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THE USE OF LOGIT MODEL FOR DESIGNING MIXTURES OF SOILS STABILIZED WITH HYDRAULIC BINDERS

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Abstract. Certain soils encountered in practice are difficult or impossible to use for road building. To improve their mechanical properties, various methods of soil stabilization are applied. A widely used means of soil stabilization is the addition of hydraulic binders. In the methodology of designing of soil-binder mixtures it is important to determine how, based on variable parameters characterizing a sample of soil, to predict the grade of the binder and the quantity in which it is to be added to the soil in order for defined requirements to be met. This work describes an application of statistical logit model in designing soil-binder mixtures intended to be used for road foundations, subject to defined requirements as to their strength and frost resistance.

Keywords: soil stabilization, soil reinforcement, hydraulic road binders, soil-binder mixtures, road foundation design, logit model.

1. Introduction

In road construction, it is sometimes difficult to obtain soils with suitable properties for the building of a road structure. This problem applies particularly to natural cohesive soils with high content of water which, as a rule, are frost-susceptible and cannot be built in within a zone which is subject to the effects of frost (Vaitkus *et al.* 2012). Soil stabilization is often applied for technical, economic and environmental reasons (Hossain *et al.* 2007; Kukko 2000), which weigh in favour of using local soils, as well as waste materials, in earthworks. There are many existing methods of soil reinforcement, including methods of mechanical, chemical and thermal stabilization. At present one observes significant growth in chemical soil stabilization, with a tendency to replace traditional binders with cheaper binders made from industrial wastes. Mixtures of various binders made from industrial wastes demonstrating binding properties are also being used in road construction with increasing frequency.

Among the industrial wastes most commonly used for soil stabilization are fluidized bed ash, activated lignite fly-ash, pulverized carbonaceous shale, and blast furnace slag (Kaniraj, Havanagi 1999; Miller, Azad 2000; Sezer *et al.* 2006). Fly-ash obtained from its binding properties, due to lignite combustion, has been used in the production of binders for soil stabilization (Edil *et al.* 2006; Shao *et al.* 2008). Soils stabilized with hydraulic binder made from activated fly-ash demonstrate high levels of strength and frost resistance, adequate for the building of road foundations (Arora, Aydilek 2005). The types of ash most commonly used in hydraulic binders are those with high calcium oxide content, which provide strong binding properties (Hatipoglu *et al.* 2008; Lav *et al.* 2006). It should be noted that the reinforcement of soil using alternative hydraulic binders is important in terms of both the protection of the natural environment and the positive impact which processed industrial wastes have on the durability of road surface structures (Ahmaruzzaman 2010; Raupp-Pereira *et al.* 2008).

The modelling and rational design of road structures continues to be the subject of much research, which has led to numerous models of the various mechanisms occurring in road structures; these include, for example, models of mechanisms of the thermal cracking of asphalt layers (Hiltunen, Roque 1994) and of mechanisms relating to the impact of the construction on the subsoil (Fedorowicz, Kadela 2012). There exist models based on purely theoretical assumptions and on assumptions resulting from empirical experiments, directly related to observed phenomena. The scope of analysis relating to the design of a given structural road layer may be extended to include analysis of experimental results using statistical modelling (Bertulienė 2012). Statistical analyses are usually regarded as an auxiliary tool, although practical applications for them continue to be sought in various fields of science (Chorin, Marsden 1990). It is considered appropriate to build a model based on a simplified process of real observation

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of a phenomenon, making it possible to give a sufficiently precise description of that process.

The composition of a soil-binder mixture is determined through laboratory-based design, with the aim of ensuring that the properties of a mixture correspond to the defined requirements. The designer's basic task is to select the appropriate strength grade of binder, and the quantity in which it is to be added, to stabilize a given type of soil. The design of a soil-binder mixture thus centres on the proper selection of two basic parameters: the strength grade of the binder (expressed in MPa), and the quantity (expressed in %) in which the binder is to be added to the soil, which has previously been analysed in terms of such parameters as grain size. A method of designing the composition of a soil-binder mixture is therefore based on an evaluation of how the properties of the soil and of the binder affect the mechanical properties of the resulting soil-binder mixture. This means that the chief aim of a design method for the composition of soil-binder mixtures is to determine how, based on variable parameters characterizing a sample of soil, to predict the appropriate grade of binder and the quantity in which it is to be added to the soil so as to fulfil defined criteria of suitability for use in road construction.

Requirements and testing methods for the classification of hydraulically bound mixtures and methods of testing them are laid down in European standards in the *EN 14227* series (e.g. *EN 14227-13:2006 Hydraulically Bound Mixtures – Specifications – Part 13: Soil Treated by Hydraulic Road Binder*). The standards in this series are product standards; that is, they define material categories and grades of mixtures, but do not indicate where they are to be used. They have introduced a new classification of hydraulically bound mixtures and new testing methods; however this has made it necessary to carry out comparative studies, on the basis of which new technical requirements have been laid down in Poland: *WT-5:2010 Wytyczne mieszanek związanych spoiwem hydraulicznym do dróg krajowych (Guidelines for Mixtures Treated with Hydraulic Binder for National Roads)*. Technical requirements were developed by the Road and Bridge Research Institute.

The present work describes the use of the statistical technique of logit model for designing soil-binder mixtures to be used for making road foundations, subject to defined requirements regarding their strength and frost resistance coefficient.

2. Materials and methods

Seven soils with different grain sizes were selected for testing, taken from borrow pits in central-western Poland, and numbered as follows:

No. 1. Soil from a site at Nowogród Bobrzański, with gravel fraction Gr = 22.1%, sand fraction Sa = 72.9% and silt fraction Si = 3.5%;

No. 2. Soil from a site at Babimost, with gravel fraction Gr = 1.4%, sand fraction Sa = 98.1% and silt fraction Si = 0.5%;

No. 3. Soil from a site at Sulechów, with gravel fraction Gr = 0.0%, sand fraction Sa = 39.0% and silt fraction Si = 49.0%;

No. 4. Soil from a site at Józefowo, with gravel fraction Gr = 13.2%, sand fraction Sa = 59.3% and silt fraction Si = 21.7%;

No. 5. Soil from a site at Chynów, with gravel fraction Gr = 0.8%, sand fraction Sa = 74.5% and silt fraction Si = 19.9%;

No. 6. Soil from a site at Kargowa, with gravel fraction Gr = 18.8%, sand fraction Sa = 67.8% and silt fraction Si = 10.3%;

No. 7. Soil from a site at Lubrza, with gravel fraction Gr = 1.2%, sand fraction Sa = 89.2% and silt fraction Si = 7.8%.

The following binders were selected to be used for stabilization of the aforementioned soils:

– binder I, composed of 90% activated lignite fly-ash and 10% CEM I 42.5 R cement, with strength grade 3 MPa;

– binder II, composed of 80% activated lignite fly-ash and 20% CEM I 42.5 R cement, with strength grade 9 MPa.

These binders were added to the individual soils in proportions of 2%, 4%, 6%, 8% and 10% relative to the dry mass of the soil. Each mixture was compacted dynamically with energy of 0.59 J/cm^3, i.e. according to a standard Proctor method, in a cylindrical steel mould with height and diameter equal to 8 cm. The samples obtained were stored in a climatic chamber at temperature +18 ± 2 °C and humidity 95–100%, and their compressive strength R_c was tested using a static method after setting for 28, 42, 90 and 180 days, while for the last 14 days prior to the compressive strength R_c testing the samples were plunged into the water.

The quantity and type of stabilizing binder were also analysed based on the results of testing of the frost resistance of the samples. Hardened soil-binder mixtures ought to demonstrate resistance to the action of frost. The frost resistance coefficient n of each mixture was determined as the ratio of the compressive strength R_c^{f-t} of a sample that had undergone 14 cycles of freezing and thawing, to the compressive strength R_c of untreated sample, according to the formula:

$$n^{(28,\ 42,\ 90,\ 180)} = \frac{R_c^{f-t(28,\ 42,\ 90,\ 180)}}{R_c^{(28,\ 42,\ 90,\ 180)}} 100\%. \qquad (1)$$

The samples used for measuring the value of R_c^{f-t} (subjected to freezing and thawing cycles) after the set hardening period (28, 42, 90 or 180 days) in a climatic chamber at temperature +18 ± 2 °C and humidity 95–100%, were immersed in water at room temperature only for 24 hours, and then over the next 14 days were subjected to freezing and thawing cycles. One freezing and thawing cycle involved freezing the sample at –23 ± 2 °C for 8 hours, followed by thawing in water at a temperature of +18 ± 2 °C for 16 hours.

Soil-binder mixtures were designed by selecting an appropriate type of binder and an appropriate quantity of that binder to be added, in the range 2–10% relative to the soil dry mass, requiring the conformity of defined criteria regarding the strength of the mixtures and their frost resistance coefficients. These requirements are presented using statistical contour maps based on a computed logit model. In total, 1680 sample test results were used to develop this model. The parameters of the logit model were estimated using the method of maximum likelihood, and the significance of the coefficients of the model was evaluated using the Wald test (Everitt, Hothorn 2011; McCullagh, Nelder 1989). In this way a statistical model was created for the soil-binder mixtures, serving as a tool indicating the possible interactions taking place between the components of those mixtures. In statistical analysis of results, the software *STATISTICA version 9* and *R version 2.12.1* were used.

In order to design a soil-binder mixture, it is necessary to consider variables characterizing the soil, followed by variables characterizing the hydraulic binder, and to impose criteria for the acceptability of the mechanical parameters of the resulting mixture. In the design procedure followed in the present work it was assumed that a bound soil-binder mixture ought to have a compressive strength in the range 2.5–5.0 MPa, while also taking account of the different times of testing, and either requiring or not requiring a minimum value for the frost resistance coefficient.

It was concluded that the significant variables relating to the type of soil and having a significant influence on the differences in the compressive strength values obtained for soil-binder mixtures include the gravel fraction (%), sand fraction (%) and silt fraction (%). Significant variables relating to the hydraulic binder are the binder's compressive strength grade (MPa) and the proportion in which it is added (%). It is possible to consider other variables, but subject to the condition that they have a significant effect on the observed statistical property. The process of designing a soil-binder mixture is summarized in the following diagram (Fig. 1).

3. Results and analysis

The results of testing of the compressive strength R_c of soil-binder mixtures after hardening for 28 days, depending on soil type, the quantity of hydraulic binder added, and the configuration of binder quantity and strength grade, are given in the following tables (Tables 1–3).

The results of testing of the compressive strength R_c of soil-binder mixtures showed that this parameter depends on the following factors:

- soil type (7 soils);
- type of hydraulic binder (two strength grades: 3 MPa and 9 MPa);
- quantity of hydraulic binder added to the soil (5 quantities: 2%, 4%, 6%, 8% and 10%);
- time of testing of mechanical properties (4 times: 28, 42, 90 and 180 days).

The tests showed that the influence of the soil type and quantity of binder caused significant differences in the compressive strength values obtained for the soil-binder mixtures. The situation is similar in the case of the quantity of added binder and its strength grade: these factors also cause significant differentiation in compressive strength values. The tabulated results also show that, as the quantity of hydraulic binder increases from 2% to 10% (regardless of the soil type and the strength grade of the binder), the compressive strength of the soil-binder mixtures increases. The same applies in the case of an increase in the strength grade of the binder from 3 MPa to 9 MPa.

The analysis confirmed all the relationships concerning the effect of the enumerated factors on differences in the compressive strength values R_c recorded for soil-binder mixtures within the scope of the observations: typical

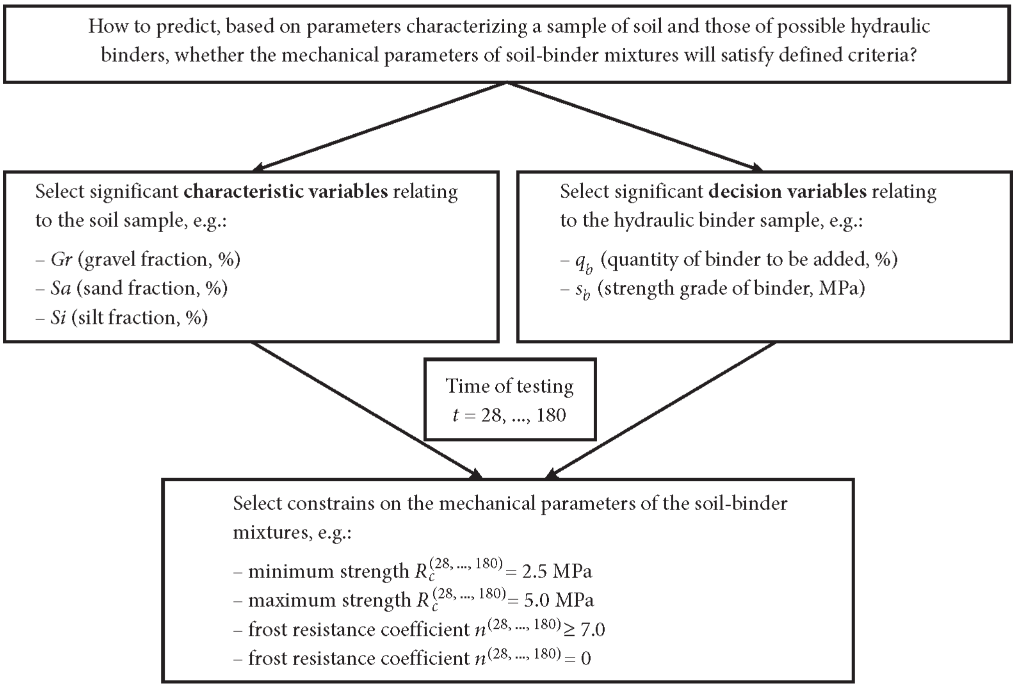

Fig. 1. Process of designing a soil-binder mixture with defined compressive strength and frost resistance coefficient n

Table 1. Statistical parameters for the compressive strength R_c of soil-binder mixtures after hardening for 28 days, depending on configuration of quantity of hydraulic binder added and strength grade of binder

Strength grade of binder, MPa	Quantity of binder, %	Compressive strength of soil-binder mixture, 1st quartile, 3rd quartile, MPa				
		Minimum	1st quartile	Median	3rd quartile	Maximum
3	2	0.00	0.12	0.36	0.41	0.50
	4	0.00	0.35	0.62	1.01	1.40
	6	0.00	0.60	1.24	1.54	2.10
	8	0.00	0.84	1.64	2.33	2.68
	10	0.21	1.47	2.55	2.82	3.28
9	2	0.00	0.26	0.42	0.50	0.68
	4	0.00	0.67	1.18	1.62	2.26
	6	0.26	1.15	2.04	2.62	3.32
	8	0.60	1.55	2.80	3.11	3.94
	10	0.74	1.78	3.10	4.19	5.46

Table 2. Statistical parameters for the compressive strength R_c of soil-binder mixtures after hardening for 28 days, depending on soil type

Soil type	Compressive strength of soil-binder mixture, 1st quartile, 3rd quartile, MPa				
	Minimum	1st quartile	Median	3rd quartile	Maximum
No. 1	0.18	0.72	1.32	2.50	4.12
No. 2	0.06	0.12	0.19	0.36	0.74
No. 3	0.00	0.00	0.00	0.37	0.92
No. 4	0.38	1.09	1.62	2.91	4.26
No. 5	0.36	0.76	1.71	2.37	2.64
No. 6	0.44	1.58	2.47	3.31	5.46
No. 7	0.50	1.13	1.92	2.69	3.10

Table 3. Statistical parameters for the compressive strength R_c of soil-binder mixtures after hardening for 28 days, depending on quantity of hydraulic binder added

Quantity of binder, %	Compressive strength of soil-binder mixture, 1st quartile, 3rd quartile, MPa				
	Minimum	1st quartile	Median	3rd quartile	Maximum
2	0.00	0.17	0.37	0.44	0.68
4	0.00	0.36	1.01	1.35	2.26
6	0.00	0.57	1.54	2.09	3.32
8	0.00	0.91	2.33	2.77	3.94
10	0.21	1.32	2.65	3.24	5.46

(including the median) and atypical (values higher than the third quartile or lower than the first quartile). This being the case, it is concluded that it is appropriate to adopt these variables characterizing the soil (*Gr*, *Sa*, *Si*) and the hydraulic binder (q_b, s_b) for the purposes of the procedure for designing soil-binder mixtures.

Based on the results of the tests, it was possible to construct a logit model to determine the probability p of conformity of the set criteria for the strength of a soil-binder mixture, according to the variables characterizing the hydraulic binder (q_b and s_b), depending on the adopted parameters characterizing the soil (*Gr*, *Sa* and *Si*). The computed statistical formula for the logit model, relating to the probability of the conformity of criteria concerning the mechanical parameters of a soil-binder mixture, depending on the adopted parameters characterizing the soil and the variables describing the binders, takes the form:

$$p\left(s_b,\ q_b\right)=\frac{1}{1+e^{-k-xs_b-yq_b}}, \qquad (2)$$

where:

$$k=\alpha Si+\beta Sa+\gamma Gr. \qquad (3)$$

The variables s_b and q_b denote respectively the strength grade of the hydraulic binder (in MPa) and the quantity of hydraulic binder added (in % by weight), while the parameter k depends on the granular composition of the soil (*Si*, *Sa* and *Gr* being respectively the silt, sand and gravel fractions, expressed in % by weight). The coefficients x, y, α, β, γ in the formulae (2) and (3) are parameters of the logit model, determined by statistical methods based on the experimental data, depending on the required mechanical parameters of the soil-binder mixtures, the time of testing, and the imposition or non-imposition of conditions on the frost resistance coefficient.

The data also contained information as to whether a given configuration of properties of the mixture satisfies the defined criteria for compressive strength and frost resistance. The parameters of the logit model are determined by the method of maximum likelihood. In this method, values of α, β, γ, x, y are determined so as to give a maximum for the likelihood function, defined by the formula:

$$\prod_{i=1}^{N} p_i^{n_i}\left(1-p_i\right)^{1-n_i}, \quad (4)$$

where N – the number of experimental mixtures; i – the index of a given mixture, $i = 1, 2,\ldots, N$; $n_i = 1$ if the mixture satisfies the criteria, $ni = 0$ if the mixture does not satisfy the criteria;

$$p_i = \frac{1}{1+e^{-k_i - xs_{b,i} - yq_{b,i}}}, \quad (5)$$

$$k_i = \alpha\, Si,_i + \beta\, Sa,_i + \gamma\, Gr,_i, \quad (6)$$

where $s_{b,i}$ – the strength grade of the hydraulic binder in the i^{th} mixture; $q_{b,i}$ – the quantity of added hydraulic binder in the i^{th} mixture; $Si,_i$ – the silt fraction in the i^{th} mixture; $Sa,_i$ – the sand fraction in the i^{th} mixture; $Gr,_i$ – the gravel fraction in the i^{th} mixture.

The values of the parameters α, β, γ, x, y giving a maximum of the likelihood function were determined using the iterative Newton–Raphson method.

For evaluation of the significance of the model parameters α, β, γ, x, y, the parametric Wald test was used. To determine whether the parameter θ (in the model this means any of the parameters α, β, γ, x, y in turn), whose estimated value based on the data was $\hat{\theta}$, takes in reality the value θ_0, the Wald statistic is computed as equal to:

$$\frac{(\hat{\theta}-\theta_0)^2}{\mathrm{var}(\hat{\theta})}, \quad (7)$$

where $\mathrm{var}(\hat{\theta})$ – the variance of the estimator. The Wald test has a χ^2 distribution. For testing the significance of the parameters of a model, the hypothesis $\theta_0 = 0$ is tested.

In the present work, the simultaneous significance of the five model parameters α, β, γ, x, y was also tested, using the multivariate version of the Wald test:

$$\hat{\eta}^T V(\hat{\eta})^{-1}\hat{\eta}, \quad (8)$$

where $\eta^T = [\alpha, \beta, \gamma, x, y]$ – the vector of model parameters; $\hat{\eta}$ – the maximum likelihood estimator; $\hat{\eta}^T$ – the transpose of vector $\hat{\eta}$; $V(\hat{\eta})$ – the covariance matrix of the estimator η. The multivariate Wald test also has a χ^2 distribution.

Table 4 contains sample values of the aforementioned coefficients, relating to a soil-binder mixture containing soil No. 1 with the addition of 10% binder of strength grade 9 MPa, for the criterion of compressive strength in the range from 2.5 MPa to 5.0 MPa.

An evaluation of how significantly the coefficients x, y, α, β, γ influence the likelihood of the computed model for the probability p of conformity of the defined criteria for soil-binder mixtures after different maturing times is given in Table 4, using symbols placed to the right of the values given for the coefficients. The level of significance of the influence of a given coefficient on the likelihood of the computed model for probability of conformity of defined

Table 4. Statistical coefficients of the logit model for soil-binder mixtures containing soil No. 1, tested after 28, 42, 90 and 180 days of hardening, with or without consideration of the frost resistance coefficient *n*, subject to the criterion of the mixture's having a compressive strength in the range from 2.5 MPa to 5.0 MPa

Time of testing, days	Frost resistance coefficient *n* +/–	Logit model coefficients					Wald χ^2 test	Test *p*-value
		x	*y*	α	β	γ		
28	+	13.25	19.23	−10.49	−3.38	2.03	< 0.001	> 0.999
	–	0.33*	1.26***	−0.15**	−0.14***	0.04	13.2	0.02*
42	+	0.5	0.92*	−0.42*	−0.14*	0.087	6.9	0.23
	–	0.45**	1.01***	−0.13***	−0.12***	0.06	15.5	0.008**
90	+	0.22	1.12.	−0.39	−0.28	0.58	4.2	0.52
	–	0.22	0.81***	−0.097***	−0.085***	0.046	17.5	0.004**
180	+	11.05	21.39	−3.15	−3.2	1.28	0.87	0.97
	–	0.28*	0.74***	−0.098***	−0.078***	0.053	18.1	0.003**

Key: + denotes that the frost resistance coefficient *n* was considered; – denotes that the frost resistance coefficient *n* was not considered; significance of *p*-value: 0*** 0.001** 0.01* 0.05 0.1 1.

criteria for the mechanical parameters of soil-binder mixtures is denoted as follows:

- three asterisks (e.g. 1.26***) – very high, defined statistically as a significance between 0 and 0.001;
- two asterisks (e.g. 0.45**) – high, defined statistically as a significance between 0.001 and 0.01;
- one asterisk (e.g. 0.33*) – low, defined statistically as a significance between 0.01 and 0.05;
- a point (e.g. 1.12.) – very low, defined statistically as a significance between 0.05 and 0.1;
- no symbol (e.g. 13.25) – no effect, defined statistically as a significance between 0.1 and 1.

The statistical significance of the logit model described by formula (2) given the experimental data was investigated using the Wald test (Table 4). The *p*-values for this test, given in the last column of Table 4, describe the significance of the particular logit models, which were computed for different times of testing and with or without consideration of the frost resistance coefficient *n* for soil-binder mixtures.

The logit models based on the criterion whereby the compressive strength of a soil-binder mixtures is required to lie in the range from 2.5 MPa to 5.0 MPa, but with the additional constraint on the frost resistance coefficient ($n \geq 0.7$), have smaller statistical significance (the *p*-values from the Wald test are greater than 0.23). This is to be explained by the small number of experimental cases in which both the compressive strength condition (from 2.5 MPa to 5.0 MPa) and the frost resistance condition ($n \geq 0.7$) are satisfied by a mixture. This significance level is to be improved by carrying out more experimental measurements with soil-binder mixtures satisfying the frost resistance conditions.

The logit models based solely on the criterion that a soil-binder mixture must have a compressive strength in the range from 2.5 MPa to 5.0 MPa, without consideration of the frost resistance coefficient *n* ($n = 0$), have very high statistical significance (Wald test *p*-values are less than 0.02) (Table 4). These means that the models for these cases are reliable, and that using appropriate coefficients it is possible with a high degree of confidence to predict (design) values for the probability of conformity of defined conditions on the mechanical parameters of soil-binder mixtures. The data in Table 4 show that the predicted values of the probability of conformity of the defined conditions on mechanical parameters are strongly influenced by the coefficients *y*, α, β, which are dependent on the quantity of hydraulic binder added and on the content of silt and sand fractions of the soil; somewhat less strongly influenced by the coefficient *x*, which is dependent on the strength grade of the binder; and not influenced at all by the coefficient γ, reflecting the gravel fraction. This means that it is possible to predict the probability with greater confidence for the coefficients *y*, α, β than for the other coefficients.

To illustrate these relationships, presented below is a sample analysis of the results of tests of conformity of the criterion that the compressive strength of a soil-binder mixture be in the range from 2.5 MPa to 5.0 MPa (without consideration of the frost resistance coefficient *n*), for a mixture containing soil No. 1 stabilized with 10% hydraulic binder with strength grade 9 MPa and tested after hardening for 180 days. The parameter *k*, which is needed for determining the formula for probability *p*, was computed using the statistical coefficients contained in Table 4, as follows:

$$k = -0.098 \cdot 3.5 - 0.078 \cdot 72.9 + 0.053 \cdot 22.1 = -4.86. \quad (9)$$

This led to the following value for the probability *p* of conformity of the compressive strength criterion (compressive strength in the range from 2.5 MPa to 5.0 MPa) for a mixture containing soil No. 1:

$$p(9,10) = \frac{1}{1 + e^{4.86 - 0.28 \cdot 9 - 0.74 \cdot 10}} = 0.994 = 99.4\%. \quad (10)$$

The above calculations show that the probability *p* of conformity of the condition that the compressive strength be in the range from 2.5 MPa to 5.0 MPa, for soil No. 1 with 10% added binder of strength grade 9 MPa, is such as to provide a guarantee at a level of 99.4%.

The results of the calculations of the probability of conformity of the defined condition (in our case, the condition of compressive strength of soil-binder mixtures, according to formula (2)), have been developed graphically in the form of statistical contour maps (Maindonald, Braun 2010), with the use of *R* software. A sample set of contour maps, relating to testing after 42 and 90 days, are to be found in Figs 2–5. These maps enable preliminary planning of the composition of a soil-binder mixture and evaluation of the effect of hardening time and of the frost resistance condition.

The graphs in Figs 2–5 show the probability *p* of conformity of the compressive strength condition by soil-binder mixtures, with different possible configurations of the strength grade and added quantity of hydraulic binder. For example, conformity of the condition of compressive strength lying in the range from 2.5 MPa to 5.0 MPa without consideration of the frost resistance is to be achieved with high probability ($p \approx 95\%$) when soil No. 1 receives an 8% addition of hydraulic binder of strength grade 9 MPa. Fulfilment of the defined compressive strength condition is also to be obtained when a lower grade of hydraulic binder (below 9 MPa) is used, but this requires a greater percentage quantity of binder to be added to the soil. In the case of a binder of strength grade 3 MPa, it is possible to obtain a high probability ($p \approx 95\%$) of conformity of the compressive strength condition when at least 10% of that binder is added to soil No. 1.

The contour maps also show the rate of change in the probability of conformity of the compressive strength criterion. This rate depends on the strength grade of the binder, the time of testing, and the consideration or non-consideration of the frost resistance coefficient *n* of soil-binder mixtures. Consideration of the frost resistance coefficient *n* narrows the area of high probability of conformity of the compressive strength criterion.

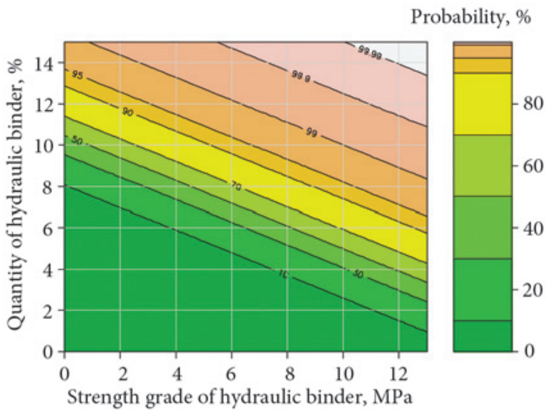

Fig. 2. Contour map of probability of conformity of the compressive strength condition by a soil-binder mixture made from soil No. 1 tested after 42 days (2.5 MPa ≤ R_c^{42} ≤ 5.0 MPa), with consideration of the frost resistance coefficient n ($n \geq 0.7$)

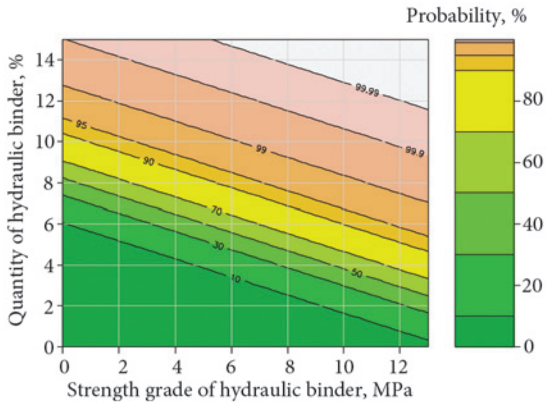

Fig. 3. Contour map of probability of conformity of the compressive strength condition by a soil-binder mixture made from soil No. 1 tested after 42 days (2.5 MPa ≤ R_c^{42} ≤ 5.0 MPa), without consideration of the frost resistance coefficient n ($n = 0$)

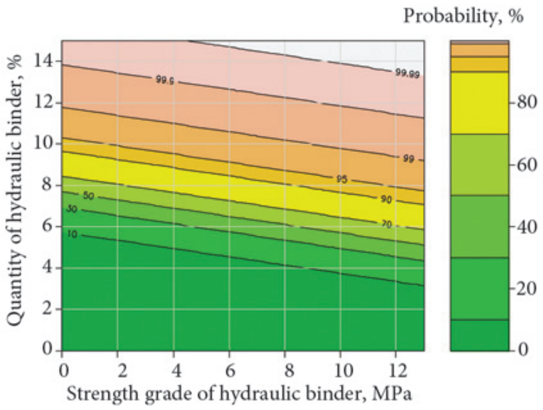

Fig. 4. Contour map of probability of conformity of the compressive strength condition by a soil-binder mixture made from soil No. 1 tested after 90 days (2.5 MPa ≤ R_c^{42} ≤ 5.0 MPa), with consideration of the frost resistance coefficient n ($n \geq 0.7$)

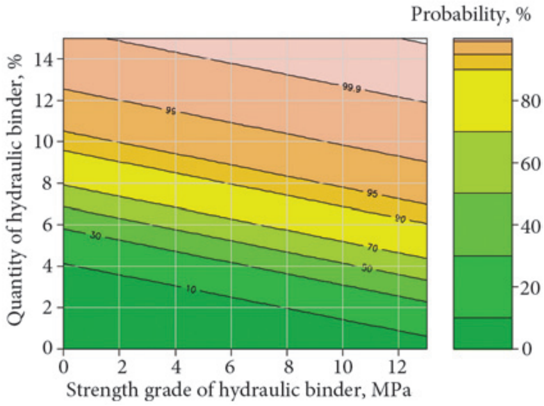

Fig. 5. Contour map of probability of conformity of the compressive strength condition by a soil-binder mixture made from soil No. 1 tested after 90 days (2.5 MPa ≤ R_c^{42} ≤ 5.0 MPa), without consideration of the frost resistance coefficient n ($n = 0$)

4. Conclusions

1. Traditional methods of designing soil-binder mixtures are time-consuming, and require the testing of samples in many configurations and analysis of the results of tests which are dependent on variable starting parameters. It is desirable to improve the method of determining the compositions of soil-binder mixtures so as to reduce the scope of necessary experimental testing.

2. The proposed new method for designing soil-binder mixtures involves determination of their composition by means of a determination of the probability of conformity of a defined condition on the compressive strength R_c of such mixtures, with or without consideration of an additional condition on frost resistance ($n = 0$ or $n \geq 0.7$). In the case of any given configuration of a soil's gravel, sand and silt fractions, it is possible to estimate appropriate values for two fundamental parameters characterizing the stabilized mixtures: the strength grade s_b of the hydraulic binder (MPa), and the added quantity q_b of binder (%) proportional to the dry mass of the soil.

3. The method of planning the composition of soil-binder mixtures using a computed statistical logit model makes it possible to construct graphs in the form of contour maps. Consequently the logit model makes it possible to predict the values of decision parameters concerning the hydraulic binder, independently of the parameters characterizing the soil, in the process of designing soil-binder mixtures. This means that it is possible to determine the composition of soil-binder mixtures satisfying various requirements relating to strength and frost resistance. The model described here also makes it possible to analyse the interactions taking place between the components of soil-binder mixtures, and thus enables a reduction in the scope of experimental testing.

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