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Utilization of incineration bottom ash amended soft marine clay in land reclamation

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ABSTRACT

Land reclamation is one of the solutions for enlarging territories, which requires a considerable amount of filling materials. Singapore is now short of conventional filling materials such as sand and gravel. Soft marine clay (MC) is a common geological material in Singapore. However, it is not preferred as a filling material for land reclamation due to its high water content and high compressibility. Meanwhile, incineration bottom ash (IBA) from the waste-to-energy plant is an aggregate-like material, which is currently landfilled in Singapore due to heavy metals. The combination of MC and IBA (IBA-MC) may complement each other's limitations. Therefore, this study aimed to explore the utilization of IBA-MC as a potential filling material in land reclamation. The stability of IBA-MC in seawater was studied because it may alter when IBA-MC encounters seawater in the field. The appearance, unconfined compressive strength, water content, mineral compositions, and microstructure of IBA-MC before and after soaking in seawater were investigated. The results showed that after soaking in seawater, IBA-MC tended to develop superficial cracks and had significantly lower strength than those cured in the sealed bag. The mineralogy and microstructure of IBA-MC suggested that the formation and growth of ettringite were responsible for the instability of IBA-MC soaked in seawater.

Keywords: Incineration bottom ash, marine clay, stability, seawater

1 INTRODUCTION

The growing economy and rapid urbanization have accelerated the generation of municipal solid wastes (MSW) in Singapore. Incineration is an effective method to deal with the increasing amount of MSW because it can largely reduce the mass and volume of MSW by 70-90% (Lam et al., 2010; Dou et al., 2017). However, MSW incineration also produces incineration bottom ash (IBA) (Wiles, 1996; Chandler et al.,1997), which is currently landfilled in Singapore (Bai and Sutanto, 2002). Since IBA, especially fine fraction of IBA, contains a certain amount of heavy metals, it may pose a threat to the environment and human beings without proper treatment (Tang et al., 2017; Loginova et al., 2019; Zhu et al., 2019).

The lack of space for waste disposal is another arising problem in Singapore, which makes the land-shortage problem even worse. Land reclamation is one of the solutions for enlarging territories, which requires a huge amount of filling materials. However, Singapore is now short of conventional filling materials such as sand and gravel (Chu and Guo, 2015). Marine clay (MC) is a common geological material in Singapore, but it is not preferred as a filling material due to its high water content and high compressibility (Chan et al. 2011; Bo et al., 2015; Chu and Guo, 2015; Lam et al., 2018). Nevertheless, the combination of IBA and MC (IBA-MC) may complement each other's limitations, e.g., the leaching of heavy metals from IBA and poor engineering properties of MC. Specifically, the negative-charged surface of marine clay enables it to absorb heavy metals from IBA (Quek et al., 2016; Guo et al., 2017); the addition of IBA lowers the water content of the MC, which results in a better compactability and strength performance (Sun and Yi, 2022). Therefore, reusing IBA-MC as a filling material for land reclamation is beneficial, because it can not only reduce the amount of solid wastes but also alleviate the reliance of landfill and natural aggregates.

Based on above considerations, this study aimed to explore the utilization of IBA-MC as a potential filling material in land reclamation. The stability of IBA-MC in seawater was studied because it may alter when IBA-MC encounters seawater in the field. The appearance, unconfined compressive strength, water content, mineral compositions, and microstructure of IBA-MC before and after soaking in seawater were investigated.

2 MATERIALS AND METHODS

2.1 Materials

IBA was collected from a local incineration plant. The fine IBA with a size less than 1.18 mm was used in this study. The MC with a natural water content of 50% was excavated from a local construction site. The chemical compositions of IBA and MC were obtained by using X-ray fluorescence (XRF), as listed in Table 1. IBA was mainly composed of CaO, SiO_2, and Al_2O_3 while MC mainly consisted of SiO_2 and Al_2O_3. Artificial seawater with a salinity of 3 wt% was formulated by dissolving sea salt in distilled water to simulate the seawater environment in Singapore (Gin et al., 2000; Kumar et al., 2021). The chemical compositions of sea salt were also listed in Table 1. The major composition of sea salt was NaCl. The contents of Mg-containing compounds (13.1%) and sulfates (16.1%) were also high.

Table 1. *XRF results of IBA and MC (% of mass)*

Chemical composition (%)	CaO	SiO_2	SO_3	Fe_2O_3	Al_2O_3	MgO	Na_2O	Cl	Others
IBA	34.6	25.7	12.9	10.2	5.7	1.7	1.3	1.7	5.7
MC	1.8	64.6	0.8	5.8	20.4	1.5	0.8	0.6	3.7
Sea salt	2.7	-	16.1	-	-	13.7	19.9	44.4	3

2.2 Experiment methods

MC with natural water content was firstly mixed with fine IBA at IBA/MC ratio of 5/5 in terms of dry mass for 20 minutes. The mixture was compacted in a cylindrical mold with 25 mm diameter and 50 mm height using a mini compactor reported by Li et al. (2019). The hammer weighed 2.5 kg, and the drop height was 20 cm. Each specimen was prepared with three layers and one compaction blow per layer, and the compaction energy per unit volume was 598.93 kJ/m^3, close to that of the ASTM standard proctor compaction test (ASTM, 2021). Two batches of specimens were prepared. One batch was cured in a sealed bag for 28 days, the other was cured in a sealed bag for 7 days and then soaked in seawater for 21 days.

After curing, visual examination of specimens was performed. The unconfined compressive strength (UCS) test was then conducted following the ASTM (2017) standard. The specimens after failure were dried in a freezing dryer and then their water contents were determined. The dried specimens were crushed for mineralogy and microstructure tests (particle size less than 0.75 mm). X-ray diffraction (XRD) was used to analyze the mineralogy. Scanning electron microscopy (SEM) was conducted on a JEOL JSM-7600F machine.

3 GUIDELINES ON REFERENCES

3.1 Visual examination

As shown in Figs. 1a and 1b, MC with natural water was similar to paste while fine IBA was similar to fine sand. When adding fine IBA into MC, MC lost its liquidity and became granular (Fig. 1c). MC was too soft to be compacted and dry IBA was not able to bind together without the presence of MC. Nevertheless, IBA-MC with IBA/MC ratio of 5/5 was compacted into intact cylindrical samples, as shown in Fig. 2. This indicated that the addition of IBA made MC compactable. Local pits can be observed on the surface of IBA-MC cured in the sealed bag, which may result from insufficient compaction.

However, after exposure to seawater, expansion cracks were abundantly found on the surface of all IBA-MC specimens (Fig. 3). The transverse cracks first developed at the interfaces between two compaction layers and longitudinal cracks then propagated from one interface to another. These cracks may be resulted from excessive water adsorption of IBA-MC in seawater, suggesting the instability of IBA-MC in seawater.

(a) (b) (c)

Figure 1. *Images of (a) MC, (b) fine IBA, and (c) IBA-MC with IBA/MC ratio of 5/5*

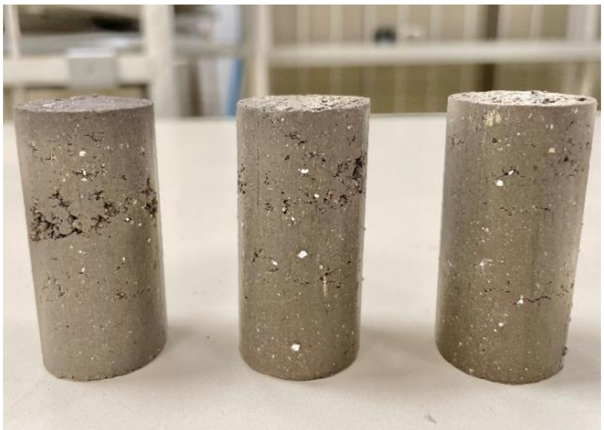


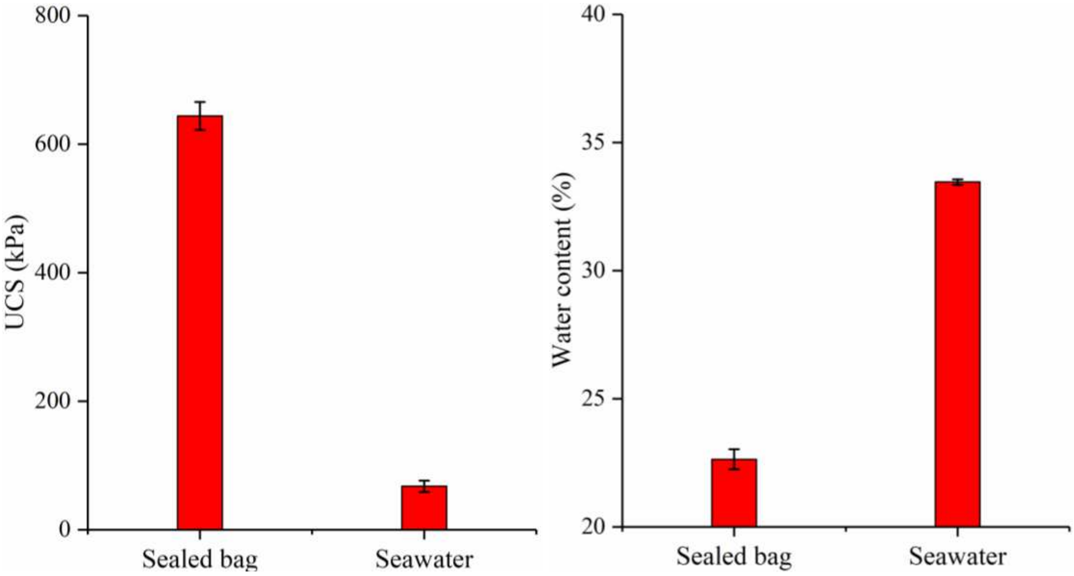
Figure 2. *Compacted IBA-MC specimens with IBA/MC ratio of 5/5 cured in the sealed bag*

Figure 3. *Compacted specimens with IBA/MC ratio of 5/5 soaked in seawater*

3.2 UCS and water content

The UCS and water content of IBA-MC under different curing conditions are plotted in Fig. 4. IBA-MC cured in the sealed bag had a 28-day UCS of 644 kPa (Fig. 4a). It is about three times the 3-day UCS of IBA-MC (213 kPa) (Sun and Yi, 2022). This may be because as curing period increased, the hydration and pozzolanic reactions in IBA-MC contributed to the strength improvement of IBA-MC. However, after exposure to seawater, IBA-MC had a much lower UCS (68 kPa) than those solely cured in the sealed bag, which was consistent with the appearance of the specimens.

The water content of IBA-MC (Fig. 4b) cured in the sealed bag for 28 days was around 23%. It is lower than the water content of IBA-MC cured for 3 days (around 25%) (Sun and Yi, 2022). This is because the hydration and pozzolanic reactions in IBA consumed water. However, after soaking in seawater, the water content increased significantly compared with IBA-MC cured in the sealed bag due to water adsorption, specifically, ~50% higher than those cured in the sealed bag.



(a) (b)

Figure 4. *Variations of (a) UCS and (b) water content of IBA-MC under different curing conditions*

3.3 XRD

The XRD results for IBA-MC under different curing conditions are shown in Fig. 5. Anhydrite, calcite, ettringite, illite, kaolinite, montmorillonite, portlandite, and quartz were identified in IBA-MC cured in the sealed bag. Among these minerals, anhydrite ($CaSO_4$), calcite (Calcite), ettringite ($Ca_6[Al(OH)_6]_2(SO_4)_3 \cdot 26H_2O$), quicklime (CaO), portlandite ($Ca(OH)_2$), and quartz (SiO_2) are usually found in IBA (Sun and Yi, 2020). Among these minerals, ettringite is a highly expansive mineral, especially when contacted with water. Ettringite is a weathering product in IBA, which was generated after quenching process (Piantone et al., 2004; Alam et al., 2019). For IBA-MC exposed to seawater, the peak intensity of ettringite was higher than that of IBA-MC cured in the sealed bag. This may be because ettringite was better formed in the presence of water and additional SO_4^{2-} from seawater (Nair and Little, 2009).

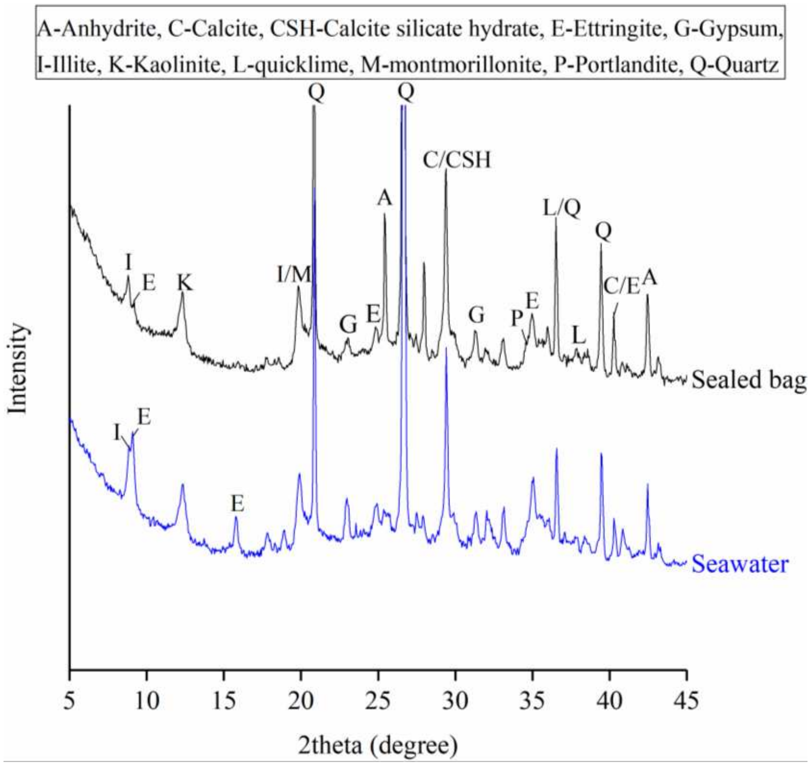
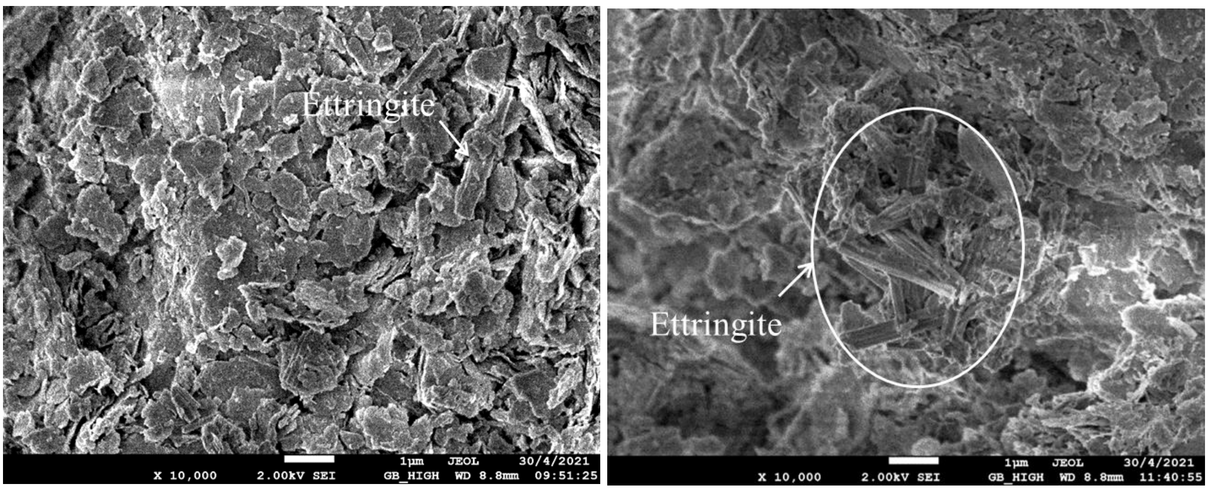


Figure 5. *XRD patterns for IBA-MC under different curing conditions*

3.4 SEM

Typical SEM images of IBA-MC specimens cured in the sealed bag, and those soaked in seawater are shown in Fig. 6. For IBA-MC cured in the sealed bag (Fig. 6a), the needle-like ettringite and platy clay particles were both detected. After exposed to seawater, more ettringite was observed in IBA-MC (Fig. 6b). The formation and growth of ettringite may mainly be affected by the availability of water and sulfates (Mehta and Hu, 1978; Rajasekaran et al., 2005; Nair and Little, 2009). This may be one of the reasons for the instability of IBA-MC in seawater.



(a) (b)

Figure 6. *SEM images of IBA-MC (a) in the sealed bag, and (b) soaked in seawater*

4 CONCLUSIONS

The study investigated the instability of IBA-MC in seawater. After exposure to seawater, abundant cracks were generated on the surface of IBA-MC. The UCS of IBA-MC soaked in seawater was much lower than that of IBA-MC cured in the sealed bag, while the trend for water content was opposite. Through mineralogy and microstructure tests, it was found that the formation and growth of ettringite were responsible for the instability of IBA-MC soaked in seawater. In general, IBA-MC was not applicable to be used as a filling material in land reclamation under the seawater scenario. Stabilization/solidification of IBA-MC with binders may be a possible solution.

5 ACKNOWLEDGEMENTS

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