sm characteristic at an estimation error of 835 MPa in the measurement temperature range of −10°C to +25°C. This is a satisfactory result allowing for a preliminary forecast of the recycled mixtures stiffness modulus.
2. The most effective predictors of S_m were UCS, ITS and the accompanying Temp. According to the regression model, an increase in UCS and ITS caused an increase in S_m values. In contrast, UCS and Temp had the most significant impact on S_m variability.
3. The proposed regression model performed well at predicting the behaviour of recycled mixtures at an equivalent temperature of +13°C. Thus, its results can support the design of road pavement structures using the mechanistic method.
4. On average, samples prepared using FB-RCM technology (with foamed bitumen) showed higher cohesion (ITS) compared to samples prepared using EB-RCM technology (with emulsified bitumen). In addition, the FB-RCM samples achieved ITS > 650 kPa, regardless of the sampling location.
5. The FB-RCM samples had a lower deformation rate with a higher ITS value than those prepared in EB-RCM technology. In addition, compared to EB-RCM technology, samples in FB-RCM technology suggest higher resistance to creep at higher cohesion.
6. The highest value of the UCS characteristic was obtained by samples made with EB-RCM technology.

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Prognozowanie modułu sztywności względem podstawowych cech fizycznych i mechanicznych podbudowy recyklowanej z asfaltem spienionym i emulsją asfaltową

Słowa kluczowe: głęboki recycling, asfalt spieniony, model regresji wielorakiej, moduł sztywności, spoiwo mieszane, odcinek doświadczalny

Streszczenie:

Mieszanki recyklowane są powszechnie wykorzystywanym materiałem do budowy podbudowy zasadniczej i pomocniczej zarówno w przebudowach jak i nowych konstrukcji drogowych. Mogą one być wykonywane w technologii asfaltu spienionego jak i również emulsji asfaltowych. Należy pamiętać, że zastosowanie materiału odpadowego lub pochodzącego z recyklingu kwalifikuje tę technologię jako rozwiązanie proekologiczne. Aplikacja spoiwa drogowego zawierającego 100% cementu jest najczęściej wykorzystywanym sposobem podnoszenia stopnia kohezji mieszanek recyklowanych. Nie mniej jednak brak poprawnie wykonanego procesu optymalizacji ilości cementu może doprowadzić do nadmiernego przesztywnienia mieszanki recyklowanej i pojawieniem się spękań. Pomimo wielu korzyści, jakie wynikają ze stosowania technologii recyklingu wciąż napotykane się ograniczenia w jej stosowaniu i popularyzacji. Główną przyczyną jest brak kompleksowej wiedzy z zakresu struktury wewnętrznej mieszanek recyklowanych oraz panujących w niej efektów reologicznych, co objawia się częstymi awariami dróg o dużym natężeniu ruchu, które zostały wykonane na podbudowie z mieszanki recyklowanej [13, 43]. W związku z tym była to jedna z przyczyn ograniczenia stosowania tej technologii w Polsce dla ruchu o natężenia pojazdów powyżej ESAL100 kN > 7,3 mln osi. W związku z tym autorzy podjęli się zadania związanego z możliwością prognozowania zmiany moduł u sztywności mieszanki recyklowanej, rozrzedzając swoje działania o efekty związane z: technologią recyklingu, rodzajem spoiwa oraz zjawiskami jakie mogą wystąpić w czasie realizacji odcinka doświadczalnego.

W artykule zostały przedstawione rezultaty prognozowania modułu sztywności mieszanki recyklowanej zawierającej mieszane spoiwo drogowe w technologii asfaltu spienionego oraz emulsji asfaltowej. Badanie modułu sztywności wykonano metodą pośredniego rozciągania IT-CY. Moduł sztywności oznaczono w temperaturach −10°C, +5°C, +13°C oraz +25°C. Prognozowanie modułu sztywności uwzględniało efekt temperatury, rodzaj spoiw drogowego, miejsce poboru próbek oraz rodzaj technologii. Wszystkie efekty, oprócz temperatury, zostały uwzględnione w modelu poprzez uwikłanie ich oddziaływania za pomocą cech fizycznych i mechanicznych recyklowanej podbudowy takich jak: wytrzymałość na pośrednie rozciąganie, wytrzymałość na ściskanie, szybkość pełzania, zawartość wolnej przestrzeni oraz odporność na oddziaływanie wody.

Jako narzędzie pozwalające prognozowanie zmiany modułu sztywności wykorzystano model regresji wielorakiej. Jest to relatywnie prosty model w zastosowaniu pod warunkiem spełnienia jego założeń wśród których do najważniejszych należy zaliczyć: zgodność dystrybucji wyników oznaczeń z modelem rozkładu normalnego oraz brak współliniowości pomiędzy zmiennymi niezależnymi. Wszystkie wspomniane zał ożenia zostały poddane weryfikacji. Zbudowanie racjonalnego modelu regresyjnego wymagało również zastosowania pewnej struktury danych. Zastosowano podejście stosowane przy uczeniu maszynowym. Zasadniczy zbiór wejściowy składał się z $\sum N = 204$ oznaczeń zawierający od 2–3 replikacji wyników. Przed zasadniczą analizą danych dokonano podziału zbioru danych na dwie części: zbiór uczący i zbiór testowy. Model musiał uwzględnić również występowanie kilku czynników (efektów): miejsce poboru próbek: w laboratorium (oznaczone jako Lab.) oraz na odcinku doświadczalnym (oznaczone jako Trial), rodzaj spoiwa drogowego: próbki zawierające 100%

cementu (oznaczone jako Ref.) oraz spoiwo mieszane 5C oraz rodzaj technologii: recykling głęboki na zimno z asfaltem spienionym (oznaczony jako FB-RCM) oraz z emulsją asfaltową (oznaczony jako FB-RCM).

W rezultacie stwierdzono, że model liniowy regresji wielorakiej w sposób zadawalający, na poziomie 78%, wyjaśnił zmienność modułu sztywności Sm przy błędzie estymacji 835 MPa w zakresie temperatury pomiaru od −10°C do +25°C. W czasie budowania modelu regresyjnego metodą eliminacji wstecznej stwierdzono, że najbardziej istotnymi cechami, które skutecznie prognozowały Sm były: UCS, ITS oraz towarzysząca: poziom temperatury. Zgodnie z modelem regresyjnym wzrost UCS oraz ITS powodowaływzrost wartości Sm. Natomiast największy wpływ na zmienność Sm miały: UCS oraz Temp. Próbki sporządzone w technologii FB-RCM (z asfaltem spienionym) odznaczały się przeciętnie wyższą kohezją (ITS) w porównaniu do próbek wykonanych w technologii EB-RCM (z emulsją asfaltową). Przeciętnie próbki FB-RCM uzyskały ITS $>$ 650 kPa bez względu miejsce pobrania próbek. Zaproponowany model regresyjny umożliwił uzyskanie dobrej zgodności wyników prognozowanych z uzyskanymi w drodze eksperymentu w ekwiwalentnej temperaturze +13°C (przyjętej w Polsce). Tym samym jego rezultaty mogę być wparciem przy projektowaniu konstrukcji nawierzchni drogowej metodą mechanistyczną.

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