# The Effect of the Dedicated Binder on the Properties of Cold Recycled Mixtures

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*Abstract*

*The most important priority in the field of environmental protection is the implementation of the principle of closed-cycle materials management in construction. This problem also plays an important role in road construction. Due to the increasing traffic load of heavy vehicles and the impact of climatic factors, the road structure is subject to destructive processes that lead to the loss of its durability in time. Therefore, the roads periodically need to be modernized. Very often, it is necessary to carry out critical activities on the foundation to improve the load-bearing capacity of the pavement structure. As part of these works, large amounts of reclaimed asphalt and aggregate are obtained during milling of the lower structural layers of the surface. Applying the principle of closed-cycled material management, the most effective technology for using this material is its re-construction using deep cold recycling technology. This technology uses hydraulic binder and bituminous emulsion, and currently, more and more often, foamed bitumen. Due to the fact that the materials obtained from road structure layers are of very different quality, it is necessary to use a binder that will be dedicated specifically to the materials used (reclaimed asphalt pavement, reclaimed stone). In experiment Portland cement CEM I 32.5, hydrated lime and cement by-pass dust as a by-product obtained from cement plants were used. All components were mixed in various proportions controlled by experiment plan. The influence of a dedicated binder on absorption, dynamic modulus, phase angle in the specific temperature range and rutting resistance of a cold recycled mixture designed with reclaimed asphalt pavement, reclaimed aggregate and foamed asphalt was examined. The obtained test results were subjected to statistical analysis using the ANOVA test in order to determine the significance of the influence of individual components of the dedicated binder on the considered parameter of the cold recycled mixtures. It was determined that the dedicated binder used for the tested recycled asphalt mixture ensures its most favorable parameters when contains: 40% CEM I 35.2, 20% hydrated lime and 40% cement by-pass dust.*

**Keywords:** *cold recycled mixtures, dedicated binder, foamed bitumen, reclaimed asphalt pavement*

## 1. Introduction

A sustainable economy seeks to make the broadest possible use of waste materials generated during road rehabilitation [1]. One of the technologies that allow such materials is the cold recycling technology (CR), whose dynamic development began at the end of the 20th century. The material derived from reconstructed pavement layers is reused to produce cold-recycled asphalt mixtures [2-3] or cement concrete [4]. Initially, asphalt emulsion was used as a binder [5-6]. However, the need to remove water from the emulsion in the mixture delayed the curing process [7-9] and placement of subsequent pavement layers. Comprehensive research performed by J.K. Jenkins at the turn of the 21st century showed that the use of water-foamed bitumen provided more favourable properties of recycled asphalt mixtures and significantly shortened the curing period to one or two days [10]. Since then, cold mix asphalt (CMA) technology using foamed bitumen has been developing very dynamically [11-14] not only in terms of its use in deep cold recycling but also in the production of half-warm mix asphalt (HWMA) [15].

A recycled mineral mixture consists of recovered asphalt (RAP), mineral material produced by milling the base layers, and aggregate, usually with a grain size of 0 to 4 mm, used to improve gradation. Cement [16], hydrated lime or various other binder types [17-18] that contain both of these components and additives such as mineral dust, blast furnace dust or cement dust are mainly used as binders.

In order to obtain the best possible properties of cold recycled asphalt mixtures, the properties of mineral material, for example, crushed rock dust or that resulting from drying aggregate in asphalt mix plants, are optimised [19]. Large-scale research is being carried out to improve the properties of bitumen recovered from RAP and asphalt emulsion and foamed bitumen [6, 20-21]by modifying the binder before foaming with various additives such as F-T synthetic wax or surface-active agents SAA [22] or zeolites [23].

Currently produced cold recycled asphalt mixtures are used for the lower layers of renovated pavements and in new pavements [24]. Particular attention is thus paid to the proper selection of the type and amount of binder to ensure the optimal mechanical properties and appropriate durability of pavement structural layers. Initially, pavements demonstrate susceptibility to permanent deformation [25] but with the time in service, excessive stiffness might lead to cracking and fatigue life reduction [26-27]. The composition of recycled bases is specified in the national and international guidelines [4,28]. Analysis of those documents indicates that the use of a recycled hydraulic binder in the form of Portland cement in the base course is limited. This generates a high risk of base course stiffening and shrinkage cracking in the pavement layers (multiple transverse cracks occurring at regular intervals across the width of the wearing course). The adverse effects of excessive recycled base stiffness and the consequences thereof have been the subject of multiple studies worldwide [16]. Researchers are looking for a dedicated hydraulic binder, the composition of which will both maintain the required load-bearing capacity of the base and limit its stiffness. The dedicated binding agent for the recycled base course technology, an alternative solution to the traditional Portland cement, will enable individual approaches to its design. In this way, it will be possible, at the stage of base composition planning, to take into account the environmental conditions in which it will work. The analysis of the literature confirms the validity of this research direction. Many researchers are looking for answers regarding additives (e.g. fly ash, cement dust, ashes from coal combustion) to cement as binders in recycled bases. However, these are single combinations of ingredients in the binder formulations. Studies of cold recycled asphalt mixtures with foamed bitumen pay particular attention to finding the composition that would provide a wide range of mechanical properties for the mixture and pavement layers. The following components were used to make the suitable binder type: cement CEM I 32.5R, hydrated lime and cement bypass dust (CBPD) [17, 29-30] blended at pre-determined ratios. Then, the influence of the amount of the obtained dedicated binder on the mechanical properties of the cold recycled asphalt mixture was investigated.

## 2. Materials and Research Program

### *2.1 Tested Materials*

Paving grade bitumen 70/100, commonly used as a foam in cold recycling, was chosen for this study [20]. Basic test results of bitumen 70/100 are summarised in Table 1. Each property was determined on nine samples [31]. The basic properties of the bitumen are compiled in Table 1 [17].

Tab. 1. Properties of bitumen 70/100 [17]

| Property | Unit | Testing method | Bitumen 70/100 |
|---|---|---|---|
| Penetration at 25°C | 0.1·mm | EN 1426 | 70 |
| Softening point $T_{R\&B}$ | °C | EN 1427 | 47 |
| Fraass breaking point | °C | EN 12593 | - 18 |
| Temperature plasticity range | °C | - | 65 |
| Expansion ratio (ER) | - | (Wirtgen Group, [10]) | 10 |
| Half-life (H-L) | s | (Wirtgen Group, [10]) | 14 |
| Foaming water content FWC | % | (Wirtgen Group, [10]) | 2.5% |

The binder used in the study was composed of three types of materials, namely cement (CEM I 32.5R), cement bypass dust (CBPD) and hydrated lime (HL) [29-30].

In addition to reclaimed asphalt pavement, RAP, with a particle size up to 31.5 mm obtained from milling a pavement wearing course during surface recycling works, the study also used 0/31.5 mm limestone aggregate recycled from pavement layers and virgin 0/2 mm granular aggregate.

The mineral mixture was designed in such a way as to give it a coarse-grained character by increasing the contribution of the coarse aggregate fraction [32]. In addition, a reference cold recycled asphalt mixture was designed with the following composition:

- famed bitumen 70/100 – 3.0%,
- cement (CEM I 32.5R) – 3.0%,
- 0/2 virgin aggregate for gradation improvement – 18.8%,
- 0/31.5 recycled natural aggregate – 37.6%,
- RAP 0/31.5 – 37.6.

### *2.2 Experimental program*

The main objective of the research was to determine the effect of the innovative binder used in the technology of deep cold recycling with foamed asphalt on the physical and mechanical properties of the designed FBM. Particular attention was paid to the determination of water characteristics and mechanical parameters that considerably affect the durability of the pavement layer made of cold recycled asphalt mixture. Each property of the cold recycled asphalt mix with foamed bitumen (FBM) was determined on nine samples. The following mixture parameters were established during the tests:

1) absorbability (nw), PN-S04001/12,
2) dynamic modulus at temperature of -10oC and 40oC,
3) phase shift angle at temperature of -10 oC i 40oC,
4) stiffness modulus under indirect tension IT-CY as a function of temperature, EN 12697-26.
5) rutting resistance using heavy wheel tester (Hamburg Wheel Tester), AASHTO T324.

The properties were selected so that they could fully reflect the purpose of the study, i.e., obtaining a hydraulic binder being a compromise between the amount of CBPD used and the best physical and mechanical properties. The present work focuses on searching for the best compromise for the hydraulic binder composition with a fixed binder content in the cold recycled mixture mass and that of foamed bitumen. Foamed bitumen was only optimised for foamability designed to disperse the binder in the recycled mixture in the best possible way and coat the mineral material's fine particles as much as possible.

The effect of the blended binder composition on the properties of the cold recycled mixture was evaluated according to the adopted simplex-centroid design [33]. The layouts of the design are created by the full permutation of pure components. In actual research, the experimental region is often subject to constraints, i.e., some values of input quantities do not occur at the values of other quantities. Therefore, the algorithm suggested by [34] was used to find the vertices and centres of gravity of the constrained region. When selecting an appropriate experimental design, D and A-optimal algorithms were used, i.e. such systems that, given the selected model, provide the maximum information from the experimental region [35]. In order to increase the statistical power (i.e. to increase the ANOVA error degrees of freedom), the entire pattern of the experimental region was repeated several times.

The diagram of the mixture design showing the limitation of the experimental region is presented in [17, 32].

To obtain the regression model, seven combinations were prepared with respect to three components of the hydraulic binder. The design of the experiment for the cold recycled foamed bitumen mixture (FBM) is shown in Table 2.

Tab. 2. Percent contribution of hydraulic binder components [17, 32]

| Mix designation | Description |
|---|---|
| Ref | 100% CEM |
| 1V | 20%CEM+20%Ca(OH)2+60% CBPD |
| 2V | 20%CEM+60% Ca(OH)2 +20% CBPD |
| 3V | 60%CEM+20% Ca(OH)2 +20% CBPD |
| 4C | 20%CEM+40% Ca(OH)2 +40% CBPD |
| 5C | 40%CEM+20% Ca(OH)2 +40% CBPD |
| 6C | 40%CEM+40% Ca(OH)2 +20% CBPD |
| 7C | 33%CEM+33% Ca(OH)2 +33% CBPD |

The selection of the model class depended on the extent to which it explained the experimental data variation and was based on analysis of variance. In addition, a "lack of fit" analysis was performed to indicate whether the explanation of the variability provided by the model is greater than the spread of the random estimation error [36].

In the next stage, coefficients were estimated of the polynomial with a degree established from the analysis of variance. To eliminate systematic bias, all the combinations were randomised. The parameter approximation was based on the least squares method. The general model of the research object function was as follows [37] (1):

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

where: ·

bijk – experimental parameters of the model,

xi - i-th independent variable (x1 – CEM, x2 - Ca(OH)2 , x3 – CBPD),

y – dependent variable.

The modified coefficient of determination R2 [36] was used as an indicator of the explanation quality for the variation in the experimental data.

### 3. Results and Discussion

The first analyzed parameter of the recycled cold mixture was the weight absorption (denoted as nw), which significantly determined its quality in terms of resistance to water and frost. The overall impact of the dedicated binder composition on water absorption was determined by developing a regression model according to formula (1). The level of effect of a given component including interactions on nw were determined using ANOVA analysis. The parameters of the regression model predicting nw were summarized in Table 3.

Tab. 3. Model of nw as a function of binder composition

| Variable | $n_w$ (%), $R^2$=0.523; MSR=0.034 | | | | |
|---|---|---|---|---|---|
| | **Reg. Coefficient** | **SE** | **$p_{value}$** | **-95 % Conf. Lmt** | **+95 % Conf. Lmt** |
| (A)CEM | 6.166 | 0.106 | <0.001 | 5.938 | 6.394 |
| (B)Ca(OH)2 | 5.900 | 0.106 | <0.001 | 5.672 | 6.127 |
| (C)UCPP | 6.200 | 0.106 | < 0.001 | 5.972 | 6.427 |
| AB | -0.533 | 0.520 | 0.322 | -1.648 | 0.582 |
| AC | -0.333 | 0.520 | 0.531 | -1.448 | 0.782 |
| BC | 0.600 | 0.520 | 0.267 | -0.515 | 1.715 |
| ABC | 8.300 | 3.659 | 0.039 | 0.452 | 16.147 |

Analyzing the results summarized in Table 3, it can be concluded that all binder components had a significant impact on the weight absorption nw, because the p-value was less than 0.05. The assessment of the power of influence of the binder composition on nw feature was graphically presented in the form of a developed regression model in Figure 1.

The test results of the weight absorption (nw) showed that the lowest value attained the recycled mixture containing hydraulic binders, i.e. 100% cement. However, among the recycled mixtures containing the analyzed dedicated binders, the composition denoted as 7C (33.33% CEM, 33.33% Ca(OH)2 and 33.33% CBPD) achieved the lowest water absorption. Another analyzed parameter of the recycled cold mixture was the dynamic modulus, which plays an important role in ensuring its durability. The power of influence of a given binder component and its interactions on the dynamic modulus |E*| in terms of temperature were determined using ANOVA analysis. The parameters of the regression model predicting the dynamic modulus |E*| were summarized in Table 4.

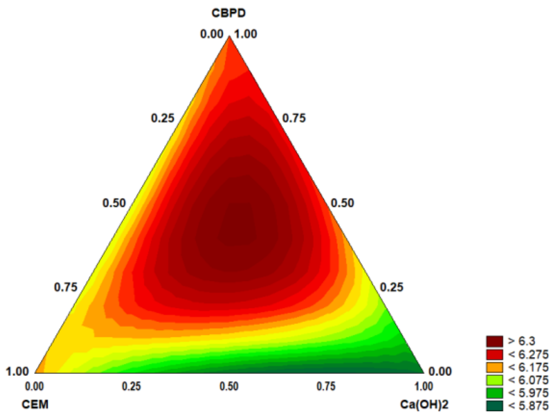
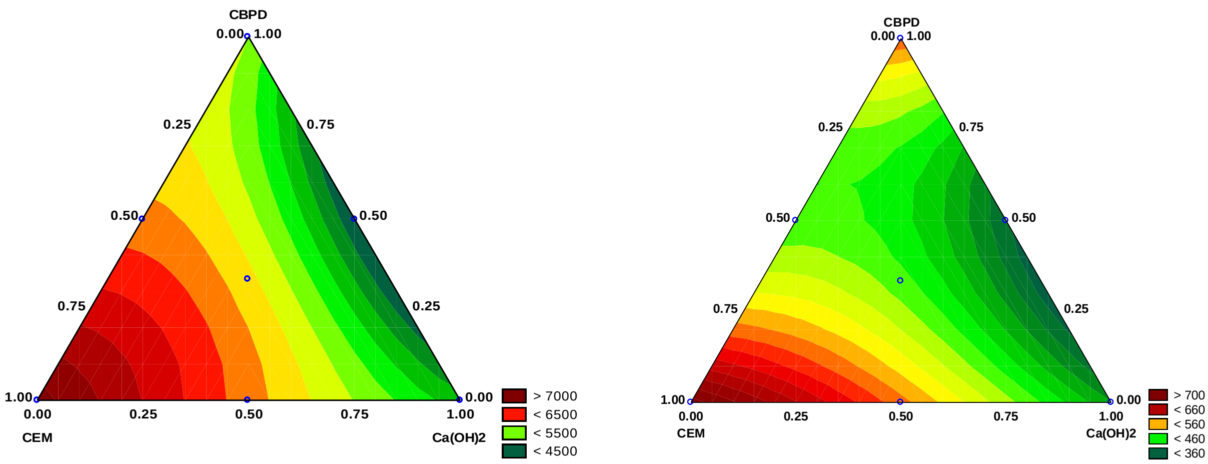



Fig. 1. The regression model of nw of recycled mixture in deep cold recycling technology versus binder composition

Tab. 4. Model parameters of dynamic modulus |E*| (MPa) as a function of binder components amount

| **Variable** | **Reg. Coefficient** | **SE** | **$p_{value}$** | **Reg. Coefficient** | **SE** | **$p_{value}$** |
|---|---|---|---|---|---|---|
| | **E*(-10deg.C,10 Hz); $R^2$=0.574; SR=761849.7** | | | **E*(40deg.C, 0.1 Hz); $R^2$=0.533; SR=13126.5** | | |
| (A)CEM | 7357.55 | 436.42 | <0.001 | 708.760 | 57.286 | <0.001 |
| (B)Ca(OH)2 | 4855.54 | 436.42 | <0.001 | 401.262 | 57.286 | <0.001 |
| (C)CBPD | 5497.69 | 390.35 | <0.001 | 576.621 | 51.238 | <0.001 |
| AB | 49.38 | 1990.38 | 0.980 | 51.493 | 261.263 | 0.845 |
| AC | -1340.76 | 2102.08 | 0.529 | -707.258 | 275.924 | 0.017 |
| BC | -3588.18 | 2102.08 | 0.101 | -502.356 | 275.924 | 0.081 |
| ABC | 12489.42 | 14847.26 | 0.408 | 908.286 | 1948.892 | 0.645 |

Based on the analysis of the results presented in Table 4, it can be concluded that Portland cement, hydrated lime and CBPD had a significant impact on the dynamic modulus E* of the cold recycled mix, because the p-value was less than 0.05. The assessment of the power of influence of the binder composition on |E*| feature was graphically presented in the form of a developed regression model in Figure 2.




(a) (b)

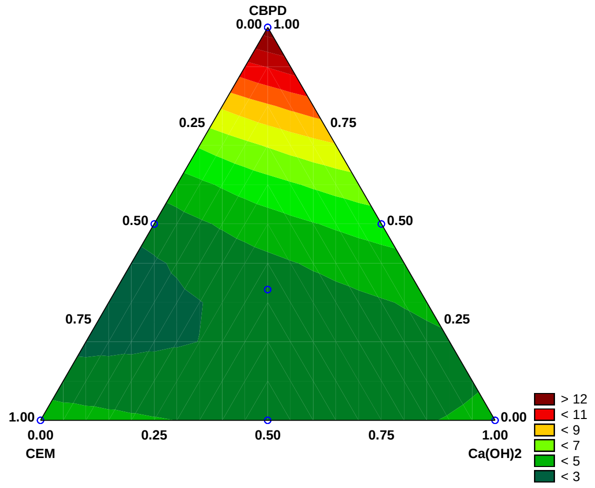
Fig. 2. The influence of binder composition on |E*| of recycled mixture at temperature of:
a) -10oC, b) 40oC

The test results of dynamic modulus |E*| presented in Figure 2 show that at a temperature of -10oC, the most favorable value of |E*| exhibited a recycled mixture containing the largest amount of hydrated lime. However, at a temperature of 40oC recycled mixture contained 100% Portland cement, obtained the highest value of the dynamic modulus. The analysis of the obtained test results shows that the recycled mixture with a dedicated binder denoted as 7C (33.33% CEM, 33.33% Ca(OH)2 and 33.33% CVBPD) was characterized by the most favorable dynamic modulus at both used temperatures. It is known that the phase shift angle δ* is related to the dynamic modulus |E*|. In case of δ* the analysis of variance was used to identified potential effects and interactions between them. In result the parameters of the regression model predicting the phase shift angle δ*, on the basis of binder composition, was presented in Table 5.

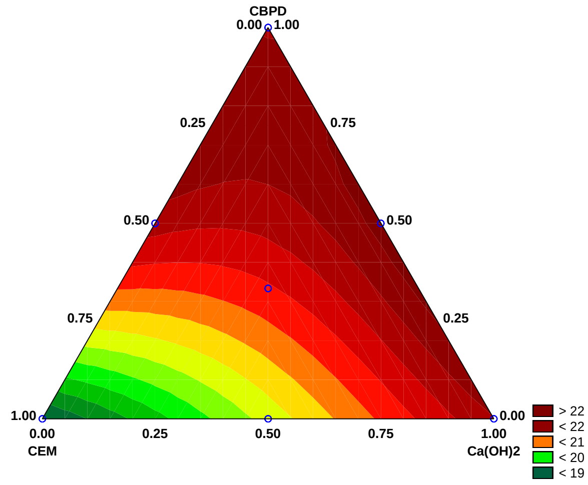
Tab. 5. Model parameters (assigned to binder composition) for predicting the phase angle δ*

| Variable | Reg. Coefficient | SE | $p_{value}$ | Reg. Coefficient | SE | $p_{value}$ |
|---|---|---|---|---|---|---|
| | δ*(-10deg.C,10 Hz); $R^2$= 0.921; MSR=1.431 | | | δ*(40deg.C, 0.1 Hz); $R^2$=0.765; MSR=0.391 | | |
| (A)CEM | 4.599 | 0598 | <0.001 | 18.983 | 0.312 | <0.001 |
| (B)Ca(OH)2 | 4.04 | 0,598 | <0.001 | 21.735 | 0.312 | <0.001 |
| (C)CBPD | 13.596 | 0.535 | <0.001 | 21.710 | 0.279 | <0.001 |
| AB | -2.321 | 2.728 | 0.403 | -0.046 | 1.427 | 0.974 |
| AC | -22.860 | 2.881 | <0.001 | 5.082 | 1.507 | 0.002 |
| BC | -13.599 | 2.881 | <0.001 | 1.494 | 1.507 | 0.331 |
| ABC | 7.967 | 20.350 | 0.699 | -8.593 | 10.647 | 0.427 |

Analyzing the results presented in Table 5, it can be concluded that all components of the dedicated binder had a significant impact on the phase shift angle δ*, because the p-value is less than 0.05. The assessment of the influence of the amount of binder component was graphically presented in the form of the response surface in Figure 3.




(a)




(b)

Fig. 3. The influence of binder content on phase shift angle δ* of recycled mixture at temperature of: a) -10oC, b) 40oC

The test results of the phase shift angle δ* showed that the lowest value exhibited the recycled mixture containing maximum amount of hydraulic binder - 100% cement. However, the mixture denoted as 7C (33.33% CEM, 33.33% Ca(OH)2 and 33.33% CBPD) achieved the lowest level of water absorption.

Evaluation of the influence of the binder on the load-bearing capacity and durability of the recycled base course required testing the mixture for stiffness modulus [38-39]. The test was conducted in an indirect tensile scheme at -10oC to +40°C. The stiffness modulus test is crucial from the point of view of pavement structure design and determines the cracking rate in the base layer. Considering the change in stiffness with respect to temperature will identify a solution to eliminate those binder compositions that may lead to excessive stiffness of the recycled mix at low temperature. The results of the stiffness modulus tests carried out for the cases defined in the mixture design are shown in the variability chart (Figure 4).

The whiskers in Figure 6 represent the non-outlying maximum and minimum values from the interquartile range: Median±1.5IRQ. The limit values of the "box" indicate the first and third quartile of the stiffness modulus results. The square inside the box shows the value of the second quartile, i.e., the median The reference mix exhibited the highest stiffness among the analysed recycled mixes, irrespective of the test temperature. In the temperature range -10oC and +5oC, the high stiffness modulus was undesirable, leading to cracking and, consequently, reduced pavement service life. High stiffness modulus values were also recorded in the simulated solutions where CBPD and Ca(OH)2 were present at 100%. In both cases, the high stiffness could be related to bitumen structuring and the consequent formation of mastic in the cold recycled mixture [39]. Furthermore, the regression models show that the two-component binders provided the most unfavorable solutions.

In the temperature range from +13oC, the use of cement was beneficial to the performance of the recycled mixture as it provided the structure with the required stiffness and thus resistance to permanent deformation. However, excessive stiffness of the base layer made of cold recycled asphalt mixture may contribute to crack generation through all pavement layers. It was found that, irrespective of the test temperature, the stiffness modulus values in the recycled mixtures with multicomponent binders were reduced substantially relative to the reference binder.

It should be noted that the most significant decrease in the stiffness modulus, taking the median value as a measure, was recorded between temperatures +13oC and +40oC. The direct cause of this result was the low viscosity of the base bitumen. Therefore, the influence of the foamed bitumen in this temperature range ceased to play such a significant role as it did at temperatures between -10oC and 13oC. The lowest thermal sensitivity was observed between +5oC and 13oC. Nevertheless, the scatter of the results in this range was the largest. Observation of the 95% confidence interval indicates that the true value of ΔSm may lie between ranges <-10oC and +5oC> and <+13oC and +40oC>. On the other hand, the comparison of equal temperature ranges: from -10oC to +5oC and +25oC to +40oC, shows that the increase in temperature sensitivity was almost twice as high at high temperatures compared to low temperatures. This confirms the effect of the rapid decrease in stiffness of the recycled mixtures due to bitumen liquefaction.

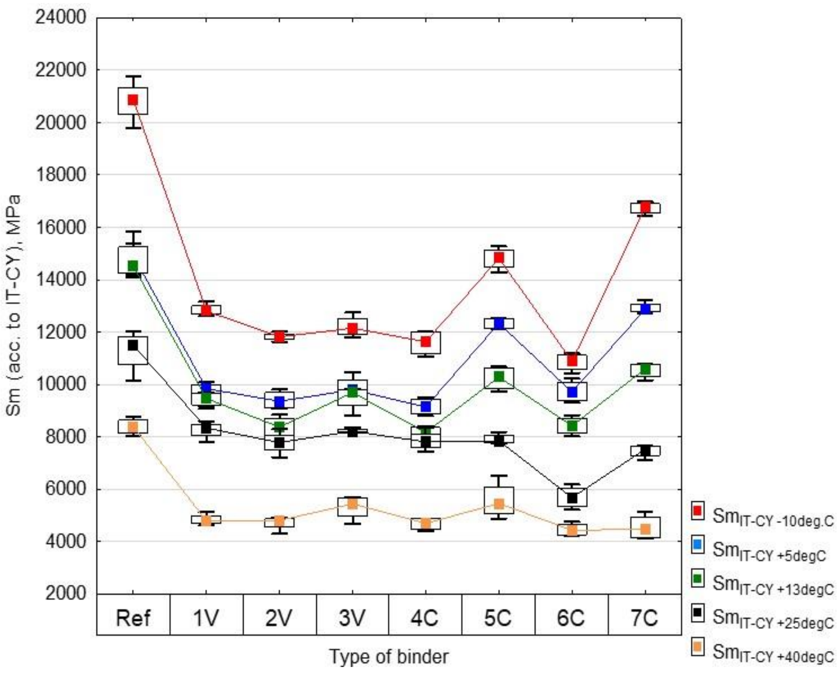



Fig. 4. Stiffness modulus Sm (IT-CY) versus temperature

A very important parameter describing the durability of a recycled cold mixture is a rutting resistance acc. to AASHTO T324. As previously for determining the significance of parameters, related to binder composition, in model the ANOVA analysis was performed. The parameters evaluation was presented in Table 6.

Tab. 6. Model parameters of the rut depth feature (P)

| Variable | P - rut depth feature (%); $R^2$= 0.868; MSR=0.001 | | | | |
|---|---|---|---|---|---|
| | Regression Coefficient | SE | $p_{value}$ | -95 % Conf. Lmt | +95 % Conf. Lmt |
| (A)CEM | 0.016 | 0.001 | <0.001 | 0.013 | 0.019 |
| (B)Ca(OH)2 | 0.023 | 0.001 | <0.001 | 0.019 | 0.026 |
| (C)CBPD | 0.022 | 0.001 | <0.001 | 0.018 | 0.025 |
| AB | -0.109 | 0.006 | 0.211 | -0.024 | 0.006 |
| AC | -0.017 | 0.006 | 0.035 | -0.032 | -0.001 |
| BC | 0.010 | 0.006 | 0.170 | -0.005 | 0.025 |
| ABC | 0.061 | 0.046 | 0.225 | -0.047 | 0.170 |

Analyzing the results presented in Table 6, it can be concluded that all components of the dedicated binder have a significant influence on the proportional rut depth (P) of the recycled cold mix, because the p-value is less than 0.05. The visual interpretation of changes of P feature as a function of binder composition of recycled mixture was presented by means of request surface in Figure 5.

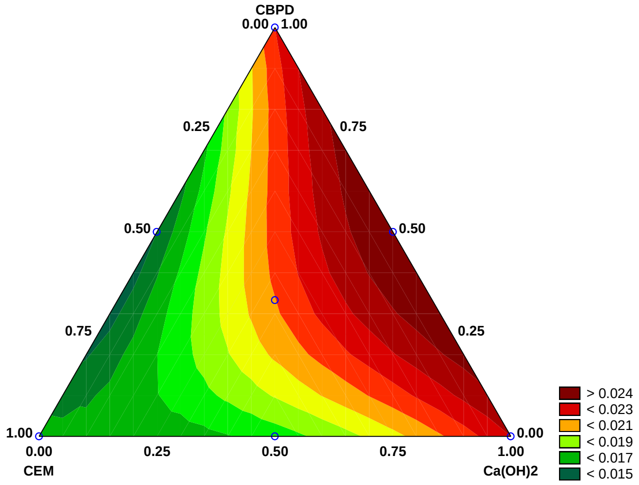



Fig.5. The influence binder composition on rut depth (P)

The results of testing the proportional rut depth P showed that the lowest value was achieved for the recycled mixture at 100% cement. Thereby, the types of binders containing considerable cement amount played the majority role. However, since the use of only cement in a dedicated binder may cause a very significant stiffening (cracking) of the cold recycled mixture, finally, the 7C binder was recommended.

## 4. Conclusion

The test results obtained in this study demonstrated that the modification of the binder composition in the recycled asphalt mixture with foamed bitumen (FBM) has a substantial effect on the properties of the mixture. This study revealed the complexity of this effect by describing how different components in the binder blend influence the physical and mechanical properties of the FBM. The following conclusions were formulated:

- Optimisation of the blended binder using a set of adequately defined criteria provides an opportunity to control the physical and mechanical properties of the recycled base layer;
- The optimisation process used in this study revealed that the most effective solution for a blended binder in the base course layer to attain reduced stiffness at low temperature and required moisture and frost resistance should be a composition containing 33% cement, 33% Ca(OH)2 and 33% CBPD;
- Clustering analysis showed that 40% CBPD could be used without compromising the quality of the base course layer. A further increase in the CBPD content might cause excess stiffness of the material and lead to cracking initiation;
- A 100% Ca(OH)2 and CBPD content does not provide the material with the required quality;
- Analysis of response surfaces showed a strong influence of the interaction among the three components of the blended binder. It was thus impossible to obtain the same results for the variant with only two components used in the studies;

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