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Engineering and environmental properties of foamed recycled glass as a lightweight engineering material

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A B S T R A C T

Lightweight fill materials, including foamed aggregates are increasingly being used in civil engineering and infrastructure applications. This research assessed the engineering properties of foamed recycled glass through a laboratory evaluation to ascertain this novel recycled material as a lightweight fill material in civil engineering applications. The engineering assessment included particle size distribution, particle density, water absorption, minimum and maximum dry densities with a vibrating table, California Bearing Ratio (CBR) and Los Angeles (LA) abrasion tests. Shear strength properties of the recycled foamed glass were studied through large-scale direct shear tests. This recycled foamed glass is classified as a gap graded material. Due to high porosity, the coarse particles of this material have high water absorption of 60% and low particle density of 4.54 kN/m^3, which is much lower than that of water. The minimum and maximum dry densities of this material are very low of 1.67 and 2.84 kN/m^3, respectively. The LA abrasion of foamed recycled glass is lower than the requirement for pavement base/subbase material, being of 94%. The shear resistance at small shear displacement is thus low as shown by low CBR value of 9–12%. However, the shear resistance at large shear displacement is high as shown by high cohesion and friction angle of 23.36 kPa and 54.7°, respectively. The environmental assessment included pH value, organic content, total and leachate concentration of the material for a range of contaminant constituents. All the hazardous concentrations in the leachate are far lower than 100 times of those of the drinking water standards, indicating the foamed recycled glass as a non-hazardous material. The energy savings assessment demonstrates that the use of foamed recycled glass as engineering material has much lower energy consumption relative to a conventional aggregate-cement material in construction projects. The lightweight properties of the foamed recycled glass coupled with its satisfactory engineering and environmental results, particularly its high friction angle, indicates that the material is ideal for usage as a lightweight construction material in engineering applications such as non-structural fills in embankments, retaining wall backfill and pipe bedding.

1. Introduction

Lightweight fill materials are increasingly being used in civil engineering applications such as backfill, slope stability, embankment fills, pavements and pipe bedding (Horpibulsuk et al., 2014). The applications of lightweight fill materials are fairly broad but the main intent of this alternative construction material is to significantly reduce the weight of fills, thereby mitigating excessive settlements and bearing failures. This can subsequently result in more economic designs for structures such as retaining walls. Various lightweight fill materials have been developed in recent years for

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usage in various civil engineering applications and these particularly include expanded polystyrene (Athanasopoulos-Zekkos et al., 2012; Deng and Xiao, 2010; Ertugrul and Trandafir, 2011; Lin et al., 2010; Trandafir and Erickson, 2012; Zou et al., 2013), lightweight cellular cemented clays (Horpibulsuk et al., 2014), tires (Cecich et al., 1996; Hodgson et al., 2012; Moghaddas Tafreshi et al., 2012; Nakhaei et al., 2012) and lightweight concrete (Chindaprasirt and Rattanasak, 2011; Wang et al., 2012; Wang and Tang, 2012). With the aim of increase in usage of recycled foamed glass for a cleaner production of lightweight materials as well as a greener and more sustainable environment, this study investigates suitability of recycled foam glass for various engineering applications.

In recent years, there has been an environmental push worldwide to continually seek new reuse applications for various waste materials inclusive of demolition wastes (Arulrajah et al., 2013b; Rahman et al., 2014a), municipal solid wastes (Reddy et al., 2009; Zekkos et al., 2006), calcium carbide residue (Phetchuay et al., 2014) and other commercial and industrial wastes (Disfani et al., 2014; Du et al., 2014; Grubb et al., 2006; Landris, 2007; Wartman et al., 2004). Industrial waste materials are increasingly being implemented in various projects for use as an aggregate in applications such as pavements (Akbulut and Gurer, 2007; Hoyos et al., 2011; Puppala et al., 2011; Taha et al., 2002) and road embankments (Puppala et al., 2011; Wartman et al., 2004).

Municipal recycled glass is obtained mostly from curbside collection and comprises mainly packaging containers for food and drinks as well as sheet glass or glass from demolition activities. While the glass recycling industry aims to process waste glass back into bottle making industry by color sorting, this is not always possible because a large amount of waste glass delivered to the recycling industry is broken into small pieces during handling and collecting, which makes it difficult to color sort waste glass. Sorting facilities in Australia for example can only color sort recycled glass particles that are larger than 10 mm in particle size and smaller sized glass particles, enter the waste stream (Arulrajah et al., 2014a). Recycled waste glass has been researched in recent years and found to be a viable construction material for embankments and pavement subbases (Arulrajah et al., 2014b; Grubb et al., 2006; Wartman et al., 2004), footpath bases (Arulrajah et al., 2013a) as well as in the manufacture of fibers for problematic soil treatment (Ahmad et al., 2012; Mujah et al., 2013).

In recent years, there has been interest in the development of foamed materials with the usage of waste materials in engineering applications (Jana et al., 2013; Wang et al., 2012, 2013a). Foamed glass has been developed particularly for usage in various structural and insulating applications (Bumanis et al., 2013; Guo et al., 2013; Kazantseva, 2013; Pawanawichian et al., 2013; Ponsot and Bernardo, 2013; Wang et al., 2013b; Wu et al., 2013). The usage of recycled glass to manufacture foamed glass is however still in its infancy, with limited works to date in this area apart from some work with the production of ceramics (Fernandes et al., 2009; Ponsot and Bernardo, 2013) and with no known work having been undertaken on its usage as a lightweight aggregate construction material.

The usage of recycled products results in significantly less energy production as well as limits the opening of new quarries for virgin quarry products. To achieve sustainability various industries and end-users seek a cleaner production usage for waste materials and view recycled materials as a resource rather than a waste material destined for landfills. The focus of this research is to assess the engineering properties of foamed recycled glass through a laboratory evaluation and to ascertain this novel recycled material as a suitable lightweight fill material in civil engineering applications. An extensive suite of engineering and environmental tests, as well as energy savings assessments were undertaken on foamed recycled glass to assess its engineering properties.

2. Materials and methods

The municipal waste glass, obtained from a glass recycling operator site, was first ground and then fired with mineral additives in a furnace at temperatures up to 950 °C. The recycled glass foams and is then removed from the furnace at which point it cools down quickly forming low weight foamed recycled glass aggregates of up to 40 mm in size. The foamed material comprises 98% ground recycled glass and 2% mineral additives. Foamed recycled glass for this research was obtained from a supplier in Melbourne, Australia. Fig. 1 shows foamed recycled glass aggregates after production. It is evident from Fig. 1 that the glass aggregates comprise vesiculars, due to the presence of air that forms small voids during the production process.

Particle size analysis was undertaken by the Australian standards (AS, 1996). Particle density and water absorption tests of coarse aggregate (retained on a 4.75 mm sieve) and fine aggregate (passing through a 4.75 mm sieve) were both undertaken (ASTM, 2007a). Maximum and minimum dry densities were undertaken using the vibratory table method, which was suitable for this material as it was cohesionless and free-draining (ASTM, 2006b). The pH value of the foamed glass was determined following the Australian standards (AS, 1997a). Organic content tests were performed by the loss of ignition method to determine the organic content of the samples (ASTM, 2007b). CBR tests under standard compaction effort were carried out on specimens in dry and soaked conditions to simulate the worst-case scenario (AS, 2003). LA abrasion test was conducted to determine the abrasion loss of the material and to ascertain if the material could be considered for higher loading applications such as pavement base/subbase applications (ASTM, 2006a).

A large-scale Direct Shear Test (DST) apparatus measuring 305 mm in length, 305 mm in width and 204 mm in depth was used to determine the shear strength of the foamed recycled glass, due to the large sizes of the aggregates. The tests were conducted as per ASTM D3080/D3080M standards (ASTM, 2011). The testing apparatus has two boxes: a fixed upper box and a moveable lower box. Initially, the lower and upper boxes were clamped when preparing samples for the tests. The samples were compacted in the shear box in three layers by using hand tamping with a plastic hammer to attain maximum dry density obtained from the vibratory table method. The samples were then submerged for 12 h before consolidation with three normal stress levels of 10 kPa, 20 kPa and 40 kPa. When the consolidation stage for the tests was completed, the connections between the lower and upper boxes was released, which provided an approximate 2 mm gap between the upper and

Fig. 1. Foamed recycled glass after production (courtesy of the Geotechnical laboratory at Swinburne University of Technology, Australia).