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Multivariate optimization of recycled road base cold mixtures with foamed bitumen

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Abstract

The paper presents an approach for identifying the optimum range of foamed bitumen and Portland cement contents in recycled mineral-bitumen road base mixtures using simultaneous optimization of response variables (i.e. properties of mixtures estimated from statistical models) with the use of desirability functions. The 16 evaluated mixtures had a common aggregate composition comprising materials from existing pavement layers (reclaimed asphalt pavement and aggregates from recycled crushed stone base layer) and virgin material. The mixtures varied in foamed bitumen contents (2.0% - 3.5%) and Portland cement contents (1.0% - 2.5%). The investigated mixture parameters included: air void content (V_m), indirect tensile strength (*ITS*), tensile strength retained (*TSR*) and indirect tensile stiffness modulus (*ITSM*) at 25°C. The use of the desirability functions and desirability index allowed to identify the effective and optimum range of binding agent dosing for the recycled mixture with respect to all of the measured mixture properties.

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Keywords: Road base; deep cold recycling; foamed bitumen; Portland cement; poisture susceptibility; multicriteria optimization

1. Introduction

Poland, similarly to other countries in the region, has seen a rapid growth in road transport in the early 1990s as an effect of the political and economic transformations taking place in that time [1]. The poor condition of road network, which was subjected to previously unseen increase in traffic loads, driven numerous endeavours for new

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road construction materials, techniques and method to face the challenges of road sustainability [2-12]. In the cold recycling technology it is possible to convert the old construction layers into a new high quality base course with adequate mechanical and service properties while preserving the environment by reducing harmful vapor and greenhouse gas emissions. The ongoing technical advancements in the Polish road construction industry resulted in first implementation (in 2010) of foamed bitumen (FB) as a new type of binder for the cold recycling technology. The use of FB in cold recycling shortens the curing time of the rehabilitated layers due to minimal water content (2% - 3% of the binder mass) compared to the bitumen emulsion (up to 50% water content). Additionally foamed bitumen can be used to stabilize a variety of materials, including reclaimed asphalt pavement (RAP) materials.

Authors attempted to optimize the design of the mineral bituminous mixtures with foamed bitumen and Portland cement (PC) in scope of the binder contents and their influence on the material properties. The optimization was carried out according to requirements for road base layers using the desirability functions proposed by Derringer and Suich [13] and the desirability index formulated by Harrington [14].

2. Materials and methodology

2.1. Experimental program and testing methodology

The aim of the research was to assess the effects of binding materials (FB, PC) on the selected properties of the recycled mineral-bitumen mixtures and to examine the boundaries of the binding agents effective dosing. It is known that higher bitumen contents result in greater flexibility of mixtures but also decrease their deformation resistance [15], whereas Portland cement contributes to the stiffness of designed layers. The evaluated binder contents (by mass) were 2.0%, 2.5%, 3.0%, 3.5% for FB and 1.0%, 1.5%, 2.0%, 2.5% for PC. The experiment was evaluated in conformity with requirements for road base layers [16,17] and the tests were carried out for all combinations of binding agents levels.

The dosing ranges of the binders were picked based on the Authors' previous work in this domain [17,18]. The tests were performed on cylindrical samples 63±3 mm high and 100 mm in diameter prepared in Marshall compactor using 75 blows per face, in compliance with [16]. Each experiment was repeated with a new sample 9 times. The influence of FB and PC on the performance of the recycled mixtures was evaluated by the following tests:

- air void content (V_m) up to EN 12697-8 – the accepted values of V_m range from 10% to 15% [16],
- indirect tensile strength (*ITS*) and tensile strength retained (*TSR*) – the minimum value of *ITS* is 225 kPa [16] and minimum accepted value of *TSR* is 0.7 [19],
- indirect tensile stiffness modulus (*ITSM*) in IT-CY test configuration at temperature of +25°C up to EN 12397-26 (Appendix C) with 124±4 ms rise time, 0.35 Poisson's ratio, 3.0 ± 0.1 s total loading cycle and 5 ± 2 µm horizontal deformation; the acceptable values of *ITSM* for mixtures with FB containing RAP/crushed stone blend in 50:50 ratio range from 2500MPa to 4000MPa [20].

2.2. Binding agents

The FB was produced in a WLB 10S laboratory foaming plant from a 70/100 bitumen (up to EN-12591) designed specifically for foaming [17,18]. Depending on the type of the material being recycled, different active fillers can be added to FB treated materials, such as PC, hydrated lime, fly ash and combinations of those at various proportions. A fly ash PC (CEM II/B-V 32,5R acc. to EN 197-1 standard) was chosen for the investigations, as Brown and Needham [21] proved that application of active filler (lime or cement) improves mechanical parameters of the cold mixtures. Xu *et al.* [22] concluded that PC is absolutely necessary to enhance the rate of increase in initial strength and to improve both moisture resistance and high temperature parameters of bitumen-foam stabilized mixtures.

2.3. Materials and mix deign procedure

All samples were prepared using a common mineral composition, comprising reclaimed material from existing road pavement and virgin aggregates (0/4 mm dolomite: 30%). The reclaimed material was derived from:

- milling of upper bitumen layers (RAP) 0/16mm grade: 50%, (RAP contained 5.4% of bituminous binder by mass, which was determined using solvent extraction test up to the EN 12274-2 standard.
- aggregates from reclaimed stone base layer 0/31.5mm grade: 20%.

Currently, only the deep cold recycling technology with bitumen emulsion mixtures is popular in Poland because official requirements for FB treated materials still aren't formulated as this technology is still in development phase. Therefore the mineral recycled mixtures were designed [17] to satisfy grading criteria for mixtures with FB in compliance the South African [23] and German guidelines [16]. Water was added to the mixture to obtain approximately 75% of the optimum moisture content (as recommended by the technical guidelines [16]) for good dispersion of the foam in the mix.

3. Method for the optimization

3.1. Desirability function and desirability index approach

The aim of the desirability function approach is to identify the optimum composition of a designed material (i.e. the contents of FB and PC in mineral-bituminous mixes) so that the final properties of the product meet the established criteria. To achieve this goal the multiple responses associated with measured properties of the material (i.e. the properties of laboratory prepared and compacted mixtures) are simultaneously optimized [14].

Usually a range of acceptable values (given by lower and upper specification limits) or a single boundary value is specified that should not be exceeded. It must be clearly stated that when it comes to designing pavement materials, failure in satisfying any of the given criteria cannot be compensated, disqualifying the evaluated design from the possibility of its practical utilization.

To compare the performance of any material in different fields it is crucial to normalize its different characteristics. This is done by means of various desirability functions (DFs), which transform the responses into "desirabilities" in the [0,1] range. The interpretations of those values tend to vary but generally "0" values are unacceptable, whereas "1" is associated with the most desired characteristics [24].

When the DFs are applied to the responses, the result is a set of desirability values (d_i) of the measured properties. It may be easy to evaluate one or two designs using those values alone, but when more parameters and alternatives are considered it is advisable to combine those separate values into a desirability index (DI), which makes comparisons more straightforward. The desirability index is computed as a geometric mean of k desirability values as given in (1):

$$\mathrm{DI} = (\Pi_{i=1}^{k} \mathrm{d_i})^{\frac{1}{k}} \tag{1}$$

An important feature of the desirability index is that whenever at least one of the desirability values equals zero then the whole expression also returns a null value, which reflects the aforementioned condition that the designed material must meet all the requirements to be considered valuable. However, interpretation of the DI is sometimes difficult as it is impossible to assign any qualitative meaning to its values without looking into the specific DF outputs – the DI itself does not give any information about the fields in which the examined material performs better or worse [25].

3.2. Derringer's approach

Derringer and Suich [13] proposed two types of desirability functions given in intervals, which normalize and transform the measured properties *Y* of a product into desirabilities (*d*) in the range of [0,1]. The advantage of this approach is the possibility of defining the specifications asymmetrically and the fact that the control over the functions and outputs is intuitive and flexible. The first type of the DFs refers to a situation where acceptable values are given by a minimum and maximum limits and additionally a target value is defined, thus the function utilizes lower and upper specification limits and a target value (LSL, USL, T). The function returns a null value if the evaluated response is below the specification limits. Non-zero values are assigned at the LSL and maximum is reached at the target value. Subsequently it declines to yield zero values again at USL. The shape of the DF is governed by parameters *s* and *r*, which can be treated as weights making it harder or easier to score high desirabilities. Similarly a one-sided can be easily defined using a LSL or USL and a target value, at which the function reaches its maximum. The functions used in the presented optimization are depicted in Figure 1.

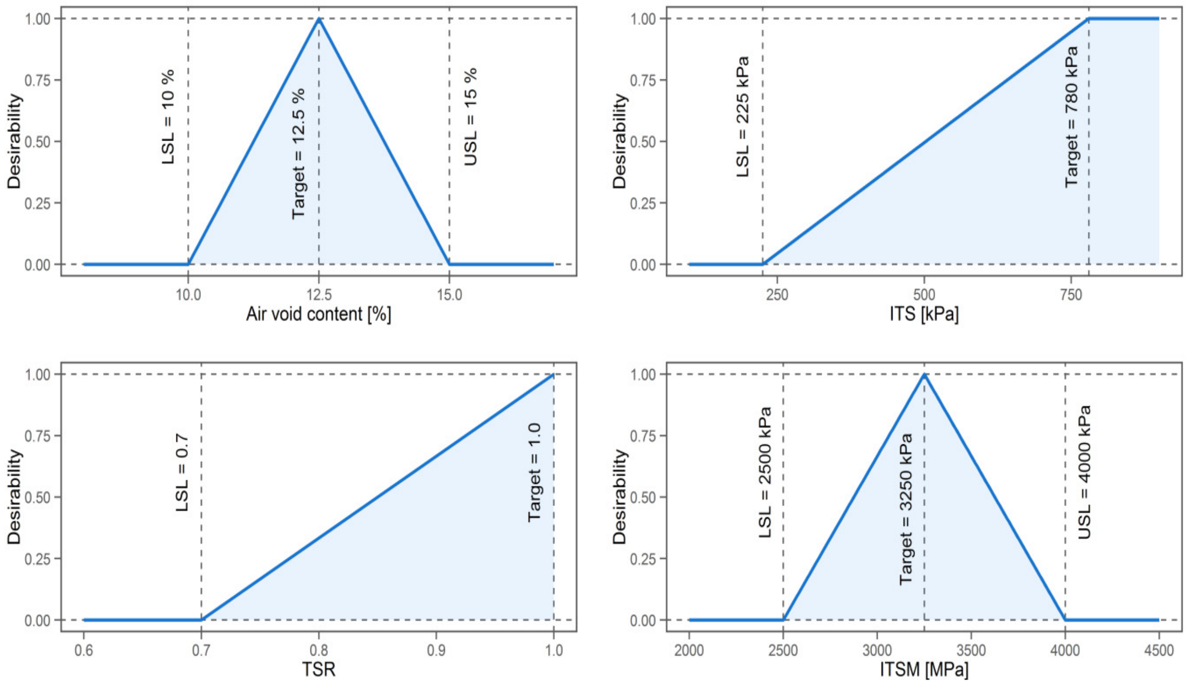

Fig. 1. Graphical representations of Derringer's desirability functions along with the specification limits used for optimizing the parameters of mineral-bituminous mixtures with FB and PC for base course layer.

3.3. Pre-optimization operations on the data

The analyses, which outcomes are here presented, were conducted using data gathered during an extensive research concerning properties of mixtures with FB and PC. Four levels of those binding agents were investigated in numerous tests. Each test was carried out nine times for every combination of the 16 factor levels.

The aim of the optimization was to find the best performing mixtures and investigate their performance in various scopes. This was done not only to evaluate the tested samples but also for the needs of future investigations. For this reason the experimental data were split into two disjoint sets: training and test. The training set was used to create statistical models, which were later subjected to optimization, and the test set was used to evaluate the outcomes of the optimization. The first step was to investigate and explore the data in search of outliers or any other possible problems. The data were assessed using plots and summary statistics to initially estimate the type of models that would be used, which resulted in conclusion that only first and second order linear models should be utilized [26].

Then the data was split into training and test sets. The training set was created by randomly selecting 6 out of 9 replicas in every factor level combination. The remaining test set data (3 out of 9 replicas) were then averaged, which resulted in 16 mean values of every measured parameter corresponding to the 16 FB and PC concentrations. The analysis of variance was performed for each model to decide which variables it should include.

What is more, models including different variables were compared to check if additional components contributed significantly to the model. As a result of the aforementioned investigations, four best performing models were chosen for further analyses. Predicted values of the V_m, *ITS*, *TSR* and *ITSM* parameters were then computed based on those statistical models.

4. Results and discussion

4.1. Investigating the effect of binding agents on road base mixtures properties

The results of the aforementioned tests in relation to the FB and PC content are shown in Figure 2. The plots show individual tests results of specimens along with the minimum/maximum required boundary values (i.e. the LSL and USL optimization limits). The outcomes of tests were consistent and the overall performance of the designed mixtures was satisfactory. Visual inspection of results and plots revealed relationships between the concentrations of binding agents and measured mixture parameters. Table 1 presents results of analysis of variance, which showed that all those effects of both considered factors (FB, PC) were statistically significant.

Table 1. Evaluation of FB and PC content statistical significance in scope of the measured mixture properties.

Feature	Factor	SS	MS	F value	P(<F)
V_m	*FB*	231.00	77.00	58.32	<0.001
	PC	13.45	4.48	3.39	<0.05
ITS	*FB*	1095177	365059	153.35	<0.001
	PC	449706	149902	62.97	<0.001
TSR	*FB*	0.15038	0.05013	64.69	<0.001
	PC	0.14175	0.04725	60.98	<0.001
ITSM	*FB*	12696818	4232273	21.74	<0.001
	PC	43753333	14584444	74.93	<0.001

The air void content was observed to decrease along with an increase in concentration of both binding agents, as a result two mixtures failed to comply with the minimum V_m criterion. Excessive air voids content in bituminous layers has a negative effect on resistance to fatigue and weather conditions (e.g. action of water) [27].

The *ITSM* is a parameter peculiar to bitumen stabilized materials, which expresses their visco-elastic properties [28]. The stiffness modulus clearly depended on the concentration of PC and this effect was further amplified by the foamed bitumen. As a result the same mixtures that failed the air void content criterion yielded *ITSM* values exceeding the upper limit. All mixtures returned satisfactory results in the *ITS* tests with the lowest indirect tensile strength well above 300 kPa. The results for the *TSR* criterion were dissatisfactory at lowest concentrations of the binding agents. All mixtures with foamed bitumen content equal to 2.5% and above fulfilled these requirements.

The analysis of variance showed that in most cases the computed p-values for the considered factors (FB, PC) were smaller than the stipulated significance level ($p=0.05$). Based on that it was assumed that both binding agents had significant impact on all the measured properties of recycled mineral-bitumen mixtures. What is more, in scope of the air void content the influence of foamed bitumen is assumed to be more significant than Portland cement.

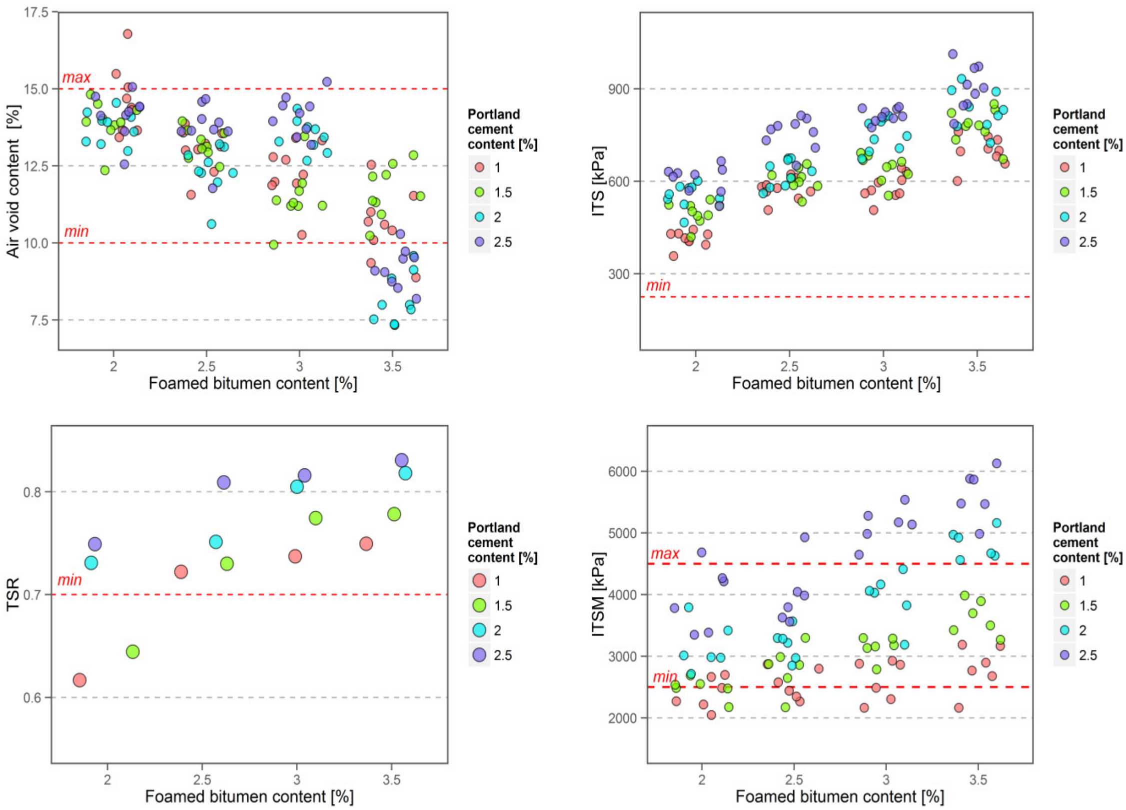

Fig. 2. The test results of specimens with different concentrations of foamed bitumen and Portland cement.

4.2. Derringer desirability function optimization

The optimization was carried out on the responses of statistical models based on the training-set data. The evaluated parameters (V_m, *ITS*, *TSR*, *ITSM*) reflect the basic and most important characteristics of road base layers, such as compaction, strength, resistance to moisture damage and stiffness. The results of this analysis are presented in Figure 3, where each combination of foamed bitumen and Portland cement content has an assigned desirability index value computed as in (1).

As shown in Figure 3, not all of the evaluated mixtures met the requirements. A total of 7 mixtures yielded null desirability index values. The non-zero cases yielded DI scores ranging from 0.185 to 0.551 and are arranged diagonally from upper left to lower right. This means that in order to comply with the requirements, either a minimum/maximum or intermediate combinations of the PC and FB should be used. The landscape of this optimization was shaped mainly by the *TSR* and *ITSM* scores as seen in Table 2. The mixes in the lower left portion of the figure (lowest concentrations of both: PC and FB) yielded null desirabilities in assessment of the *TSR* parameter corresponding to resistance to moisture damage. On the other hand the mixes in the upper right portion of the figure failed to sufficiently perform under the stiffness criterion exceeding its upper limit, meaning that the stiffness of those mixtures was too high.

The conclusions drawn from this optimization correlate well with the present state of knowledge in this area: high concentrations of cement cause over-stiffening of the mixtures while insufficient dosing of PC and FB results in increased susceptibility to moisture damage. Based on this analysis it can be said that the optimum performance of the road base mix is achieved at the intermediate range (FB: 2.5% - 3.0%; PC 1.5% - 2.0%) of the evaluated components and the best performing mixtures with DI scores above 0.5 were characterized by binder contents of FB=2.5%, PC=2.0% and FB=3.0%, PC=1.5%. Those mixtures performed exceptionally well in the *ITSM* criterion (yielding stiffness modulus values close to the target value of 3250 kPa) and slightly below average in the *TSR* range.

Table 2. Results of the foamed bitumen and Portland cement content optimization in scope of air void content, indirect tensile stiffness modulus, indirect tensile strength and tensile strength retained.

Binding agent content (%)	FB	2.0				2.5				3.0				3.5			
	PC	1.0	1.5	2.0	2.5	1.0	1.5	2.0	2.5	1.0	1.5	2.0	2.5	1.0	1.5	2.0	2.5
DF values	V_m	0.106	0.636	0.687	0.261	0.559	0.737	0.644	0.279	0.822	0.881	0.959	0.945	0.038	0.219	0.120	0.000
	ITSM	0.074	0.246	0.815	0.221	0.000	0.359	0.805	0.000	0.032	0.740	0.156	0.000	0.415	0.609	0.000	0.000
	ITS	0.378	0.483	0.589	0.694	0.544	0.653	0.761	0.870	0.710	0.822	0.934	1.000	0.877	0.991	1.000	1.000
	TSR	0.000	0.000	0.073	0.202	0.000	0.058	0.177	0.296	0.062	0.172	0.281	0.390	0.186	0.285	0.385	0.484
Desirability Index		0.000	0.000	0.394	0.300	0.000	0.316	0.514	0.000	0.185	0.551	0.445	0.000	0.226	0.441	0.000	0.000

The quality of the performed optimization was assessed with the test-set initially detached from the experimental data, which was used to create the statistical models and to optimize the foamed bitumen mixture design. The data from the test set (3 replicas for each of the 16 factor levels) were averaged and afterwards those values were transformed with the Derringer's desirability functions and desirability index was computed for each factor level. As a result two desirability indexes were obtained: one computed based on the statistical models and the other corresponding directly to the actual experimental data. Such procedure is commonly used in machine learning to evaluate statistical models and here it was utilized to assess the quality of the models as well as the optimization itself at the same time. Figure 4 depicts the outcomes of this verification.

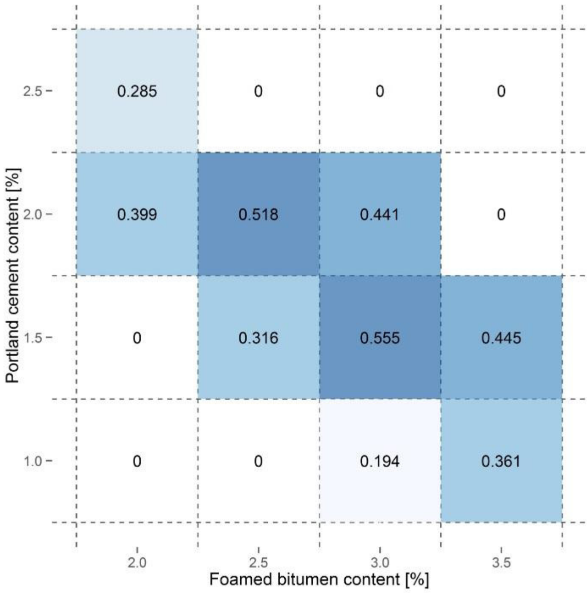

Fig. 3. Results of FB and PC contents optimization in compliance with the requirements for road base mixes using Derringer's desirability functions. Each combination of FB and PC content has an assigned desirability index and a color for visual representation (every color spans over a 0.1 range of the DI).

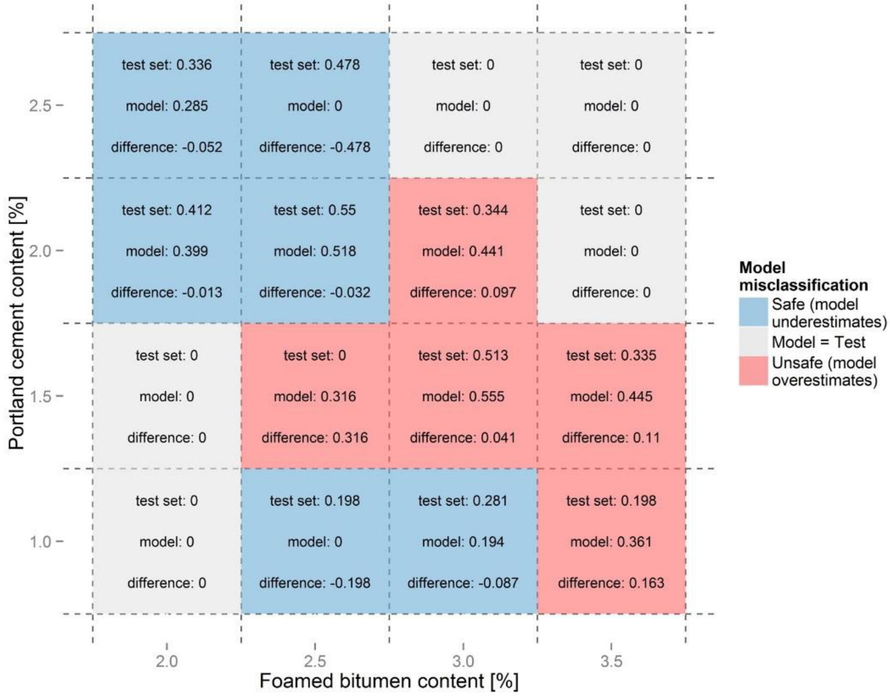

Fig. 4. Verification of the optimization of the binder agents in mineral-bituminous mixtures with foamed bitumen and Portland cement. The plot presents differences between the optimized model responses and the optimized actual data from a test-set.

The results were divided into three types of outcomes: a situation where DI from the model was lower than the one from actual data (this being a safe situation in scope of mixture design as the desirability is underestimated), a situation where DI computed from the model is higher than the result actual data (unsafe) and a third case where the DI's were the same.

It can be stated that the overall performance of the models was satisfactory. The unsafe misclassifications were mostly minor in magnitude and not significant (with the exception of FB: 2.5%, PC: 1.5% mixture) and the biggest safe misclassification occurred at the boundaries of the area of experiment. Large portion of this variation was caused by a very complex relationship between cement content and air void content, which was poorly estimated by the linear models. Apart from that it can be said that the actual experimental data were predicted and optimized adequately.

5. Conclusions

The conclusions that come from the performed analyses are as follows:

- the tolerance of dosing of the considered binding agents is narrow (0.5%) according to the optimization with Derringer's desirability functions,
- overdosing of both, foamed bitumen and Portland cement results in excessive stiffness of mixtures, whereas insufficient amounts of binding agents lead to failure in tests for resistance to moisture damage,
- the amount of binding agents had an impact on the air void contents; high levels of binding agents resulted in insufficient air voids content,
- mixtures with higher amounts of foamed bitumen and less Portland cement performed best (specifically FB=2.5%, PC=2.0% and FB=3.0%, PC=1.5%),

- as a rule of thumb it can be said that once the requirements were initially met, a specific amount of foamed bitumen could be replaced by the same amount of Portland cement and vice versa.
- proper fitting and adequate use of statistical models backed by their evaluation and testing are necessary to provide an optimization yielding meaningful and unbiased results,
- the Derringer's desirability functions are sensitive to events when one of the criteria is not satisfied, instantly eliminating such cases.

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