The water resistance recycled base with the foamed bitumen in the aspect of hydraulic road binder

Iwański Marek[1, a], Buczyński Przemysław[1, b], Mazurek Grzegorz[1, c]

[1] *Transportation Engineering, Faculty of Civil Engineering and Architecture, Kielce University of Technology, Kielce, Poland*

[a] iwanski@tu.kielce.pl
[b] p.buczynski@tu.kielce.pl
[c] gmazurek@tu.kielce.pl

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ABSTRACT

This paper describes preliminary research results of recycled base properties which was performed in cold deep recycling technology with the foamed bitumen and different kind of the hydraulic road binder in the aspect of water resistance. The design of the recycled base layer simulated a deep cold recycling process with materials derived from crushed bituminous pavement layers ("in-situ" technology). To manufacture the foam bitumen was used a road bitumen of penetration grade 50/70. As a binders were used road binders. They were manufactured in the laboratory through the mixing of the three basic components in the proportions set according to the plan of the experiment. For the purpose of determine the influence of such hydraulic road binder on the water resistance of the recycled base the following test were carried out: void contents Vm, absorbability nw, indirect tensile strength ITSDRY at 25OC, tensile strength ratio TSR (water resistance). Additionally the evaluation of the increase in indirect tensile modulus (IT-CY) was made. On the basis of received test results it was observed the different impact of tested hydraulic road binders on properties of the recycled base with the foamed bitumen. With regard to the design of experiment plan it was possible to determine the recommended road binder composition that allows to obtain requisite the water resistance of the recycled base with foamed bitumen.

Keywords: Design Mix, Dust, Foam, Modified Binders, Reclaimed asphalt pavement (RAP) Recycling

1. INTRODUCTION

The analysis of the applicability of building materials is subjected primarily to assessing the durability of the finished item (pavement structural layer, concrete cement for bridges) in terms of its physical and mechanical parameters. Equivalent factor in the durability of the construction product subjected to exploitation is its assessment in relation to weather conditions. Many researchers have focused their attention on identifying configuration of the individual minerals percentages that will ensure the sustainability of obtained parameters in terms of the water and frost resistance [1, 2, 3, 5, 6]. Both in building construction and road construction it is required to meet the criterion of protection against the negative climatic effects. Road base layers which are formed in the deep cold recycling technology with foamed asphalt are predominantly exposed directly to moisture. This is due to their location in the structural layers [7] and protection slightly against freezing by the layers placed above. This increases the importance of defining water resistance of recycled substructures in deep cold recycling technology with the foamed asphalt. In addition, the ability to apply road binders in the composed recycled road base [8] forces to determine their impact in terms of water resistance. The use of traditional binders as Portland cement in a recycled base to improve the water resistance of the recycled base has been recognized by many researchers [1, 4, 9, 15, 16] for demonstrating the positive impact of the foamed binder. The varied composition of the road binder [10, 11, 12], which results from the availability of complementary ingredients may have different influence on the recycled base properties in both physical and mechanical properties and protection against negative water impacts as well.
In this case it seems necessary to define the parameters of a recycled base with foamed asphalt in terms of the road binder components type. For this purpose three most popular binder components are used: Portland cement, hydrated lime and cement kiln dust. Each of the components is characterized by different properties in the composition of the binder. The work approach to the data analysis will facilitate the composition of the binder composition according to the required performance of a recycled foundation.

2. RESEARCH SUBJECT

The research subject in terms of the binder component effect on the water resistance of the recycled base with foamed asphalt is the designed mineral-binder mixture using the particle size distribution analysis specified in the guidelines [13, 14]. Specimens were compacted in the Marshall forms with the optimum moisture equal to 5.3% as a result of which the maximum density of the mineral-binder mix was obtained equal to 2.227 Mga/m^3. Optimum humidity was determined by using the Proctor method according to EN 13286-2. For the foam formation the neat bitumen with penetration grade 50/70 in an amount of 3% was used. The binder in a recycled foundation was constituted 2.5% of mineral mixture.

2.1. Project of mineral-binder mixture with foamed asphalt

Project of the recycled base mixture included the use of mineral materials which matching allowed to simulate cold deep recycling in technology "in situ". In a recycled mixture four minerals were used: reclaimed asphalt (RAP) with grain size of 0/31.5 mm in an amount of 50% (m/m), natural limestone aggregate from the existing base with a grain size of 0/31.5 mm in an amount of 20 % (m/m), natural dolomite aggregate with continuous grain size 0/4 mm in an amount of 22% (m/m) and mineral dust gabbro origin in an amount of 5% (m/m). It should be noted that the purpose of mineral dust use was to give the required content of the filler fraction (less than 0.063 mm), which in the case of deep recycling technology in cold with foamed asphalt is desired. During foaming the foam bitumen is combined with particulate material to form a "fiber reinforcement" of the thus formed mastic [13, 17]. The applicability of mineral dust to the recycled foundation with foam bitumen has been described in detail in [18,19]. The designed grading curve course of the recycled base is shown in Figure 1.

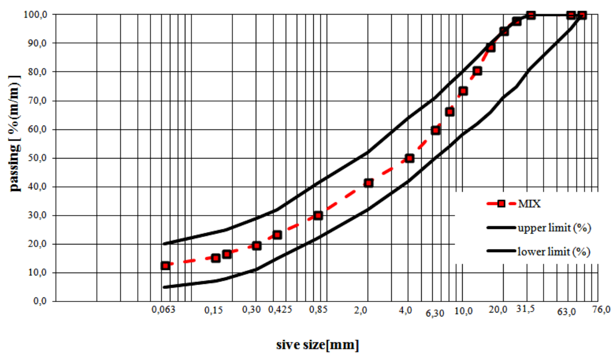

Figure 1: The course of the designed grading curve MCAS

2.2. The properties of foamed bitumen

In the deep recycled technologies with the foamed bitumen this type of bitumen is required which allows to obtain the recommended foaming parameters. These properties are evaluated on the basis of the expansion ratio E_{Rm} (maximum Expansion Ratio) and half-life HL [14, 19]. Minimal bitumen foaming parameters according to the guidance [14, 13] should be equal: to the aggregate at a temperature of 10°C to 15°C where expansion ratio is $E_{Rm} \geq 10$ and half-life HL≥6s [14,13]. If the aggregate temperature is higher than 15°C, then we should apply asphalt binder which parameters are respectively $E_{Rm} \geq 8$ expansion ratio and half-life HL≥6s [13,14].
For the analyze mineral mix asphalt binder with foamed asphalt (MCAS) the road asphalt with penetration grade 50/70. The properties of asphalt are shown in Table 1.

Table 1. Road asphalt properties used in the recycled base

Properties	Research methodology	Measurement units	Average	Coefficient of variation
			χ	v [%]
Penetration Grade at 25ºC	PN-EN 1426	0,1 mm	56	1,2
Softening Point Temperature	PN-EN 1427	ºC	49	2,5
Penetration Index PI (Pen25/T_{PiK})	-	ºC	1,14	1,8
Braking Point Temperature according to Fraass	PN-EN 12593	ºC	- 13,5	3,9

Based on the results of basic road asphalt properties research its classification was found in relation to the requirements of PN-EN 12591: 2010. The number of specimens was consistent with the methodology research for the parameter in the standard for road bitumen. The obtained variation coefficient of less than 5% indicates a high accuracy of the test results.
The road bitumen suitability assessment to the cold deep recycling technology with foamed bitumen in terms of half-life HL and the expansion coefficient E_{Rm}, carried out in accordance with the requirements of the guidelines [13, 14] using asphalt foaming devices. The results of the foam bitumen 50/70 is shown in Figure 2.

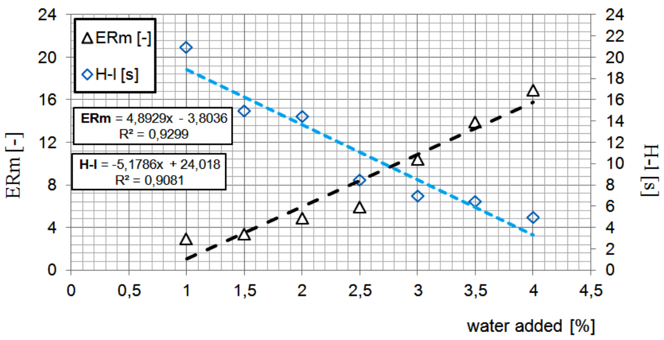

Figure 2: Half-life coefficient (H-L) versus expansion ratio (E_{Rm}) coefficient of the foamed bitumen

The foam asphalt properties evaluation was determined on the basis of changes in the water dosage for the foaming in the range of 1.0% to 4.5% in steps of 0.5% and defining the expansion ratio (E_{Rm} Maximum Expansion Ratio) as well as the half-life HL (Half life). Based on the obtained results, it is concluded that the optimum water content required for analyzed foaming asphalt is equal to 2.9%. This value was determined on the basis of the guidelines [13]. It is the result of the line intersection of the expansion trend (E_{Rm}) and half-life (HL) and determination of the range center for the minimum values E_{Rm} and HL, which allows to determine the optimal foaming value at the optimum water amount needed to obtain the maximum expansion of a colloidal system. While the expansion ratio value for the tested bitumen was obtained E_{Rm}=11.0 with a half-life HL =9,0s. It should also be noted that the variability of test results obtained for the expansion coefficient is equal to (E_{Rm}: R^2= 0.9299), whereas in the case of half-life variation is described on the level of 90.81% (R^2 = 0.9081).

2.3. The binder components

The starting materials applied to form the road binder in order to include in the recycled base composition with foamed bitumen were: hydrated lime $Ca(OH)_2$, cement dust (CKD) and Portland cement CEM I 32.5R. The chemical analysis of the components are shown in Table 2.

Table 2. The binder chemical components

	LOI	$Ca(OH)_2$	SiO_2 *	CaO **	SO_3	Na_2O ***	MgO	Cl	P_2O_5	Al_2O_3	Fe_2O_3
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
CEM I 32,5R	3,1	-	20,2	63,5	3,4	0,16	2,4	0,07	0,33	4,4	2,4
$Ca(OH)_2$		92,2	-	95,1	0,2	-	0,7	-	-	0,4	0,3
CKD	25,2	-	14,9	54,4	1,5	0,3	1,6	4,0	-	3,6	1,9
	* - reactive, ** - free, *** -equivalent .										

The binders used were the most common binders used in road construction and building constructions like: hydrated lime, cement and cement kiln dust. Table 3 shows the connection of the individual components of road binders and the results of specific surface area determined by laser diffraction [20].

Table 3. Determination of binders and surface area

Mixture determination	Binders components	Surface area (cm^2/g)
MIX-R	CEM	3800
MIX-1	$Ca(OH)_2$	5432
MIX-2	CKD	7543
MIX-3	CEM+$Ca(OH)_2$	4803
MIX-4	$Ca(OH)_2$+CKD	4930
MIX-5	CEM+CKD	5403
MIX-6	CEM+$Ca(OH)_2$+CKD	5517

The Portland cement mark I 32.5 R used in the composition of a recycled base with foamed asphalt in terms of water resistance was the reference mix which was defined as MIX-R. The hydrated lime is used due to its coagulation effect and ion exchange. In the case of the mineral materials used the presence of silsty-clay parts will reduce their negative impact on the recycled base properties. The deep cold recycling technologies allow to use the mineral materials characterized by a lower parameter [12, 18, 21, 13], in which composition clay parts may appear. Dust from the cement kilns is the waste material in cement production. Therefore, it is necessary to attempt its disposal what many researchers have already undertaken [21, 23]. Due to the presence of calcium oxide at a level of 30-40% [22] it is characterized by high reactivity.

3. PLAN OF EXPERIMENT

A comprehensive assessment of the recycled base with the foamed asphalt together with seven binders composition project are implemented on simplex centroid assumptions. Experimental plan of road hydraulic binders composition is shown in Table 4. The basic assumption of the experiment plan was to obtain a mixture of components where the sum is 100%. Such an assumption is the basic criterion for the simplex centroid plan applicability which is also called the mixture plan [24, 25]. They allow for the research results analysis with three basic components (factors). The three components mixture can be clearly defined by specifying them as a point. In the triangular coordinate system defined by three variables the plan of experiment layouts is created through a full permutation of the basic components.

Table 4. Simplex centroid experimental plan

Mixture determination	Binder component name			Binders ingredients (combined)
	CEM	$Ca(OH)_2$	CKD	
	Proportions of the binder component regarding to 2,5% (m/m)			
MIX-R	1,0	0,0	0,0	CEM
MIX-1	0,0	1,0	0,0	$Ca(OH)_2$
MIX-2	0,0	0,0	1,0	CKD
MIX-3	0,5	0,5	0,0	CEM + $Ca(OH)_2$
MIX-4	0,0	0,5	0,5	$Ca(OH)_2$ + CKD
MIX-5	0,5	0,0	0,5	CEM + CKD
MIX-6	0,33	0,33	0,33	CEM + $Ca(OH)_2$ + CKD

Visual presentation of experiment plans with the field experiment designation which results from the three components dosing reduction (isosceles triangle) is shown in Figure 3.

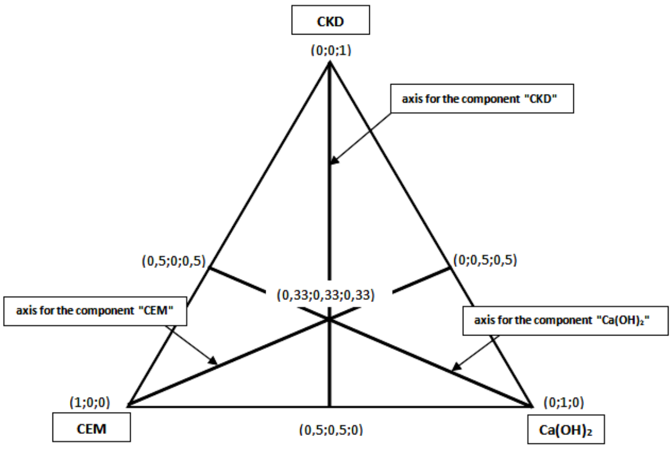

Figure 3: The experiment plan assumption [source: www.statsoft.pl]

The different axes correspond to the following binder components: Axis A - Portland cement, the B axis - hydrated lime, C axis - cement dust.

4. PLAN OF RESEARCH, RESEARCH RESULTS

The research plan included two analysis stages. In the first stage the influence of hydraulic binders on the basic physical and mechanical properties changes of the recycled base was determined, made in the technology in cold condition with foamed bitumen. In the second stage the water resistance was evaluated. Optionally, the second stage comprises optimizing the binder composition in terms of water resistance (TSR).
In the first stage, the physical properties were evaluated ie. the content of void contents V_m, absorbability n_w and mechanical properties for the consideration of mineral binder formulation of foamed asphalt. For this purpose the following parameters were assessed:
- Indirect tensile strength - study at 25°C to EN 12697-23,
- Stiffness modulus in indirect tension IT-CY after 7 and 28 days in accordance with EN 12697-26.

4.1. Physical properties

The basic parameters quality assessment of the recycled base are the free space content V_m and absorbability n_w. These parameters are responsible for ensuring the consistency and the cohesion of the recycled mix. A lower water absorption and the void contents have a positive influence on limiting the water penetration into the structure of a recycled base and its reliable operation in use across the pavement. With respect to the requirements [13, 14, 21] free space content limit is specified $V_m = 5 \div 12$ [%]. The results obtained for the analyzed physical properties are shown in Figure 4 and Figure 5. To evaluate the parameters changes the aforementioned simplex centroid experiment plan was used. To describe the results obtained a model of the second degree was used which is described by formula 1 and a cubic (third degree - formula 2) which significance is shown in Table 5 as well as the coefficients describing the resulting pattern with the significance assessment are shown in Table 6.

$$y_Q = b_1*x_1 + b_2*x_2 + b_3*x_3 + b_{12}*x_1*x_2 + b_{13}*x_1*x_3 + b_{23}*x_2*x_3 \quad (1)$$
$$y_{S.C} = b_1*x_1 + b_2*x_2 + b_3*x_3 + b_{12}*x_1*x_2 + b_{13}*x_1*x_3 + b_{23}*x_2*x_3 + b_{123}*x_1*x_2*x_3 \quad (2)$$

where:
y_Q - second-degree polynomial model,
$y_{S.C}$ - third degree polynomial model,
b_1 ; b_2 ; b_3 - regression function coefficients forming the model,
x_1 ; x_2; x_3 - independent input quantities, factors.

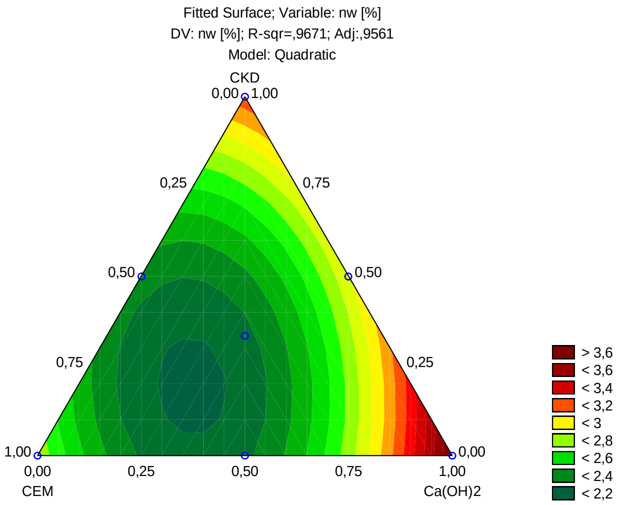

Figure 4: The result of the experiment mixtures plan for the absorption parameter n_w

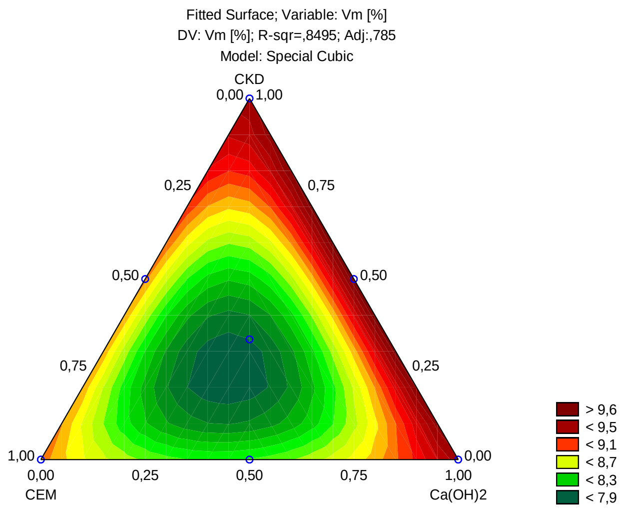

Figure 5: The result of the mixture experiment plan for the free space parameter V_m

Table 5. The mathematical model adjustment for the characteristics distribution nw and V_m

Parametr	Model	F	p	R-Sqr	R-Sqr Adjusted
n_w	Linear	4,32658	0,029222	0,324658	0,249620
	Quadratic	97,50939	0,000000	0,967060	**0,956079**
	Special Cubic	5,51903	0,034011	0,976373	0,966248
V_m	Linear	2,21740	0,137769	0,197675	0,108528
	Quadratic	5,79839	0,007735	0,628498	0,504664
	Special Cubic	20,56169	0,000467	0,849515	**0,785021**

The results of statistical analysis showed that to describe absorption characteristics changes (n) of the recycled bases in terms of the road binders components the second degree polynomial model is the most appropriate. For the changes in the characteristics of the free space contents (V_m) the third degree polynomial model best fits. The determination coefficient describing their fit is at a high level of R^2 above 0.75. The linear model of "Linear" type is not enough to explain the variability of studied parameters.

Table 6. The experimental characteristic factors nw and V m

	CEM	$Ca(OH)_2$	CKD	CEM*$Ca(OH)_2$	CEM*CKD	$Ca(OH)_2$*CKD	CEM* $Ca(OH)_2$*CKD
n_w	2,77803	3,70378	3,1724	-3,8497	-2,5061	-2,1997	-
V_m	8,9545	9,4678	9,4656	-3,2075	-1,1008	0,8778	-27,785
Gray fields represent the binder component significant impact to the tested parameter at a given level of significance α = 0.1							

Based on the obtained results of the absorption and the free space content it can be concluded that the highest value of analyzed parameters the recycled base with foamed asphalt obtained in the dosage ranged from 0% to 100% for hydrated lime and cement dust. The biggest tightness regardless of the analyzed parameters has the recycled base in which composition all the binder ingredients are used. It should also be added that, in relation to the guidelines requirements [13, 14, 21], all the recycled bases meet the required void content Vm = 5÷12 [%]. A statistically significant effect on the analyzed features distribution (n_w and V_m) has the essential binder components. In addition, in case of the absorption the significant influence arises in the all binders components interaction whereas for the void content characteristics was not observed. Furthermore, in the case of V_m the all binder components interaction significantly affected the analyzed characteristics distribution (CEM * $Ca(OH)_2$* CKD). This suggests that during the hardening the chemical process between the components occurs.

4.1. Mechanical properties

Evaluation of the recycled base mechanical properties with foamed bitumen consisted of the analysis of the indirect tensile strength ITS_{DRY} [MPa] and the tensile stiffness modulus evaluation S_m [MPa]. The indirect tensile strength determines the internal consistency of a recycled base and the stress limit beyond which the loss of capacity occurs. The tensile stiffness modulus determines the recycled base carrying capacity in the elastic field ie. with the traffic load at time 0,02s. The results of the analysis to indirect tensile strength ITS_{DRY} at 25°C is shown in Figure 6. To evaluate the parameters changes the simplex centroid experimental plan was used. To describe the obtained results using a second-degree polynomial model represented by the formula (1) which the significance assessment is shown in Table 7 and coefficients that describe the resulting model with the significance assessment are shown in Table 8.

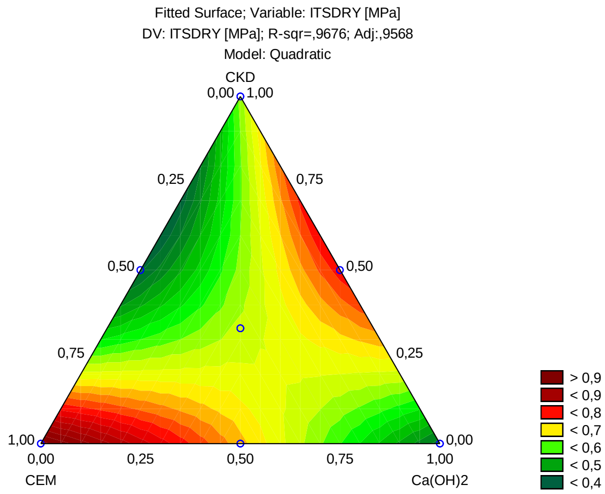

Figure 6: The mixture experiment plan result for the parameter IT DRY

Table 7. The mathematical model adjustment for the characteristics distribution of ITS_{DRY}

Parametr	Model	F	p	R-Sqr	R-Sqr Adjusted
ITS_{DRY}	Linear	2,971	0,0767	0,248	0,1647
	Quadratic	111,149	0,000	0,968	0,957
	Special Cubic	0,243	0,630	0,9688	0,954

The results of statistical analysis showed that for the indirect tensile strength changes description (ITS_{DRY}) of recycled base in terms of the binders road components the most appropriate is a second degree polynomial model. The determination coefficient describing its fit is at a level above 0.9 R^2.

Table 8. The experimental coefficients for characteristic ITS_{DRY}

	CEM	$Ca(OH)_2$	CKD	CEM*$Ca(OH)_2$	CEM*CKD	$Ca(OH)_2$*CKD
ITS_{DRY}	0,96078	0,43832	0,60937	0,04048	-1,4588	1,06736
Gray fields represent the binder component significant impact to the tested parameter at a given level of significance α = 0.1						

Based on the indirect tensile strength study results it can be concluded that the highest strength ITS_{DRY} characterized by recycled base with cement composition. The lowest strength ITS_{DRY} is found for the combination of components CEM-$Ca(OH)_2$-CKD of 50% -0% -50% to the axis of the CEM-CKD (dark green color in Figure 4) and combinations of CEM-$Ca(OH)_2$-CKD of 0% -100% -0%. This is related to the lack of the right components in the cement responsible for the formation of mostly hydrated calcium silicate (CSH phase), hydrated aluminates, calcium ferrites and calcium hydroxide that are responsible for binding the mixture. The studies have shown that the recycled base with foamed asphalt reaches maximum indirect tensile strength to 0.9 MPa. The stiffness of a recycled base in terms of maintenance time is specified in the indirect tension test (IT-CY). The results are shown in Figure 7 and Figure 8 for description of test results obtained using a second degree polynomial model described by formula (1) which the significance evaluation is shown in Table 9 and the coefficients values describing the resulting model with the significance assessment are shown in Table 10.

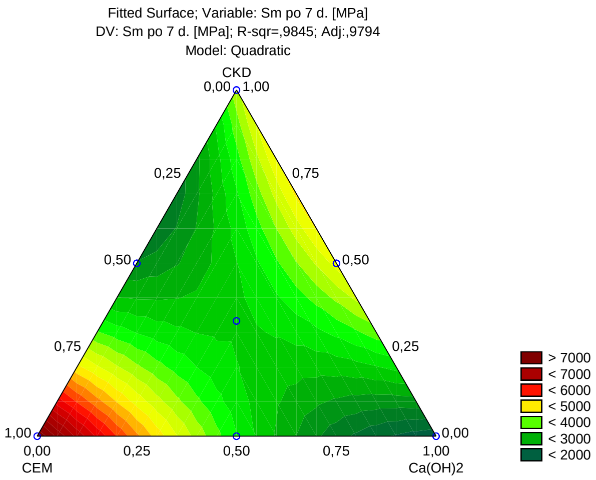

Figure 7: The experiment mixtures plan result for the stiffness modulus parameter Sm [MPa] after 7 days of maintenance.

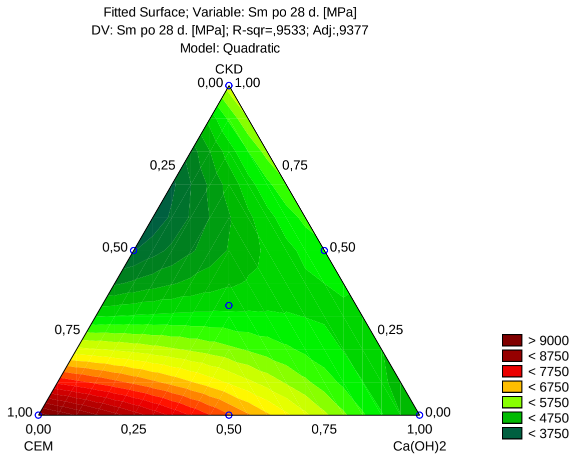

Figure 8: The experiment mixtures plan result for the stiffness modulus parameter Sm [MPa] after 28 days of maintenance.

Table 9. Adjusting the mathematical model for the characteristics distribution S_m after 7 days and after 28 days S_m

Parametr	Model	F	p	R-Sqr	R-Sqr Adjusted
$S_{m\ after}$ 7 days	Linear	6,7201	0,00661	0,42748	0,36387
	Quadratic	180,236	0,0000	0,98455	0,9794
	Special Cubic	0,2423	0,63021	0,98481	0,9783
$S_{m\ after}$ 28 days	Linear	6,57443	0,00719	0,42213	0,35792
	Quadratic	56,84	0	0,95328	0,9377
	Special Cubic	4,27687	0,05763	0,96421	0,94887

The statistical analysis results showed that to describe characteristics changes (S_m after 7 days and S_m after 28 days) of the recycled base in terms of the road binders components the second degree polynomial model is the most appropriate. The determination coefficient describing its fit is at a level above 0.9 R^2.

Table 10. The experimental coefficients of the characteristics Sm after 7 days and after 28 days Sm

	CEM	$Ca(OH)_2$	CKD	CEM*$Ca(OH)_2$	CEM*CKD	$Ca(OH)_2$*CKD
S_m after 7 days	7730	1839,3	4171,7	-5079,8	-13750	6408,9
S_m after 28 days	9121,3	4480	5882,6	908,7	-15070	14,00
Gray fields represent the binder component significant impact to the tested parameter at a given level of significance α = 0.1						

When analyzing the tensile stiffness modulus obtained results (Figure 7 and Figure 8) for a recycled base with foamed asphalt in terms of road binder component it is possible to say that the greatest stiffness regardless of the curing time was observed at 100% of Portland cement participation. It should be noted that, in the component axis area after 7 days of maintenance cement reveals the interaction with the remaining components. The gradual decrease of the compressive strength is revealed by increasing other binder ingredients relatively to the cement amount. It should be also added that the lowest stiffness modules were obtained for recycled base with a hydrated lime. The hydrated lime interaction with the other binder components does not affect the increase of the tensile stiffness modulus in time what the components interaction significance evaluation confirms in relation to the compressive strength after 7 and 28 days curing time.

4.3. The cold recycled base water resistance

To assess the recycled base with foamed asphalt water resistance in terms of road binder used the research methodology described in the guidelines was applied[13]. The index value TSR according to the guidelines [13] should be at least 0.7. The study aims are to determine the recycled base moisture effect on the foamed bitumen bonding weakening and used road binders with the aggregate. The recycled base stability depends on the cycles, the impact of which will decrease structure capacity. In the absence of water resistance the significant decrease in the indirect tensile strength causes the reduction in service life of structural layer. This situation may occur during transitional seasons: winter-spring, autumn and winter when there is a large rainwater and surface water influx into the interior structure. The recycled base with foamed bitumen and road binders water resistance results are shown in Figure 9. To describe the obtained results a second-degree polynomial model was used represented by the formula (1) which significance assessment is shown in Table 11, and coefficients that describe the resulting model together with the significance assessment are shown in Table 12.

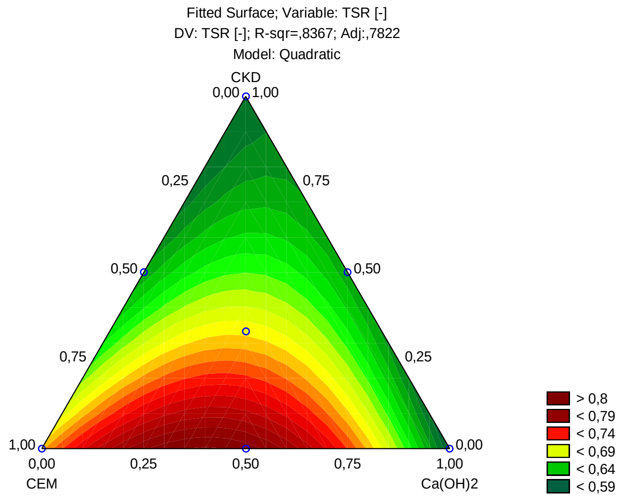

Figure 9: The mixture experiment plan result of the recycled base water resistance TSR

Table 11. Matching the mathematical model for the water resistance distribution.

Parametr	**Model**	**F**	**p**	**R-Sqr**	**R-Sqr Adjusted**
TSR	Linear	5,50112	0,01366	0,37936	0,3104
	Quadratic	14,001	0,00013	0,83668	0,78224
	Special Cubic	0,38954	0,54258	0,8411	0,773

The statistical analysis results showed that the changes description of tensile strength ratio (TSR) of recycled base in terms of the road binders components the most appropriate model is squared.

Table 12. The coefficients of experimental characteristics Sm after 7 days and after 28 days Sm

	CEM	**Ca(OH)2**	**CKD**	**CEM*Ca(OH)2**	**CEM*CKD**	**Ca(OH)2*CKD**
TSR	0,70696	0,58946	0,60068	0,59026	-0,1251	0,11347
Gray fields represent the binder component significant impact to the tested parameter at a given level of significance α = 0.1						

Based on the obtained results it can be concluded that the binder to which cement will not be applied is characterized by a lack of the required water resistance. The maximum value of the index TSR obtained the mixture wherein the composition of the applied binder consisted cement and hydrated lime in the proportion of 50% CEM + 50% $Ca(OH)_2$ the value of the TSR = 0.80. In addition, it should be noted that the binder that is formed with a percentage of hydrated lime (30%) and a small amount of cement dust (10%) is characterized by the desired value of the ratio TSR.

5. DETERMINATION OF THE RECOMMENDED BINDERS COMPOSITION IN TERMS OF WATER RESISTANCE

To solve the optimization problem linear optimization function defined by three characteristic sections was proposed. The utility function assumes a value of 1 for the parameter level equal to 0.8 TSR, for an acceptable parameter level of 0.7 TSR utility function has a value of 0.5. In contrast to the minimum level for the parameter TSR equal to 0.5 [13] function takes a value of 0.

Therefore, by using the Simplex method [25,26] and Statistica batch recommended values of mixture additives were estimated of the recycled base with foamed asphalt relatively to obtain a satisfactory solution with regard to the water resistance parameter TSR. The optimization result of the satisfactory solution lower end of about 0.5 is shown in Figure 10, whereas to obtain the best solution for which the utility function has a value 1, the result is shown in Figure 11.

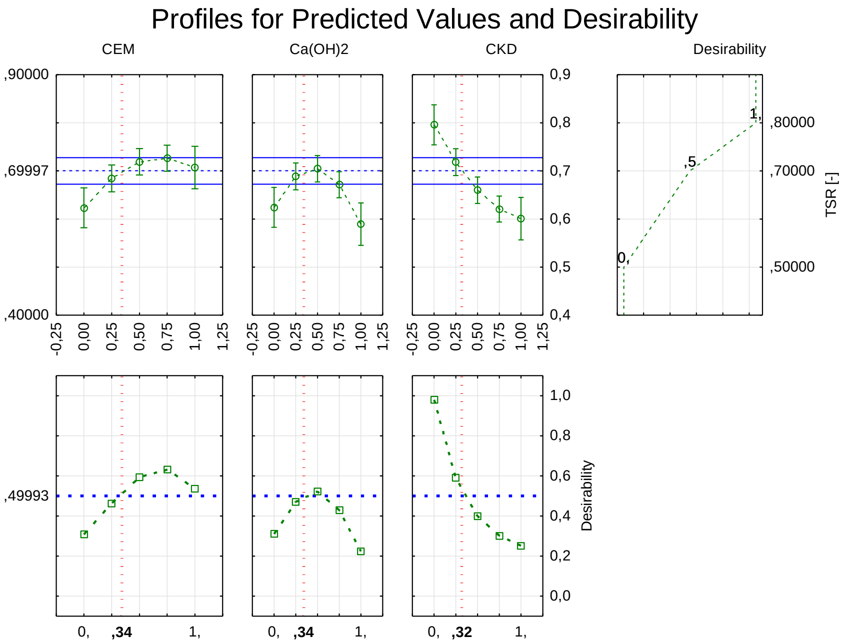

Figure 10: The solution for the utility function of 0.5 (TSR = 0.7)

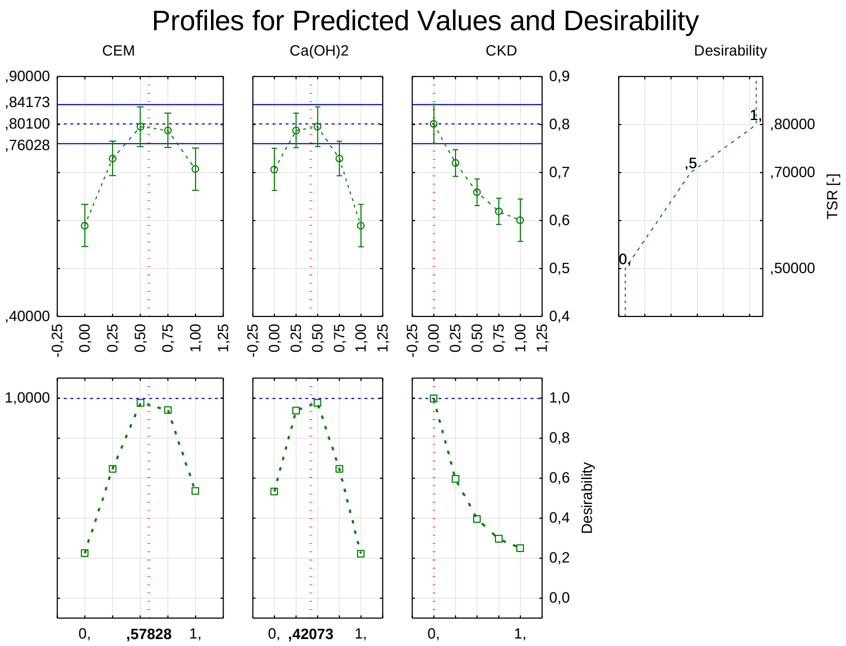

Figure 11: The solution for the utility function of 1

The analysis indicates that the satisfactory interval results in the parameter change of TSR from 0.7 to 0.8. This result suggests a significant insensitivity to percentage changes of each additive in the final binder and is thus insensitive to small errors in dosing. This will be particularly important in practical application. The worrying issue is the fact that the results of the optimization for the parameter TSR = 0.7 (Figure 11) is characterized by a confidence interval that contains the results of TSR below 0.7. Therefore, the lower limit of solution is the parameter average value of the TSR with the confidence interval which results is not less than 0.7. The result is shown in Figure 12.

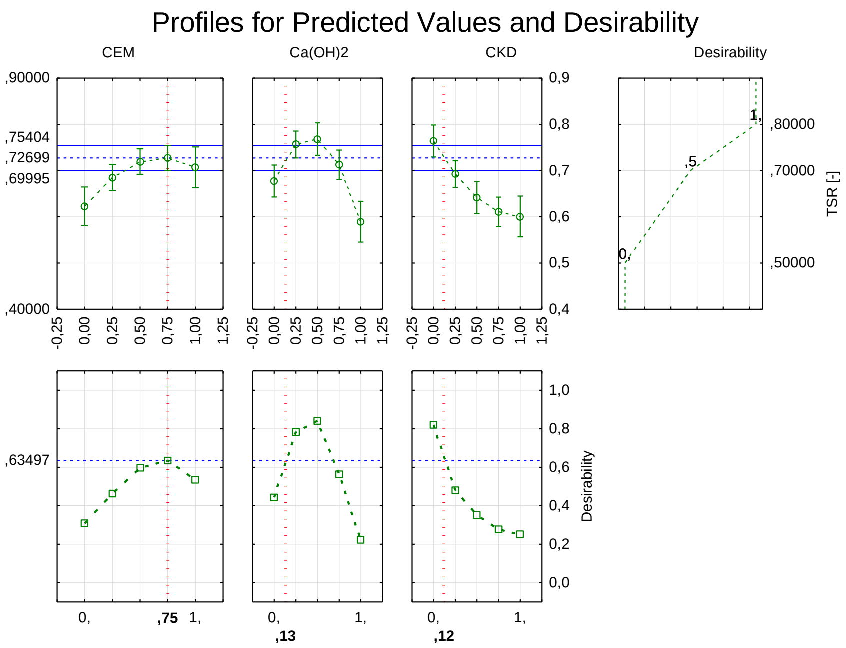

Figure 12: The solution for the utility function of 0.73

Analyzing the three optimize options the recommended values are shown in Table 13.

Table 13. Optimization result

Utility function	Parameter TSR	95% Average confidence parameter TSR	Cement amount (CEM)	Lime amount ($Ca(OH)_2$)	Dust amount (CKD)
[-]	[-]	[-]	[%]	[%]	[%]
0,5	≈0,7	0,67 ; 0,73	34	34	32
0,63	≈0,73	0,7 ; 0,75	75	13	12
1,0	≈0,8	0,76 ; 0,84	58	42	0

As a result it was found that the preferred amount of cement ranges from 34% to 75%, hydrated lime from 13% to 42% and dust CKD up to 32%. It should be noted that the use of cement alone will not ensure a high water resistance. To ensure maximum water resistance, the presence of dust CKD should be exchanged for the CEM-$Ca(OH)_2$ formulation of 58%/42%. The solution in which we get the result parameter equal to 0.7 TSR may contain the results, with a probability of 95%, which will be less than 0.7. Therefore, the safest solution is to adopt the same binders proportion for which the lower limit of the confidence interval parameter TSR equals 0.7. As a result, it was found that the proportion of ingredients CEM-$Ca(OH)_2$ would be 75% / 13% while CKD dusts will amount to 12%.

In conclusion, the recommended cement amount (CEM) must be in the range of about 58% to 75%, hydrated lime ($Ca(OH)_2$) in the range of 13% to 42% and the dust extraction system of not more than 12%. Such a composition of ingredients will provide the required water resistance at TSR parameter equal to 0.7.

6. CONCLUSION

The obtained results analysis allow for the conclusions:

- binders used in the analysis demonstrate that it is possible to use alternative binders in the composition of a recycled base depending on the design requirements and function of the recycled mixture in a layer while maintaining the required water resistance,
- the best results of mechanical and physical properties obtained for blends containing in its composition the additive like hydrated lime in combination with cement,
- all recycled base with foamed asphalt fulfill the requirement of a minimum content of free space. The lowest content of free space equal to V_m = 7.9% obtained the mixture wherein the composition of the applied binder consisted all the analyzed components (CEM CKD + $Ca(OH)_2$),
- cement applied alone will not provide sufficient water resistance of a recycled mix.

- recommended binder composition satisfying the condition of water resistance above the required criterion TSR = 0.70 is as follows: (58% - 75%), CEM (13% - 42%) Ca $(OH)_2$ + max. 12% CKD.

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