THE MODELLING OF SOIL-BINDER COMPOSITES

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ABSTRACT

The development of an appropriate soil-binder composite (stabilized soil) is associated with the selection of the appropriate strength class of the hydraulic binder (e.g. ash-cement) and its amount to stabilize the soil. Advanced statistical methods based on the use of the *spline* function were used in the analysis of tests of soil--binder composites. The analysis presents statistical modelling as a tool helpful in the design of soil-binder composites, showing possible interactions between the components of materials included in the mineral composition of composites. A logarithmic model of the compressive stress forecast was developed for soil-binder composites both with freezing cycles of the soil composition and without freezing cycles, in which the composites hardening time and the addition of ash-cement binders to the soil were continuous variables.

Key words: soil stabilization, soil-binder composite, modelling of composites

INTRODUCTION

The issues related to the modelling and design of soil-binder composites are still of interest to many scientists and engineers (Giergiczny, 2006; Kraszewski, 2009). The composition of soil-binder composites is determined on the basis of a laboratory design procedure, which ensures compliance of the composite parameters with the requirements contained in the PN-S-96012:1997 standard (Polski Komitet Normalizacyjny [PKN], 1997). For the soil materials used to strengthen and improve the road structure, an appropriate technological process should be developed that will ensure the achievement of the optimal mechanical parameters and frost resistance of soil-binder composites (Kruger, 1997; Raupp-Pereira, Ball, Rocha, Labrincha & Allen, 2008; Bajpai, Choudhary, Srivastava, Sangwan & Singh, 2020).

The main task of the designer is to select the appropriate strength class of the hydraulic binder and its amount to stabilize the soil (Kaniraj & Havanagi, 1999; Sebök, Šimoník, & Kulísek, 2001; Škvára, Kopecký, Šmilauer & Bittnar, 2009). The designer optimally selects the composition of the composite in order to obtain the expected effect of meeting the mechanical properties of soil-binder composites, in accordance with the requirements adopted in the standard. Designing soil-binder composites consists in selecting two basic parameters: the strength class of a binder and its addition in relation to the soil which was previously recognized, e.g. in terms of graining (Kukko, 2000). The method of designing the composition of a soil-binder composite is based on the assessment of the impact of the parameters identifying the selected natural soil and the parameters of the hydraulic binder on the mechanical properties of the obtained soil-binder composites, and thus, it is possible to assess the suitability of these composites in road structures (Cleary & Ungs, 1992; Kasprzyk, Kordylewski & Zacharczuk, 2003).

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METHODOLOGY

In order to properly design the composition of a soil-binder composite, first the soil identification variables and then the hydraulic binder decision variables and the criteria of meeting the requirements should be assumed. The assumption of soil identification variables and hydraulic binder decision variables is the task of the designer, and the proper selection of the quality and quantity of these variables is conditioned by the significance of their influence on the mechanical properties of soil-binder composites (Hossain, Lachemi & Easa, 2007; Shao, Liu, Du, Jing & Fang, 2008).

Designing the composition of soil-binder composites, on the basis of variable parameters identifying the soil, makes it possible to find an answer to the question of what class of binder and in what amount should it be added to the soil to meet the standard conditions, i.e. for the soil to have features that make it useful in road construction (Wu, Bryant & Wall, 2000; Siswosoebrotho, Widodo & Augusta, 2005; Sobczyk, 2008). In the design procedure, the conditions speci-

fied in the standard (road base layer) were assumed as examples of conditions that must be met by the composite (PKN, 1988). The general scheme of designing soil-binder composites is shown in Figure 1 (Rafalski & Ćwiąkała, 2014).

Important variables identifying the soil, and having a significant impact on the different values of the compressive strength of soil-binder composites, are (Querol et al., 2002; Yan, Gupta & Wall, 2002; Rafalski, 2007; Rafalski, Ćwiąkała, Gajewska & Kraszewski, 2008): gravel fraction content [%], sand fraction content [%], and dust and clay fraction content [%], while for hydraulic binder decision variables: compressive strength [MPa] and addition [%].

It is most advisable to assume other parameters (identification and decision variables) than those adopted in the design procedure, provided that they significantly affect the observed statistical feature. Otherwise, when designing soil-binder composites, it is not advisable to consider parameters that do not significantly affect the mechanical properties of the composite (Wigley, Williamson & Gibb, 1997; Widuch, 2012).
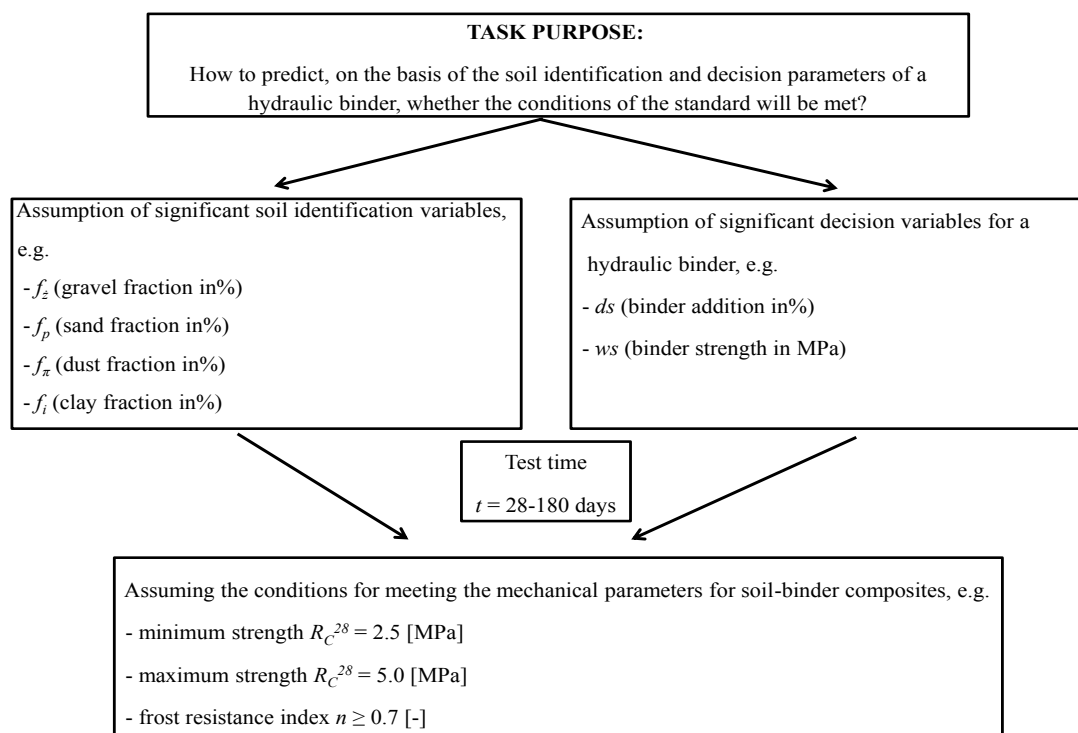

Fig. 1.   General scheme of designing a soil-binder composite and assumed sample parameters (Rafalski & Ćwiąkała, 2014)

In order to develop a statistical model of the complex relationships between the properties of soil, binder, and the proportions between the amount of soil and binder, the results of the research published in Widuch's work (2012) were used, taking into account the wide spectrum of soils in terms of graining, amount of hydraulic binder added to the soil, and the time of testing the composites. For the development of the statistical modelling of soil-binder composites, the results of compressive strength tests of soil-binder composites of seven types of soil (Widuch, 2012) were used, with various additions (2, 4, 6, 8 and 10%) of hydraulic road binders observed after 7, 14, 28, 42 and 180 days of hardening and frost resistance indexes of these composites (tested after 28, 42, 90 and 180 days).

RESULTS AND DISCUSSION

Statistical modelling based on the use of the *spline* function was used for the analysis. The data were taken from Table 1. In this table, the type of *RK_ord* is ordered according to the increasing average value of the compressive strength. The type of *RK* is the original numbering. The models used the *RK_ord* type.

According to the forecast value of compressive strength with freezing cycles (*WM*), the following mathematical model was estimated:

$$\log_{10}(WM) \sim t + DS + C + RK\_o\_3 + RK\_o\_4 + RK\_o\_5 + RK\_o\_6 + RK\_o\_7, \tag{1}$$

in which time (*t*) and binder addition (*DS*) are continuous variables; the remaining variables are factor variables with values of 0 and 1. Factor variables assume the value of 1 when the following conditions are met:

– *C80* – when the cement content is 80%,
– *RK_o_3*, …, *RK_o_7* – when the type of soil has an index of at least 3, at least 4, …, at least 7.

The coefficients of this model were determined using the regression method and then corrected using the lasso method (Table 2).

Table 1. Types of soil

Type of soil (*RK*)	Clay fraction (F_I) [%]	Dust fraction (F_{PI}) [%]	Sand fraction (F_{PS}) [%]	Gravel fraction ($F_Ż$) [%]	Ordering according to the increasing mean value of compressive strength (*RK_ord*)
3	12.00	61.01	38.99	0.00	**1**
2	0.00	0.50	98.12	1.38	**2**
5	4.80	24.70	74.47	0.83	**3**
7	1.80	9.58	89.25	1.17	**4**
1	1.50	5.00	72.92	22.08	**5**
4	5.70	27.40	59.35	13.25	**6**
6	3.08	13.40	67.84	18.76	**7**

Table 2. Coefficients for the *WM* model value forecast of soil-binder composites with freezing cycles

Coefficient	Slow	Hardening time (*t*)	Binder addition (*DS*)	Cement addition in the amount of 80% (*C80*)	Factor variables *RK_o_3*	Factor variables *RK_o_4*	Factor variables *RK_o_5*	Factor variables *RK_o_6*	Factor variables *RK_o_7*
Regression	−1.870	0.002	0.124	0.267	0.606	0.079	0.228	−0.221	0.207
Lasso	−1.862	0.002	0.124	0.266	0.603	0.078	0.223	−0.213	0.203
Factor coefficient [%]	–	–	–	85	301	20	67	−39	60

All coefficients, with the exception of the coefficient at *RK_o_4*, are significant at a level of $p < 0.001$. The coefficient of determination of this model is 82%, which means a very good predictive ability.

For example, the compressive strength (*WM*) prediction equation corresponding to the mixture of Soil 5 and C80 cement has the form (2), and that corresponding to the mixture of Soil 5 and C60 cement has the form (3). The final result is in MPa.

$$\log_{10}(WM) = -1.862 + t \cdot 0.002 + DS \cdot 0.124 + \\ + 1 \cdot 0.266 + 0.603 + 0.078 + 0.223, \tag{2}$$

$$\log_{10}(WM) = -1.862 + t \cdot 0.002 + DS \cdot 0.124 + \\ + 0 + 0.603 + 0.078 + 0.223. \tag{3}$$

The symbol *W* stands for the compressive strength without freezing cycles in MPa. To make a forecast of the *W*, a model was estimated in the form of:

$$\log_{10}(W) \sim t + DS + C + RK\_o\_3 + RK\_o\_4 + \\ + RK\_o\_5 + RK\_o\_6 + RK\_o\_7, \tag{4}$$

in which *t* and *DS* are continuous variables; the remaining variables are factor variables with values of 0 and 1.

Factor variables assume a value of 1 when the following conditions are met:
– *C80* – when the cement content is 80%,
– *RK_o_3*, …, *RK_o_7* – when the type of soil has an index of at least 3, at least 4, …, at least 7.

The coefficients of this model were also determined using the regression method and then corrected using the lasso method (Table 3).

All coefficients, with the exception of the coefficient at *RK_o_6*, are significant at a level of $p < 0.001$. The coefficient of determination of this model is 82%, which means a very good predictive ability.

Table 3. Coefficients for the forecast of the value of the *W* model of soil-binder composites without freezing cycles

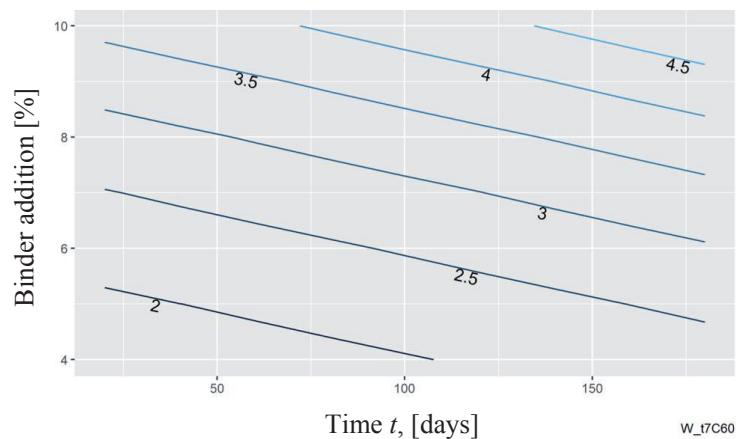| Coefficient	Slow	Hardening time (*t*)	Binder addition (*DS*)	Cement addition in the amount of 80% (*C80*)	Factor variables *RK_o_3*	Factor variables *RK_o_4*	Factor variables *RK_o_5*	Factor variables *RK_o_6*	Factor variables *RK_o_7*
Regression	−0.714	0.001	0.056	0.154	0.508	0.047	0.046	−0.017	0.112
Lasso	−0.686	0.001	0.055	0.149	0.499	0.045	0.035	0.000	0.100
Factor coefficient [%]	–	–	–	41	215	250	279	279	378

Fig. 2. The chart of *W* forecasts from the model as a function of time (*t*) and binder addition (*DS*) content for Soil 7 and 60% cement content (forecast *W_t7C60*). The grey background indicates the forecast *W* values and the lines are the contour lines for *W* values

For example, a contour line diagram of the forecast for this model, corresponding to Soil 7, is shown in Figure 2. Where stands for the compressive strength of the composite without freezing cycles, while *t* stands for time in days.

The presented method of processing the results makes it possible to construct, for seven soils, 28 formulas expressing compressive strength (with and without freezing cycles) depending on the technological components.

CONCLUSIONS

The presented method of developing the experimental results is based on advanced statistical methods using spline functions. This gives the opportunity to formulate equations expressing stress as a function of multiple arguments that correspond to technological components.

The demonstrated example of statistical modelling is a helpful tool in the design of soil-binder composites.

In the analysis of soil-binder composites, one can use the logarithmic model of the compressive stress forecast (both with the soil composition freezing cycles and without the soil composition freezing cycles):

$$\log_{10}(WM \text{ or } W) \sim t + DS + C + RK\_o\_3 +$$
$$+ RK\_o\_4 + RK\_o\_5 + RK\_o\_6 + RK\_o\_7, \qquad (5)$$

in which *t* and *DS* are continuous variables; the remaining variables are factor variables with values of 0 and 1. These models (*W* and *WM*) differ in the values of the coefficients presented in Tables 2 and 3.

Improvement and stabilization are commonly used methods of soil improvement. Improvement and stabilization using hydraulic binders based on fly ash are one of the many methods used. The results of the statistical modelling of the compressive strength of soil-binder composites provided a new solution in the field of the approach to the design of mixtures, and an important element was the determination of statistical relationships between the stress and composition of a mixture. The statistical analysis made it possible to describe the influence of the combination of several components, thanks

to which the optimal selection of the components of the soil-binder composite in the design process is possible.

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MODELOWANIE KOMPOZYTÓW GRUNTOWO-SPOIWOWYCH

STRESZCZENIE

Opracowanie odpowiedniego kompozytu gruntowo-spoiwowego (gruntu stabilizowanego) jest związane z dobraniem właściwej klasy wytrzymałości spoiwa hydraulicznego (np. popiołowo-cementowego) i jego ilości do stabilizowania gruntu. W analizie badań kompozytów gruntowo-spoiwowych zastosowano zaawansowane metody statystyczne oparte na wykorzystaniu funkcji *spline*. W analizie przedstawiono modelowanie statystyczne jako narzędzie pomocne w projektowaniu kompozytów gruntowo-spoiwowych, pokazujące możliwe interakcje zachodzące między komponentami materiałów znajdujących się w składzie mineralnym kompozytów. Opracowano model logarytmiczny prognozy naprężenia ściskającego kompozytów gruntowo--spoiwowych zarówno z cyklami zamrażania kompozycji gruntu, jak i bez cykli zamrażania, w którym zmiennymi ciągłymi były czas twardnienia kompozytów i dodatek spoiw popiołowo-cementowych do gruntu.

Słowa kluczowe: stabilizacja gruntu, kompozyt gruntowo-spoiwowy, modelowanie kompozytów