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Predicted and experimental methodology for estimation of cement quantity to achieve optimum curing conditions of stabilized soil

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Abstract

The theoretical concepts for design of stabilized soils incompliance with Pareto principle, interaction of basic soil parameters as well as an analysis of system “structure – soil property”, including cation exchange capacity factor of clay minerals relative to Ca^{2+} are developed.

The predicted and experimental methodology for estimation of minimum cement quantity required to achieve optimum conditions to form of monolithic structure of stabilized soil is offered.

Introduction

Clay soils are the materials with complex structure, which are polydisperse, polyminerals, multicomponent and polygenetic systems (that typically for industrial soils).

So an important moment to develop new reinforced materials such as soil concretes for road construction as well as to chose suitable binders is to know proportion and properties of it.

Soils as multicomponent systems consist of solid, liquid and gaseous phases as well as biotical component. Their volume and weight content in soils can vary in wide range. In some rocks the content of individual components are as small, that it can be neglected (for example, biotical and gaseous). So we can speak about mono- or two-component soils.

Each of the component of soils depending on its content and composition can do some effect for soil characteristics.

It is required many time and labor for complete study of composition and properties of the soil.

Hence, we can suppose, that not all ingredients of soil effect on it characteristics equally. More over not all properties commensurately determine a possibility of soil stabilization with any binders. For that reason it is required to use the Pareto principle, which consist in suggestion, the most of results is simulated by small number of factors. The Pareto principle dramatically characterizes the relationships “cause – effect” into the system and it is one of the useful method to make a decision.

For soil stabilization the Pareto principle is interpreted as “80% results when soils stabilization induced by 20% causes (specific soils properties, cohesive materials as well as technology of mixture preparation etc.)”. In other words, it should be enough to separate specific soils characteristics, which have most influence on structuration of soil-concrete and therefor on an effectiveness and possibility of it consolidation.

Experimental

1. Materials

In this paper two pure mineral clays and two industrial soils (sand clay and opoka clay) were used to study. The first clay is alluvial type of kaolin from Procyanovsk deposit (Russia). The argillic part of used kaolin consists of 96, 7% of leprose kaolinite. There are few additions of hydrargillite, halloysite and hydrous ferric oxides. Sand substance consists of microcline and quartz in the ratio 1/2; an alkaline content presented by potassium oxide is 4, 8%.

The second type of the clay is montmorillonite from Greece littoral area. Clay particle content in this monmorillonite is 93–94% and it is for the most part Na montmorillonite. Also in the sample are illite (1, 2%), carbonates (0, 61%) and free quartz (3,8%). Sand clay used in the work is an overburden and supplied from Arhangelsk diamantiferous named after M. V. Lomonosov deposit. This clay soil consists of dominant quartz and clay minerals such as montmorillonite and hydra mica. The sand clay has a high pH level and low cation exchange capacity. The opoka clay was supplied from Korkino coal deposits (Russia). It is rich in amorphous silica.

2. Methods

Soils activity for calcium hydroxide was measured with Zaporozhets' method; the principle of it is followed: 1100 ml of lime solution with the concentration of 1,1–1,2 g(CaO)/litre is placed in a cylindrical container. After 10–15 min of mixing, 100 ml of lime solution is selected and filtered. 50 ml of the filtrate was pipette to be determining an initial concentration for CaO by titrimetry with chlorhydric acid.

Then, when mixing in the solution added 10 g preliminary weighted component we study. Through a fixed period of time as from adding the studied component, the samples of 100 g is selected with pipette.

The samples are filtered in retort (250 ml), after that 50 ml of filtrate is selected and titrated. Concentration for CaO in the solution estimated by titration of 0,05N HCl solution. Concentration of CaO is calculated from the equation:

$$C_{CaO}=758\cdot A\cdot T/B, \qquad (1)$$

where, C_{CaO} – concentration of CaO, g/litre ; A – amount of HCl, used for titration, ml; T –HCl titre; B – quantity of solution selected from a cylindrical vessel, ml.

Quantity of CaO absorbed with additive agent in lime mortar is estimated as a difference of initial concentration for CaO and its value at a time. On the base of its data a lime amount absorbed by 1 g soil is calculated.

Total acid for soils and soil-concretes on its base measured with ionometric converter I-500 according to the Russian standard (GOST 26423-85) [2]. This parameter is composed of dissociated ions (actual acidity) and fixed ions (potential acidity) of H^+, where a general indicator is pH value.

Structure formation into the stabilized soil occurs in system "soil–cement–water", where as a cohesive component is Portland cement and soil presented by clay rocks [3, 4]. An effectiveness of it process is a determining factor to operational characteristics of composite materials.

Formation of structure depends on numerous parameters, which are not only initial characteristics of soil and binder but also technology factors, controlled in accuracy dosing of cement-soil components, homogenization degree, wetting and compacting of mixture as well as hardening conditions. It is possible to express this dependence as function of numerous variables:

$$X = f(x_1, x_2, \ldots x_n) \qquad (2)$$

The analysis of structure and properties for clay rocks showed that the most effect on final properties of stabilized soil has a solid soil substance, which includes solid mineral particles, organic compounds and organo-mineral complexes. A solid component structure has importance when property formation of the soils [5, 6, 7, 8]. At that, we can mark adsorptive and ion-exchange properties, which are characterized with adsorptive capacity and acid-alkaline properties where the main parameter is pH value.

The key parameters for cement, which provide its efficiency of application when soil stabilization are grinding fineness (or specific surface) and mineral composition.

Significant influence during structuring of stabilized soil also makes processing factors. Maximum efficiency of soil stabilization can be achieved, only with appropriate using of the characteristics of raw materials and accurate maintenance of technology. Thus, it is required to optimize hardening terms of soil-concrete. First of all, the optimal conditions for hardening of soil-concrete is determined by optimal curing condition for hydration products of clinker minerals, where the determination factors is high pH value of medium.

Strongly alkaline medium is reached by saturation of pore solution with $Ca(OH)_2$, extracted when hydration of calcium silicates.

However, when stabilization process, soils having fine clay minerals react with $Ca(OH)_2$. The main chemical reactions in this case are cation exchange and puzzolanic reactions. Also, for a long-time curing the carbonization of $Ca(OH)_2$ is observed due to carbon dioxide absorption from atmosphere.

Presence of oversaturation solution $Ca(OH)_2$ into the soil pores makes a saturation of one with Ca-cations instead of Na^+ or H^+. Cation exchange defines follow processes:

- Reduce in electric double layer and corresponding decrease of soil receptivity to water;
- Flocculation and aggregation of clay particles, that leads to reduce in flexibility;
- Increasing in internal friction between aggregates;
- Changing in physical and mechanical properties of soils: plastic clay transform to granulated and crushed material; powdery soils lose gilgaied properties; swelling properties for clay soils decreases.

At that time the chemical reactions between lime and soil colloids are important [9, 10]. In result of such interaction between $Ca(OH)_2$, silica and alumina, stable compounds such as hydrated silicates and calcium hydrated aluminates are formed in the soils.

Gel-like products from puzzolanic reactions effect as an adhesive on particles interface that significantly enhances strength of stabilized soil.

Cementation is a long-time process and puzzolanic reactions proceed extremely slowly, so a strength generation of the system is in progress for years.

The CO_2 absorption from ambient or from soil (it is carbonization) is undesired reaction, since a powder-like lime carbonate does not have enough cementing capacity. More over, lime carbonate presence leads to increasing in flexibility of material and linking of lime that prevents the puzzolanic reaction development. Carbonization takes place intensively only with water and when the big pores, considering the fact that the reaction develops none deeply in the curing material. At cation exchange and puzzolanic reactions a deficit of Ca^+ ions occur, that decreases pH level. In the terms of Ca impoverishment into pores solution of the system, a failure of neoformed hydrisilicates is occurred with portlandite formation, which makes up for deficit of $Ca(OH)_2$.

So, we can say, the optimal hardening terms for cement stone in stabilized soil could be obtained solution to both main problems. First of all, it is required to fully saturate soil's clay substance with Ca cations. Secondly, it is needed to prepare a strongly alkaline medium in porous solution. Previous stabilization of clay minerals with lime is a rational process [3, 9]. Alternatively, both of the goals can be reached when forming enough quantity of the portlandite. Other words, the total of $Ca(OH)_2$, required to achieve optimal hardening conditions for cement stone is possible to present as an equation (3):

$$C_{Ca(OH)_2} = C^1_{Ca(OH)_2} + C^2_{Ca(OH)_2}\,, \tag{3}$$

where, $C_{Ca(OH)_2}$ – total of $Ca(OH)_2$, required to achieve optimal hardening terms; $C^1_{Ca(OH)_2}$ – quantity of $Ca(OH)_2$, required for full saturation of the soil's clay substance with Ca cations; $C^2_{Ca(OH)_2}$ – quantiity of $Ca(OH)_2$, required to prepare of strongly alkaline medium.

This $Ca(OH)_2$ forms when hydration of alite and belite. Therefore, on the base of knowledge of cement mineral composition, it is possible to calculate $Ca(OH)_2$ quantity. In terms of cement we obtain:

$$C_{cem} = \frac{C_{C_3S+C_2S} \cdot 100}{S_{C_3S} + S_{C_2S}} \qquad (4)$$

where, C_{cem} – required quantity of cement (by weight); $C_{C_3S+C_2S}$ – required total quantity of C_3S and C_2S (by weight); S_{C_3S} and S_{C_2S} - percentage of clinker minerals in cement, %.

In view of the above it may be concluded, that the cement amount C_{cem} needed to make favorable terms for soil-concrete structurization is calculated with the equation (5):

$$C_{cem} = C_{cem}^1 + C_{cem}^2 \qquad (5)$$

where, $C_{цем}^1$ - cement quantity required to produce $Ca(OH)_2$, which fully satiates soil's clay substance; C_{cem}^2 - required cement quantity to produce amount of $Ca(OH)_2$ is needed, which is enough to saturate porous solution of soil-concrete, when the failure of hydration products not occurs.

These problems are possible to solve consecutively.
The first one is to determine some quantity of cement $C_{цем}^1$, which is enough for full saturation of soil's clay substance with Ca cations.

For that is followed to know:

1) soil adsorptive capacity;
2) quantity of $Ca(OH)_2$, formed at cement hydration.

The soil adsorptive capacity E_a *is* determined by experiment.

Minerals C_2S and C_3S, which are predominate in Portland cement (≈ 40 – 70 % and 15 – 30 % by weight respectively), when hydration process produce hydrated calcium silicate (it is almost amorphous product with variable stoichiometry) and crystal hydrated lime [11, 12, 13]. The reaction of C_3S and C_2S with water most of all is described by the equations:

$$2(3CaO{\cdot}SiO_2) + 5H_2O \Rightarrow 3CaO{\cdot}2SiO_2{\cdot}2H_2O + 3Ca(OH)_2 + Q$$
$$2(2CaO{\cdot}SiO_2) + 3H_2O \Rightarrow 3{,}3CaO{\cdot}2SiO_2{\cdot}2{,}3\,H_2O + 0{,}7Ca(OH)_2 + Q$$

Since portland cement is a polymineral binder the reaction of it components proceed in the same system and make mutual effect each other. Thus both stoichiometry of the reaction and neoforms could be differing than ones above.

At ideal conditions proceeds full hydration of the binder. Other words, for soil with low activity from 2 molecules of C_3S results 3 molecules of $Ca(OH)_2$ and from 2 molecules of C_2S – 0,7 molecules of $Ca(OH)_2$.

Referred to above equations, subject to molecular mass data for compounds, it's could be calculated a quantity of $Ca(OH)_2$, which must form when in hydration of the clinker minerals:

$$C_{Ca(OH)_2} = 0{,}48677 \cdot C_{C_3S} \qquad (6)$$

$$C_{Ca(OH)_2} = 0{,}15056 \cdot C_{C_2S} \qquad (7)$$

If the soils adsorption capacity value E_n and mineralogy cement composition have known, we can determine quantity for calcium silicates and cement required for full saturation of active soil with $Ca(OH)_2$:

$$C_{C_3S+C_2S} = \frac{S_{C_3S} + S_{C_2S}}{S_{C_3S} \cdot 0{,}48677 + S_{C_2S} \cdot 0{,}15056} \cdot E_n , \qquad (8)$$

and required cement amount could be presented as an equation (9):

$$C'_{cem} = \frac{100}{S_{C_3S} \cdot 0{,}48677 + S_{C_2S} \cdot 0{,}15056} \cdot E_n \qquad (9)$$

This formula is applied only for ideal terms at cement hydration as well as assuming full interaction of the products with clay minerals.

If there is a possibility to determine the quantity of $Ca(OH)_2$ when in cement hydration by experiment ($S_{Ca(OH)2}$), we can present the equation as follows:

$$C'^{*}_{cem} = \frac{E_n}{S_{Ca(OH)_2}} \qquad (10)$$

Second problem of this work is to determine quantity of $Ca(OH)_2$, needed to increase pH level of porous solution, when the crystalline hydrates formation proceed without destruction.

Quantity analysis for porous solution at cement hydration in the system “soil – cement – water” is significantly difficult challenge.

For that reason, to be simplifying of the calculations, water amount appears for a porous solution quantity, which determines optimal soils moisture. Its need to note, the premises is possible on this research stage only.

The hydrated silicates with less stability ($2CaO{\cdot}SiO_2{\cdot}nH_2O$), forming when in cement hydration, can exist in saturated solution of $Ca(OH)_2$, i.e. if its concentration is not less than 1,18 g/litre (or $1{,}18{\cdot}10^{-3}$g of $Ca(OH)_2$ into 1 g of water) in porous solution (at 20 ^{0}C)[11]. Thus, to achieve this value, $Ca(OH)_2$ quantity is possible to calculate with the equation (11):

$$C_{Ca(OH)_2} = 1{,}18 \cdot 10^{-3} \cdot W_{opt} \qquad (11)$$

where, W_{opt} - optimal soils moisture.
Cement amount, required to saturate the solution is equated with the formula (9):

$$C''_{cem} = \frac{100}{S_{C_3S} \cdot 0{,}48677 + S_{C_2S} \cdot 0{,}15056} \cdot 1{,}18 \cdot 10^{-3} \cdot W_{opt} \qquad (12)$$

With experimental data:

$$C''_{cem} = \frac{1{,}18 \cdot 10^{-3} \cdot W_{opt}}{S_{Ca(OH)_2}} \qquad (13)$$

Resulting above, we can conclude, the total cement, required to achieve optimal curing conditions for stabilized soils is calculated as:

$$C_{cem} = \frac{100}{S_{C_3S} \cdot 0{,}48677 + S_{C_2S} \cdot 0{,}15056} \cdot (E_n + 1{,}18 \cdot 10^{-3} \cdot W_{opt}) \qquad (14)$$

With experimental data (15):

$$C^{*}_{cem} = \frac{E_n + 1{,}18 \cdot 10^{-3} \cdot W_{opt}}{S_{Ca(OH)_2}} \qquad (15)$$

Thereby, the predicted methodology for estimation of cement quantity to achieve optimum structuring conditions of stabilized soil in “ideal terms” was obtained.

Results

Some different types of soils were studied; also the calculations for determination of required cement quantity were carried out in this work (table 1).

As a cohesive was used cement CEM I 32,5N with content of C_3S and C_2S 52 and 24% respectively.

Table 1

Minimum quantity of cement estimated in depend on type of the clay soil (at ideal conditions)

Material	Soil exchange capacity of $Ca(OH)_2$, mg/g	Optimal moisture, %	pH of water extract	Required quantity of cement, %
Kaolinite (Prosyanovsk deposit, Russia)	4	30	9,2	1,5
Na–montmorillonite (Greece)	11	46	9,8	4
Sand clay (Arhangelsk diamantiferous deposits, Russia)	4	16	8,7	0,72
Opoka clay (Korkino coal deposits, Russia)	65	40	6,9	24

For approximation of the calculations to real terms, the formula correction is required with adding of the parameters, which consider impossibility of full reaction between clay substation of soil and calcium hydroxide because of

- partial cement hydration;
- operational factors such as grinding size of soil, mixture homogenization and others, which effect to soil-concrete structuring.

Thus, it is needed to include a technological coefficient and the formula (14) will be presented as follows:

$$C_{cem} = \frac{100}{S_{C_3S} \cdot 0{,}48677 + S_{C_2S} \cdot 0{,}15056} \cdot (E_n + 1{,}18 \cdot 10^{-3} \cdot W_{opt}) \cdot \alpha \cdot k_T \qquad (16)$$

If the amount of $Ca(OH)_2$, formed when cement hydration has known, we can use the equation (17):

$$C^*_{cem} = \frac{(E_n + 1{,}18 \cdot 10^{-3} \cdot W_{opt})}{S_{Ca(OH)_2}} \cdot \alpha \cdot k_T \qquad (17)$$

where, α – hydration degree for cement; k_T – technological coefficient.

Thereby, the predicted and experimental methodology for estimation of minimum cement quantity required to achieve optimum conditions for structuring of cement-soil is offered. As a binder is cement, and clay soil as an active admixture makes particular influence to form monolithic structure of the stabilized material.

Discussions

The theoretical concepts for design of soil stabilization by reference to Pareto principle, mutual effect of basic characteristics of soils as well as an analysis of system "composition – soil characteristics" subject to integral characteristic of clay rocks, which is derivative of mineral composition – cation exchange capacity factor relative to Ca^{2+} are developed.

The predicted and experimental methodology for estimation of minimum cement quantity required to achieve optimum conditions to form of monolithic structure of stabilized soil is offered. Optimal conditions for cement stone hardening in soil-cement can be obtained by two ways:

- full saturation of clay component in soil with Ca cations;
- creation of beneficial terms to form silicate crystallohydrates and calcium aluminates due to accumulation of portlandite into porous solution of the soil-concrete till definite concentration and consequently till the pH level of medium begins to increase.

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