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Characteristics of pervious concrete using incineration bottom ash in place of sandstone graded material

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HIGHLIGHTS

- The incineration bottom ash replaced the aggregate of pervious concrete.
- Bottom ash (#4) and water-cement ratio 0.55 has maximum compressive strength.
- Compressive strength of permeable bricks is higher than traditional red bricks.
- Permeability coefficients reach requirement of permeable pavement (10^{-2} cm/s).
- It is recommended for general bicycle ways, sidewalks or landscaping.

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ABSTRACT

The effects of replacing sandstone with incineration bottom ash and different water-to-cement ratios and aggregate sizes in pervious concrete bricks preparation were investigated. Among the various permeable brick specimens, the compressive strengths of 11 different mix proportions exceeded that of traditional red bricks (by 14 MPa), and was maximum for the specimen with bottom ash aggregate size #4 and a water-to-cement ratio 0.55. The permeability coefficients, although smaller than that of general pervious concrete, were within general permeable pavement specifications (10^{-2} cm/s). Therefore, it is recommended for general bicycle ways, sidewalks, and landscaping, not roads with high traffic flow.

1. Introduction

Taiwan produces about 7.5 million MT of municipal solid wastes (MSW) annually. Since 2008, apart from resource recovery, about 97% of the waste has been incinerated. At present, there are 24 large incineration plants in Taiwan, which treat more than 6 million MT of waste annually, and produce about 1 million MT of incineration bottom ash and 0.3 million MT of fly ash [1]. In the past, the incineration bottom ash was primarily treated by sanitary landfilling; however, due to growing resource deficiencies and the introduction of the "zero waste" concept in Taiwan in 2007, the reuse of incineration bottom ash has received gradual attention; it has since been used in paving road and backfill materials in large quantities. The incineration bottom ash recycling ratio was 80% in 2011, with plans to increase year by year up to 100%.

Since Taiwan has exploited sandstone for a long time, natural sandstone has become a limited resource. It is possible to combine natural sandstone with incineration bottom ash for its application in road, brick, and pavement construction. This enables reduction in the quantity of incineration bottom ash buried in landfills, while reducing the exploitation and consumption of natural sandstone. Therefore, replacing natural sandstone with incineration bottom ash in roads, aggregates, concrete, and soil amendments is a means of recycling this bottom ash.

At present, various engineering applications require the use of concrete, due to the strength requirements of the facilities being built. Normal concrete can guarantee a certain level of strength for buildings and facilities, but it is a challenge to effectively conserve water since the water permeability and pervious area of the ground are reduced. This reduction results in heat islands in cities, and is adverse to the ecological environment. Therefore, pervious concrete can be used as an alternate material. Pervious

Abbreviations: MSW, municipal solid wastes; TCLP, Toxicity Characteristic Leaching Procedure.

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concrete is a porous, lightweight, no-fines concrete that is formed by point contact between the short cement slurry covering the outer layer of aggregate grains and the aggregate grains themselves. Generally, the porosity of this concrete type is 11–35% [2–4], and the structures have good water permeability. The permeability coefficient is usually between 1.4 and 12.3 mm/s; however, the high porosity reduces the strength of pervious concrete, resulting in typical compressive strengths between 3.5 and 28 MPa [4]. The high porosity of pervious concrete can increase the water permeability, meanwhile the rainwater penetrating into the earth's surface is increased, thereby maintaining a higher level of groundwater [5]. Additionally, the heat and moisture exchange between the earth's surface and the air can be enhanced, reducing the earth's temperature, which is favorable for relieving the heat island phenomenon [6]. Therefore, pervious concrete has economic and environmental benefits.

Pervious concrete consists of cement, mixing water, and aggregate. The ratio of mixing water (water-to-cement ratio, w/c) and aggregate size have a significant effect on the strength, water permeability, and production convenience of pervious concrete. The mixing water and aggregate are described below:

1.1. Mixing water

The quality requirements of mixing water for pervious concrete are similar to those of traditional concrete; it shall not contain oil or fat, acids, chloride, or organic impurities since these materials often have adverse effect on concrete. Pervious concrete materials are very sensitive to water consumption. The solidification time and pore structure of concrete is affected by the water-to-cement ratio. Hu et al. [7] investigated the effects of cement fineness and the water-to-cement ratio on the heat of hydration and calorimetry set time. The results showed that the hydration heat and set time generated from cement with higher fineness were larger and faster, respectively, compared with those of coarser cements in early ages. Lower water-to-cement ratios resulted in a higher heat of hydration rate at earlier hours and a reduced heat of hydration in subsequent hours. Chen and Wu [8] studied the effect of water-to-cement ratio and age on the pore structure of cement mortar, and found that porosity and hydration degree of mortar increased with increasing water-to-cement ratio, and the total porosity of the mortar decreased as the curing period increased. Additionally, Haach et al. [9] found that the workability increased as the water-to-cement ratio increased. Therefore, a good water-to-cement ratio design results in good workability; the cement slurry covers the aggregate grains perfectly and the hardened pervious concrete shows excellent mechanical strength. If the water-to-cement ratio is too high, then the pervious concrete is unlikely to have high mechanical strength. In addition, if the slurry flowability is too high, it is unlikely to cover the aggregate, and instead will flow downward under the effect of gravity, forming vertical flow. When the slurry flows vertically to the bottom of pervious concrete and hardens, the water permeability is lost, the aggregate grains cannot be covered with slurry uniformly due to the vertical flow of slurry, and the mechanical strength is compromised [9]. Additionally, Nikbin et al. [10] also studied the effects of water-to-cement ratio and powder content on mechanical properties and found that increasing the amount of limestone powder increased the compressive and tensile strengths. When using a lower w/c, additional limestone powder increased the compressive strength more noticeably. Water-to-cement ratio had a greater effect on the tensile and compressive strengths than it did on the E-modulus. When the water-to-cement ratio was too low, the amount of water required for cement hydration was insufficient, so the concrete microstructure had microcracks, which adversely affected the overall concrete strength and durability.

1.2. Aggregate

The aggregate comprises the main structure of pervious concrete, and is the main component that provides strength. The aggregates include conventional aggregate (gravel, cobblestone, sand) or special aggregate (lightweight aggregate, recycled construction materials, and so on). The aggregate grain gradation is the important factor determining overall water permeability and mechanical strength. Pores resulting from stacking of large sized aggregates must be larger than the pores resulting from stacking of small sized aggregates. The larger the interconnected pore size, the better is the water permeability. Therefore, in order to guarantee good water permeability and mechanical strength of pervious concrete, the coarse aggregate typically uses a single size grading of either 10–20 mm, or 5–10 mm. In addition, the needle-shaped and flaky grains of the crushed rock aggregates shall be reduced as much possible, and the aggregate silt content should ideally be no greater than 1%.

Pervious concrete can be used in sidewalks, parking lots, and light traffic lanes. It conserves water, and enlarges the water retention area of the soil, thereby reducing the heat island effect. In recent years, economic growth in many countries has caused an increase in demand for high-grade gravel ingredients. The river sand resources in Taiwan have been nearly exhausted, resulting in an aggregate source shortage. This has created an urgency to find an alternative source. Supporting Taiwan's implementation of the "zero waste" policy, incineration bottom ash can be used to partially replace natural sandstone in the construction of road, brick, and pavement. The reuse of bottom ash both reduces the amount of incineration bottom ash into landfills and decreases exploitation and consumption of natural sandstone. This has a considerable positive impact on sustainable development. However, the incineration bottom ash composition varies largely, and does not have as specific a composition as natural sandstone. If bottom ash is to become a component of pervious concrete bricks, the material characteristics need to be studied. Therefore, the study investigates the effects of replacing conventional pervious concrete aggregate with incineration bottom ash using different water-to-cement ratios and aggregate sizes to make bricks. Interconnected porosity tests, unit weight measurements, water absorption measurements, and water permeability tests are used to elucidate the basic properties of bottom ash pervious concrete. Furthermore, compressive strength tests and direct shear tests are used to assess the potential of using bottom ash pervious concrete bricks in pavement. The results of this study may serve as a reference for the reuse of incineration bottom ash in pervious concrete bricks.

2. Materials and methods

2.1. Material characterization

Bottom ash is a porous lightweight material, spherically or irregularly shaped, and it is comprised of molten particles, ferrous metal, nonferrous metal, tile fragments, potsherds, and glass fragments [11,12]. The incinerated ash has no fixed proportion of its chemical components, including Si, Ca, Al, Fe, Na, K, Mg, and trace amounts of Mn, Zn, Ti, Ba, Cd, Cr, Pb, Hg, I, Sr, Br and Mo [13,14]. The oxidation that occurs during incineration causes most of the elements to exist in their oxidized state. The major oxides in the incineration bottom ash are SiO_2, CaO, Fe_2O_3 and Al_2O_3 [15,16]. The specific gravity of small particles in incineration bottom ash is 1.8–2.0, and the specific gravity of large or rough components is 1.8–2.4. Bottom ash is a lightweight material compared to natural sandstone having a specific gravity of 2.6–2.8.

The composition of incineration bottom ash is complex and heterogeneous, and has chemical characteristics different from natural materials. For example, the pH of fresh bottom ash is relatively high at 11.1–12.6 [17,18]. Moreover, its salt content is high, and includes chloride and sulfate [19]. Lastly, it contains heavy metals, which could potentially cause environmental problems during reutilization. Therefore, it must be inspected and pass validation criteria before it is used [17,20].