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Development of controlled low-strength material derived from beneficial reuse of bottom ash and sediment for green construction

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HIGHLIGHTS

- Municipal solid waste bottom ash and dredged sediment can be used to produce CLSM.
- The utilization of wastes was up to 80% by mass for the studied CLSMs.
- The compressive strength of CLSM made with bottom ash is higher than with sediment.
- The CLSMs are classified as non-hazardous according to the U.S.EPA regulations.
- Based on the properties, CLSMs are suitable for various construction applications.

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ABSTRACT

Controlled low-strength material (CLSM) was newly designed using municipal solid waste bottom ash and dredged sediment as raw materials. Up to 80% of waste utilization by mass was achieved with all requirements fulfilled as general CLSM. The compressive strength of CLSMs made with bottom ash is generally higher than that of sediment. The formation of C–S–H gel contributes to the strength development and heavy metal immobilization from wastes. The heavy metal concentrations in the TCLP leachates of CLSM are far below the U.S.EPA regulatory standards, and the CLSMs are suitable for a wide range of construction applications.

1. Introduction

With continued population growth and considering the scarcity of land, solid waste disposal and on-demand infrastructure have become the major challenges in Hong Kong. Nowadays, Hong Kong relies solely on landfills for solid waste disposal, and about 9000 tonnes of municipal solid waste (MSW) are discarded every day [1]. In response to this problem, the Hong Kong Environmental Protection Department has proposed to implement an Integrated Waste Management Facility, with the advanced incineration facility as the core technology [2]. As such, MSW bottom ash will be one of the by-products generated during incineration and should be thoroughly considered for sustainable treatment. Meanwhile, in the course of on-demand construction, reclamation and infrastructure development, dredging is indispensable and gives rise to the generation of considerable amount of sediment. The dredged sediment is regulated by the Hong Kong Special Administrative Region Government and is designated for marine dumping or landfill disposal. However, in view of the possible marine contamination and scarcity of land for landfill, beneficial reuse of dredged sediment is encouraged as a sustainable alternative. Because of the tense situation of waste management, MSW bottom ash and dredged sediment commonly identified as waste should be reused in a tenable way for the continuing development of Hong Kong.

In order to reuse MSW bottom ash and dredged sediment beneficially, both wastes can be substituted for the fine aggregates as the raw materials of controlled low-strength material (CLSM). According to American Concrete Institute (ACI) [3], CLSM is not considered to be a type of low-strength concrete, but is defined as a cementitious self-compacted material, with a compressive strength of 8.3 MPa or less, which primarily used for backfill in lieu

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of conventional compacted fill. Over the past decade, it has been a burgeoning trend for various applications of CLSM due to its advantages of easy distribution in complex sites [3], no compaction and vibration required [3], and low in-place costs [4]. Although conventional CLSM is prepared by mixing standard materials such as fly ash and fine aggregate with water and Portland cement, more economical nonstandard materials are also accepted and encouraged as long as the requirements of the intended applications are fulfilled. With the flexibility upon the selection of raw material, blast furnace slag [5], cement kiln dust [5], crushed scrap-tire rubber [6] and oyster shell [7] have been individually investigated for CLSM in different countries to mitigate environmental problems caused by local wastes. Nevertheless, CLSM made of combined wastes has not been widely studied due to complicated interactions between cement and various wastes. In particular, no CLSM application regarding the combination of MSW bottom ash and dredged sediment has been studied. Therefore, utilizing both wastes for CLSM not only sheds light on the future of waste management in Hong Kong, but also provides an insight into how distinct wastes influence the properties of CLSM.

The design of nonstandard CLSM is waste specific and primarily depends on the chemical composition and physical property of the particular waste. It has been arduous to contrive CLSMs with high extent of waste utilization. With up to 15% by mass of cement replaced by blast furnace slag and cement kiln dust, all CLSM requirements, based on fresh and hardened properties, were fulfilled according to ACI [5]. However, with such replacement, the stiffening time notably increased and thereby limited the field applications of CLSM for road and footpath. On the other hand, the required flowability of 200 mm for CLSM was not reached, albeit the usage of crushed scrap-tire rubber was maximized to about 33% by mass [6]. Furthermore, although 5–20% by mass of oyster shell has been investigated as a replacement of fine aggregate, only 5% of such replacement was recommended due to the improper compressive strength development with poor pore-filling effect of CLSMs made with higher percentages of oyster shell [7]. For feasible engineering applications, increasing the utilization rate of wastes is necessary to promote the beneficial reuse of waste. Therefore, the objectives of this study were to maximize the usage of MSW bottom ash and dredged sediment for CLSM by varying the mix proportion of CLSM, and to assess the potential of the studied CLSMs for different construction purposes by evaluating their physical and mechanical properties.

2. Materials and methods

2.1. Materials preparation and characteristics

The cement used was Hong Kong manufactured ordinary Portland cement which is equivalent to American Society for Testing Material (ASTM) type I cement. The dredged sediment was collected from 10 to 100 cm below the seawater/sediment interface at a contaminated site in Hong Kong. The sediment was then kept in a sealed plastic bag, placed in a covered bucket and stored in a cold room at 4 °C to minimize any possible deterioration. In addition, since there is currently no incineration facility in Hong Kong, the studied bottom ash resulting from the combustion of MSW was collected from an incineration facility in the southern part of Mainland China. In order to mitigate the odor problem in the course of incineration, the MSW bottom ash has been washed with water in the incineration plant. The washing process enables significant removal of soluble salt from the bottom ash [8] which, as a result, enhances the reusability of bottom ash for engineering purposes. Both the dredged sediment and MSW bottom ash were air dried for 14 days prior to the preparation of CLSM, then passed through a 10 mm sieve to eliminate oversize waste material. The particle size distributions of the dredged sediment and MSW bottom ash are given in Fig. 1. The particle sizes of both wastes fall within the range of medium fine aggregate as given in British Standards (BS 882:1992). Potable water was used for the preparation of the CLSM samples in this study.

An X-ray fluorescence (XRF) spectrometry (JEOL JSX-3201Z) was used to determine the chemical composition of the raw materials. The chemical compositions shown in Table 1 suggest that SiO_2 and Al_2O_3 dominate in the sediment, whereas

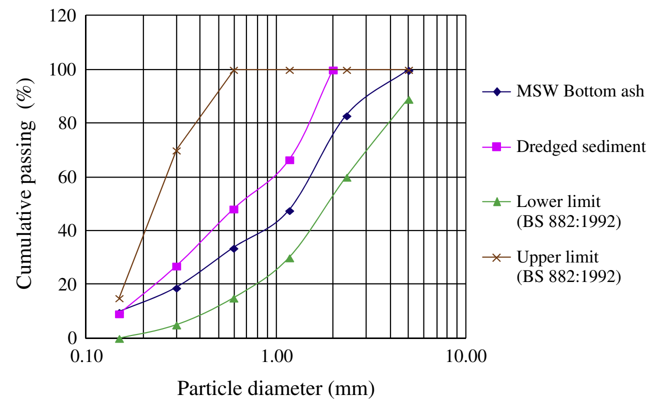

Fig. 1. Particle size distribution of MSW bottom ash and dredged sediment.

Table 1
Chemical compositions and physical properties of sediment, bottom ash and ordinary Portland cement.

	Sediment	Bottom ash	Cement
Chemical compositions (weight%)			
CaO	3.30	50.85	65.75
SiO_2	52.45	14.05	19.40
Al_2O_3	23.05	5.90	3.90
Fe_2O_3	5.70	5.80	3.40
SO_3	9.55	8.90	5.30
MgO	1.80	2.55	1.25
K_2O	2.95	1.70	–
P_2O_5	–	4.50	–
TiO_2	0.50	1.45	–
ZnO	0.10	1.00	–
Loss of ignition	0.60	3.30	1.00
Physical properties			
Plastic limit (%)	31.2	–	–
Liquid limit (%)	58.0	–	–
Plasticity index	26.8	–	–
Water absorption (%)	24.2	15.2	–
Heavy metal content (mg/kg by dry weight)			
As	N.D.	N.D.	–
Ag	N.D.	N.D.	
Ba	2650.7 ± 145.9	1134.0 ± 138.6	–
Cd	N.D.	N.D.	–
Cr	261.2 ± 21.6	140.0 ± 39.6	–
Pb	220.7 ± 29.6	614.0 ± 108.0	–
Hg	N.D.	N.D.	–
Se	N.D.	N.D.	–
Organic content			
TOC (%)	2.37 ± 0.01	0.07 ± 0.01	–

Note: N.D. refers to non-detectable.

CaO and SiO_2 dominate in the bottom ash and in ordinary Portland cement. The physical properties of bottom ash and sediment are also shown in Table 1. The results show that the plastic limit, liquid limit and plastic index of the sediment are 31.2%, 58.0% and 26.8, respectively. In addition, both the sediment and bottom ash are able to absorb water with capacities of 24.2% and 15.2%, respectively. Considering the nature of the wastes, the contamination levels of the sediment and bottom ash are included in Table 1. The heavy metal content in the sediment and bottom ash were determined by inductively coupled plasma atomic emission spectrometry (ICP-AES) (Optima 3000XL, Perkin Elmer) after complete acid digestion of the wastes. In order to determine if a waste is hazardous, eight heavy metals (i.e., As, Ag, Ba, Cd, Cr, Pb, Hg and Se) were studied according to the U.S.EPA regulatory standards. Only Ba, Cr and Pb were found in the sediment and bottom ash, while the concentrations of Ba in both wastes are the highest among other heavy metals. Furthermore, their organic content was measured by a solid module total organic carbon (TOC) analyzer. The TOC contents of the sediment and bottom ash are 2.37% and 0.07%, respectively. An X-ray diffractometer (Philips PW 1830 diffractometer with Cu Kα radiation) was used to determine the mineralogy of the sediment and bottom ash. The XRD patterns were obtained with Cu Kα radiation operating at 40 kV and 40 mA, and are shown in Fig. 2. The XRD pattern shown in Fig. 2a