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Feasibility of using a mixture of an electroplating sludge and a calcium carbonate sludge as a binder for sludge solidification

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Abstract

"Wastes treating wastes" and resource recycling are the basic concepts of this study. In this work, two industrial wastes (an electroplating sludge and a water-purification calcium carbonate sludge) were obtained, mixed, and heated at 1000 °C for four hours. The resulting material was then tested to determine whether it could be used as a binding material for solidification of the original electroplating sludge. It was found that the heat-treated sludge mixture did exhibit a binding capability in a cement-based solidification of its original electroplating sludge. In this study, a modified Taguchi method was employed for the experimental design of solidification. The heat-treated sludge mixture was used to partially replace (10 wt%, 20 wt%, or 40 wt% replacement) the ASTM Type I portland cement as a binding material. The solidified monoliths were then tested to determine their unconfined compressive strengths, TCLP leaching toxicity, and long-term chemical durability (by Multiple TCLP). Experimental results were found to be satisfactory. The concepts of "wastes treating wastes" and resource recycling are thus realized.

1. Introduction

The volume of wastewater sludges generated by various industries in Taiwan has been increasing over the past years. Previously, these sludges were improperly disposed of, including midnight dumping. It is believed that a great amount of these sludges would classify as hazardous. An increase in environmental concerns would not allow an illegal dumping of these hazardous sludges any more. Thus, proper treatment and final disposal of hazardous sludges are necessary. Incineration, solidification, and secure landfilling are among common technologies that have been used. Aside from these technologies, using wastes to treat wastes and resource recycling might be rather new and promising technologies.

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In fact, "wastes treating wastes" and resource recycling are the basic concepts of this study. Many studies have been carried out by various researchers concerning the use of municipal wastewater sludge as a nonconventional building and construction material [1–4]. There is at least one other investigation concerning the use of lime-blended sludge for production of cementitious material [5]. Therefore, in the present work it was tried to produce a heat-treated mixture of an electroplating sludge and a calcium carbonate sludge and to study the feasibility of using this heat-treated material as a binder for sludge solidification.

2. Experimental

2.1. Materials

In this work, an electroplating sludge was obtained from a local factory having electroplating activities; whereas a calcium carbonate sludge resulting from a water-purification process was obtained from a nearby petrochemical plant. ASTM Type I portland cement was used as a major binding agent for sludge solidification.

A heat-treated mixture of two industrial wastes was used as a cement substitute in sludge solidification. This heat-treated material was prepared as follows: (1) equal amounts (dry basis) of the aforementioned sludges are weighed (2) mixed and ground in a ball mill with ceramic balls, and subsequently (3) heated at 1000 °C for four hours, and then (4) cooled off, after which (5) the resulting material is ground till passing a 20-mesh sieve (i.e., particle size smaller than 850 μm).

All chemicals used in this study were of reagent grade as specified in the various standard methods adopted by R.O.C. EPA and/or U.S. EPA for evaluating solids. Water used in this work was ASTM Type I deionized water.

2.2. Methods

The electroplating sludge was characterized by various standard methods for evaluating solid wastes recommended by R.O.C. EPA and U.S. EPA [6, 7]. The determined properties included moisture content, ash content, total contents of heavy metals of interest, and heavy metal concentrations of the leachate from the Toxicity Characteristic Leaching Procedure (known as the TCLP test). In addition, loss on ignition was determined according to ASTM C 114. On the other hand, the calcium carbonate sludge was not subjected to any characterization tests because its composition was provided by the supplier.

To simultaneously take into account the effects of all major experimental factors and to obtain the optimal experimental conditions for solidification, an experimental design established by the Taguchi method [8] with a minor modification was adopted in this work. The L_9 (3^4) orthogonal arrays with three levels of variation were employed using the following as the experimental factors: (1) weight percent of cement replacement by the heat-treated

TABLE 1

Solidification recipes based on a modified Taguchi method

Monolith No.	Solidification recipe			
	A[a]	B[b]	C[c]	D[d]
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1
Level No.	**Solidification recipe**			
	A (wt%)	B (g)	C	D
1	10	300	0.8	2
2	20	500	0.7	3
3	40	700	0.6	4

[a] A denotes amount of cement replacement by the heat-treated material.
[b] B denotes the total weight of the binding agents.
[c] C denotes the weight ratio of water to the binding agents.
[d] D denotes the weight ratio of the binding agent to electroplating sludge.

material, (2) total weight of the binding agent(s), (3) weight ratio of water to binding agent(s), and (4) weight ratio of binding agent(s) to electroplating sludge. Details are shown in Table 1.

Solidification of the electroplating sludge was carried out in the following manner: (1) mixing the dried sludge and the binding agent(s) thoroughly in a Hobart-like mixer for a few minutes, (2) adding the desired amount of water into the mixing bowl for further mixing, (3) pouring the mortar into an adequate size of PVC molds of cylindrical shape, (4) curing under ambient conditions for one day, (5) demolding, (6) curing the solidified specimen in an environmental chamber maintaining 23 °C and 98% relative humidity for a desired length of time. After this stage, the solidified monoliths were tested for a variety of purposes. In this investigation, solidification was conducted according to CNS 1230 A3043; unconfined compressive strength, CNS 1232 A3045; leaching toxicity, TCLP test; chemical durability, Multiple TCLP test [9]; and heavy metals concentration, flame atomic absorption spectroscopy (AAS).

3. Results and discussion

3.1. Characterization of the electroplating sludge

Characterization results for the electroplating sludge used in this work are shown as follows: moisture content, 64.5%; ash content, 27.7%; pH 8.17; and loss on ignition, 39.66%. The total contents of heavy metals (mg/l) were found to be: Zn, 1293; Cd, 35.25; Pb, <0.2; and Cu, <0.09. On the other hand, the heavy metal concentrations (mg/l) of the TCLP leachate were found to be 168.63 and 28.80 for zinc and cadmium, respectively. The TCLP result indicate that both zinc and cadmium concentrations are greater than the current R.O.C. EPA regulatory thresholds (25.0 mg/l for Zn and 0.5 mg/l for Cd). Thus, the electroplating sludge sample used in this work is classified as a hazardous waste. An appropriate treatment/disposal of this sludge is inevitably needed.

3.2. Characterization of the calcium carbonate sludge

The chemical composition (wet basis) of the calcium carbonate sludge was provided by the supplier of the sludge, to be: moisture content, 50.20 wt%; $CaCO_3$, 33.88 wt%; $CaSO_4$, 3.52 wt%; $Mg(OH)_2$, 0.79 wt%; and others, 11.61 wt%.

3.3. Unconfined compressive strength (UCS)

To study whether the heat-treated mixture of two industrial wastes exhibits the nature of cementitious materials, in this work, unconfined compressive strengths (UCS) of monoliths solidified by portland cement alone (designated "control group") and by a mixture of portland cement and the heat-treated material (designated "sample group") were compared. From Table 2, it is seen that by using the same solidification recipes other than the binder type the UCS for each monolith in the sample group is greater than the corresponding one in the control group. This finding holds true for all solidified monoliths regardless of the curing time. Besides, the UCS for any solidified monolith in the sample group is greater than the current R.O.C. EPA regulatory threshold for landfilling of solidified monoliths (i.e., 10 kg/cm^2).

3.4. TCLP leaching toxicity

To further verify the improved binding properties of the heat-treated material, the TCLP leaching toxicity was also compared for 28-day old monoliths in the sample group and the control group. Experimental results are shown in Table 3. It was found that by using the same solidification recipes except for the binder type any monolith in the sample group had a lower concentration of zinc than that of the corresponding one in the control group. More importantly, the leached concentrations of zinc are all smaller than the current R.O.C. EPA regulatory threshold. For cadmium, however, the leached concentrations for sample groups are slightly higher than that of the control group. Again, these concentrations of cadmium are all much lower than the current R.O.C. EPA regulatory threshold. A low leaching toxicity is not surprising

TABLE 2

Effects of cement replacement by the heat-treated material on unconfined compressive strengths for solidified monoliths of different ages

Monolith No.	Unconfined compressive strength (kg/cm^2)					
	Control group[a]			Sample group[b]		
	UCS_3[c]	UCS_7	UCS_{28}	UCS_3	UCS_7	UCS_{28}
1	8.94	13.69	26.30	14.55	30.76	35.28
2	8.02	13.00	21.85	15.58	26.03	35.47
3	8.02	12.74	23.46	14.26	25.99	32.93
4	7.24	12.51	16.95	13.62	19.25	24.34
5	16.90	16.36	39.81	28.06	68.13	76.43
6	7.14	11.99	17.83	14.01	23.17	27.15
7	10.08	15.19	28.45	25.32	54.34	62.96
8	6.94	11.57	14.36	13.18	16.32	23.46
9	10.86	14.96	31.83	33.99	48.92	70.29

[a] Control group denotes monoliths solidified by portland cement alone.
[b] Sample group denotes monoliths solidified by portland cement with a partial replacement by the heat-treated material.
[c] UCS_n denotes unconfined compressive strength of a solidified monolith measured at an age of n days.

TABLE 3

Effects of cement replacement by the heat-treated material on TCLP leaching toxicity for solidified monoliths with an age of 28 days

Monolith No.	Heavy metal concentration of TCLP leachate (mg/l)					
	Control group[a]			Sample group[b]		
	Zn	Cd	Final pH	Zn	Cd	Final pH
1	0.732	0.064	12.22	0.265	0.079	12.23
2	0.660	0.064	12.33	0.483	0.080	12.25
3	0.669	0.063	12.35	0.437	0.078	12.27
4	0.729	0.064	12.31	0.444	0.078	12.23
5	0.446	0.063	12.16	0.337	0.075	12.02
6	0.512	0.065	12.29	0.209	0.078	12.21
7	0.509	0.062	12.34	0.196	0.078	12.00
8	0.582	0.064	12.31	0.330	0.079	12.19
9	0.333	0.063	12.25	0.238	0.078	11.58

[a] Control group denotes monoliths solidified by portland cement alone.
[b] Sample group denotes monoliths solidified by portland cement with a partial replacement by the heat-treated material.

because the final pHs of all TCLP leachates are in the neighborhood of 12. Under such an alkaline condition, the TCLP extraction fluid (i.e., glacial acetic acid) will be immediately neutralized (or buffered), thereby resulting in a low leaching capability.

3.5. Multiple TCLP (MTCLP)

Multiple TCLP is a modified test of the Multiple Extraction Procedure (MEP) while remaining the design principles of MEP [9]. Therefore, MTCLP is designed to simulate the leaching of a solid waste (including the one in a solidified form) that will result from repetitive precipitation of acid rain.

In this work, the Multiple TCLP test was also carried out for the electroplating sludge and the solidified specimen having the greatest UCS value in the sample group (i.e., monolith No. 5 in Table 2). Experimental results are given in Tables 4 and 5. By using the solidification recipe employed by monolith No. 5 it is evident that solidification would be capable of reducing the cumulative leached zinc from 2.830 wt% to 0.034 wt% and the cumulative leached cadmium from 18.853 wt% to 0.397 wt%. This finding again verifies that the heat-treated material exhibits a very good binding ability for heavy metals in its original electroplating sludge.

3.6. Role of the heat-treated material in solidification

The major components of the portland cement composition are C_3S (i.e., $3CaO{\cdot}SiO_2$), C_2S (i.e., $2CaO{\cdot}SiO_2$), C_3A (i.e., $3CaO{\cdot}Al_2O_3$), and C_4AF (i.e.,

TABLE 4

Comparison of the long-term leachability of the electroplating sludge before and after solidification (zinc)[a]

MTCLP Sequence No.	Electroplating sludge			Solidified monolith No. 5		
	Zn Conc. (mg/l)	Wt. of Zn leached (mg)	% of Zn leached (wt%)	Zn Conc. (mg/l)	Wt. of Zn leached (mg)	% of Zn leached (wt%)
1	168.630	337.260	2.608	0.337	0.674	0.005
2	10.150	20.300	0.157	0.256	0.512	0.004
3	0.891	1.782	0.014	0.185	0.370	0.003
4	0.606	1.212	0.009	0.288	0.576	0.004
5	0.474	0.948	0.007	0.172	0.344	0.003
6	0.561	1.122	0.009	0.168	0.336	0.003
7	0.479	0.958	0.007	0.265	0.053	0.004
8	0.435	0.870	0.007	0.210	0.042	0.003
9	0.398	0.796	0.006	0.175	0.350	0.003
10	0.375	0.750	0.006	0.150	0.300	0.002

[a]All calculations were based on 100 g of solid sample in 2000 ml of extraction fluid.

TABLE 5

Comparison of the long-term leachability of the electroplating sludge before and after solidification (cadmium)[a]

MTCLP Sequence No.	Electroplating sludge			Solidified monolith No. 5		
	Cd Conc. (mg/l)	Wt. of Cd leached (mg)	% of Cd leached (wt%)	Cd Conc. (mg/l)	Wt. of Cd leached (mg)	% of Cd leached (wt%)
1	28.800	57.600	16.340	0.075	0.150	0.043
2	3.510	7.020	1.991	0.069	0.138	0.039
3	0.308	0.616	0.175	0.068	0.136	0.039
4	0.165	0.330	0.094	0.067	0.134	0.038
5	0.074	0.148	0.042	0.072	0.144	0.041
6	0.091	0.182	0.052	0.070	0.140	0.040
7	0.072	0.144	0.041	0.070	0.140	0.040
8	0.069	0.138	0.039	0.069	0.138	0.039
9	0.070	0.140	0.040	0.068	0.136	0.039
10	0.068	0.136	0.039	0.068	0.136	0.039

[a]All calculations were based on 100 g of solid sample in 2000 ml of extraction fluid.

$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$). The setting of portland cement is mainly due to the hydration of the first three components. Overall speaking. the first two components together contribute the most to the compressive strength of a cement mortar.

In this investigation, the heat-treated material is a product of a mixture of two industrial wastes (an electroplating sludge and a calcium carbonate sludge) that has been subjected to a heat treatment at 1000 °C for four hours. Calcining is the decomposing of carbonates into metallic oxides and CO_2. Since calcining is an endothermic reaction, the carbonates must be heated above a certain temperature before calcination begins. The calcining of calcium carbonate to form quicklime is sometimes called burning. The melting point of calcium carbonate is about 1339 °C. The heating temperature used in this work is only 1000 °C. Although the temperature might not be high enough for calcination of calcium carbonate to form calcium oxide, it might cause some phase conversions of the original materials during the pyroprocessing. X-ray diffraction analysis of the heat-treated material also showed that no CaO was formed in the final product, which turned out to be a very complex material. This complex material, however, has shown its outstanding binding ability for sludge solidification. To better understand the composition of the heat-treated material and its reaction mechanisms with the heavy metals, further studies are needed.

4. Conclusions

In this investigation, a heat-treated waste mixture (an electroplating sludge and a calcium carbonate sludge) was used to study whether it can replace portland cement as a binding material for sludge solidification. With the aid of the L_9 orthogonal arrays established by a modified Taguchi method, numerous solidified monoliths were prepared using different solidification recipes. These solidified specimens were further tested for their physical and chemical properties.

Experimental results have indicated that solidified monoliths in the sample group (with 10, 20 or 40 wt% replacement of cement by the heat-treated material) outperformed the ones in the control group (pure portland cement with no substitutes) in terms of unconfined compressive strength and TCLP leaching toxicity. That is, greater unconfined compressive strengths and lower heavy metal concentrations in TCLP leachates for the former. Furthermore, monolith No. 5 in the sample group also exhibited a very good long-term chemical durability, as determined by the Multiple TCLP test.

Therefore, it is evident that the heat-treated material prepared in this work does exhibit cementitious properties. The solidified monoliths prepared with a partial replacement of portland cement by the heat-treated material have much better physical and chemical properties than do monoliths solidified by portland cement alone. Thus, the concepts of using wastes to treat wastes and resource recycling are realized in this work.

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