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PULVERIZED FUEL ASH SOLIDIFICATION/STABILIZATION OF WASTE: COMPARISON BETWEEN BENEFICIAL REUSE OF CONTAMINATED MARINE MUD AND SEDIMENT

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Abstract. This study aimed to maximize the utilization of contaminated marine mud and sediment for beneficial reuse by solidification/stabilization (S/S) treatment with cement and pulverized fuel ash (PFA). For the purposes of waste maximization and enhancing the mechanical property of the S/S mixtures, mixing 75% by mass of either contaminated marine mud or sediment with 20% and 5% of cement and PFA, respectively, was found to be the optimal mix design. Their unconfined compressive strengths reached up to 8.32 MPa and 4.47 MPa, respectively. Apart from the mechanical property, according to the U.S.EPA, the TCLP results show that all regulated heavy metals were immobilized to a safe level and are available for engineering application such as fill material. The results of XRD reveal that the formation of CSH gel in the S/S treated mud and sediment is responsible for the strength development and heavy metal immobilization.

Keywords: cement, compressive strength, fill material, heavy metal immobilization, TCLP.

Introduction

Solidification/stabilization (S/S) is a widely used technology to treat contaminated soils in many countries, so as to minimize the level of contaminant leaching prior to landfill disposal. Cement has been intensively utilized as the binder for S/S treatment due to its low material cost and abundance in resources (Ubbrìaco, Calabrese 1998; Conner 1999; Gong, Bishop 2003). To further reduce the treatment cost and promote the concept of green remediation, partial replacement of cement with pulverized fuel ash (PFA), which is the residue resulting from the coal combustion process, has been applied to S/S technology recently for the purpose of engineering applications such as road bases (Lav *et al.* 2006; Ghosh, Dey 2009) and concrete products (Siddique 2004; Durán-Herrera *et al.* 2011). Apart from the waste utilization and reduction of treatment cost, the use of PFA has been proven to enhance the strength of cement mixed soil (Kogbara *et al.* 2013) and to reduce the extent of contaminant leaching (Perera, Al-Tabbaa 2005; Moon *et al.* 2010). The silica and alumina contents of PFA were considered to play important roles in improving the quality of the S/S treated soil for beneficial reuse, as both silica and alumina react with the calcium hydroxide in cement to form calcium silicate hydrates or calcium aluminium silicate hydrates, which are the main products of cement hydration to provide strength and contaminant binding in cement-based soil (Bouzalakos *et al.* 2008; Li *et al.* 2012).

Comparatively, the development of S/S technology in relation to contaminated marine mud and sediment for beneficial reuse is not as comprehensive as that of soil. The high plasticity index of marine mud and sediment was reported to be inversely related to the strength of cement mixture (Saadeldin, Siddiqua 2013) thus limiting most of

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their engineering applications. In addition, the contamination levels of sediment and marine mud are relatively higher than that of coarse soil due to their large surface areas and abundant clay content (Sparks 2003). Two common ways to handle dredged marine mud and sediment are ocean dumping and landfill disposal. With consideration of the adverse environmental impacts, the US Federal regulations – marine protection, research and sanctuaries act of 1972 (MPRSA) have restricted the ocean dumping of dredged sediment from harbours such as those of New York and Newark, and thus left the local port authorities no choice, but an unsustainable option to dispose of the dredged sediment in landfills.

In view of the recent developments of S/S technology, dredged marine mud and sediment indeed can be potentially reused for various construction purposes such as pavement bases (Yan *et al.* 2014) and fill material (Zhang *et al.* 2011). Due to the successful strength enhancement of cement mixed soil after the addition of PFA, PFA was recently studied regarding S/S processes in mud and sediment. It was found that PFA can successfully overcome the low strength development of cement mixed sediment and red mud. By mixing 15% by mass of red mud and 15% PFA with 53% cement, the compressive strength of the cement mixture reached up to 35 MPa after 28 days of the curing process (Yao *et al.* 2013). However, from the sustainability point of view, the percentage of red mud utilization is considered rather low to promote the beneficial reuse of waste. On the contrary, the waste utilization was maximized by 94% and 3% by mass of sediment and PFA, respectively, for S/S treatment (Zentar *et al.* 2012). The unconfined compressive strength of the resulting cement-based material at the 28th day was about 0.6 MPa which may not be enough for most engineering applications. With all the aforementioned concerns, striking a balance between waste maximization and broadened engineering application is believed to be one of the potential perspectives in the sustainable development of S/S treatment for sediment and marine mud.

This study aimed at the maximization of using contaminated sediment and marine mud for beneficial reuse as sustainable fill material by S/S treatment with cement and PFA. The physical and mechanical properties and the contaminant leaching behavior of the S/S treated sediment and marine mud was evaluated. In order to provide an in-depth understanding of S/S treated contaminated sediment and marine mud, their performances were compared with the consideration of feasible engineering applications. This study enables further improvements of the S/S technology in relation to contaminated sediment and marine mud, and provides an alternative for sustainable management of dredged sediment and marine mud.

1. Experimental

1.1. Materials

The contaminated marine mud and sediment were obtained from a contaminated site in Hong Kong. The contaminated marine mud was collected from 10–12 cm below the ground surface and the contaminated sediment was dredged from 10 to 100 cm below the seawater/sediment interface. The samples were then sealed in plastic bags, placed in covered buckets and stored in a cold room at 4 °C to avoid any possible deterioration. Both the contaminated marine mud and sediment were air dried for 2 weeks prior to S/S treatment and then sieved through a 5 mm size sieve to remove oversized debris. The particle size distribution of the contaminated marine mud and sediment are shown in Figure 1, whereas their physical properties are given in Table 1. The particle size of the marine mud was smaller than that of sediment, with about 20%, 50% and 30% of sand, silt and clay for marine mud, and 45%, 50% and 5% of sand, silt and clay for sediment, respectively. According to the Unified Soil Classification System (ASTM D 2487), the marine mud (with plasticity index of 30.1) and sediment (with plasticity index of 23.2) were classified as CH (fat clay with sand) and MH (sandy elastic silt), respectively. Both marine mud and sediment were contaminated and their corresponding heavy metal contents are shown in Table 1. The marine mud was mainly contaminated by Ba and Mn, with 323.3 and 481.0 mg/kg, respectively. On the other hand, high concentration of Ba, Cr, Pb, Zn, Mn and especially Cu were found in the sediment, registering 224.7, 232.3, 152.0, 638.3, 573.3 and 2171.9 mg/kg, respectively.

The cement used was Hong Kong commercially available ordinary Portland cement (OPC) which is equivalent to the American Society Testing and Material (ASTM) type I cement. The pulverized fuel ash used was obtained from a power plant in Hong Kong and is equivalent to the ASTM Class F fly ash. The chemical compositions of OPC

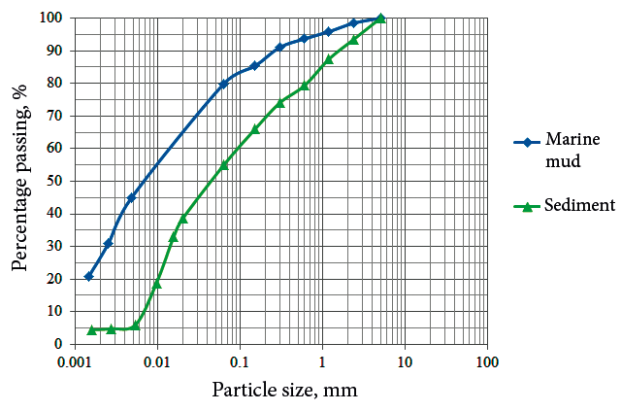

Fig. 1. Particle size distribution of contaminated marine mud and sediment

Table 1. Physical properties and heavy metal contents of contaminated marine mud and sediment

	Mud	Sediment
Physical properties		
Sand (> 63 μm) (% by mass)	20.4±1.0	45.0±0.6
Silt (63 ~ 2 μm) (% by mass)	49.6±0.6	50.4±0.6
Clay (< 2 μm) (% by mass)	30.0±1.0	4.6±0.1
Moisture Content (%)	28.3±0.92	56.6±1.27
pH	8.39±0.04	8.54±0.03
Liquid Limit	50.9	52.4
Plastic Limit	20.8	29.2
Plasticity Index	30.1	23.2
Group Symbol	CH[1]	MH[2]
Heavy metal content (mg/kg by dry weight)		
Sb	45.7±3.6	49.1±5.7
As	36.3±0.9	27.0±1.9
Ba	323.3±56.8	224.7±25.2
Cd	6.0±3.0	3.8±0.6
Cr	55.1±2.4	232.3±27.5
Pb	51.5±4.9	152.0±17.4
Hg	0.9±0.2	2.3±0.4
Ni	31.8±3.6	41.1±3.1
Zn	98.0±8.1	638.3±58.9
Co	5.3±4.4	2.8±6.4
Cu	18.4±5.0	2171.9±117.1
Mn	481.0±9.2	573.3±37.5
Mo	11.7±1.8	18.4±1.8
Sn	5.3±0.2	8.8±5.5

[1] CH refers to clay with a high liquid limit.
[2] MH refers to silt with a high liquid limit.

Table 2. Chemical compositions of ordinary Portland cement and pulverized fuel ash

Chemical Composition	Cement (% by dry mass)	PFA[1] (% by dry mass)
CaO	65.4	13.9
SiO_2	19.5	44.0
Al_2O_3	3.8	17.9
MgO	1.5	4.7
Fe_2O_3	3.2	13.6
SO_4	5.3	2.5
Loss on ignition	1.3	3.4

[1] PFA refers to pulverized fuel ash.

and PFA are shown in Table 2. The OPC comprises CaO, SiO_2, Al_2O_3 and Fe_2O_3 (i.e. 65.4%, 19.5%, 3.8% and 3.2%, respectively), while PFA comprises less CaO (13.9%) but more SiO_2 (44.4%) and fair amounts of Al_2O_3 and Fe_2O_3 (i.e. 17.9% and 13.6%, respectively). Potable water was used for the S/S treatment in this study.

1.2. Preparation of S/S treated contaminated marine mud and sediment

The design mixes of the S/S treatment for contaminated marine mud and sediment are shown in Table 3. Symbols are used to represent their corresponding materials (i.e. M: mud, S: sediment, C: OPC, F: PFA). For instance, the sample M70C15F15 refers to 70% mud mixed with 15% OPC and 15% PFA. The dry contaminated marine mud and sediment were mixed with OPC and PFA in a mechanical mixer for 2 min to ensure homogenous mixing. Portable water was then added and mixed with the dry components for another 2 min. Afterwards, the maximum dry density and optimum moisture content of the S/S treated contaminated marine mud and sediment were determined according to the standard Proctor compaction test (BS 1377-4: 1990) as shown in Figures 2a and 2b, respectively, and summarized in Table 3.

Table 3. Mix proportions of S/S treated marine mud and sediment

Sample ID	Mass Ratio (%)			Water/ Binder Mass Ratio[1]	Maximum Dry Density[2] (kg/m³)
	Mud	Cement	PFA		
M70C15F15	70	15	15	0.64	1724
M70C10F20	70	10	20	0.68	1683
M70C5F25	70	5	25	0.71	1675
M70F30	70	0	30	0.73	1660
M75C20F5	75	20	5	0.64	1700
M75C15F10	75	15	10	0.66	1694
M80C15F5	80	15	5	0.63	1672
Sample ID	Mass Ratio (%)			Water/ Binder Mass Ratio[1]	Maximum Dry Density[2] (kg/m³)
	Sediment	Cement	PFA		
S70C15F15	70	15	15	0.73	1435
S70C10F20	70	10	20	0.80	1421
S70C5F25	70	5	25	0.83	1402
S70F30	70	0	30	0.84	1398
S75C20F5	75	20	5	0.83	1380
S75C15F10	75	15	10	0.86	1359
S80C15F5	80	15	5	0.83	1372

[1] Binder refers to cement and pulverized fuel ash.
[2] Water/Binder ratio is obtained based on the optimum moisture content and maximum dry density of the S/S samples.

The compacted S/S treated contaminated marine mud and sediment samples were then cast into cubic stainless steel moulds (with a dimension of 50×50×50 mm) with the same effort as the maximum dry density obtained previously in the standard Proctor compaction according to BS EN 12390-2:2009. All S/S samples were prepared in duplicate to show the reproducibility and reliability of the experiments. All samples were demoulded after 1 day and placed in a 100% relative humidity curing room at room temperature prior to testing.

1.3. Testing procedures

The unconfined compressive strength (UCS) of the hardened S/S treated contaminated marine mud and sediment, after curing for 7, 14 and 28 days, was determined according to ASTM D 1633-00, 2000. The UCS of the S/S samples was measured by an automatic compressive testing machine (MTS 815 Test System) at a constant loading rate of 0.1 mm/min. The experimental data points were plotted with error bars and are reported in terms of mean ± standard deviation. To provide a better understanding of the strength development of S/S treated contaminated marine mud and sediment, the micro-structural characterization was also studied through X-ray diffraction (XRD) analysis. The samples after curing for 28 days were crushed into powder for investigation of their crystalline information. The XRD analysis was carried out by a Powder X-ray Diffraction System (Philips PW 1830) with an X-ray source scanning the sample between 2θ angles from 5° to 80° at a speed of 0.02° per minute.

To assess the potential environmental impacts of the S/S treated contaminated marine mud and sediment, the heavy metal leachability of the S/S mixtures at the 28th day were studied through toxicity characteristic leaching procedure (TCLP U.S.EPA method 1311). The samples were crushed to a size of less than 1 cm in diameter and mixed with glacial acetic acid (pH 4.93±0.05) at a solid to solution ratio of 1:20 by maintaining an end-over-end rotation of 30 rpm for 18 h. The crushed S/S samples were then separated from the TCLP leachates with 0.45 um cellulose acetate membranes. The heavy metal concentrations of the TCLP leachates were determined by inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Varian 725-ES). All TCLP tests were performed in triplicate and the average concentrations of the leachates were reported with corresponding standard deviations.

2. Results and discussion

2.1. Compaction characteristics of S/S treated marine mud and sediment

The correlation between maximum dry density and optimum water content of various mixes of S/S treated marine mud and sediment are given in Figures 2a and 2b, respectively. It was found that the optimal water content of S/S treated marine mud and sediment decreased from 21% to 18.5% and 24% to 21.5%, respectively, when their cement content increased from 5% to 15% at a fixed amount of marine mud/sediment (i.e. 70% by mass). Indeed, a similar reduction of optimal water content was also found in a previous study (Zentar *et al.* 2012) and the reason for such is related to the small specific area of cement. Since the ability of water absorption is proportionally related to the specific area of particles, increasing the amount of cement, which has a smaller specific area compared with that of sediment and marine mud, possibly reduces the optimal water content of the S/S mixtures. Nevertheless, by increasing the amount of cement from 5% to 15%, the maximum dry densities of the S/S mixtures increase. The increase of the maximum dry density with increasing cement content is attributed to the higher specific gravity of the cement (i.e. 3.15 g/cm^3) which may benefit the strength

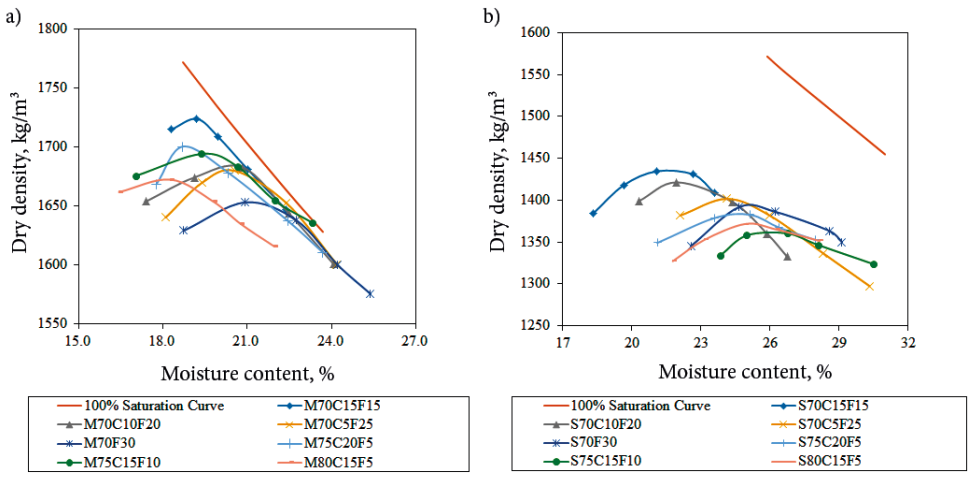

Fig. 2. Compaction curves of (a) S/S treated marine mud and (b) S/S treated sediment

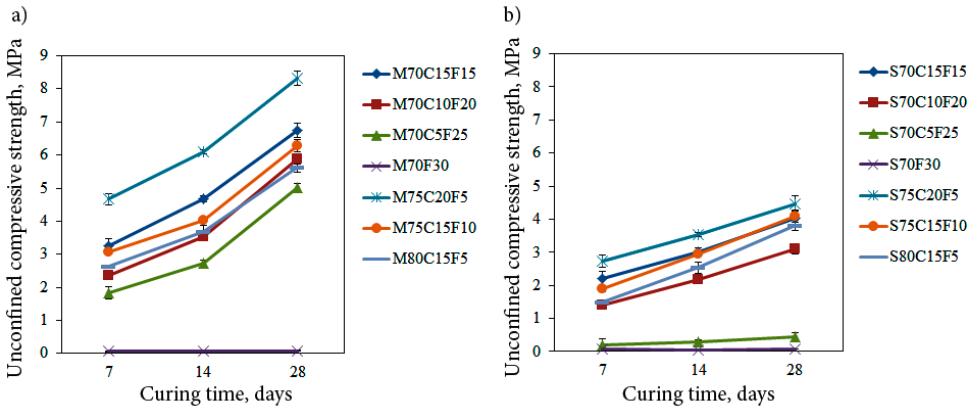

Fig. 3. Unconfined compressive strength of (a) S/S treated marine mud and (b) S/S treated sediment

development of S/S treated marine mud and sediment. However, instead of further increase, the maximum dry densities of both S/S treated marine mud and sediment decreased when the cement content increased to 20% by mass. Since the purpose of this study was to maximize the utilization of marine mud and sediment for S/S treatment so as to enable the reuse of waste for engineering application, the amount of marine mud and sediment increased to 75% by mass whereas the percentage of cement increased to 20%. It is suspected that the reduction in maximum dry densities of the corresponding S/S mixtures is due to the relatively low specific gravity of marine mud and sediment (i.e. 2.65 g/cm^3).

2.2. Unconfined compressive strength of S/S treated marine mud and sediment

The unconfined compressive strengths of the S/S treated contaminated marine mud and sediment samples at the curing time of 7, 14 and 28 days are given in Figures 3a and 3b, respectively, and were found to increase gradually from the 7th to 28th day. In the absence of cement, neither the UCS of PFA-marine mud mixture nor the UCS of PFA-sediment mixture built up with time, even with 30% by mass of PFA. In addition, by utilizing 70% by mass of marine mud or sediment, the UCS of the S/S mixtures decreased with increasing amount of PFA (i.e. from 15% to 25% by mass). PFA is considered as an alternative of cement due to its pozzolanic components. However, it was found that there was no enhancement in the compressive strength of the S/S mixtures after applying PFA. By comparing the chemical composition between cement and PFA, it was found that the PFA used in this study contained less calcium oxide, but higher silica and alumina contents (Table 2). In view of the essential elements for the formation of C-S-H or C-A-H gel (i.e. CaO, SiO_2 and Al_2O_3), apparently CaO is the limiting factor of the PFA used in this study. By increasing the utilization rate of marine mud and sediment from 70% to 80% by mass (with 15% of cement), the UCS at the 28th day reduced from 6.74 to 5.62 MPa and 4.02 to 3.82 MPa, for S/S treated marine mud and S/S treated sediment, respectively. As previously discussed, the role of cement in strength development of the S/S mixtures is much more significant than that of PFA due to its limited CaO content. In order to maintain the UCS of the S/S mixtures with increased amounts of marine mud and sediment, more cement is required instead of PFA. In consideration of waste and UCS maximization, 20% by mass of cement was applied on 75% marine mud and sediment for S/S treatment, respectively. The corresponding UCS at the 28th day was 8.32 MPa and 4.47 MPa, respectively. In view of the various engineering applications, on-site reuse of S/S treated waste as fill material is one of the most common ways to beneficially reuse hazardous waste. According to the U.S.EPA Handbook for Solidification/Stabilization of Hazardous Wastes (U.S.EPA 540/2-86/001), the cylinder strength of S/S samples should be at least 1 MPa. Assuming that the cube strength of S/S samples is 0.8 times higher than that of the cylinder, the maximum UCS of the designed S/S treated marine mud and sediment samples (i.e. 20%, 75% and 5% of cement, marine mud/sediment and PFA by mass) satisfied the mechanical requirement for on-site reuse as fill material. To provide a better understanding of the strength development of S/S treated contaminated marine mud and sediment, XRD analysis was performed after 28 days of sample curing and the results are given in Figure 4. For both S/S treated contaminated marine mud and sediment, C-S-H gel dominated the cement hydration product, while a small amount of ettringite was found in the S/S treated contaminated sediment. The result indicates that the strength development of the S/S mixtures was mainly contributed by C-S-H gel, but not C-A-H gel. The cement used consists of 3.8% of Al_2O_3, while 17.9% for PFA (Table 2). Since only 5%

by mass of PFA was added, the content of Al_2O_3 in the S/S mixtures was not enough to form C-A-H gel. Therefore, further study of the different types of PFA may enable improvement of waste utilization and UCS enhancement.

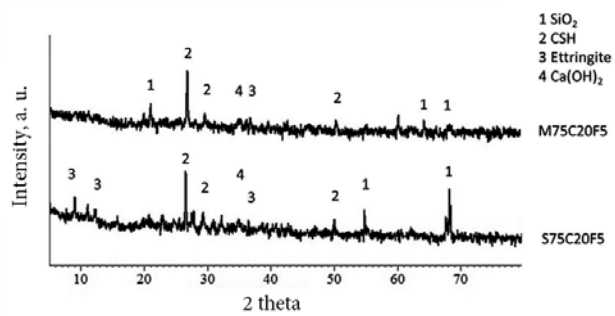

Fig. 4. XRD patterns of S/S treated marine mud and S/S treated sediment after 28 days of curing.

2.3. Comparison between marine mud and sediment on UCS after S/S treatment

Based on the UCS presented in Figure 3a and 3b, it can be concluded that S/S treated marine mud performs better than sediment. The maximum UCS obtained by S/S treated marine mud is almost double that of sediment (i.e. 8.32 MPa and 4.47 MPa, respectively). In view of the plastic limit of the marine mud and sediment (i.e. 30.1 and 23.2, respectively), the S/S treated marine mud should have a lower UCS than sediment as it was reported that material with a high plastic index tends to possess a low UCS for its S/S mixture (Saadeldin, Siddiqua 2013). It is believed that the high UCS of S/S treated marine mud is caused by its high maximum dry density (Table 2) and small particle size (Fig. 1). According to the result of standard Proctor compaction, the average maximum dry density achieved by

Table 4. TCLP results of S/S treated marine mud after 28 days of curing

Metals	TCLP limits of UTS[2] (mg/L)	TCLP leachate of marine mud and PFA mixture (mg/L)	M70C15F15 (mg/L)	M70C10F20 (mg/L)	M70C5F25 (mg/L)	M70F30 (mg/L)	M75C20F5 (mg/L)	M75C15F10 (mg/L)	M80C15F5 (mg/L)
Sb (mg/L)	1.15	0.146	N.D.[1]	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
As (mg/L)	5	0.025	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ba (mg/L)	21	0.172	0.89±0.07	0.86±0.04	0.97±0.08	0.65±0.01	0.31±0.01	0.70±0.03	0.64±0.06
Cd (mg/L)	0.11	0.018	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cr (mg/L)	0.6	0.037	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Pb (mg/L)	0.75	1.266	0.74±0.04	0.90±0.01	1.08±0.12	1.23±0.09	0.71±0.09	0.63±0.06	0.70±0.03
Hg (mg/L)	0.025	0.022	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ni (mg/L)	11	0.057	0.06±0.00	0.10±0.00	0.12±0.00	0.23±0.00	0.02±0.00	0.05±0.00	0.07±0.00
Zn (mg/L)	4.3	0.169	0.05±0.00	0.07±0.00	0.06±0.00	0.28±0.00	0.01±0.00	0.03±0.00	0.08±0.00
Metals	**TCLP requirement of UTS (%)**	**TCLP leachate of marine mud and PFA mixture (mg/L)**	**M70C15F15 (%)**	**M70C10F20 (%)**	**M70C5F25 (%)**	**M70F30 (%)**	**M75C20F5 (%)**	**M75C15F10 (%)**	**M80C15F5 (%)**
Co (%)[3]	90%	0.063	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cu (%)[3]	90%	0.010	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Mn (%)[3]	90%	2.961	95.5±1.6	90.8±3.0	90.2±9.1	93.0±0.1	99.8±0.1	88.4±1.9	55.3±7.1
Mo (%)[3]	90%	0.038	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sn (%)[3]	90%	0.004	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

[1] N.D. refers to non-detectable.
[2] UTS refers to Universal Treatment Standards (UTS 40 CFR 268.48).
[3] For Co, Cu, Mn, Mo and Sn, at least 90 percent reduction in mobility is required after Stabilization/Solidification treatment according to Universal Treatment Standards.

S/S treated marine mud is higher than that of sediment (i.e. 1711 and 1395 kg/m^3 for S/S treated marine mud and sediment with 20% by mass of cement, respectively). Since marine mud contains more clay portion and it is generally finer than sediment which can easily fill up the void spaces in cementitious material, its strength is thereby increased (Neville 1995).

Apart from their mechanical property, in order to beneficial reuse of contaminated marine mud and sediment, the S/S mixtures have to be minimized as suggested by the U.S.EPA. The TCLP results of S/S treated marine mud and sediment at the 28th day are given in Tables 4 and 5, respectively. The addition of cement to the contaminated marine mud and sediment resulting in a S/S matrix shows positive effects on decreasing the mobility of heavy metals. Usage of more than 15% cement in 70% and 75% contaminated marine mud and sediment presents reliable S/S effectiveness such that these TCLP results all met the TCLP regulatory standard. Usage of less than 15% cement in both 70% and 75% contaminated marine mud and sediment for S/S treatment were unable to effectively immobilize heavy metals, especially Pb and Mn. Before the S/S treatment, over hundreds mg/kg of Ba and Mn was found in the marine mud. The extent of contamination in the sediment was found to be more serious, with over hundreds 100 mg/kg of Ba, Cr, Pb, Zn and Mn, and even over two thousands mg/kg of Cu. However, with slightly more cement addition (i.e. 20% cement in both 75% contaminated marine mud and sediment), the extent of heavy metal leaching was well controlled within the universal treatment standard, especially for Cu in the sediment with 93% reduction in its leachability, not posing any adverse health and environmental impacts. Overall of the regulated heavy metals were immobilized.

Table 5. TCLP results of S/S treated sediment after 28 days of curing

Metals	TCLP limits of UTS[2] (mg/L)	TCLP leachate of sediment and PFA mixture (mg/L)	S70C15F15 (mg/L)	S70C10F20 (mg/L)	S70C5F25 (mg/L)	S70F30 (mg/L)	S75C20F5 (mg/L)	S75C15F10 (mg/L)	S80C15F5 (mg/L)
Sb (mg/L)	1.15	0.113	N.D.[1]	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
As (mg/L)	5	0.031	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ba (mg/L)	21	0.461	0.41±0.07	0.67±0.03	0.66±0.02	0.32±0.00	0.27±0.01	0.41±0.03	0.32±0.01
Cd (mg/L)	0.11	0.043	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cr (mg/L)	0.6	0.123	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Pb (mg/L)	0.75	0.984	0.69±0.08	0.92±0.09	0.95±0.00	0.99±0.01	0.57±0.03	0.92±0.09	0.97±0.01
Hg (mg/L)	0.025	0.033	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Ni (mg/L)	11	1.388	0.14±0.00	0.25±0.02	0.63±0.06	0.91±0.00	0.11±0.00	0.13±0.01	0.09±0.00
Zn (mg/L)	4.3	13.650	0.07±0.01	0.19±0.01	3.73±0.42	8.98±0.93	0.04±0.01	0.08±0.00	0.04±0.00
Metals	TCLP requirement of UTS (%)	TCLP leachate of marine mud and PFA mixture (mg/L)	S70C15F15 (%)	S70C10F20 (%)	S70C5F25 (%)	S70F30 (%)	S75C20F5 (%)	S75C15F10 (%)	S80C15F5 (%)
Co (%)[3]	90%	0.085	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Cu (%)[3]	90%	13.619	92.7±1.0	87.7±1.0	85.7±0.5	86.1±2.1	92.9±3.3	90.6±4.1	80.2±3.1
Mn (%)[3]	90%	7.954	95.3±5.0	85.3±3.3	57.3±3.5	43.5±1.4	99.9±0.0	92.8±4.0	96.6±1.2
Mo (%)[3]	90%	0.048	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Sn (%)[3]	90%	0.012	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

[1] N.D. refers to non-detectable.

[2] UTS refers to Universal Treatment Standards (UTS 40 CFR 268.48).

[3] For Co, Cu, Mn, Mo and Sn, at least 90 percent reduction in mobility is required after Stabilization/Solidification treatment according to Universal Treatment Standards.

Conclusions

The present study investigated the sustainable and economic management of contaminated marine mud and sediment by mixing them with abandoned PFA in S/S treatment. Based on the result in this study, conclusions are drawn as follows:

1. By increasing the amount of cement from 5% to 15% by mass, the optimal water content of the corresponding S/S treated mixture (with 70% of marine mud and sediment, individually) decreases, but the maximum dry densities increase. However, the increases of either marine mud or sediment in the S/S mixtures decrease their maximum dry densities.
2. The UCS of the S/S treated marine mud and sediment using cement and PFA as binders reached up to 8.32 MPa and 4.47 MPa, respectively, at the curing time of 28 days. The UCS achieved enables engineering applications with a high strength requirement. As the most common way to reuse waste, the S/S treated marine mud and sediment qualify as fill material which generally require 1 MPa of UCS.
3. With 15% by mass of cement, most of the heavy metals were immobilized to acceptable levels, except Pb and Mn. However, by increasing the amount of cement to 20% with 5% of PFA, according to the U.S.EPA, all regulated heavy metals, including Sb, As, Ba, Cd, Cr, Pb, Hg, Ni, Zn, Co, Cu, Mn, Mo and Sn, were successfully immobilized.
4. The results of XRD proved that the formation of CSH gel in the S/S treated mud and sediment is responsible for the strength development and heavy metal immobilization.
5. For the purposes of waste maximization and enhancing the mechanical property of the S/S mixtures, mixing 75% by mass of either contaminated marine mud or sediment with 20% and 5% of cement and PFA, respectively, were found to be the optimal mix designs to provide a sustainable green remediation alternative in the future.

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