Improving performance of soil stabilizer
by scientific combining of industrial wastes

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Abstract. In this paper, based on understanding the design theories on soil stabilization, a series of soil stabilizers were prepared with different kinds of industrial wastes such as calcined coal gangue (CCG), blast furnace slag (SS), steel slag (SL), carbide slag (CS), waste alkali liquor (JY), and phosphogypsum (PG). The results indicated that when the Portland cement (PC) proportion was lower than 20% in the stabilizer, for the soil sample selected from Wuhan (WT) and Beijing (BT), the unconfined compress strength (UCS) of the stabilized soil specimens could increase 4.8 times and 5.4 times respectively than that of the specimens stabilized only by PC; compared with the UCS of the specimen stabilized only by PC, the UCS of the specimen which was made from soil sample WT and stabilized by the stabilizer composed only by CCG, CS, and PG increased 1.5 times, and UCS of the specimen which was made from soil sample BT and stabilized by the stabilizer composed only by SS, JY, and PG increased 4.5 times.

Keywords: industrial wastes; character classification; scientific combination; stabilizer; soil stabilization

1. Introduction

The amount of industrial wastes increases rapidly with the constant development of industry and technology. At present, the stock of industrial wastes are more than 6.7 billion tons in China, and this number increases 1.0 billion per year (National Bureau of Statistics of China 2013). The treatment of industrial wastes becomes an important problem needed to be solved urgently to satisfy the requirement of sustainable development of society. Resource utilization technology of wastes is the main tendency of industrial wastes treatment.

Soil stabilization technique is broadly used in soil foundation stabilization, by which soil are well-mixed with stabilizer and become stiff stabilized soil (Anagnostopoulos and Chatziangelou 2008, Zhou and Ye 2008). Nowadays Portland series cement is the main type of stabilizer used in soil stabilization, and the estimative amount of Portland (PC) used as soil stabilizer is several

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hundred million tons per year in China. PC is the best cementitious material used to bind sand and stone to prepare concrete. While the effect of PC as soil stabilizer is rather poor in many cases, because there are significant differences in physical and chemical characters between clayey soil and sand or stone. In addition, producing PC consumes a large amount of energy and pollutes environment. Therefore, a kind of efficient and environment friendly soil stabilizer is needed urgently.

Many researchers studied utilizing industrial wastes to prepare soil stabilizer (Degirmenci *et al*. 2007, Horpibulsuk *et al*. 2012, Kamon *et al*. 1989, Kamon and Nontananandh 1990, Kim *et al*. 2010, Kolias *et al*. 2005, Peethamparan *et al*. 2008, Khalid *et al*. 2012). The results showed that the stabilizers prepared with industrial wastes were better than PC in many soil stabilization cases. Furthermore, industrial wastes have special advantages on soil stabilization. For example, some kinds of industrial wastes cannot be used as construction materials but can be used as soil stabilizer, such as the industrial wastes which have high content of alkali, sulphur, chlorine, or aluminium, the industrial wastes which have low early strength or poor purity, etc. Although these features limit the utilization of industrial wastes, these features may be advantages in preparing soil stabilizer. Utilizing industrial wastes to prepare soil stabilizer would be beneficial to technology, economic, and environment significantly.
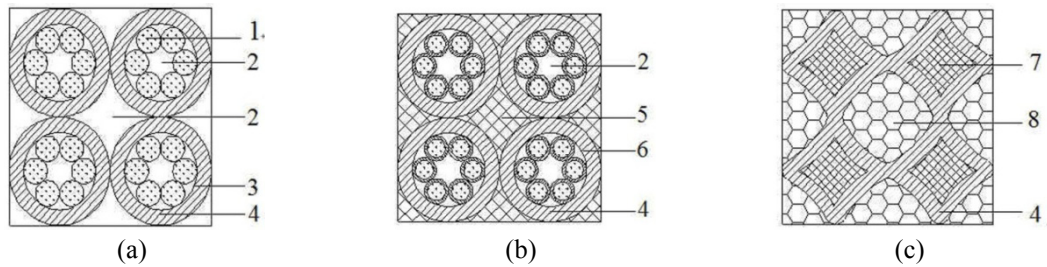
There is no report about the design theories on soil stabilizer preparation utilizing industrial wastes. The most widely used method for preparing soil stabilizer with industrial wastes is trying and error method or trying based on personal experience. So the increment of the stabilized soil's strength was limited. Therefore, it is important to explore the design theories on soil stabilizer preparation by utilizing industrial wastes.

In this study, based on understanding the design theories, proposed by the author' group, on soil stabilization including the characters of the hydrate system needed by the structure formation of stabilized soil and the characters of the formation environment and formation process of the hydrates in the stabilized clay soil, and analyzing the functions and advantages of different kinds of industrial wastes on preparing soil stabilizer, the stabilizer design theories are expanded to the scope of utilizing industrial wastes, then a series of soil stabilizers were prepared by utilizing different kinds of industrial wastes such as calcined coal gangue (CCG), blast furnace slag (SS), steel slag (SL), carbide slag (CS), waste alkali liquor (JY), and phosphogypsum (PG) in order to enhance the stabilization effect of the stabilizer that was scientific combination of industrial wastes.

2. Optimization design theories of soil stabilizer

2.1 Hydrate system in stabilized soil

According to tests and theoretic analysis, Huang *et al*. (2006a) proposed a structure formation model of stabilized soil as shown in Fig. 1. The structure of stabilized clayey soil is formed by three portions as follows: (i) the clayey soil aggregates are wrapped and bound by cementitious hydrates (Fig. 1(a)); (ii) the pores between the clayey soil aggregates are filled by cementitious hydrates and/or expansive hydrates whose volume can expand during the formation, such as calcium sulfoaluminate hydrate ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$, i.e., ettringite, AFt) (Fig. 1(b)); (iii) the pores inside the clayey soil aggregates are squeezed and filled by expansive hydrates (Fig. 1(c)). The stabilizer that only produce cementitious hydrates, such as PC, cannot fill the pores inside the clayey soil aggregates, which limit the strength of stabilized soil increasing further.
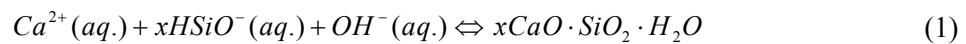
1-clay particle; 2-pore; 3-clay soil aggregate; 4-cementitious slurry film;
5-stabilizer slurry in pore; 6-clay soil aggregate after pozzolanic reaction;
7-clay soil aggregate after pozzolanic reaction and squeezed by expansion;
8-pore filled by expansive hydrates

Fig. 1 Stabilized soil structure formation model

While the expansive hydrates can squeeze and fill the pores inside the clay soil aggregates. If the formation rate of the expansive hydrates is suitable, the expansive hydrates can fill the pores inside the clay soil aggregates and increase the strength of stabilized clayey soil. Therefore, the expansive hydrates should be included in the hydrate system of efficient stabilizer.

2.2 Influence of chemical factors in soil on stabilized soil strength and countermeasures

PC hydration mainly produces calcium silicate hydrates (C-S-H) and calcium hydroxide ($Ca(OH)_2$, CH). CH does not directly contribute to the strength of stabilized soil, while C-S-H is the main contributor of the strength. C-S-H forms according to the thermodynamic equation as below (Taylor 1997)

$$Ca^{2+}(aq.) + xHSiO^-(aq.) + OH^-(aq.) \Leftrightarrow xCaO \cdot SiO_2 \cdot H_2O \tag{1}$$

Eq. (1) indicates that the amount of C-S-H produced in PC stabilized soil depends on the concentration of Ca^{2+} and OH^- ions in the pore solution of the stabilized soil.

Soil may absorb Ca^{2+} and OH^- ions, in turn consume CH, because of the effect of the soluble salt in soil, cation exchange, physical absorption, pozzolanic action and so on. Ning *et al.* (2007) reported that CH in the solution of stabilized soil might be under-saturated, under this condition, further absorption of Ca^{2+} and OH^- ions by the soil might consume the Ca^{2+} and OH^- ions which should be used to produce C-S-H originally, so the amount of C-S-H in the stabilized soil reduced, which results in the strength decrease of the stabilized soil. Although there were many chemical factors of soil that can affect the strength of stabilized soil, the influence of the soil chemical factors on the strength of stabilized soil were attributed to that the factors could decrease CH saturation of the solution in the stabilized soil, and in turn decrease the production of C-S-H. Therefore, by increasing CH saturation of the solution in stabilized soil, the negative influence of soil chemical factors on the strength of stabilized soil can be eliminated.

2.3 Formation rate coordination between cementitious hydrates and expansive hydrates

The hydrates of efficient soil stabilizer should include cementitious hydrates and expansive hydrates as mentioned above. Huang *et al.* (2007) reported that the function of expansive hydrates

was double-edged, the expansive hydrates not only could squeeze and fill the pores inside clay soil aggregates, but also could destroy the structure formed by cementitious hydrates such as C-S-H. The coordination of the formation rate between the cementitious hydrates and the expansive hydrates determined whether the expansive hydrates could enhance the strength of stabilized soil. The coordination of the formation rate is defined as the time sequence of the formation of the cementitious hydrates and the expansive hydrates. If the expansive hydrates formed before the cementitious hydrates and the structure constructed by the cementitious hydrates had just formed rather little, the positive function of the expansive hydrates was in predominant over its negative function, which benefited increasing the strength of stabilized soil. Therefore, by increasing the formation rate of the expansive hydrates or decreasing the formation rate of the cementitious hydrates the formation rate coordination of two types of hydrates in stabilized clay soil could be improved.

3. Sorting and advantages of industrial wastes on preparing clay soil stabilizer

According to the above theories, an efficient soil stabilizer should offer the hydrates that could increase CH saturation in the pore solution, the cementitious hydrates that could bind the clayey soil aggregates, and the expansive hydrates that could squeeze and fill the pores, especially the pores inside the clayey soil aggregates, in the stabilized soil. Besides, the stabilizer needs to ensure the formation rate coordination between cementitious hydrates and expansive hydrates.

However, for soil stabilization PC hydration does not always produce enough CH, and produces just a little expansive hydrates; besides, the formation rate of cementitious hydrates C-S-H is too fast in many soil cases, which cannot coordinate with the formation rate of the expansive hydrates. These defects of PC could be remedied by proper industrial wastes.

According to the requirement of efficient soil stabilizer analyzed above, the industrial wastes can be sorted into three categories as follows:

(1) Industrial wastes that can increase the CH saturation of the solution in stabilized soil. The experimental studies finished by the authors' group showed that some chemical reagent such as sodium hydrate, magnesium hydrate, CH, sodium carbonate, calcium chloride, magnesium chloride, etc. can increase CH saturation of the solution in stabilized soil. Therefore, the wastes which include these components may be utilized. For example, the waste alkali liquor (contain NaOH) such as produced in bleaching process in textile mill, the carbide slag (the main component is CH) produced in acetylene preparation, etc.

(2) Industrial wastes which can produce expansive hydrates. The expansive hydrate used conveniently in soil stabilization is AFt. AFt can be produced through several ways as follows: (i) the reaction between hydrated calcium aluminate (one of PC hydrates) and calcium sulfate ($CaSO_4$); (ii) the reaction between CH and aluminium sulfate; (iii) the reaction between active aluminum oxide (Al_2O_3), CH and $CaSO_4$. In addition, many kinds of sulphate can react with other substances to produce $CaSO_4$ and in turn produce AFt. Therefore, the industrial wastes which contain mostly gypsum, the industrial wastes contain aluminum, and the sulphate wastes can be used as stabilizer components to produce expansive hydrates. For example, the industrial wastes contain gypsum, such as the flue gas desulfurization gypsum produced in the process of removing SO_2 from waste smoke or gas by lime, the phosphogypsum produced in the manufacture of phosphoric acid, the fluorgypsum produced in the manufacture of hydrofluoric acid, the boron-

gypsum produced in the manufacture of boric acid; the industrial wastes mostly contain Al_2O_3, such as alum sludge (the wastes produced in the manufacture of alums), the calcined ash of paper mill sludge, and the red mud residue, etc..

(3) Industrial wastes that can produce C-S-H, but the C-S-H formation rate of them is slower than that of PC, which benefit the formation rate coordination between C-S-H and expansive hydrates. For example, the industrial wastes that have potential hydraulic cementing ability and the pozzolanic industrial wastes that contain active silicon dioxide (SiO_2) and Al_2O_3, such as the blast furnace slag produced in the process of iron manufacture, the SL produced in steelmaking, the phosphorous slag produced in phosphate manufacture, fly ash, CCG, the rice husk ash produced by burning rice husk fully, and the calcined ash of paper mill sludge, etc.

4. Tests

4.1 Program

In this study, CCG, SL, and SS were used to substitute PC as cementitious components in the stabilizer in order to adjust the formation rate coordination between the cementitious hydrates and the expansive hydrates; PG was used as expansive component in the stabilizer, which can react with the components in the stabilizer that contain aluminium or with the active Al_2O_3 in the soil to produce the expansive hydrate AFt, whose solid volume increases about 120% during the formation process; CS and JY were used as alkaline components in the stabilizer.

The content of cementitious components, expansive components, and alkaline components in the stabilizer were calculated according to the method in the reference (Huang *et al*. 2006b). CCG is a kind of pozzolanic industrial wastes, and need to react with CH in order to produce C-S-H. The optimal ratio of CCG/CH was 100/84 (Dai *et al*. 2010). The content of CS was determined according to net CH content in CS and above optimal ratio of CCG/CH. The proportions of the stabilizer used in this study were shown in Table 3 and Table 4. The ratios in the tables were the mass ratio of the stabilizer components/wet soil sample, and the content of JY was the mass ratio of JY solution/ wet soil.

4.2 Materials

Soil samples: The soil samples used in this study were selected from Wuhan and Beijing, China, which were named as WT and BT respectively. The physical and chemical characters of them were shown in Table 1.

PC: Ordinary Portland Cement produced by Qiangli Cement Mill (based on the standard Common Portland Cement, GB175-1999);
SS: Supplied by Shougang Group, Beijing, China;
CCG: Calcined in 800°C and supplied by China Building Materials Academy, Beijing, China;
SL: Supplied by Chengri Steel Co. Ltd, Jiangsu Province, China;
PG: Supplied by Wengfu Group, Guizhou Province**,** China;
CS: Supplied by Dagu Chemical Industry Co. Ltd, Tianjin, China;
JY: Supplied by Jiekang Abstersion Mill, Shandong Province, China; the main component was NaOH, and the concentration was 28%;

Table 1 Physical and chemical characters of soil samples

Index*	$\rho/g/cm^3$	e	$\omega/\%$	$\omega_L/\%$	$\omega_P/\%$	pH	CEC/cmol/kg
WT	1.73	0.81	40.11	41.30	25.10	6.25	22.0
BT	1.69	1.05	30.00	27.38	16.10	7.10	4.0

* Index symbols in Table 1: ρ: wet soil density; e: void ratio; ω: water content;
ω_L: liquid limit; ω_P: plastic limit; CEC: cation exchange capacity

Table 2 Chemical composition of industrial wastes (%)

Name	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	MnO
SS	19.84	11.00	1.12	57.00	6.20	-	1.16
SL	24.60	23.90	6.30	44.20	-	0.90	-
CCG	57.95	19.02	5.32	3.16	0.82	0.90	0.33
CS	4.61	3.14	0.32	66.14	0.38	-	-
PG	3.62	0.08	0.05	31.57	0.17	42.48	-

CH: Analytical reagent;
Water: Tap water;

The chemical compositions of the industrial wastes used in this study are shown in Table 2.

The physical properties of the soil samples were measured based on Standard for Soil Test Method (GB/T50123-1999). The determination of soil samples' CEC was conducted based on the standard Cation exchange capacity of soils (sodium acetate) (US EPA Method 9081).

4.3 Method

The mixing apparatus was SJ-160 mortar mixer (based on the standard *Mortar mixers for testing*, JG/T 3033-1996); the specific specimen's preparation procedure was as follows (based on the standard Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering (JTG E51-2009):

(1) Weigh each stabilizer components and tap water according to the proportions in Tables 3 and 4, and put them into the mixer pot, then mix them for 30 s with mixing rate of 60 r/min;
(2) Put the soil into the mixer pot, and mix 1min with mixing rate of 60 r/min;
(3) Scrape the soil adhering to blade and pot wall into the pot center, and finally mix 2 min with mixing rate of 120 r/min;
(4) Fill the mixtures into the cube steel mold with size of $50 \times 50 \times 50$ mm^3 in 3 equal layers; vibrate the mold after each layer was filled for 60 s on ZT-1×1 jolting table (based on the standard Jolting table for compacting mortars specimen, JC/T 682-2005), then shape it entirely; cover plastic film on the surface;
(5) Remove the mold at 24 h, cure the specimens for 27 d in standard curing chamber with temperature of 20°C ± 2°C and humidity ≥ 95%, then test the unconfined compressive strength (UCS) of them. The UCS test was conducted based on the standard JTG E51-2009.

Table 3 Stabilizer proportion and UCS of stabilized clay soil specimens (WT)

Number	PC (%)	CCG+CS (%)	CCG+CH (%)	SL (%)	CS (%)	CH (%)	PG (%)	UCS (MPa)
W1	25							0.80
W2	19				6			0.71
W3	14				6		5	2.12
W4	6	8 (4.1+3.9)			6		5	3.00
W5	5	9 (4.6+4.4)			6		5	2.80
W6		14 (7.1+6.9)			6		5	2.00
W7	20					5		0.75
W8	15					5	5	2.44
W9	6		9 (4.9+4.1)			5	5	4.00
W10	3		12 (6.5+5.5)			5	5	3.11
W11			15 (8.1+6.9)			5	5	2.41
W12	6			9		5	5	3.28
W13	3			12		5	5	4.60
W14				15		5	5	2.30

Table 4 Stabilizer proportion and UCS of stabilized soil specimens (BT)

Number	PC (%)	SS (%)	JY (%)	PG (%)	UCS (MPa)
B1	12	-	-	-	1.24
B2	10	-	2	-	1.94
B3	8	2	2	-	1.97
B4	6	4	2	-	2.01
B5	4	6	2	-	2.09
B6	2	8	2	-	2.01
B7	0	10	2	-	1.54
B8	8	2	2	2	5.01
B9	6	4	2	2	6.47
B10	4	6	2	2	7.11
B11	2	8	2	2	7.92
B12	0	10	2	2	6.78

5. Results and discussions

The UCS of the stabilized soil specimens were shown in Tables 3 and 4.

In Table 3, the stabilizer proportions of specimen W7~W11 were corresponding to W2~W6 respectively, only the component CS in W2~W6 was substituted with CH in W7~W11; and the UCS change law of specimen W7~W11 were also similar with that of specimen W2~W6. The UCS of specimen W7~W11 were higher than specimen W2~W6, because the net content of the stabilizers of specimen W7~W11 were higher than that of specimen W2~W6 (net CH in CS was only 87.4% according to Table 2. In the stabilizer proportions of specimen W12~W14, the

component SL substituted the component CCG+CS, compared with W9~W11, and the UCS change law of W12~W14 were also similar with that of W9~W11 and W2~W6. The UCS of specimen W12~W14 were higher than that of W9~W11, because the net content and the active of SL were higher than those of CCG+CS.

In Table 3, the UCS of specimen W1, W2, and W7 differed a little, although in specimen W2, and W7 partial of PC was substituted by 6% CS or 5% CH, which indicated that when CH of the pore solution in the specimen was under-saturated, the production of C-S-H produced by 25% PC was almost equal to that produced by 20% PC in the pore solution with high CH saturation. In Table 4, the UCS of B2 increased 56.6% compared with that of B1, just because in the stabilizer proportions of B2, 2% PC was substituted by JY, which indicated that as CH saturation of the pore solution was increased by JY, the C-S-H production was increased in turn. These results further proved the theory in Section 1.2, and confirmed that utilizing proper industrial wastes can increase CH saturation of the pore solution in stabilized soil specimens was benefit to ensure PC producing C-S-H fully.

As shown in Table 3, the UCS of the specimen**s** increased when 5% PC in the stabilizer proportion was substituted by 5% PG. For example, the UCS of specimen W3 and W8 increased 1.99 times and 2.25 times than that of specimen W2 and W7 respectively. Similar law was also showed in Table 4. The UCS of specimen B8 increased 3.04 MPa than that of specimen B3, as the result of adding 2% PG into the stabilizer proportion of specimen B8. According to the theories in Section 1.1 and (2) of Section 2, these results indicated that the AFt which was formed by the reaction between PG and the PC hydrates containing aluminium or active Al_2O_3 in the soil sample, increased the UCS of the specimens obviously by its volume expansion which filled the pores of the specimens.

Table 3 showed that comparing specimen W4 with W3, W9 with W8, and W13 with W8, when about 10% of PC was substituted by CCG or SL, the UCS of the specimens increased 42%, 64%, and 86% respectively. In Table 4, the stabilizer proportions of specimen B8~B12 were corresponding to B3~B7, only 2% PG was added, but the UCS of specimen B8~B12 were much higher than that of specimen B3~B7, and the increment of the UCS increased with the increase of SS content. For example, the UCS of specimen B11 increased 2.94 times than that of B6, and the UCS of specimen B11 increased 0.58 times than that of B8. According to the theories in Section 1.1 and (3) of Section 2,These UCS increment were contributed by the improvement of the formation rate coordination between cementitious hydrate C-S-H and expansive hydrate AFt, which was achieved by substituting PC in the stabilizers with CCG and SS, because the hydration rate of CCG and SS were slower than that of PC in early stage, thus the structure formation formed by C-S-H binding was postponed, and the damage of the structure caused by AFt expansion was weakened.

The results in Tables 3 and 4 showed that the soil stabilizer prepared by scientifically combining different industrial wastes could improve the UCS of the stabilized soil obviously. For the soil sample WT, the UCS of specimen W1 which was stabilized only by PC was only 0.8 MPa, while the UCS of W4, which was stabilized by the stabilizer whose component included 76% industrial wastes, was 3.0 MPa, increased 2.75 times than that of W1; the UCS of specimen W9, whose stabilizer component only included 24% of PC, was 4.0 MPa and increased 4.0 times than that of W1; the UCS of specimen W13, whose stabilizer component only included 12% of PC, was 4.6 MPa and increased 4.75 times than that of W1; the UCS of specimen W6 which was stabilized by the stabilizer composed by industrial wastes completely reached 2.0 MPa, and increased 1.5 times than that of W1; the UCS of specimen W11 and W14 whose stabilizer component did not

include PC reached 2.41 MPa and 2.30 MPa, and increased 2.0 times and 1.88 times than that of W1 respectively. For the soil sample BT, the UCS of specimen B1 which was stabilized only by PC was only 1.24 MPa, while the UCS of B11, whose stabilizer component only included 16.7% of PC, was 7.92 MPa and increased 5.4 times than that of B1; the UCS of specimen B12 whose stabilizer component did not include PC reached 6.78 MPa, and increased 4.5 times than that of B1. These results reflected the notable advantages of industrial wastes on preparing soil stabilizer and the great environmental and economical benefit.

   Above test results show that based on understanding the characters of the hydrate system needed by structure formation of stabilized soil, the characters of the formation environment and formation process of the hydrates in stabilized clay soil, and cognizing the advantage of industrial wastes on preparing soil stabilizer, preparing soil stabilizer by scientifically combining of different industrial wastes not only can alleviate environment pollution and save resources, but also can increase the UCS of stabilized soil. Therefore, it is an important way of resource utilization of industrial wastes with high added-value.

6. Conclusions

   The performance of soil stabilizer can be enhanced greatly by prepared with industrial wastes based on following theories: to construct dense structure of stabilized soil, the hydrate system generated by the stabilizer should include the cementitious hydrates such as C-S-H that can wrap and bind the clayey soil aggregates, the expansive hydrates such as AFt that can squeeze and fill the pore in the stabilized soil, especially the pore inside the clayey soil aggregates, and the hydrate that can make the pore solution in the stabilized soil CH saturated so as to ensure PC produce C-S-H fully; in additional, the formation rate of the cementitious hydrates should coordinate with that of the expansive hydrates. Many kinds of industrial wastes have advantages on preparation of soil stabilizer, they can supply alkaline hydrates or expansive hydrates, or can adjust the formation rate coordination between cementitious hydrates and expansive hydrates. Therefore, by scientifically combining different kinds of industrial wastes, efficient and environment friendly soil stabilizer can be prepared, which provide a resource utilization technology for industrial wastes with high added-value.

   The test results indicated that even when the PC proportion included in the stabilizer component was lower than 20%, for the soil sample WT and BT, the UCS of the specimens could increase 4.8 times and 5.4 times respectively than that of the specimens stabilized only by PC; compared with the UCS of the specimens stabilized only by PC, the UCS of the specimen which was made from soil sample WT and stabilized by the stabilizer composed only by CCG, CS, and PG increased 1.5 times, and UCS of the specimen which was made from soil sample BT and stabilized by the stabilizer composed only by SS, JY, and PG increased 4.5 times.

Acknowledgments

References

Anagnostopoulos, C.A. and Chatziangelou, M. (2008), "Compressive strength of cement stabilized soils: A new statistical model", *Electron. J. Geotech. Eng.*, **13**, 1-10.

Dai, L. Li, Z.G. and Huang, X. (2010), "Feasibility of soil stabilizer production with industrial wastes", *Eng. Sci.*, **12**(3), 56-60.

Degirmenci, N., Okucu, A. and Turabi, A. (2007), "Application of phospho-gypsum in soil stabilization", *Build. Environ.*, **42**(9), 3393-3398.

General Administration of Quality Supervision (1999), Common Portland Cement, GB175-1999, Beijing, China.

Horpibulsuk, S., Phetchuay, C. and Chinkulkijniwat, A. (2012), "Soil stabilization by calcium carbide residue and fly ash", *J. Mater. Civ. Eng.*, **24**(2), 184-193.

Huang, X., Ning, J.G. and Xu, S. (2006a), "Structure formation model of stabilized soil", *Indust. Construct.*, **36**(7), 1-6.

Huang, X., Ning, J.G. and Xu, S. (2006b), "A method of designing hardening agent for soft soil according to characteristics of the soil samples", *Indust. Construct.*, **36**(7), 13-18.

Huang, X., Xu, S. and Ning, J.G. (2007), "Experimental research on stabilized soft soil by alumina bearing modifier", *Chinese J. Rock Mech. Eng.*, **26**(1), 156-161.

Kamon, M. and Nontananandh, S. (1990), "Combining industrial waste with lime for soil stabilization", *J. Geotechn. Eng.*, **1**(1), 1-17.

Kamon, M., Nontananandh, S. and Katsumi, T. (1989), "Effective utilization of stainless steel slag for soil stabilization", *Proceeding of the 24th Japan National Conference on Soil Mechanics and Foundation Engineering*, Tokyo, Japan, June.

Khalid, N., Mukri, M., Kamarudin, F., Arshad, M.F. (2012), "Clay soil stabilized using waste paper sludge ash (WPSA) mixtures", *Electron. J. Geotech. Eng.*, **17**, 1215-1225.

Kim, Y.T., Ahn, J., Han, W.J., Gabr, M. (2010), "Experimental evaluation of strength characteristics of stabilized dredged soil", *J. Mater. Civil Eng.*, **22**(5), 539-544.

Kolias, S, Kasselouri-Rigopoulou, V. and Karahalios, A. (2005), "Stabilization of clayey soils with high calcium fly ash and cement", *Cement Concrete Compos.*, **27**(2), 301-313.

Ministry of Transport of the People's Republic of China (2009), Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering, JTG E51-2009, Beijing, China.

Ministry of Housing and Urban-Rural Development of the People's Republic of China (1996), Mortar Mixers for Testing, JG/T 3033-1996, Beijing, China.

Ministry of Resources of the People's Republic of China (1999), Standard for Soil Test Method, GB/T 50123-1999, Beijing, China.

National Bureau of Statistics of China (2013), *China Statistical Yearbook*, In: Chapter 7. Source and Environment, China Statistics Press, Beijing, China.

National Development and Reform Commission (2005), Jolting Table for Compacting Mortars Specimen, JG/T 682-2005, Beijing, China.

Ning, J.G., Huang, X. and Xu, S. (2007), "Effect of pH value of soil on strength increasing of the stabilized soil", *Chinese J. Geotech. Eng.*, **29**(1), 98-102.

Peethamparan, S., Olek, J. and Lovell, J. (2008), "Influence of chemical and physical characteristics of cement kiln dusts (CKDs) on their hydration behavior and potential suitability for soil stabilization", *Cement Concrete Res.*, **38**(6), 803-815.

Taylor, H.F. (1997), *Cement Chemistry*, (2nd Ed.), Thomas Telford, London, UK.

U.S. Environmental Protection Agency (1986), *Cation Exchange Capacity of Soils* (*sodium acetate*) (US EPA Method 9081), USA.

Zhou, G.J. and Ye, G.B. (2008), *Foundation Treatment Manual*, In: Chapter 11. Cement-Soil Mixing Method, (Third ed.), China Architecture & Building Press, Beijing, China.

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