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Optimization of the road binder used in the base layer in the road construction

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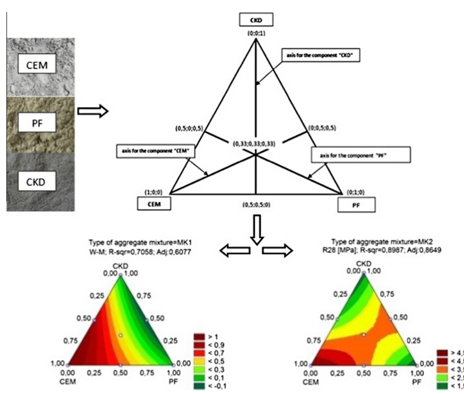
HIGHLIGHTS

- The use of simplex centroid design for the binder composition.
- The composition of a road binder has a significant effect on the quality of road base.
- The optimum road binder composition for HBMs is presented.
- The type of aggregate mixture used in HBMs generates variability in binder composition.

GRAPHICAL ABSTRACT



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ABSTRACT

The research focused on the application of mixed binder system to the hydraulically bound mixes used in road base (HBM). This paper presents the outcome of the tests for the mechanical characteristics of the HBM road base in terms of the binder type used. Seven binders were prepared in a laboratory by blending three primary constituents: Portland cement CEM I 32,5R, fluidised bed combustion fly ash and cement kiln dust (CKD). The proportions were selected according to the experimental design. The percent amount of the binder in the hydraulically bound mixture was 6%. Two types of aggregate were used as the mineral material in the base. The composition of the mixtures was designed based on the Proctor method. The influence of the binders on the properties of the HBM road base was evaluated by determining the compressive strength at 7, 14, 28 and 42 days of curing, frost resistance and water absorption. The test results were used to optimise the binder composition with respect to the road base characteristics and to establish the recommended road binder composition.

1. Introduction

Cement, lime and hydraulic binders are widely used in road building industry [1,2]. In the pavement structural layers, cement is used in recycled base courses made with foamed bitumen and bitumen emulsion [3,4], in base courses made of hydraulically bound mixtures (HBMs) [5] and in subgrades to improve their bearing capacity [6]. In the case of hydraulically bound mixtures, the content of cement, dependent on the gradation and design strength, is typically from 3% to 8% and is calculated relative to the amount of aggregate in the mixture [7]. The amount of road binder in cold deep recycled mix bases is smaller that in HBMs and ranges from 1.5% to 4.0% [8]. Limiting the amount of the binder

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and adding asphalt emulsion or foamed asphalt leads to reduced stiffness [9]. Low content, 2%, of the binder (cement) is a feature of hydrated cement treated crushed rock base [10]. A higher content of the binder is used in the soil stabilization process. Due to high diversification of the soil subgrade and its fine gradation the binder (a mix of cement, hydrated lime, fly ash, etc.) is added in the amounts from 2% to 12% [11].

Cement is a component in many structural elements of auxiliary facilities of linear construction projects. In response to the requirement for limiting the volume of by-product materials and improving waste management solutions, research teams are attempting to optimise building materials by replacing primary ingredients with alternative options [12–14]. Materials such as cement kiln dust (CKD), fly ash from fluidized bed furnaces, or mineral dust are used in conjunction with cement as a supplementary cementitious material in the production of cement bound base layers. Waste materials can be used as high-value components provided that their influence on the properties of the base material is thoroughly identified. In the case of road binders, fly ash, cement kiln dust or mineral dust are applied as a substitute for a portion of cement [18]. The reduction in cement consumption and new applications found for the by-product waste materials work together towards reducing the risk to the environment. Numerous attempts to supplement binder composition with glass powder or fly ash from fluidized bed furnaces have been reported [15,16]. These attempts have not been limited exclusively to the areas related to road engineering [14,17].

A properly composed road binder mixture in conjunction with the mineral aggregate mixture is the basis for constructing hydraulically bound base mixtures, the development of which is a result of the introduction of the harmonised PN-EN 14227-x standards, which replaced a number of national normative documents. Hydraulically bound mixtures have a continuous grading curve and optimum water and binder (e.g. cement) content. This ensures the required strength parameters and frost resistance [19]. They set and harden by hydraulic reaction [21]. The parameters of the hydraulically bound base layers are lower than those of the upper courses of rigid pavements [28] made with cement-based concrete. Therefore, there is a potential for the utilization of waste materials and for the reduction in the consumption of the high value component such as cement.

Although the application of hydraulic road binders (HRB) in the base layer provides the pavement with higher load bearing capacity [19], poor design of the layers may lead to excessive stiffness of the base resulting in cracking due to shrinkage and in the reflective cracking in the upper layers [20]. Thus the optimization of binder composition will lower the risk of excessive base stiffness and the interaction of its constituents may improve physical and mechanical parameters of the base [29].

Alternative solutions have to be found for a typical binder such as cement in hydraulically bound base layers. A well-designed binder will enhance the properties of the base and create an opportunity for the utilization of waste materials. Technical specifications [21] structured the requirements in terms of materials and HBM base design parameters, which translated into their wider application, including their use in semi-rigid structures.

2. Materials and methods

This study aimed at defining possibilities of combining the additions (fluidised bed combustion fly ash and cement dust, CKD) and Portland cement CEM I 32,5R to produce a road binder for the hydraulically bound base mixture. The additions have to be selected so that the required characteristics of the HBM base are maintained. The parameters of the HBM base were determined by measuring compressive strength at 7, 14, 28 and 42 days of curing and frost resistance according to the guidelines [21]. The content of the road binder in the hydraulically bound base was 6%. This amount was in compliance with the guidelines [21] binding in Poland. The guidelines refer to the requirements laid down in the EN 14227-1 standard, which specifies that for the cement bound mixture with gradation from 2.0 to 8.0 mm, the binder content should be ⩾4.0%. To emphasize the influence of binder constituents with binding properties poorer than those of cement, the input amount of binder was increased to the level of 6%. The composition of the road binder is in compliance with the assumptions of the simplex centroid design (a detailed description is provided in Section 2.1). The bound mixture composition was designed relative to the maximum density of the HBM base skeleton and the optimum moisture content determined with the use of the Proctor compaction test.

2.1. Design of the experiment for the evaluation of the results

In order to define the changes in the properties of HBM base layer depending on the road binders used, seven combinations of constituents were prepared. The composition of road binders was obtained in accordance with the simplex-centroid design assumptions [22]. The design assumes the possibility of assessing the effect of the additions to cement such as fluidised bed combustion fly ash and cement dust, CKD and their interaction. At the limiting point of the design, the parameters were determined of the HBM mixture containing 100% share of particular constituents. The values of individual constituents can be interpreted as their proportions. If these data are represented as points on a 3D diagram, the points will form a triangle in a 3D space. Percent contents of individual constituents were standardized in the range 0–1. This the value 0.33 seen in the design of the experiment represents a 33% content of the constituent in the overall volume of the design binder. In the case under analysis it was 6%. The number of degrees of freedom of the experimental design was selected so that it met the criteria such as informativeness, feasibility and effectiveness [30]. Moreover, seven combinations of proportions allow the models of polynomials of second degree at least, which makes the search for local extremes much easier. The experimental design of the HRB compositions and bases obtained from the combination of the binder and aggregate mixture (HBMs) is shown in Fig. 1.

Seven road binders were made, which in combination with the aggregate mixture will allow a comprehensive evaluation of the binder constituents influence on the properties of hydraulically bound base layers. This approach will help find the optimum road binder composition, with fluidised bed combustion fly ash and cement kiln dust CKD as alternatives for cement.

The evaluation of the effect of the HRB on HBM base properties was conducted with two types of mineral aggregates found in great quantities in the Świętokrzyskie Region.

2.2. Materials

The input materials for road binders included: fluidised bed combustion fly ash (P-F), cement kiln dust (CKD) and Portland cement CEM I 32,5R. Table 1 compiles the chemical compositions of these constituents.

The mineral skeleton of the road binder (HRB) was made up of natural stone crushed aggregates with the composition as in Table 2. The aggregate mixtures, derived from the regional quarries, represent carbonate aggregate from limestone and dolomite rocks. The physical, mechanical and chemical parameters of the carbonate rocks from these quarries make the aggregate mixtures suitable for road bases. The mineral aggregate was produced without the washing stage, which resulted in a 10% content of the

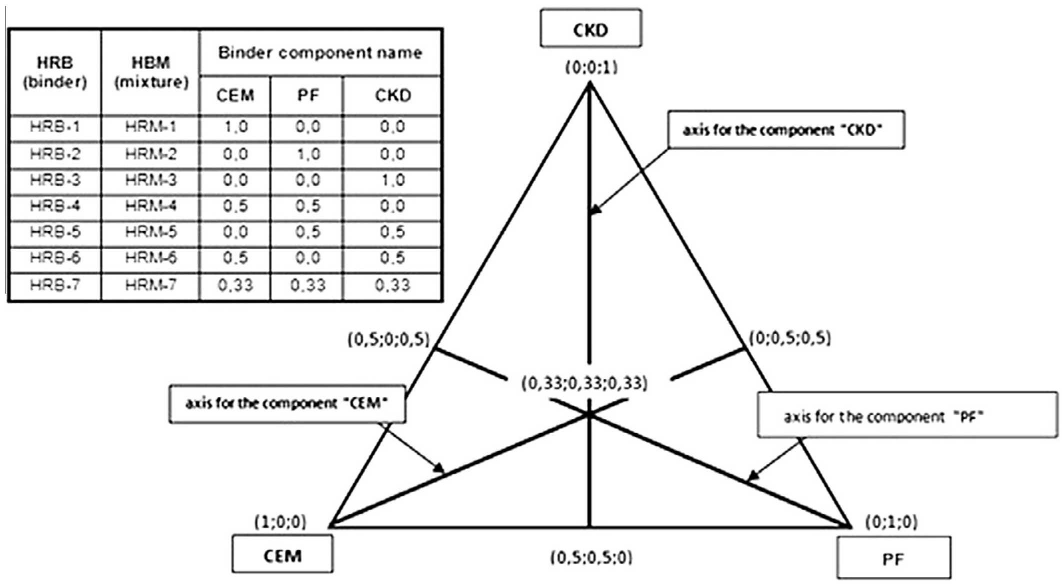

Fig. 1. Experimental design, bound mixtures and binders.

Table 1
Chemical analysis results for the HBR constituents.

	LOI [%]	SiO_2 [%]	SiO_2* [%]	CaO** [%]	CaO** [%]	SO_3 [%]	Na_2O*** [%]	MgO [%]	Cl [%]	P_2O_5 [%]	Al_2O_3 [%]	Fe_2O_3 [%]
CEM I 32,5R	3.1	–	20.2	1.0	63.5	3.4	0.16	2.4	0.07	0.33	4.4	2.4
P-F	2.4	39.0	15.5	6.8	16.2	5.7	3.0	1.3	0.09	9.5	43.7	
CKD	25.2	–	14.9	–	54.4	1.5	0.3	1.6	4.0	–	3.6	1.9

* Reactive.
** Free.
*** Equivalent.

Table 2
Aggregate with continuous grading of 0/8 mm.

		<0.063	0.063	0.125	0.25	0.5	1.0	2.0	4.0	5.6	8.0	10.0
Aggregate mixture 1 (MK1)	Retained [%]	9.4	2.8	4.8	7.6	14.0	19.9	21.4	13.3	5.4	1.4	0.0
	Passing [%]		9.4	12.2	17.0	24.6	38.6	58.5	79.9	93.2	98.6	100
Aggregate mixture 2 (MK2)	Retained [%]	10.4	2.6	3.7	6.3	11.4	20.6	31.3	13.5	0.2	0.0	0.0
	Passing [%]		10.4	13.0	16.7	22.9	34.3	55.0	86.3	99.8	100	100

fraction below 0.063 mm. The use of not pre-washed aggregates (dusty) was dictated by the need to obtain minimum void space content in the hydraulically bound mixture with continuous grading of aggregates (HBM). According to the requirements [21] and EN 14227-1, the optimum content of dust fraction below 0.063 mm in a hydraulically bound mixture of CBGM 0/8 mm should be from 6.5% (m/m) to 15% (m/m). According to the nomenclature of EN 13242, a continuously graded aggregate for hydraulically bound base courses is "a well-graded aggregate" with sizes determined by lower and upper sieve sizes ($d/D \geqslant 0/8$ mm). Lack of the lower sieve size limit forces the presence of the dust fraction. Thus the use of aggregate containing the dust fraction (aggregate produced without the washing stage) was dictated by the need to meet the condition about the required content of fines below 0.063 mm.

The aggregate mixtures were classified into appropriate types with the use of sieve analysis conducted to [23]. Based on the guidelines specified in [21], the aggregates were defined as type 4 for the use in subbase and base layers of roads under light to moderate traffic load and for the improved foundation layer of roads with light to heavy traffic load. The aggregate mixtures varied in terms of mineralogy and origin. The mixture denoted as MK1 was derived from the dolomite aggregate quarry, whereas that denoted as MK 2 from the limestone quarry.

The aggregate grading of 0–8 mm is one of the types used in designing base course hydraulically bound mineral mixtures. The grading range was specified in the Polish guidelines [21] and EN 14227-1.

In summary, the evaluation of the road binder composition was conducted for two road bases. The aggregates used in the bases were from two quarries and had different mineralogical composition. The combination of the binder constituents allowed preparing seven different road binders with the compositions based on three primary components (cement, fluidized bed combustion fly ash and cement dust) used in varied proportions. At the vertices of the design scheme, the binder consisted of only 100% of the primary constituent, e.g., cement. The variability of the binder composition and aggregate origin made it possible to perform a comprehensive evaluation of the base layer properties.

Table 3
Test results for pastes and mortars.

Binder	Composition	Paste w/b	Initial setting time [min]	Final setting time [min]	Hardening time [min]	Mortar w/b	Slump diameter [cm]
HRB-1	CEM	0.33	188	280	92	0.50	16.0 × 16.5
HRB-2	PF	0.60	240	550	310	0.71	17.0 × 16.5
HRB-3	CKD	0.60	595	985	390	0.74	17.0 × 17.0
HRB-4	CEM+PF	0.39	245	345	100	0.62	17.0 × 16.5
HRB-5	PF+CKD	0.50	285	370	85	0.68	16.0 × 16.5
HRB-6	CEM+CKD	0.40	190	310	120	0.62	16.0 × 16.0
HRB-7	CEM+PF+CKD	0.38	154	264	110	0.60	16.5 × 16.5

2.3. Tests and procedures

The quality of the HBM base layer was performed based on compressive strength results at 7, 14, 28 and 42 days of curing of cylindrical specimens prepared with the use of the Proctor method [24]. The HBM bases were also assessed in terms of their frost resistance by determining the frost resistance factor (W-M) [21].

Compressive strength is the fundamental parameter used to evaluate and classify bound mixtures. According to EN 14227-1, determination of compressive strength (System I) does not affect the tensile strength with the modulus of elasticity (System II) and vice versa. Therefore only the compressive strength was adopted for the initial quality evaluation and classification of bound mixtures. In addition, time intervals in the compressive strength tests to be able to assess the effect of the binder on compressive strength in time.

The compressive strength test was conducted to PN-EN 13286-41 on cylindrical specimens with the Height/Diameter ratio of 1.0. The frost resistance factor (W-M) for the HRB bound mixture base was defined as a ratio between the compressive strength $R_{cz\text{-}o}$ of

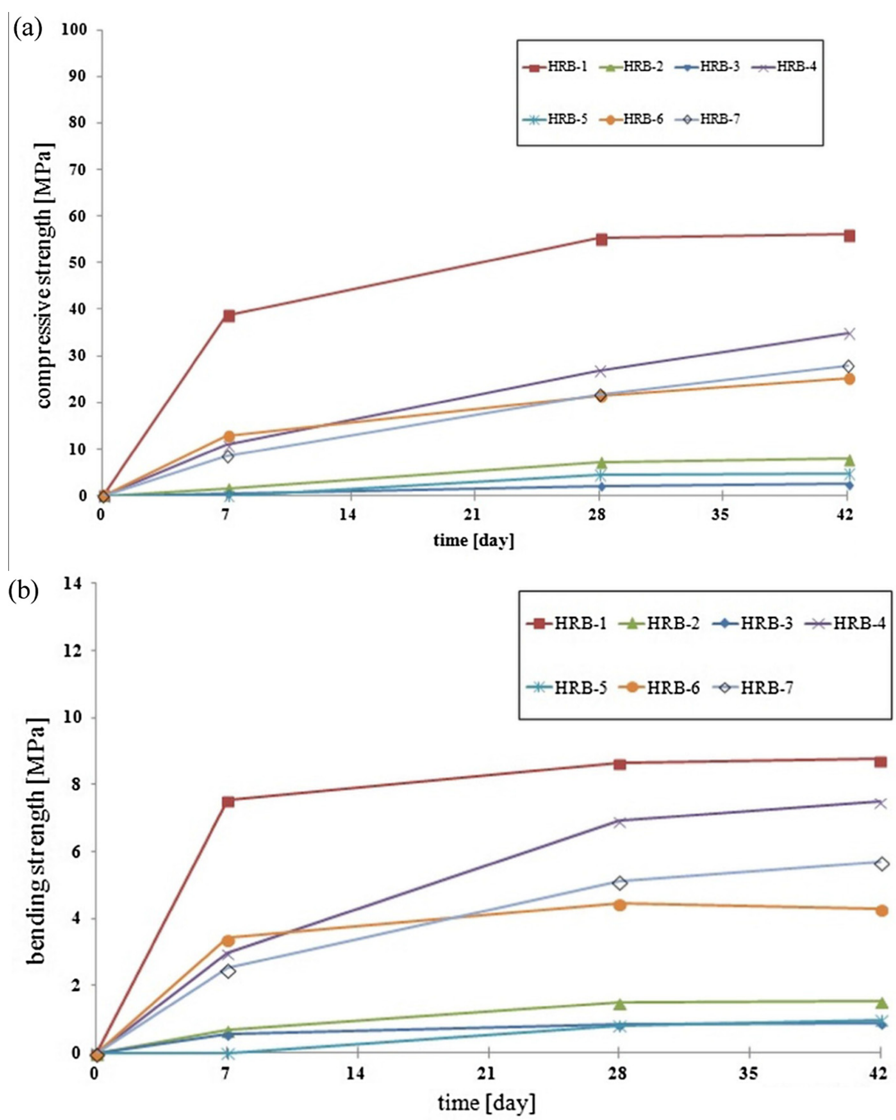

Fig. 2. Mortar test results for (a) compressive strength; (b) flexural strength.

the specimen at 42 days of curing and after 14 freeze-thaw cycles (one freeze-thaw cycle consists of freezing the specimen at -23 °C ± 2 °C for 8 h and thawing in water at + 18 °C ± 2 °C for 16 h) and compressive strength R_c of the specimen at 42 days of curing. The curing procedure of the specimens used in the tests followed the methodology specified in [21].

3. Test results analysis

3.1. Test results for road binders

After establishing water-to-binder ratios for the pastes, the test for determining the initial and final times of setting were performed. The consistency of mortars was determined to EN 1015-3. Results for the pastes and mortars are summarized in Table 3.

Analysis of the results obtained for the pastes from binders made according to the experimental design indicates that the binder containing Portland cement have a shorter initial setting time compared with the binders produced without this constituent. The longest initial setting time, 595 min, was recorded for the binder designated as HRB-3. This binder contains 100% cement by-pass dust. This constituent had the longest hardening time, 985 min. Binders HRB-2 and HRB-3 showed the highest water demand. Blending all the constituents in the amount of 1/3 lowers the water demand level to that of the water-to-binder ratio, which is close to the characteristics obtained for CEM I 32,5R. In addition, HRB-7 has the lowest initial setting time, at the level of 154 min.

The next stage of road binder evaluation involved testing for compressive and tensile strengths performed to EN 196-1. The test results are shown in Fig. 2.

Analysis of the results from the tests for compressive and flexural strengths of the mortars indicates that Portland cement as a constituent of road binders increased both compressive and flexural strengths. The lowest strengths were obtained for the binders that instead of Portland cement included 100% CKD (HRB-3), fluidized bed fly ash (HRB-2) and the blend of the two materials (HRB-5).

3.2. The impact of the binder composition on HBM base parameters

The first stage of the analysis focused on determining the influence the input quantities have on the output quantity. To this end, analysis of variance was used and verified with the Fisher test. The aim of the analysis was to determine whether the change in the quantity of the binder constituents caused a significant change in the evaluation of the parameters determined for road bases, that is, whether the differences between the means of the parameters of HBM bases are not equal to zero. The necessary condition for the analysis to be conducted is testing the assumption of homogeneity of variance for each base with different aggregate type. The Brown-Forsythe test [25] with the division into aggregate mixture types was used as its effect on the change in the measured parameters was suspected. In the following step, as mentioned above, the importance of input variables effect on the output variables was determined. The results from both analyses are summarized in Table 4.

The results for the homogeneity of variance indicate that regardless of the aggregate mixture type used for the HBM base, homogeneity of variance in the groups is retained (in this case for p-value > 0.05). It was demonstrated that at least one of the HRB constituents has a significant effect, at the significance level of 0.05, on the values of dependent variables in Table 3 representing the properties of the bound mixture. This indicates a linear relationship between the quantity of HRB constituents and the change in properties of the base. Fig. 3 presents a graphical interpretation of the distribution of the means and the corresponding confidence intervals in the form of error bars. The dashed lines represent strength classes of the HBM base ($C_{1,5/2}$ and $C_{3/4}$). The results for compressive strength, R, are shown relative to the values of destructive stress. The frost resistance factor (W-M) is a dimensionless quantity that takes the maximum value of 1 (1 = 100%).

It has to be noted that the type of aggregate mixture in the base layer causes variability in changes of the measured parameters. The change trend in the means of dependent variables relative to the combination of the binder compositions (HRB) is similar for both types of the base. Decomposition of total variability with the use of variance evaluation for two grouping variables proved helpful in testing the effect of input variables. The type of the aggregate mixture for the base defines the first grouping variable and the second grouping variable represents the combination of the binder (HRB) constituents. Blending the components results in the HBM base. The outcome of the analysis of variance is shown in Table 5.

The result of the analysis indicates that the type of binder constituents (HRB) has an evident effect on the parameters of the HBM base. Also the aggregate type and synergy between the aggregate type and the binder type affects significant variability. Only in the case of compressive strength at 42 days of curing, the aggregate type used in the base layer and the synergy effect with the type of binder constituents turned out to be insignificant. The interaction diagram was helpful in the interpretation of this phenomenon (Fig. 3). The lack of significance is related to the parallel plots of the base means when summarized for both aggregate types (MK1 and MK2), with the only difference in the values of the means, and in the case of MK2 the means in the diagram are located slightly upper than the results obtained for the HBM base with MK1. But the trend of changes and the proportions between the resulting means of the HBM bases are similar. The results for the HBM bases which had $C_{1,5/2}$ strength class satisfy the requirements for the improved subgrade and subbase for light traffic. This group comprises bases that result from the introduction of additions to cement and their interaction. The HBM bases that had $C_{3/4}$ strength class can be used in subbases for moderate traffic and in bases for light traffic provided that appropriate frost

Table 4
Qualitative analysis and homogeneity of variance analysis in groups.

Dependent variable	Aggregate mixture type MK1		Aggregate mixture type MK2	
	Homogeneity of variance Brown-Forsythe test p-value	ANOVA Fisher test p-value	Homogeneity of variance Brown-Forsythe test p-value	ANOVA Fisher test p-value
nw [%]	0.361443	0.000001	0.845945	0.000088
R7 [MPa]	0.573892	0.000000	0.244545	0.000000
R14 [MPa]	0.167619	0.000000	0.896215	0.000000
R28 [MPa]	0.673940	0.000000	0.294256	0.000000
R42 [MPa]	0.746199	0.000016	0.380320	0.000000
W-M [MPa]	0.481991	0.000007	0.136352	0.000000

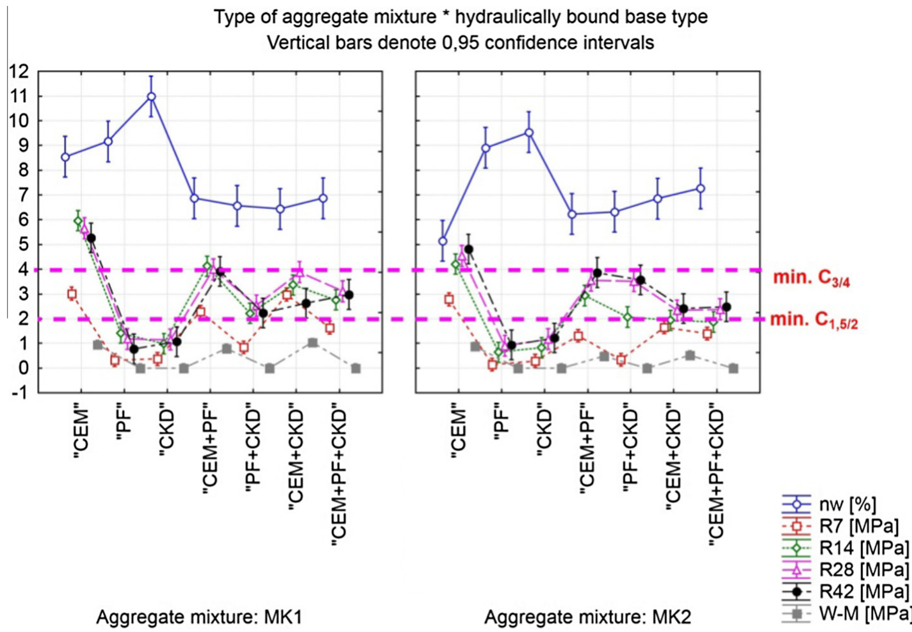

Fig. 3. Diagram of interaction between the type of aggregate mixture and hydraulically bound base type.

Table 5
One-way analysis of variance for HBM base parameters.

Factor	Univariate ANOVA Sigma-restricted parameterization Effective hypothesis decomposition						
	DoF	nw [%]	R7 [MPa]	R14 [MPa]	R28 [MPa]	R42 [MPa]	W-M [MPa]
Intercept	1	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGGREGATE MIXTURE TYPE	1	0.001837	0.000000	0.000000	0.000422	0.699781	0.006862
BINDER TYPE (HRB)	6	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
AGGREGATE MIXTURE TYPE*BINDER TYPE (HRB)	6	0.000712	0.000112	0.002233	0.000055	0.070635	0.020103

resistance is ensured. This group comprises the HBM mixture that uses 50% fluidized bed combustion fly ash as the addition to cement. The relationship is a result of the reduction in the binder compressive strength [10] by introducing additions to cement. The diagram also shows that the highest compressive strength at 7, 14, 28 and 42 days as well as the frost resistance parameter are recorded for the HBM base that uses only cement, regardless of the type of aggregate mixture. Note that the highest compressive strength of $C_{5/6}$ class is recorded for the base that uses MK1 aggregate mixture and cement without additions. The worst compressive strength results were recorded for HBM bases that use 100% of additions (100% of PF (HRB-2) or CKD (HRB-3)) as the binder. The remaining cases have moderate compressive strength results but still higher than the minimum compressive strength level corresponding to class $C_{1,5/2}$. The strength increase rate in the first curing period varies depending on the aggregate mixture type used in the base layer/mixture. This suggests that the type of rock in the aggregate mixture affects the HBM in terms of compressive strength increase rate in different ways. Nevertheless, the type of the rock in the aggregate mixture has to be taken into account while designing the optimum quantity of additions to cement.

Analysis of the interaction diagram (Fig. 3) indicates that water absorption and compressive strength are inversely correlated. HBM bases with high absorption had lower compressive strengths. The differences and similarities observed suggest that an appropriate grouping technique be used such that can be helpful in classifying individual bases to subgroups of significantly distinct results.

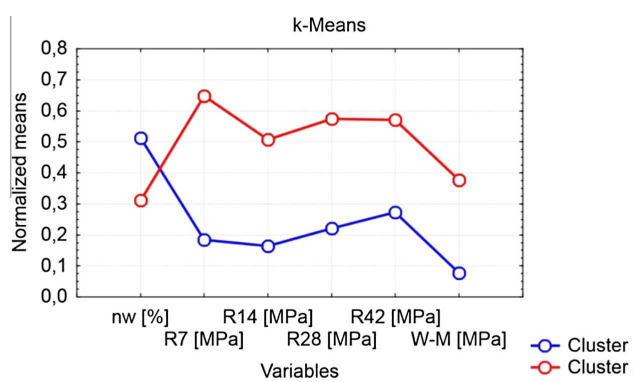

Fig. 4. K-means clustering diagram.

To this end, the method of k-means clustering was used [25], as shown in Fig. 4.

It was established that there are two groups of bases with markedly different characteristics, independent of the aggregate type and binder type used in the HBM base production. The first group includes the HBM bases with high absorption and low compressive strength and frost resistance. The other group is the opposite and includes the bases with low absorption and high average compressive strength and frost resistance. The results of the classification of the HBM bases assigned to one of the two groups are compiled in Table 6.

Table 6
Classification of bases with the use of k-means method.

Group 1 High absorptionLow compressive strength		Group 2 Low absorptionHigh compressive strength	
Aggregate mixture type	Binder type	Aggregate mixture type	Binder type
K1	"100% PF"	K1	"100% CEM"
K1	"100% CKD"	K1	"50%CEM+50%PF"
K2	"100% PF"	K1	"50%PF+%CKD"
K2	"100% CKD"	K1	"50%CEM+50%CKD"
K2	"50%CEM+50%PF"	K1	"33%CEM+33%PF+33%CKD"
K2	"50%PF+50%CKD"	K2	"100%CEM"
K2	"50%CEM+50%CKD"		
K2	"33%CEM+33%PF+33%CKD"		

The result from this analysis shows that the use of 100% PF (HRB-2) or CKD (HRB-3) in the binder does not provide the HBM base with durability, independently from the type of aggregate mixture added. But various dusts in combination with cement applied to the base mixture based on the aggregate mixture MK1 are capable of ensuring the normative parameters. In the HBM base that uses aggregate mixture MK2, only 100% of cement in the binder is capable of ensuring similar mechanical parameters to those in Group 2 bases. The analysis suggests that it is necessary to accurately determine the composition of the road binder with the use of response surface modeling.

3.3. Optimization of mixed binder composition

3.3.1. General assumptions

Given the results of homogeneity tests and those of analysis of variance, it seems possible to find the function of the test object in the form of a regression model. Consequently, it is possible to find the probable optimal solution. In this experiment, the design of the mixture was based on the simplex centroid design [25]. The model in the form of a polynomial defined by a canonical form was used to describe the changes in compressive strength.

$$y = b_1 \cdot x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3$$

where y – dependent variable, x_i – independent input quantities, i.e. factors, b_{ij} – experimental parameters of the function model.

Optimization is the process involving the construction of an objective function which requires strictly defined constraints. Two parameters were used to find the optimal solution:

- compressive strength after 28 days of curing R_{28days} [26].
- frost resistance test – determining the W-M factor [21].

The selection of only two parameters is due to the fact that their limiting values are defined in the normative documents [21] and EN 14227-1÷5.

3.3.2. Regression model of the effect of the binder constituents on compressive strength R_{28days}

Since the aggregate mixture had a significant effect on the level of the compressive strength means at 28 days of curing, two regression models had to be defined. The results of fitting the function using the least square method [27] are shown in Fig. 5, with fitting parameters summarized in Table 7.

The result from fitting the square model to the values (Fig. 5) determined for parameter R_{28days} indicates good fit to the significant correlation coefficients higher than 0.9 at the average estimation error of 0.22 MPa. Contour plots confirm the findings of the previous analysis. Regardless of the type of the aggregate mixture used in the base composition, the application of only fly ash PF of cement dust CKD does not provide the required strength class $C_{1,5/2}$. When the cement is used without additions (100% cement) in the binder or with the minor addition of dust and ash of up to 10% (PF+CKD <10%), the base with MK1 can be provided with the compressive strength of class $C_{5/6}$. This mixture type can be used for the base course if frost resistance requirements are met. According to the data from the models, both aggregate mixtures can obtain class $C_{1,5/2}$ even if cement is completely eliminated from the binder. This HBM base can be used for subbases under moderate traffic load at the required frost resistance level. The model fit for the strength parameters of the base that used MK1 indicates that the interaction of cement and additions, i.e. CKD and PF was not significant, which may be related to the presence in the aggregate of a factor that reduced the effectiveness of the binder

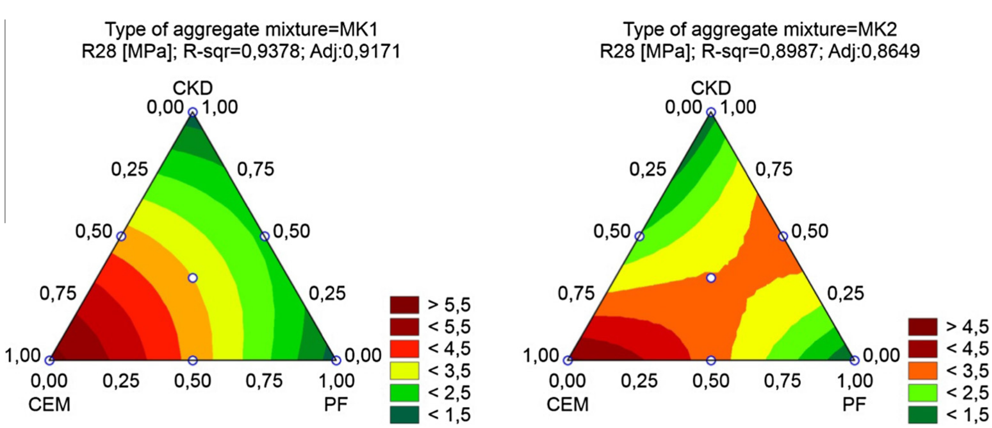

Fig. 5. Response surface for variable R_{28days} (normalized scale).

Table 7
Fit coefficients of the model for variable R_{28days}.

Factor	Aggregate type = MK1 Var.:R28 [MPa]; R-sqr=,9378; MS Residual=,20516		Aggregate type = MK2 Var.:R28 [MPa]; R-sqr=,8987; MS Residual=,2214231	
	Coeff.	p	Coeff.	p
(A) CEM	5.695277	0.000000	4.61482	0.000000
(B) fluidised bed combustion ash	1.225001	0.000283	0.97892	0.002536
(C) CKD	1.195144	0.000356	1.24910	0.000337
AB	1.474506	0.237166	1.83824	0.160205
AC	1.053859	0.392721	−3.52140	0.012655
BC	4.617553	0.001555	8.46208	0.000006

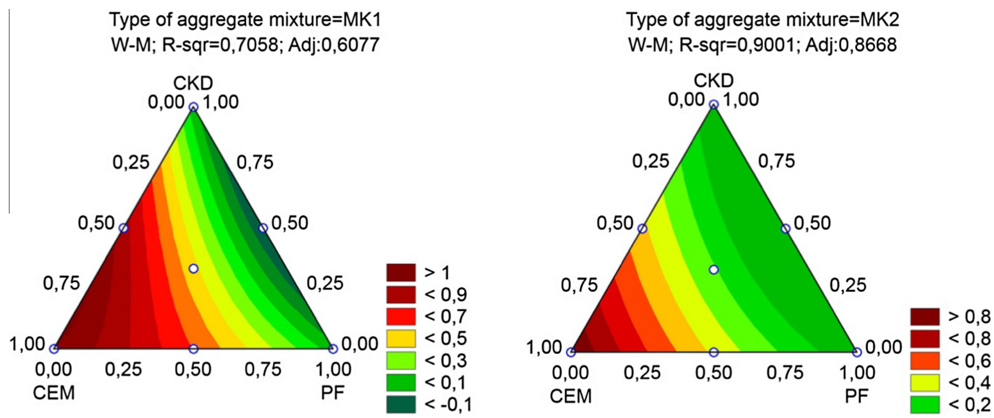

Fig. 6. Response surface for variable W-M (normalized scale).

Table 8
Fit coefficients of the model for variable W-M.

Factor	Aggregate type = MK1 Var.: W-M [–]; R-sqr = 0.7058; MS Residual = 0.1004508		Aggregate type = MK2 Var.: W-M [–]; R-sqr = 0.9001; MS Residual = 0.0152801	
	Coeff.	p	Coeff.	p
(A) CEM	1.004052	0.000060	0.898703	0.000000
(B) fluidized bed combustion ash	0.048259	0.794816	0.023423	0.746374
(C) CKD	0.048259	0.794816	0.023423	0.746374
AB	0.286306	0.737333	-0.318561	0.345142
AC	1.286141	0.145632	-0.152406	0.647672
BC	−0.965180	0.267411	-0.468451	0.172260

Table 9
Optimization criteria for R_{28days} and W-M.

	Parameter	Unit of measure	Optimization interval
1	Compressive strength at 28 days (R_{28days})	MPa	Form 2.0–4.0
2	Frost resistance factor (W-M)	–	From 0.6 to 0.7

constituents in the reaction with the cement. In the case of the base layer with incorporated aggregate mixture MK2, only the interaction between the cement and the fluidized bed combustion ash addition was not significant. The interaction of the cement with the cement dust CKD in the HBM base with MK2 was significant, but the sign assigned to the binder CKD constituent suggests that its presence lowers the compressive strength of the base. It is important to note that regardless of the aggregate mixture type and of the road binder constituents the base layers satisfy the strength requirement (Rc ⩾ 0.5 MPa) for the improved subgrade for the light, moderate and heavy traffic load.

3.3.3. Regression model of the effect of road binder constituents on frost resistance WR+M

Similarly to the case of regression models for the compressive strength at 28 days of curing, for the evaluation of the resistance to the action of water and frost the regression models of the response surface will be determined separately for the bases with different aggregate mixture type. With the adopted model of the second degree polynomial, the results of the regression function are presented graphically in Fig. 6, with the fit parameters evaluation summarized in Table 8.

The fit of the resistance to the action of water and frost model for both base layers, regardless of the aggregate mixture type, is at the minimum level of 0.7, at the average frost resistance estimation error of 0.15. In the case of both bases, the required frost resistance can be attained through the use of mixed binder containing much more than 50% of cement. Only this composition of the binder is capable of warranting the required minimum frost resistance higher than 0.6 for the subbase under light and moderate traffic and higher than 0.7 for the base layer under light and moderate traffic. Despite the fact that the required

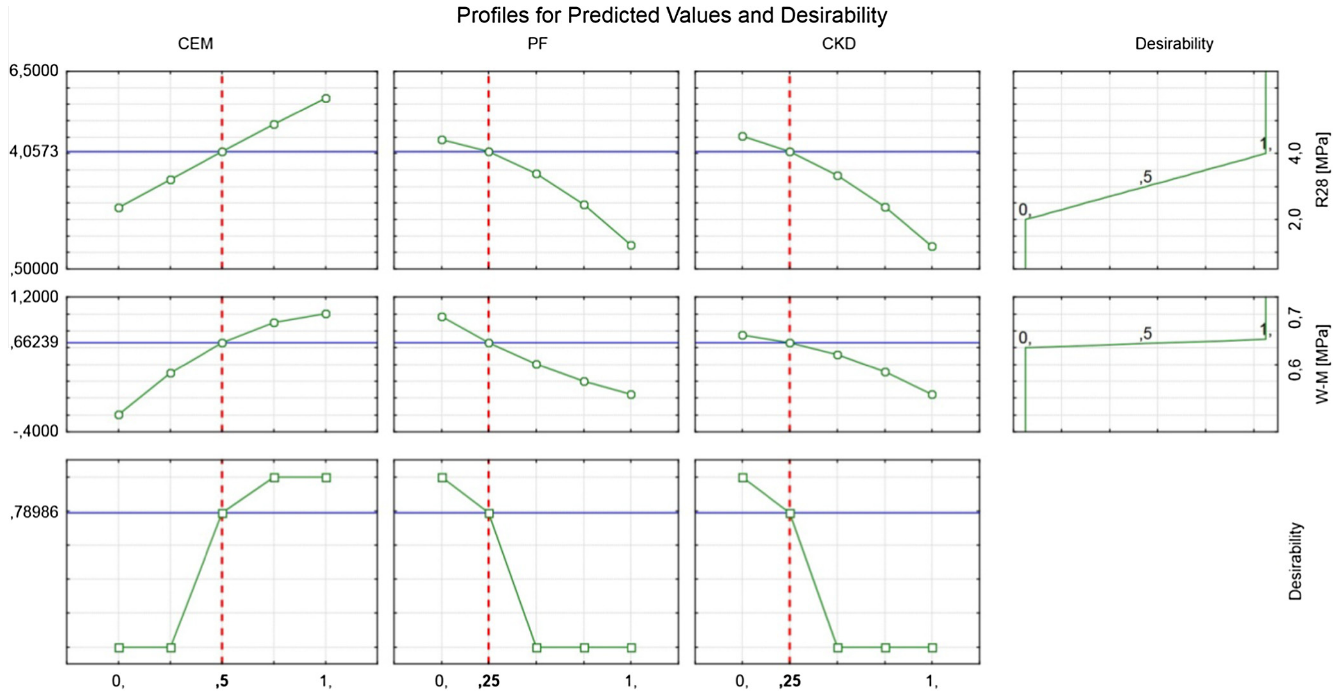

Fig. 7. Optimization results for hydraulically bound base layer with MK1.

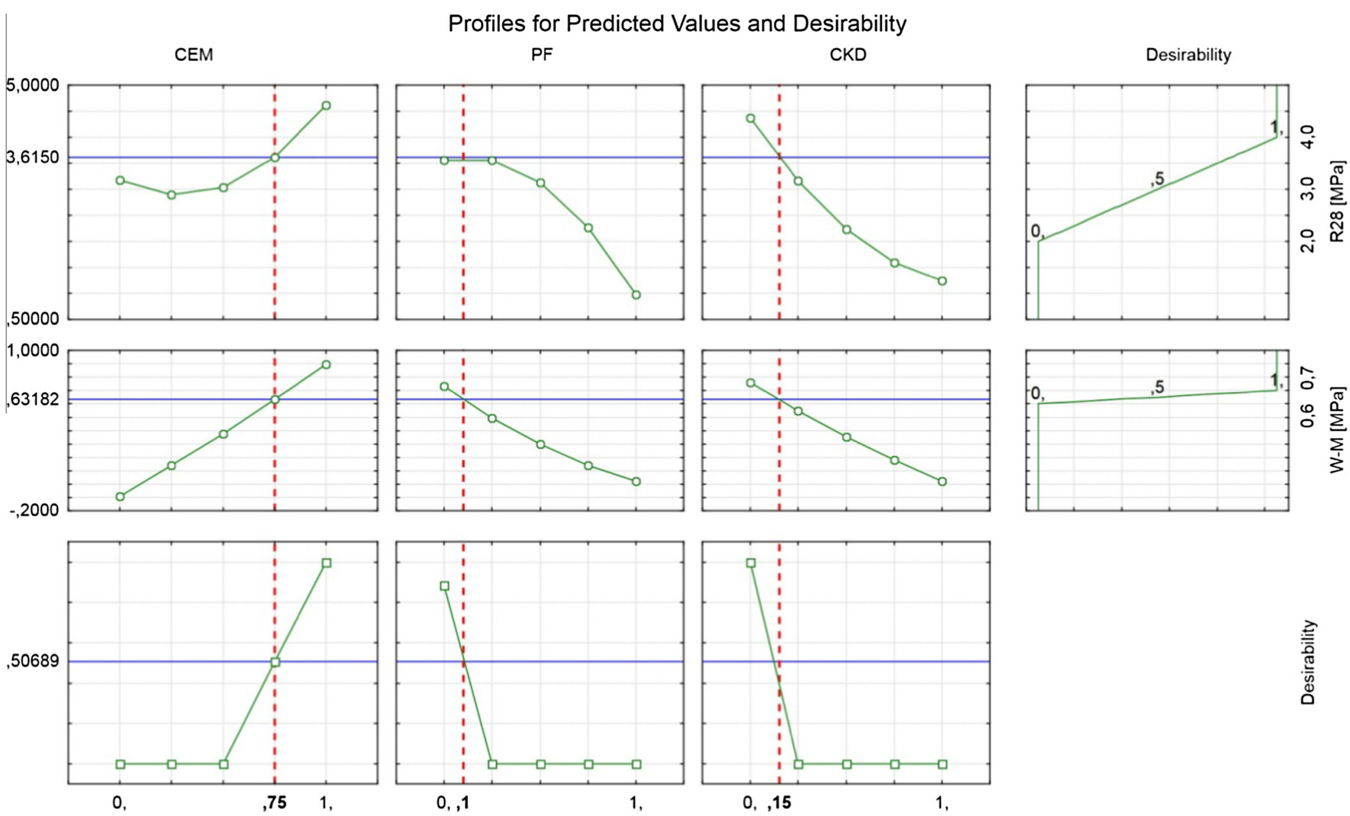

Fig. 8. Optimization result for the hydraulically bound base layer with MK2.

compressive strength can be obtained using less cement, in the case of the resistance to climatic factors, the combinations of only cement dusts and fluidized bed combustion ash cannot be used in the binder. The significance evaluation of the model parameters in Table 8 indicates that only the quantity of the cement in the road binder is significantly important for achieving frost resistance required. The shapes of the response surface of the study results are similar regardless of the base layer type and are subject to a rapid curvature for a large amount of cement, as confirmed by its key share in the composition of HRB intended for the HBM base.

3.3.4. Determining the optimal solution for the quantities of road binder constituents for hydraulically bound base $C_{1,5/2}$

Optimization was based on the results from the regression models. Multivariate optimization involved the transformation of many approximated variables from the model into one variable representing the utility value [25,27]. To find the optimal solution, the criteria or constraints in the optimization process have to be given. Moreover, the values of dependent variables must be normalized in the interval of {0;1} with the use of a transformation function expressing our satisfaction from the results at a given level. Here, the most simple and most suitable from the engineering perspective linear function profile was used. The optimal solution was searched separately for two types of aggregate, for the bound base intended for the subbase under light and moderate traffic. To define the optimal solution, the constraints shown in Table 9 were used.

Optimization results in Fig. 7 refer to the hydraulically bound base layer made with aggregate mix MK1 and in Fig. 8 to the hydraulically bound base layer made with aggregate mix MK2.

The optimization results indicate that with the use of a certain amount of dust and ash in the HRB composition, it is possible to obtain the hydraulically bound base for the subbase layer satisfying the requirements laid in [21]. In the case of the base with MK1, which attained an average frost resistance (about 0.65), the solution found was as follows: cement – 50%, fluidized bed combustion ash – 25% and cement dust CKD – 25%. In the case of the base with MK2 aggregate mixture, the binder included: cement CEM I 32,5R – 75%, fluidized bed combustion ash PF – 15% and cement dust CKD – 10%. Both solutions had different values of the utility function: 0.79 for the bound base with MK1 and 0.51 for the bound base with MK2. The criterion of the end of the search for the bound base solution for both aggregate mixtures was obtaining frost resistance level of about 0.65. Thus the result from the utility function should be interpreted in the following way. The hydraulically bound base layer with aggregate mixture MK2 achieved the middle values from the imposed intervals for the criteria and had the $C_{1,5/2}$ strength class. The hydraulically bound base layer with aggregate mixture MK1 attained similar frost resistance level, but had a markedly higher resistance to compression, of about 0.5 MPa, that is, it had the $C_{3/4}$ strength class. Its final value of the utility function was higher (0.79). The optimization results indicate that the process of optimum selection of HRB constituent quantities requires that the origin of the aggregate mixture to be incorporated in the hydraulically bound base layer be taken into account.

4. Conclusions

The optimization of the composition of the road binder for the hydraulically bound base layer, preceded by relevant tests and analyses leads to the following conclusions:

- The optimization process revealed the potential of cement dusts and fluidized bed combustion ash as additions to the cement used as the binder in the bound base layers.
- The analysis of the k-means clustering showed two groups of base layers varying considerably, regardless of the type of aggregate and binder incorporated in the HBM base layer. The first group includes the hydraulically bound bases of high absorption and low strength and frost resistance. The second group includes the opposite of the bases from the first group having low absorption and high values of strength and frost resistance means.
- The composition of the road binder with no cement constituent taken into account reduces possible applications of the hydraulically bound mixture made up from the combination of the road binder and the aggregate mixture, to the layer of improved foundation. Ash or dust based binder does not guarantee frost resistance parameters required for HBM base layer.
- The type of aggregate incorporated in the hydraulically bound base layer is the major factor in the variability of the binder composition. The combination of the binder constituents guarantees the attainment of the required durability parameters. In the case of the base layer made with aggregates from dolomite rocks, larger amounts of fluidized bed combustion ash and cement dusts can be utilized than in the case of limestone aggregates.
- The optimum quantities of additions for HBM base layers with dolomite MK1 are as follows: 25% fluidized bed combustion ash, 25% cement dust CKD and 50% cement (25%PF+25%CKD +50%CEM). For the base layer with limestone aggregates, the quantities of additions are smaller: 15% fluidized bed combustion ash, 10% cement dust CKD and 75% CEM I 32,5R – 75% (15%PF+10%CKD+75%CEM).

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