PRZEMYSŁAW BUCZYŃSKI[1)]
GRZEGORZ MAZUREK[2)]
MAREK IWAŃSKI[3)]

PREDICTING THE PROPERTIES OF A MIXTURE PRODUCED USING “COLD” TECHNOLOGY WITH FOAMED BITUMEN IN TERMS OF THE PROPERTIES OF HYDRAULIC BINDER MORTARS

PROGNOZOWANIE WŁAŚCIWOŚCI MIESZANKI MINERALNO-SPOIWOWEJ WYTWARZANEJ W TECHNOLOGII NA „ZIMNO” Z ASFALTEM SPIENIONYM W ASPEKCIE WŁAŚCIWOŚCI ZAPRAW ZE SPOIW HYDRAULICZNYCH

STRESZCZENIE. W artykule przedstawiono korelację pomiędzy właściwościami mechanicznymi mieszanki mineralno-spoiwowej z asfaltem spienionym (MCAS) a właściwościami mechanicznymi zapraw, w których składzie zastosowano spoiwo hydrauliczne. Istotą prezentowanych wyników badań była próba wyjaśnienia, czy za pomocą wstępnych wyników badań uzyskanych dla zapraw możliwe jest prognozowanie właściwości recyklowanej mieszanki na zimno z asfaltem spienionym (MCAS). Prognozę cech MCAS przez właściwości zapraw ograniczono do podstawowych właściwości mechanicznych zapraw, tj. wytrzymałości na ściskanie (R_C) oraz wytrzymałości na rozciąganie przy zginaniu (R_f). Do osiągnięcia zamierzonego celu zaprojektowano siedem spoiw hydraulicznych o składzie kontrolowanym poprzez plan eksperymentu sympleksowo-centroidowy, zwany planem mieszaniny. Składniki spoiw hydraulicznych, które zostały wykorzystane do jego kompozycji to: cement portlandzki CEM I 32,5R, wapno hydratyzowane $Ca(OH)_2$ oraz uboczne cementowe produkty pylaste (UCPP). Zaprojektowane i przygotowane w warunkach laboratoryjnych spoiwa hydrauliczne zastosowano w składzie mieszanki mineralno-spoiwowej z asfaltem spienionym w ilości 3,0% (m/m). Następnie w warunkach laboratoryjnych przygotowano mieszankę mineralno-spoiwową z asfaltem spienionym i wykonano badania właściwości mechanicznych, tj. wytrzymałość na pośrednie rozciąganie ITS_{DRY}, wytrzymałość na ściskanie osiowe UCS, moduł sztywności (S_m), odporność na pękanie (K_{IC}) oraz moduł dynamiczny |E*| wyznaczony w funkcji częstotliwości i temperatury. Wyniki analiz pozwalają stwierdzić, że istnieje potencjalnie możliwość prognozowania wybranych właściwości mechanicznych mieszanki MCAS dzięki analizie wyników mechanicznych dla zapraw. Ma to jednak ograniczone zastosowanie. Wyniki badań uzyskane dla właściwości nieniszczących, tj. dla modułu dynamicznego |E*|, w sposób zadowalający zostają opisane przez wyniki wytrzymałości zapraw na ściskanie po 28 dniach pielęgnowania. Pozostałe analizowane cechy nie wykazały istotnej zależności.

SŁOWA KLUCZOWE: podbudowa recyklowana, asfalt spieniony, spoiwo hydrauliczne, recykling głęboki na zimno, korelacja.

ABSTRACT. The paper presents the correlation between the mechanical properties of the mineral-aggregate mixture with foamed bitumen (MCAS) and the mechanical properties of mortars containing hydraulic binder. A significant aspect of the presented research results was an attempt to determine whether it is possible to predict the properties of the recycled cold mix with foamed bitumen (MCAS) based on preliminary results obtained for mortars. The prediction of MCAS properties through mortar properties was limited to basic mechanical properties of mortars, namely compressive strength (R_C) and flexural tensile strength (R_f). To achieve this goal, seven hydraulic binders were designed with a controlled composition using a simplex-centroid experimental plan known as the mixture design plan. The components of the hydraulic binders used in its composition were Portland cement CEM I 32.5R, hydrated lime $Ca(OH)_2$, and by-products of cement production in powder form (UCPP). The designed and prepared hydraulic binders were then used in the composition of the mineral-aggregate mixture with foamed bitumen at a quantity of 3.0% (m/m). Subsequently, in laboratory conditions, the mineral-aggregate mixture with foamed bitumen was prepared, and mechanical property tests were conducted, including indirect tensile strength (ITS_{DRY}), axial compressive strength (UCS), modulus of stiffness (S_m), fracture toughness (K_{IC}), and the dynamic modulus |E*| determined as a function of frequency and temperature. The analysis results suggest that there is potentially the ability to predict selected mechanical properties of the MCAS mixture by analyzing the mechanical results for mortars. However, this application is limited. The research results obtained for non-destructive properties, such as the dynamic modulus |E*|, are satisfactorily described by the compressive strength results of mortars after 28 days of curing. Other analyzed characteristics did not show a significant correlation.

KEYWORDS: cold-recycled asphalt mixture, foamed bitumen, hydraulic binder, deep cold recycling, correlation.

DOI :10.7409/rabdim.023.019

[1)] Kielce University of Technology, Kielce; p.buczynski@tu.kielce.pl ✉
[2)] Kielce University of Technology, Kielce; gmazurek@tu.kielce.pl
[3)] Kielce University of Technology, Kielce; miwanski@tu.kielce.pl

[*)] An extended version of the article from the conference „Modern Road Pavements – MRP2023” – Recycling in road pavement structures co-edited by Martins Zaumanis and Marcin Gajewski, published in frame of the Ministry of Education and Science project No. RCN/SP/0569/2021/1

1. INTRODUCTION

The implemented pro-environmental policy worldwide contributes to the development and application of technologies aimed at reducing energy consumption, limiting pollution, and preventing environmental degradation. Numerous industries face significant pollution due to the overproduction of by-products [1]. Among these processes is road construction, involving various activities related to the dismantling of damaged pavements. To minimize waste production, various recycling technologies [2, 3, 4] are employed. One widely used method for managing waste material is the technology of deep cold recycling with foamed bitumen [5] (MCAS) and bitumen emulsion (MCE) [6, 7]. The rapid development of cold recycling technology is driven by the needs of the road network users. Increased traffic intensity, leading to accelerated pavement structure deterioration, necessitates more frequent repairs and reconstruction of road sections. Due to its quick implementation and cost-saving potential, road network managers opt for deep cold recycling technology. However, like any technology, cold recycling technology has both benefits and drawbacks. One drawback is the potential occurrence of layer stiffening due to a significant increase in stiffness. Therefore, the need to limit the stiffness of the subbase layer made of the MCAS mixture has led to the search for alternatives to cement as binding agents. As literature [8, 9, 10] analysis indicates, restricting the use of cement in the MCAS mixture raises the risk of layer stiffening and shrinkage cracking. The presence of these issues can manifest as numerous reflected cracks, extending to the upper asphalt layers of the pavement structure. Consequently, there is a need to explore solutions that allow reducing stiffness while maintaining the required performance properties. In response to this demand, a three-component binder was developed within the Techmatstrateg I project [11] to ensure the required subbase strength and enable stiffness reduction [12]. The binder composition resulted from the simplex-centroid experimental plan [13, 14], with points distributed inside an equilateral triangle defining the composition of seven road binders formed by combinations of three basic components: Portland cement CEM I 32.5R, hydrated lime ($Ca(OH)_2$), and by-products of cement production in powder form (UCPP).

The research results presented here aim to address the market demand for alternative binding agents dedicated to deep cold recycling technology. Current guidelines for MCE mixtures [15] solve this problem at a general level, indicating the possibility of using road binders, provided positive results are obtained during MCE mixture design. The presented research results attempt to explain the impact of alternative road binders, both normally and rapidly setting, on the properties of the MCAS mixture, pointing to the possibility of predicting MCAS mixture characteristics based on the fundamental properties of hydraulic binders.

2. PURPOSE AND SCOPE OF RESEARCH

The primary goal of the research was to determine the relationship between the properties of the mineral-binder mixture produced using the cold technology with foamed bitumen and the properties of mortars made from hydraulic binders. The use of Portland cement in the composition of recycled cold mixtures has been recognized and extensively described in the literature [16, 17]. However, the influence of hydraulic binders has not been thoroughly investigated.

The scope of the research included determining the mechanical properties of hydraulic binders and the mechanical properties of the mineral-binder mixture with foamed bitumen. The examination of hydraulic binders included determining basic mechanical properties, specifically:

- compressive strength (R_C) after 7 and 28 days of curing according to PN-EN 196-1 requirements,
- flexural tensile strength (R_f) according to PN-EN 196-1 requirements.

For the mineral-binder mixture with foamed bitumen, the following properties were determined:

- indirect tensile strength (ITS_{DRY}) at +25°C according to PN-EN 12697-23 requirements,
- uniaxial compressive strength (UCS) at +25°C according to PN-EN 13286-41 requirements,
- stiffness modulus (S_m) at +25°C according to PN-EN 12697-26 requirements (IT-CY system),
- dynamic modulus $|E^*|$ according to PN-EN 12697-26 requirements (DTC-CY system),
- fracture toughness (K_{IC}) according to PN-EN 12697-44 requirements (SCB system).

The results of the mortar strength and MCAS mixture are the outcome of the TECHMATSTRATEGI research work [11]. The mortar results have been detailed in the paper

[18], while the results of the MCAS mixture are described in the paper [19].

The developed research plan allowed for determining the relationship between the properties of the mineral-binder mixture produced using cold technology with foamed bitumen and the properties of mortars made from hydraulic binders.

3. MCAS MIXTURE DESIGN AND CHARACTERIZATION OF THE THREE-COMPONENT BINDER

3.1. THREE-COMPONENT BINDER

The composition of the three-component binder, dedicated to the deep cold recycling technology, was developed using a simplex-centroid experimental design. The experimental domain defines the position of points located inside an equilateral triangle, determining the composition of seven road binders formed by combinations of three basic components: Portland cement CEM I 32.5R, hydrated lime ($Ca(OH)_2$), and by-products of cementitious materials (UCPP).

The primary goal of the research and analysis was to investigate the influence of normally binding binders (HRB-N) and fast-binding binders (HRB-E) on the properties of the mineral-binder mixture with foamed bitumen. The composition of each binder is presented in Table 1. Graphically, Fig. 1 illustrates the arrangement of the analyzed compositions on the equilateral triangle, with its sides representing the boundary of the experimental domain.

Table 1. Symbol and quantitative composition of three-component binders

Symbol	CEM [%]	$Ca(OH)_2$ [%]	UCPP [%]
1 V	20	20	60
2 V	20	60	20
3 V	60	20	20
4 C	20	40	40
5 C	40	20	40
6 C	40	40	20
7 C	33.33	33.33	33.33

The composition of the binder resulted from the adopted simplex-centroid plan with an additional constraint eliminating situations where binders consist of 100% basic components. To illustrate the method of determining the expected value of properties for both MCAS mixtures and mortars, the methodology for reading data from the nomogram is presented in Fig. 1

As the approximating function, a polynomial function was adopted. The degree of the polynomial depended on the significance of the contribution that its form made to explaining the variability of the research results. The analysis was a “lack of fit” test, aiming to indicate whether the explanation of variability provided by the model is greater than the range of random estimation error. For this purpose, the ANOVA procedure was used. The next step of the analysis was the estimation of polynomial coefficients with a degree determined based on the analysis of variance. The approximation of parameters was based on

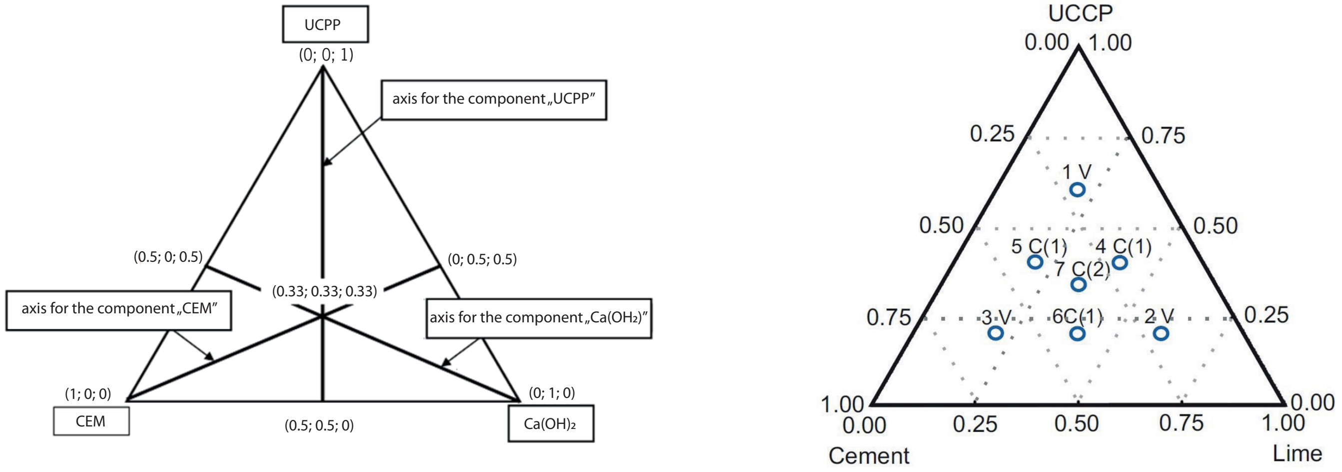

Fig. 1. Methodology for determining the composition of the binder

the method of least squares (MLS). The general model of the function of the research object was as follows:

$$y = b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_{12} \cdot x_1 \cdot x_2 + \\ + b_{13} \cdot x_1 \cdot x_3 + b_{23} \cdot x_2 \cdot x_3 + b_{123} \cdot x_1 \cdot x_2 \cdot x_3 \quad , \qquad (1)$$

where:

b_{ijk} – experimental parameters of the model,

x_i – the i-th independent variable,

y – dependent variable.

3.2. MINERAL-BINDER MIXTURE WITH FOAMED BITUMEN (MCAS)

According to the adopted experimental plan, seven mineral-binder mixtures with foamed bitumen (MCAS) were designed, differing in the type of hydraulic binder. The signature of the mixtures followed the assigned numbering of combinations of binder components, for example, MCAS-1V, indicating that the composition of the MCAS mixture includes a binder consisting of: 20% Portland cement CEM I 31.5R, 20% hydraulic lime $Ca(OH)_2$, and 60% by-products of cementitious materials. The percentage share of individual fraction groups for the MCAS mixture is presented in Table 2, and the grain size distribution curve for the MCAS mixture is shown in Fig. 2.

Table 2. Percentage of MCAS mixture components

No.	Component	MM [%, m/m]	MCAS [%, m/m]
1	Recycled Asphalt Pavement (RAP)	40.0	37.6
2	Aggregate with continuous grain size of 0/31.5 mm, dolomite.	50.0	47.0
3	Fine aggregate 0/2 mm, dolomite.	10.0	9.4
4	Three-component binder (1V; 2V; 3V, 4C, 5C, 6C, 7C)	0.0	3.0
5	Foamed bitumen 70/100	0.0	3.0

In the mixture, road bitumen 70/100 was used as the binder, and its viscosity was reduced through the foaming process. This is required when dosing bitumen for mixtures produced using cold mix technology [20, 21, 22]. The optimal amount of water necessary to obtain bitumen foam was determined according to the guidelines [20]. The foaming of the binder was performed at a temperature of 160°C, water pressure of 6.0 kPa, air pressure of 5.5 kPa, and foaming water content equal to 2.5% by weight of the asphalt binder. The result of the evaluation is presented in Fig. 3.

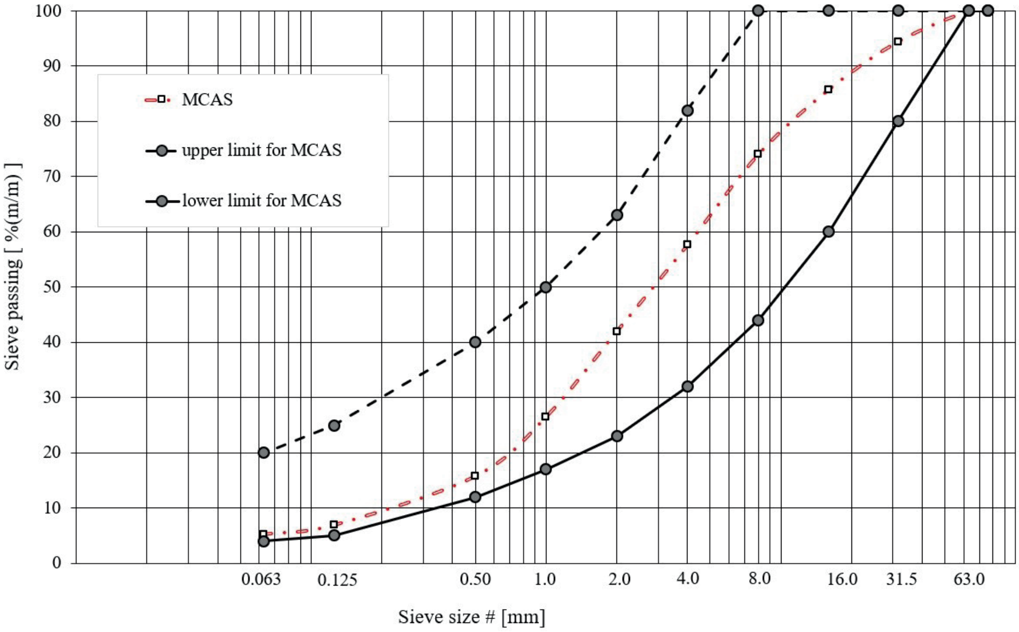

Fig. 2. Designed grain size curve of the MCAS mixture

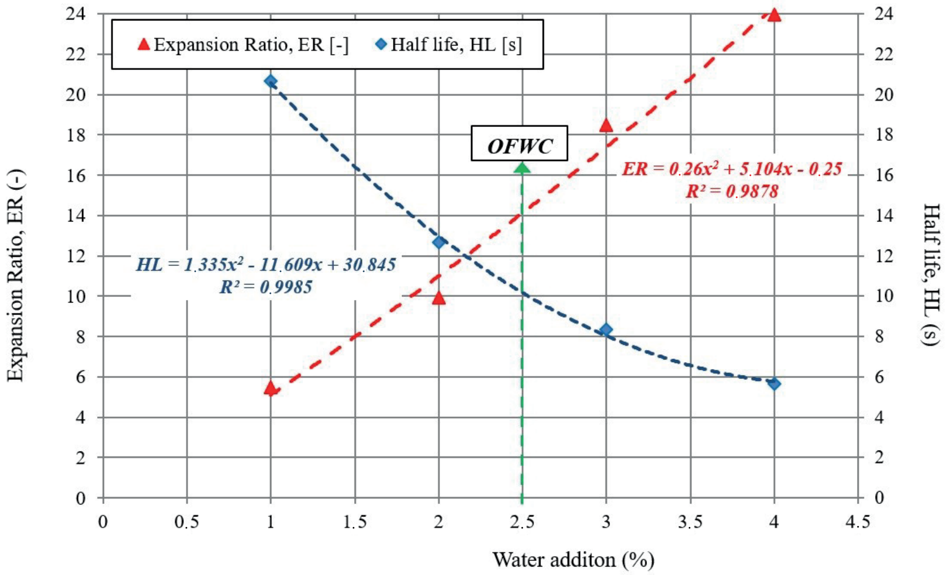

Fig. 3. Determination of the optimal water content for foaming 70/100 bitumen

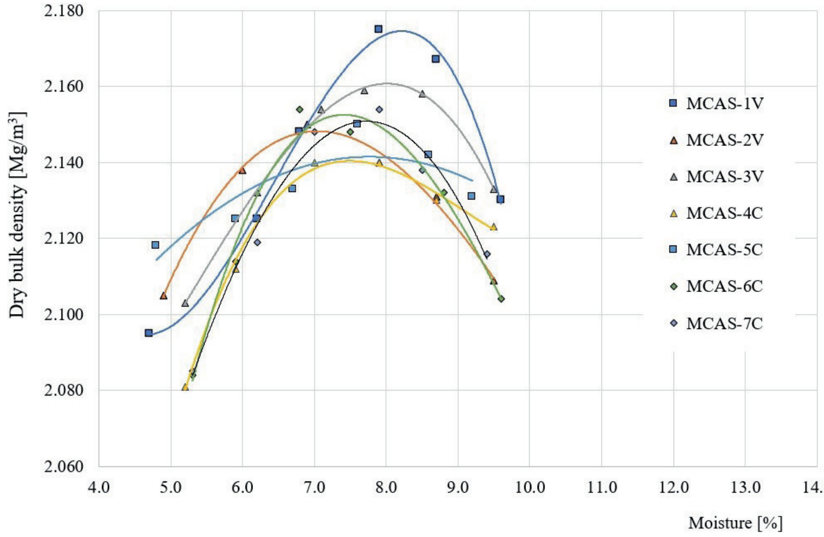

Fig. 4. Relationship between moisture and volumetric density of the skeleton in the MCAS mixture

Detailed results of the tests on the base bitumen 70/100 before and after foaming are presented in the study [23].

To ensure proper compaction of the MCAS mixture, the optimal amount of water was determined according to the requirements of standard PN-EN 13286-2 using the Proctor method [24].

The results of this study, in the form of the relationship between the maximum density of the MCAS mixture skeleton and moisture content, are presented in Table 3 and Fig. 4.

Table 3. Optimal amount of water in the MCAS mixture

Mixture	Research method	Measurement unit	OMC
MCAS-1V	EN 13286-2	%	7.9
MCAS-2V			6.9
MCAS-3V			7.7
MCAS-4C			7.9
MCAS-5C			7.6
MCAS-6C			7.5
MCAS-7C			7.9

4. STUDY RESULTS

4.1. THREE-COMPONENT BINDER

The evaluation of binder parameters was one of the elements assessing its suitability for the MCAS technology and the possibility to determine the relationship between the mechanical properties of binders and the mechanical properties of the MCAS mixture. The presented results of tricomponent binders are part of the research plan of the Techmatstrateg I project [11]. The quality of the binder was assessed according to the normative requirements for rapid-setting binders (HRB-E) [25] and normally-setting binders (HRB-N) [26] in terms of mechanical properties. The results of the binder tests are presented in Table 4 and graphically in Fig. 5.

Table 4. Mortar test results [11, 27]

Binder symbol	Compressive strength of mortars R_C according to [28] [MPa]		Flexural tensile strength R_f according to [28] [MPa]	
	after 7 days	after 28 days	after 7 days	after 28 days
CEM	**34.2**	**46.8**	**6.4**	**7.1**
1 V	3.9	6.7	1.4	2.4
2 V	1.4	2.1	0.1	0.3
3 V	17.1	21.1	4.0	3.7
4 C	3.0	5.9	1.1	1.9
5 C	7.7	13.6	2.3	3.8
6 C	6.9	10.9	2.0	3.1
7 C	5.9	9.2	1.8	2.9

The regression models for the analyzed characteristics describing the influence of the binder composition on mechanical properties, such as compressive strength and flexural tensile strength, are presented in Table 5. Regression models can be used to predict the properties of mortars depending on the composition of the hydraulic binder.

The graphical interpretation of the influence of the percentage composition of binder components on the mechanical properties of mortars can be assessed based on the nomograms presented in Fig. 5. Determining the value of a specific characteristic is done in a manner similar to the commonly used Feret's triangle method [29]. The intersection point of the bisectors of the triangle's vertex angles (Fig. 1) allows for the approximate determination of the sought-after characteristic. The exact value of the sought-after characteristic can be calculated using the determined regression models (Table 5).

It should be observed that the smallest impact on the analyzed mechanical properties of mortars (Fig. 5) is exerted by the component $Ca(OH)_2$ and interactions between $Ca(OH)_2$ – UCPP. Analyzing the results in Fig. 5a-b, it can be stated that the highest predicted compressive strength value of the mortar after 7 and 28 days can be read for 100% CEM. Combining cement with lime and by-product cementitious powdery materials up to 20% allows achieving compressive strength after 7 days above 25MPa but less than 32.5MPa. Such a combination of components classifies such a binder as

Table 5. Material models of the influence of hydraulic binder composition on mortar properties

Material model for the feature:	RMSE	R^2
$R_{C\text{-}7\ days} = 34.45 \cdot CEM + 0.25 \cdot Ca(OH)_2 + 1.53 \cdot UCPP - 18.36 \cdot CEM \cdot Ca(OH)_2 + - 2.30 \cdot CEM \cdot UCPP - 1.81 \cdot Ca(OH)_2 \cdot UCPP - 111.01 \cdot CEM \cdot Ca(OH)_2 \cdot UCPP$	0.75	0.99
$R_{C\text{-}28\ days} = 46.50 \cdot CEM + 0.38 \cdot Ca(OH)_2 + 3.88 \cdot UCPP - 57.00 \cdot CEM \cdot Ca(OH)_2 + - 24.78 \cdot CEM \cdot UCPP - 18.63 \cdot Ca(OH)_2 \cdot UCPP + 109.91 \cdot CEM \cdot Ca(OH)_2 \cdot UCPP$	1.69	0.99
$R_{f\text{-}7\ days} = 6.46 \cdot CEM - 0.01 \cdot Ca(OH)_2 + 0.35 \cdot UCPP - 4.73 \cdot CEM \cdot \cdot Ca(OH)_2 + 3.60 \cdot CEM \cdot UCPP - 3.17 \cdot Ca(OH)_2 \cdot UCPP$	0.11	0.97
$R_{f\text{-}28\ days} = 7.29 \cdot CEM + 0.01 \cdot Ca(OH)_2 + 1.90 \cdot UCPP - 20.50 \cdot CEM \cdot Ca(OH)_2 + - 8.91 \cdot CEM \cdot UCPP - 16.06 \cdot Ca(OH)_2 \cdot UCPP + 140.62 \cdot CEM \cdot Ca(OH)_2 \cdot UCPP$	0.17	0.96

CEM – percentage of Portland cement CEM I 32,5R (from 20% to 100% by mass in the binder composition)
$Ca(OH)_2$ – percentage of hydrated lime (from 20% to 100% by mass in the binder composition)
UCPP – percentage of by-product cementitious powdery materials (from 20% to 100% (m/m) in the binder composition)
RMSE – root mean square error
R^2 – correlation coefficient
NOTE: CEM + $Ca(OH)_2$ + UCPP = 100% (m/m)

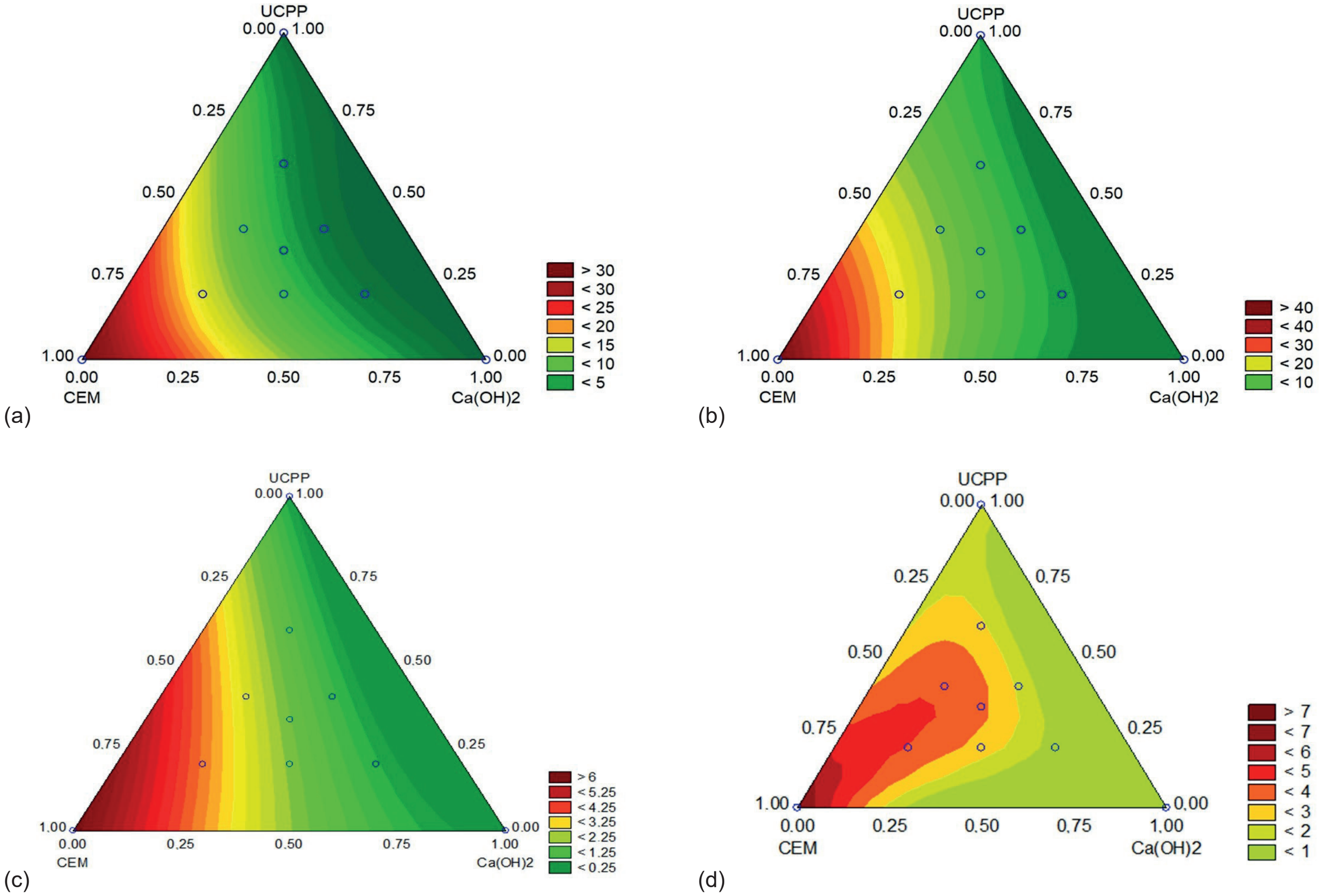

Fig. 5. Results of tests on mortars and pastes based on three-component binder: a) compressive strength after 7 days; b) compressive strength after 28 days; c) flexural tensile strength after 7 days; d) flexural tensile strength after 28 days

a fast-setting binder [25]. Adding UCPP and $Ca(OH)_2$ to the binder composition above 20% but not more than 30% individually or as the sum of $Ca(OH)_2$ and UCPP allows reducing compressive strength. Similar dependencies to those obtained for compressive strength of mortars were obtained for flexural tensile strength (Fig. 5c-d). Analyzing the results in Fig. 5d, it can be stated that the highest estimated value of flexural strength (R_f) after 28 days of the binder can be read for 100% CEM and its combination with a small admixture of UCPP and $Ca(OH)_2$ in equal proportions, totaling 25%. It should be noted that for flexural strength after 28 days, it is much more advantageous to use UCPP as an admixture to the CEM component than $Ca(OH)_2$. However, the lowest flexural strength of mortars after 28 days was obtained for $Ca(OH)_2$ and its mixture with UCPP.

4.2. MINERAL-BINDER MIXTURE WITH FOAMED BITUMEN

Table 6 presents the results of basic mechanical properties of the MCAS mixture, which will be used to correlate the results of mechanical tests of mortars in which a three-component binder was used. The obtained results of the tests are characterized by relatively high uniformity for coarse-grained mixtures made according to the assumptions of the deep cold recycling technology.

The results show a significant influence of the binder composition on the properties of the MCAS mixture. As expected, the MCAS mixture containing Portland cement CEM I 32.5R exhibits the highest stiffness among all analyzed mixtures. The obtained values of the stiffness modulus, regardless of the testing method, are higher than those of mixtures containing the three-component binder.

Table 6. Results of mechanical tests for the MCAS mixture

Mixture symbol	ITS_{DRY}		UCS		S_m at 25°C		K_{IC}		|E*| +13°C; 1Hz	
	X [kPa]	V [%]	X [MPa]	V [%]	X [MPa]	V [%]	X [$N/mm^{1.5}$]	V [%]	X [MPa]	V [%]
MCAS-CEM	838	1.9	2.8	2.1	10649	3.3	12.5	16.5	12535	3.4
MCAS-1V	593	2.5	2.0	10.6	5272	7.3	8.9	8.6	8215	1.9
MCAS-2V	587	4.8	2.2	7.9	4675	10.6	7.9	11.0	5574	2.3
MCAS-3V	494	1.2	2.3	16.2	3840	6.4	7.4	17.5	7424	1.4
MCAS-4C	608	1.8	2.2	6.8	4756	6.3	8.8	7.3	6548	1.7
MCAS-5C	720	2.5	2.1	7.4	4840	1.2	10.2	14.2	7295	3.9
MCAS-6C	639	1.9	2.0	15.8	4816	4.8	7.6	15.1	7295	3.7
MCAS-7V	721	2.4	2.4	2.4	5257	4.5	8.4	22.3	8738	2.5

X – mean
V – coefficient of variation

This indicates that the use of hydraulic binder allows for a reduction in stiffness by up to 65%. However, it should be emphasized that the use of hydraulic binder does not significantly affect the reduction of basic mechanical properties. In the case of indirect tensile strength (ITS_{DRY}) and fracture toughness (K_{IC}), a decrease in values of approximately 40% was noted.

Due to the observed significant influence of the hydraulic binder composition on mechanical properties, detailed analyses assessing the significance of the binder composition's impact on mechanical properties have been presented in the paper [19]. It is necessary to check the correlation between the mechanical characteristics of the MCAS mixture and the mechanical properties of the mortars. Recognizing this scope can be an element of forecasting in the design of the MCAS mixture composition and the selection of the type of hydraulic binder.

The regression models describing the influence of the binder composition on the properties of the MCAS mixture are presented in Table 7, forming part of the project results [11]. These models have been discussed in detail in the paper [19]. Regression models can be used to predict the properties of MCAS mixture depending on the composition of the hydraulic binder.

5. CORRELATION OF MECHANICAL PROPERTIES OF MORTARS AND MCAS MIXES

The results of the studies of mechanical properties of the MCAS mixture presented in Table 6 demonstrate a strong

Table 7. Material models of the influence of hydraulic binder composition on MCAS properties

Regression model for material features	RMSE	R^2
$\mathbf{ITS_{DRY}} = 493.67 \cdot CEM + 587.33 \cdot Ca(OH)_2 + 592.67 \cdot UCPP + 394.00 \cdot CEM \cdot Ca(OH)_2 + 708.67 \cdot CEM \cdot UCPP + 70.67 \cdot Ca(OH)_2 \cdot UCPP + 893.00 \cdot CEM \cdot Ca(OH)_2 \cdot UCPP$	274.3	0.97
$\mathbf{UCS} = 2.33 \cdot CEM + 2.20 \cdot Ca(OH)_2 + 1.97 \cdot UCPP + 0.93 \cdot CEM \cdot Ca(OH)_2 + 0.33 \cdot CEM \cdot UCPP + 0.60 \cdot Ca(OH)_2 \cdot UCPP + 7.40 \cdot CEM \cdot Ca(OH)_2 \cdot UCPP$	0.05	0.36
$\mathbf{S_{m+25°C}} = 3840.25 \cdot CEM + 4675.25 \cdot Ca(OH)_2 + 527.25 \cdot UCPP + 233.00 \cdot CEM \cdot Ca(OH)_2 + 113.00 \cdot CEM \cdot UCPP - 87.00 \cdot Ca(OH)_2 \cdot UCPP + 10361.25 \cdot CEM \cdot Ca(OH)_2 \cdot UCPP$	94012.8	0.74
$\mathbf{K_{IC}} = 7.42 \cdot CEM + 7.94 \cdot Ca(OH)_2 + 8.91 \cdot UCPP - 0.251 \cdot CEM \cdot Ca(OH)_2 + 8.012 \cdot CEM \cdot UCPP + 1.63 \cdot Ca(OH)_2 \cdot UCPP - 20.63 \cdot CEM \cdot Ca(OH)_2 \cdot UCPP$	1.5	0.38

CEM – percentage of Portland cement CEM I 32,5R (from 20% to 100% by mass in the binder composition)
$Ca(OH)_2$ – percentage of hydrated lime (from 20% to 100% by mass in the binder composition)
UCPP – percentage of by-product cementitious powdery materials (from 20% to 100% (m/m) in the binder composition)
RMSE – root mean square error
R^2 – correlation coefficient
NOTE: CEM + $Ca(OH)_2$ + UCPP = 100% (m/m)

correlation between the mechanical characteristics of the MCAS mixture and the composition of hydraulic binder. Therefore, it seems necessary to search for correlational relationships between the mechanical characteristics of these two materials. Studies on mineral-cement composites show [30, 31] that there is a possibility of predicting the properties of the composite by assessing the properties of the hydraulic binder intended for composite production. In this regard, it can be hypothesized that similar dependencies occur in the case of MCAS mixtures.

To determine the strength of the linear relationship between individual properties, the correlation coefficient (R^2) was calculated. Various criteria for assessing correlation are presented in the literature [32, 33]. In this paper, it was assumed that when the correlation coefficient (R^2) value is:

- < 0.2 – there is no linear relationship between the examined features;
- 0.2 ÷ 0.4 – there is a clear but low linear relationship;
- 0.4 ÷ 0.7 – the linear relationship is moderate;
- 0.7 ÷ 0.9 – the linear relationship is significant;
- above 0.9 – the linear relationship is very strong.

Each time, the correlation between two basic mortar features, compressive strength (R_C), and flexural tensile strength (R_f), with the mechanical characteristics of the MCAS mixture, such as indirect tensile strength (ITS_{DRY}), axial compressive strength (UCS), modulus of rigidity (S_m), dynamic modulus $|E^*|$, and fracture toughness SCB (K_{IC}), was evaluated. It was observed that dividing the strength of mortars into those with lower and higher parameters improves the correlation of the analyzed results. As a result, the mechanical features of mortars were divided as follows:

- compressive strength of mortar RC<10.0 MPa and RC≥10.0 MPa,
- flexural tensile strength Rf<3.0 MPa and RC≥3.0 MPa.

As a result of the division, binders and MCAS mixtures were separated, grouped according to the rate of increase in the strength of hydraulic binders, with reference to the indicated division presented in the standards [25, 26]. The division of hydraulic binders is presented in Table 8.

Table 8. Division of binders

Binder type	Binder symbol	Mixture symbol
Normally setting binders	1V; 2V; 4C; 7C	MCAS-1V; MCAS-2V; MCAS-4C; MCAS-7C
Quick-setting binders	CEM; 3V; 5C; 6C	MCAS-CEM; MCAS-3V; MCAS-5C; MCAS-6C

The correlation results are shown in Fig. 6 to 12. Table 8 shows the correlation matrix of the analyzed features. Analysis of the correlation between the properties of mortars and MCAS mixtures (Fig. 6 to 12) indicates a large number of very strong linear correlations (R^2>0.90)

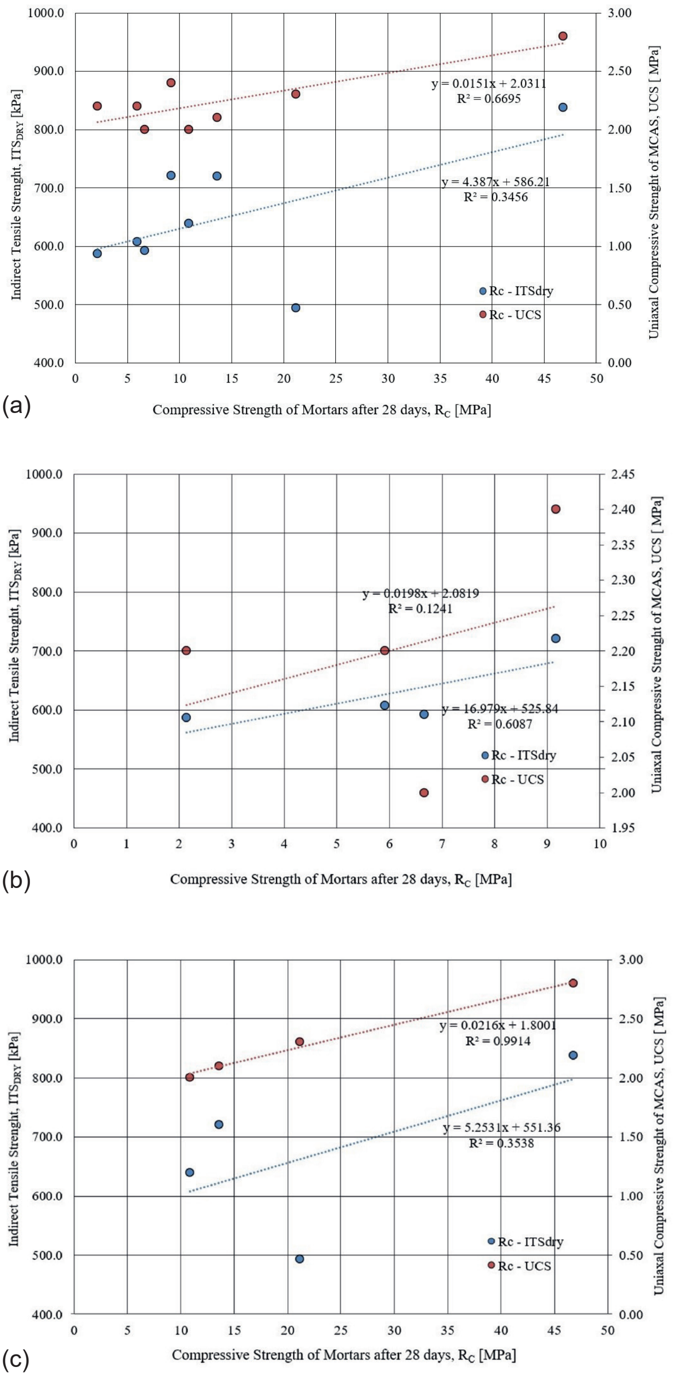

Fig. 6. Feature correlation in terms of: a) R_C–ITS_{DRY} / UCS, b) R_C<10.0 MPa–ITS_{DRY} / UCS–, c) R_C≥10.0 MPa–ITS_{DRY} / UCS

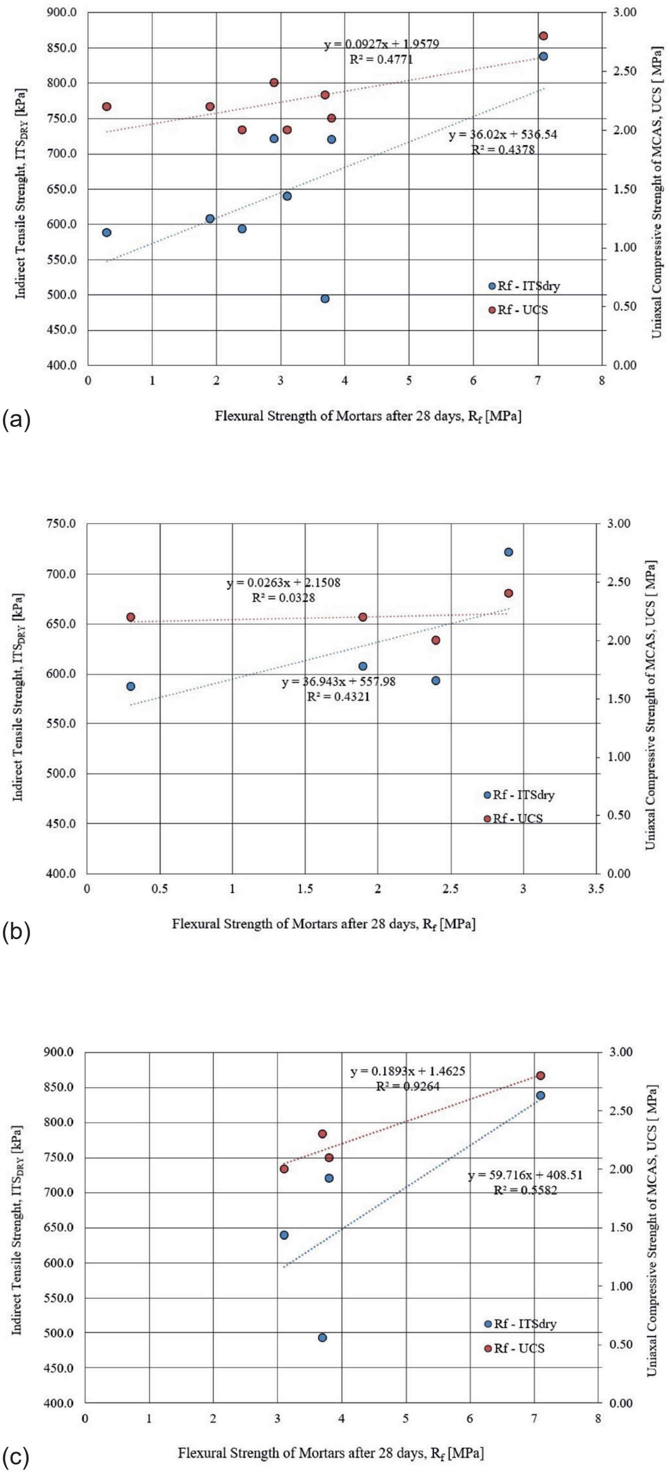

Fig. 7. Feature correlation in terms of: a) R_f–ITS_{DRY} / UCS, b) R_f<3.0 MPa–ITS_{DRY} / UCS–, c) R_f≥3.0 MPa–ITS_{DRY} / UCS

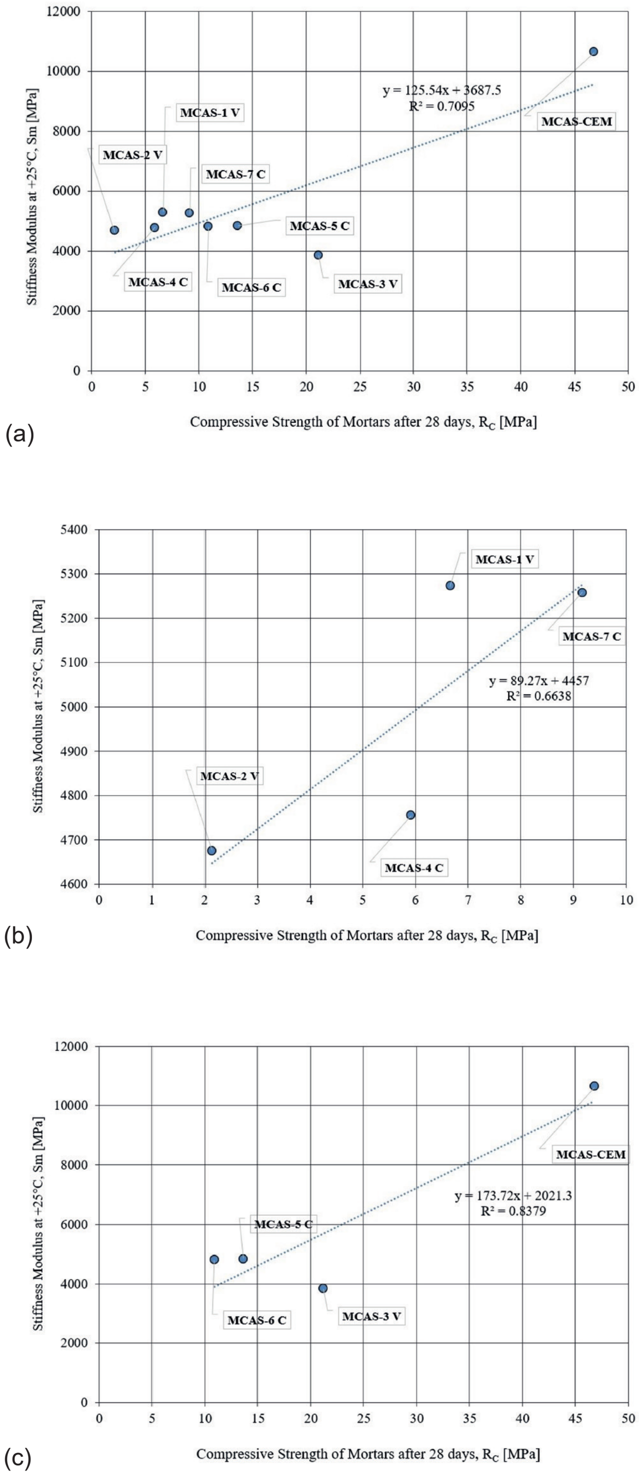

Fig. 8. Feature correlation in terms of: a) R_C–$S_{m+25°}$, b) R_C<10 MPa – $S_{m+25°C}$, c) R_C≥10 MPa – $S_{m+25°C}$

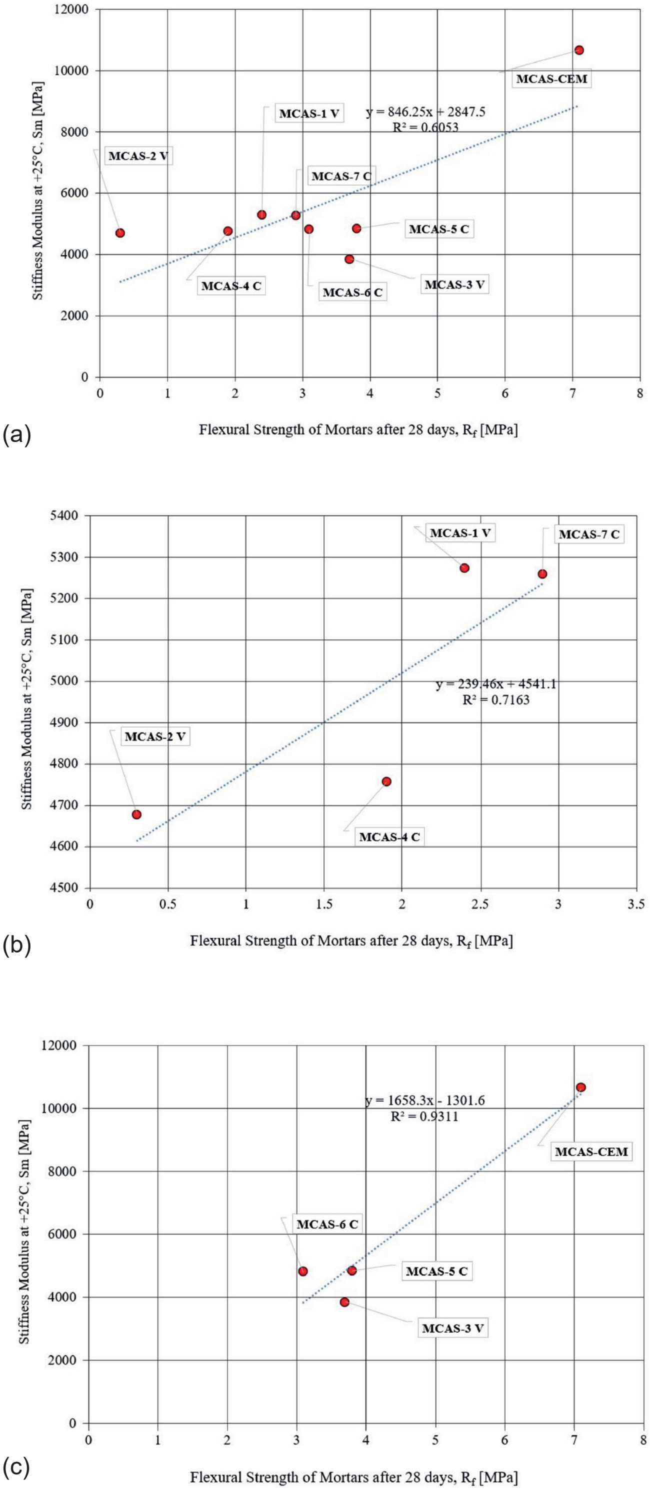

Fig. 9. Feature correlation in terms of: a) R_f–$S_{m+25°}$, b) R_f<3.0 MPa–$S_{m+25°C}$ c) R_f≥3.0 MPa–$S_{m+25°C}$

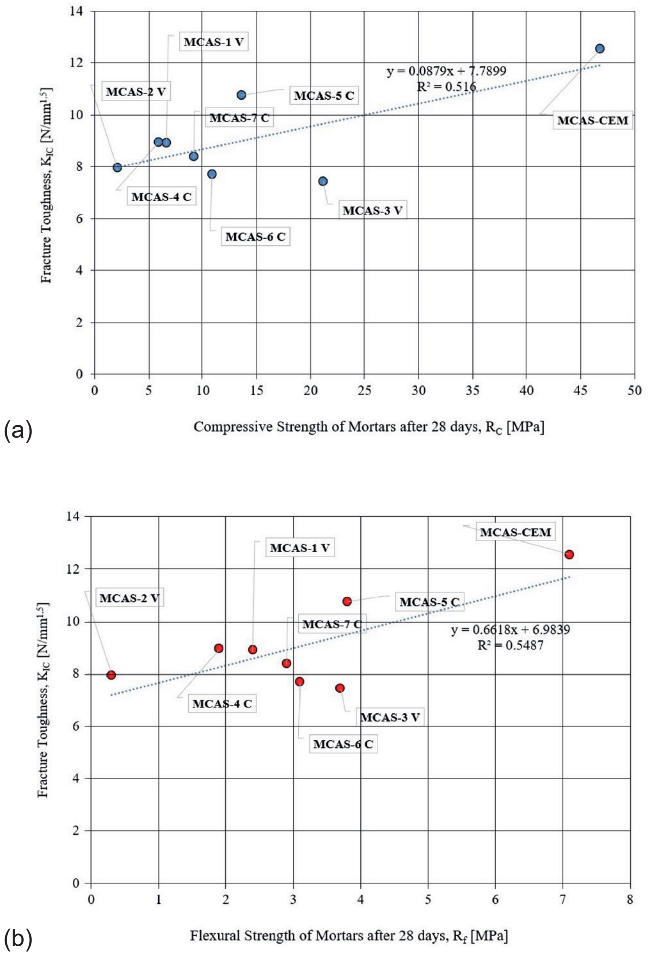

Fig. 10. Feature correlation in terms of: a) K_{IC}–R_C, b) K_{IC}–R_f

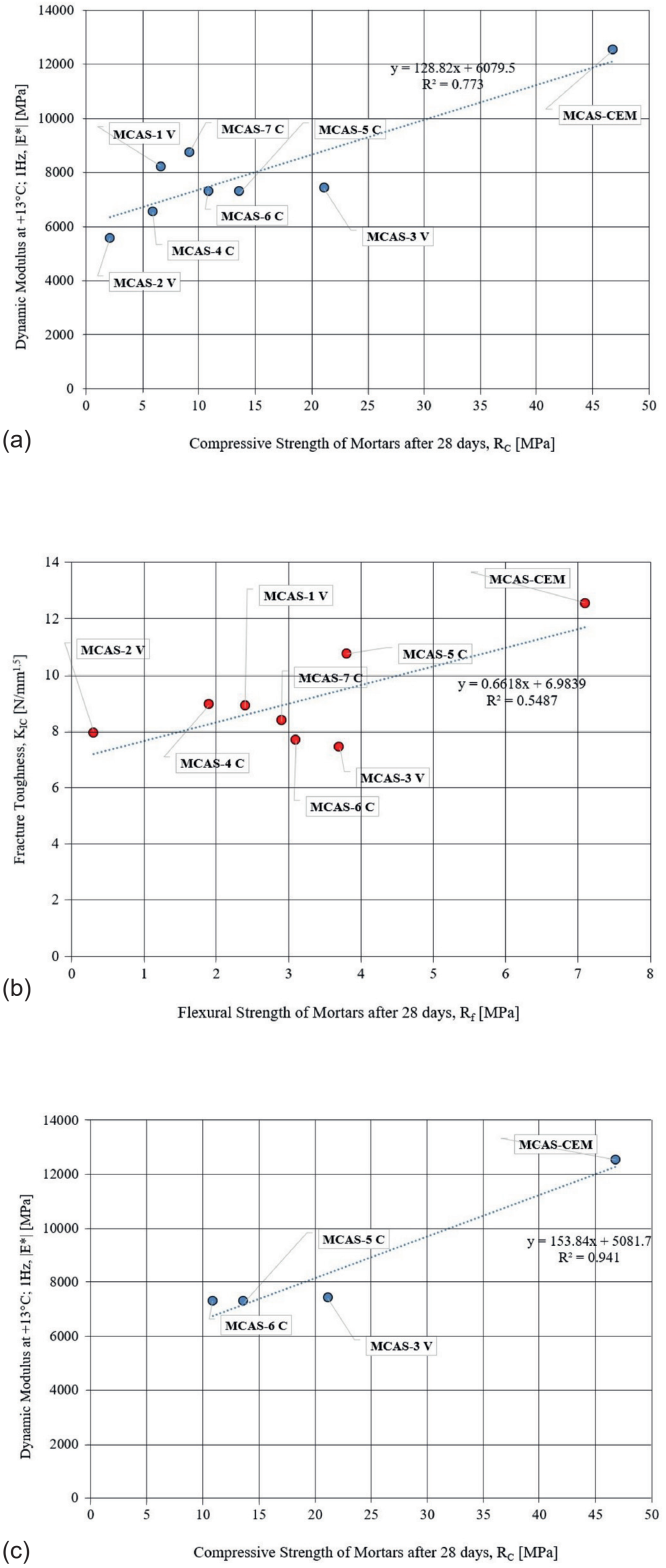

Fig. 11. Feature correlation in terms of: a) R_C–|E*| 13°C; 1 Hz; b) R_C<10 MPa–|E*| 13°C; 1 Hz; c) R_C≥10 MPa–|E*| 13°C; 1 Hz

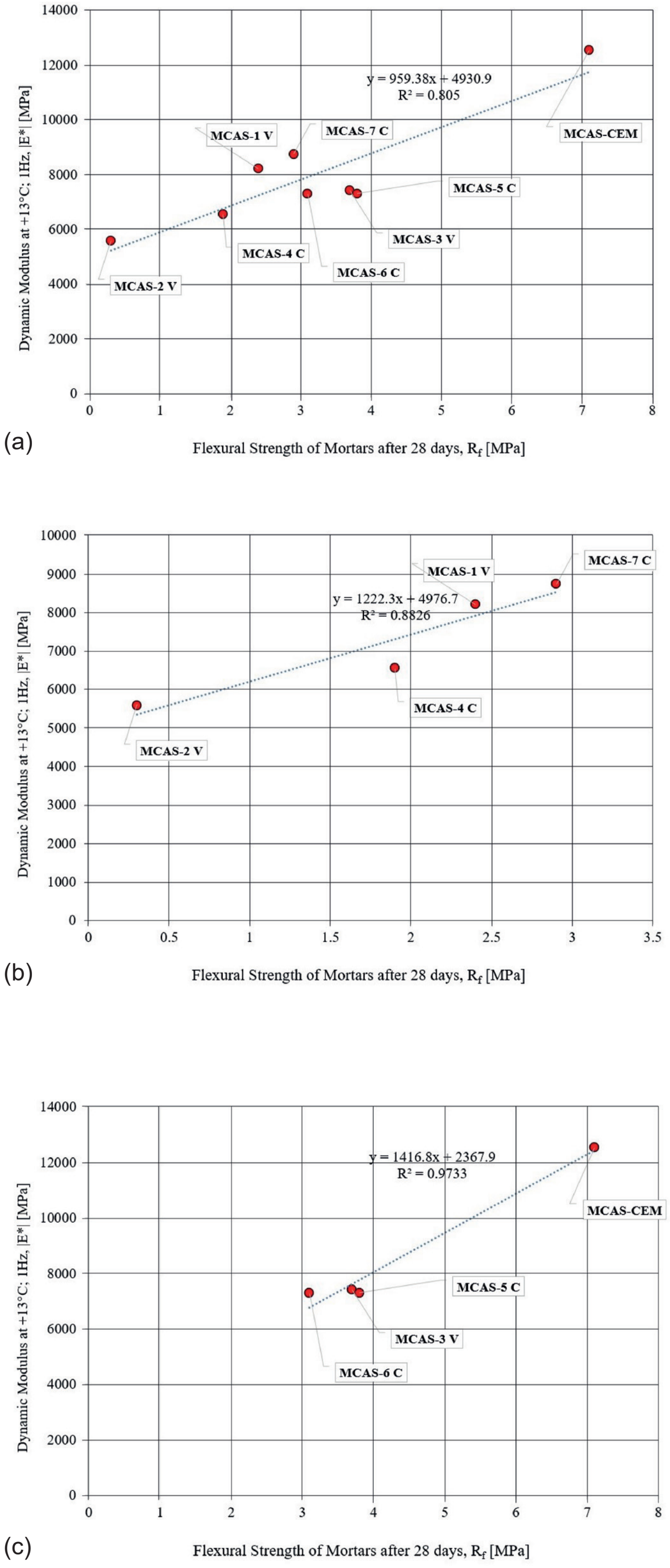

Fig. 12. Feature correlation in terms of: a) R_f–|E*| 13°C; 1 Hz; b) R_f<3.0 MPa–|E*| 13°C; 1 Hz c) R_f≥3.0 MPa – |E*| 13°C; 1 Hz

Table 9. Correlation matrix

	ITS_{DRY}	UCS	S_m	K_{IC}	$\|E^*\|$
R_C	0.35	0.67	0.71	0.56	0.77
$R_C < 10.0$ MPa	0.61	0.12	0.66	-	0.86
$R_C \geq 10.0$ MPa	0.35	0.99	0.84	-	0.94
R_f	0.44	0.48	0.61	0.55	0.81
$R_f < 3.0$ MPa	0.43	0.03	0.72	-	0.88
$R_f \geq 3.0$ MPa	0.56	0.93	0.93	-	0.97

- < 0.2 – there is no linear relationship between the examined features;
- 0.2 ÷ 0.4 – there is a low linear correlation
- 0.4 ÷ 0.7 – the linear relationship is moderate
- 0.7 ÷ 0.9 – the linear relationship is significant
- above 0.9 – the linear relationship is very strong

and significant R^2 in the range of 0.70 to 0.90. These relationships were observed for the following mechanical properties of the MCAS mixture: compressive strength (UCS), stiffness modulus (S_m), and dynamic modulus ($|E^*|$). Higher correlations were observed in the case of the correlation of these properties with mortars prepared with a fast-setting hydraulic binder, regardless of the analyzed mortar strength (R_C; R_f). An interesting observation is the high correlation of the stiffness modulus and dynamic modulus with the tensile strength at bending ($R_f \geq 3.0$ MPa). In both cases, the R^2 coefficient is greater than 0.90. This indicates the possibility of predicting the stiffness of the MCAS mixture in terms of properties of mortars with hydraulic binders. A similar relationship was obtained for the compressive strength (UCS) of the MCAS mixture with the compressive strength of the fast-setting mortar ($R_C \geq 3.0$ MPa). Regardless of the analyzed properties, the trend line of the correlation indicates that the mechanical parameters of the MCAS mixture increase with the increase in mortar strength.

In the case of the property of indirect tensile strength (ITS_{DRY}), knowledge of the properties of mortars with hydraulic binders moderately describes the relationship $ITS_{DRY} - R_F$; $ITS_{DRY} - R_C$. There is an increase in the ITS_{DRY} strength of the MCAS mixture with the increase in the compressive strength and tensile strength at bending of the mortars, but the established relationships do not have a linear connection between the analyzed features. A similar relationship exists between mortar properties and fracture toughness (K_{IC}). The observed correlation is moderate, with an R^2 coefficient at the level of 0.55. Therefore, predicting the tensile strength (ITS_{DRY}) and fracture toughness (K_{IC}) in the context of the type of hydraulic binder in the composition of the MCAS mixture is difficult to determine unequivocally and should not be taken into account when designing the composition of the MCAS mixture.

Obtaining a strong or significant correlation or its absence ($R^2 < 0.70$) for the properties of the MCAS mixture on the properties of compressive strength and tensile strength at bending is due to the significant correlation between R_C vs. R_f (Fig. 13).

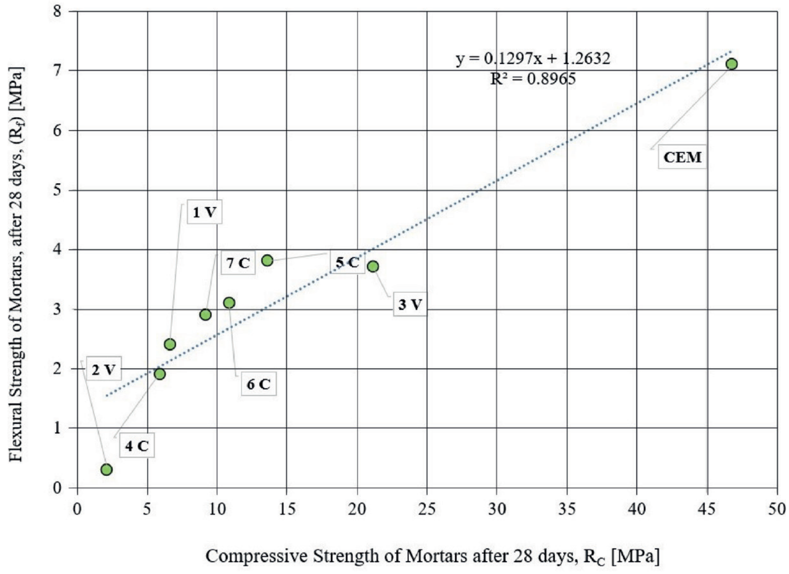

Fig. 13. Feature correlation in terms of R_f vs. R_C

Table 10. Material models of the influence of binder properties on MCAS mixture properties

Material model for the feature	R^2
$\mathbf{UCS} = 0.0216 \cdot R_{C>10MPa} + 1.8001$	0.99
$\mathbf{UCS} = 0.1893 \cdot R_{f>3MPa} + 1.4625$	0.92
$\mathbf{S}_{\mathbf{m\ +25°C}} = 173.72 \cdot R_{C>10MPa} + 2021.3$	0.84
$\mathbf{S}_{\mathbf{m\ +25°C}} = 1658.3 \cdot R_{f>3MPa} - 1301.6$	0.93
$\mathbf{E^*}_{\mathbf{+13°C;1Hz}} = 153.84 \cdot R_{C>10MPa} + 5081.7$	0.94
$\mathbf{E^*}_{\mathbf{+13°C;1Hz}} = 1416.8 \cdot R_{f>3MPa} + 2367.9$	0.97

In cases where the correlation between the results obtained for the MCAS mixture and the results obtained for mortars is very strong ($R^2 \geq 0.90$), a mathematical model describing this relationship has been proposed. The developed relationships expressed by linear equations are presented in Table 10.

The presented equations (Table 10) can be used to predict the properties of the mineral-binder mixture produced in cold technology with foamed asphalt in terms of the properties of mortars with hydraulic binders.

6. CONCLUSIONS

Based on the research and analysis performed, the following conclusions were formulated:

- By demonstrating a very strong correlation between the properties of the MCAS mixture and the properties of mortars, it can be concluded that there is a potential possibility to predict the properties of the MCAS mixture based on the properties of the hydraulic binder.
- Achieving a correlation of mechanical properties of mortars (R_C; R_f) with an R^2 above 0.90 is possible for the following properties of the MCAS mixture: compressive strength (UCS), stiffness modulus (S_m), and dynamic modulus (|E*|).
- Higher correlations of properties of the MCAS mixture occur in the case of fast-setting binders, where the compressive strength (R_C) is greater than 10MPa and the tensile strength in bending (R_f) is greater than 3.0MPa.
- No significant correlation was found between the intermediate tensile strength (ITS_{DRY}) and the characteristics of the hydraulic binder.

ACKNOWLEDGEMENTS

The results of the research were developed within the framework of the project titled "Innowacyjna technologia wykorzystująca optymalizację środka wiążącego przeznaczonego do recyklingu głębokiego na zimno konstrukcji nawierzchni zapewniająca jej trwałość eksploatacyjną" (TECHMATSTRATEG1/349326/9/NCBR/2017) under the Strategiczny program badań naukowych i prac rozwojowych „Nowoczesne Technologie Materiałowe" TECHMATSTRATEG I, which is funded by the National Center for Research and Development.

REFERENCES

[1] *Czapik P., Zapała-Sławeta J., Owsiak Z., Stępień P.*: Hydration of cement by-pass dust. Construction and Building Materials, **231**, 117139, 2020, DOI: 10.1016/j.conbuildmat.2019.117139

[2] *Szyller A., Król J., Bańkowski W.*: Współczesne doświadczenia ze stosowania recyklingu na gorąco w wytwórni mieszanek mineralno-asfaltowych w Polsce. Nawierzchnie asfaltowe, 1, 2017

[3] *Dołżycki B.*: Polish experience with cold in-place recycling. IOP Conference Series: Materials Science and Engineering, **236**, 012089, 2017, DOI: 10.1088/1757-899X/236/1/012089

[4] *Skotnicki Ł., Kuźniewski J., Szydło A.*: Stiffness Identification of Foamed Asphalt Mixtures with Cement, Evaluated in Laboratory and In Situ in Road Pavements. Materials, **13**, 5, 1128, 2020, DOI: 10.3390/ma13051128

[5] *Iwański M., Mazurek G., Buczyński P.*: Bitumen Foaming Optimisation Process on the Basis of Rheological Properties. Materials, **11**, 10, 1854, 2018, DOI: 10.3390/ma11101854

[6] *Niazi Y., Jalili M.*: Effect of Portland cement and lime additives on properties of cold in-place recycled mixtures with asphalt emulsion. Construction and Building Materials, **23**, 3, 2009,1338–1343, DOI: 10.1016/j.conbuildmat.2008.07.020

[7] *Kukiełka J,. Bańkowski W.*: The experimental study of mineral-cement-emulsion mixtures with rubber powder addition. Construction and Building Materials, **226**, 2019, 759–766, DOI: 10.1016/j.conbuildmat.2019.07.276

[8] *Dołżycki B.*: Spękania nawierzchni z podbudową mieszanki mineralno-cementowo-emulsyjnej na przykładzie drogi krajowej nr 7. Drogownictwo, 12, 2009, 411–417

[9] *Baghini M.S., Ismail A., Bin Karim M.R.*: Evaluation of cement-treated mixtures with slow setting bitumen emulsion as base course material for road pavements. Construction and Building Materials, **94**, 2015, 323–336, DOI: 10.1016/j.conbuildmat.2015.07.057

[10] *Kavussi A., Modarres A.:* Laboratory fatigue models for recycled mixes with bitumen emulsion and cement. Construction and Building Materials, **24**, 10, 2010, 1920–1927, DOI: 10.1016/j.conbuildmat.2010.04.009

[11] Raport z Projektu Badawczego – Nowoczesne Technologie Materiałowe TECHMATSTRATEG I „Innowacyjna technologia wykorzystująca optymalizację środka wiążącego przeznaczonego do recyklingu głębokiego na zimno konstrukcji nawierzchni zapewniająca jej trwałość eksploatacyjną”. (TECHMATSTRATEG1/349326/9/NCBR/2017). NCBiR, 2017–2021

[12] *Iwański M., Mazurek G., Buczyński P., Iwański M.M.*: Effects of hydraulic binder composition on the rheological characteristics of recycled mixtures with foamed bitumen for full depth reclamation. Construction and Building Materials, **330**, 127274, 2022, DOI: 10.1016/j.conbuildmat.2022.127274

[13] *Montgomery D.C.*: Design and analysis of experiments. 10th Edition. John Wiley & Sons Inc., Hoboken, 2013

[14] *Deming S.N., Morgan S.L.*: Experimental design: a chemometric approach. Second, revised and expanded edition. Amsterdam, Elsevier, 1993

[15] *Dołżycki B.*: Instrukcja projektowania i wbudowania mieszanek mineralno-cementowo-emulsyjnych (MCE). Warszawa, GDDKiA, 2014

[16] *Dołżycki B., Jaczewski M., Szydłowski C., Bańkowski W., Gajewski M.*: Analysis of selected mechanical properties of mineral-cement-emulsion mixtures (MCE). Roads and Bridges – Drogi i Mosty, **22**, 1, 2023, 41–61, DOI: 10.7409/rabdim.023.003

[17] *Iwański M., Buczyński P.*: Properties of the Recycled Base Course with Respect to the Road Binder Type. The 9th International Conference „Environmental Engineering” 22–23 May 2014, Vilnius, Lithuania, DOI: 10.3846/enviro.2014.156

[18] *Owsiak Z., Czapik P., Zapała-Sławeta J.*: Properties of a Three-Component Mineral Road Binder for Deep-Cold Recycling Technology. Materials, **13**, 16, 2020, DOI: 10.3390/ma13163585

[19] *Iwański M., Mazurek G., Chomicz-Kowalska A., Buczyński P., Cholewińska M., Iwański M.M., Maciejewski K., Ramiączek P.*: Influence of mixed hydraulic binder on the properties of recycled asphalt mixtures with foamed bitumen. Roads and Bridges – Drogi i Mosty, **22**, 1, 2023, 81–114, DOI: 10.7409/rabdim.023.005

[20] Cold – Recycling Technology. Wirtgen Group, 2012

[21] *Csanyi L.H.*: Foamed asphalt. American Road Builders Association (ARBA), Technical Bulletin, **240**, 1959, 3–14

[22] *Guatimosim F.V.K., Vasconcelos L., Bernucci L.L.B., Jenkins K.J.*: Laboratory and field evaluation of cold recycling mixture with foamed asphalt. Road Materials and Pavement Design, **19**, 2, 2018, 385–399, DOI: 10.1080/14680629.2016.1261726

[23] *Iwański M., Chomicz-Kowalska A., Mazurek G., Buczyński P., Cholewińska M., Iwański M.M., Maciejewski K., Ramiączek P.*: Effects of the Water-Based Foaming Process on the Basic and Rheological Properties of Bitumen 70/100. Materials, **14**, 11, 2021, DOI: 10.3390/ma14112803

[24] PN-EN 13286-2 :2010 Mieszanki niezwiązane i związane hydraulicznie. Część 2: Metody badań laboratoryjnych gęstości na sucho i zawartości wody. Zagęszczanie metodą Proctora

[25] PN-EN 13282-1:2013-07 Hydrauliczne spoiwa drogowe: Część 1: Hydrauliczne spoiwa drogowe szybkowiążące. Skład wymagania i kryteria zgodności

[26] PN-EN 13282-2:2015-06 Hydrauliczne spoiwa drogowe: Część 2: Hydrauliczne spoiwa drogowe normalnie wiążące. Skład wymagania i kryteria zgodności

[27] *Owsiak Z., Zapała-Sławeta J., Czapik P.*: Raport 1/1/PŚk/2018 – Wyniki badań innowacyjnego środka wiążącego. Politechnika Świętokrzyska, Kielce, 2018

[28] PN-EN 196-1 Metody badania cementu: Część 1: Oznaczanie wytrzymałości

[29] *Wiłun Z.*: Zarys geotechniki: podręcznik akademicki. Warszawa, WKŁ, 2013

[30] *Tayeh B.A., Hamada H.M., Almeshal I., Bakar B.H.A.*: Durability and mechanical properties of cement concrete comprising pozzolanic materials with alkali-activated binder: A comprehensive review. Case Studies in Construction Materials, **17**, e01429, 2022, DOI: 10.1016/j.cscm.2022.e01429

[31] *Neville A.M., Ajdukiewicz A., Degler A., Kasperkiewicz J.*: Właściwości betonu. Kraków, Stowarzyszenie Producentów Cementu, 2012

[32] *Sobczyk M.*: Statystyka. Wyd. 5 uzup. Warszawa, Wydawnictwo Naukowe PWN, 2007

[33] *Steczkowski J., Zeliaś A.*: Statystyczne metody analizy cech jakościowych. Warszawa, PWE, 1981