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Strength assessment of spent coffee grounds-geopolymer cement utilizing slag and fly ash precursors

Teck-Ang Kua [a], Arul Arulrajah [a,*], Suksun Horpibulsuk [a,b,*], Yan-Jun Du [c], Shui-Long Shen [d]

[a] Swinburne University of Technology, Department of Civil and Construction Engineering, Hawthorn, Victoria 3122, Australia
[b] School of Civil Engineering, and Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima, Thailand
[c] Institute of Geotechnical Engineering, Jiangsu Key Laboratory of Urban Underground Engineering & Environmental Safety, Southeast University, Nanjing, China
[d] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

HIGHLIGHTS

- Geopolymerisation of spent coffee ground, slag and fly ash as an alternative cement.
- Evaluation of unconfined compressive strength with respect to material composition and curing conditions.
- Unconfined compression, scanning electron microscope, and other tests.

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ABSTRACT

The grinding of coffee beans and subsequent brewing of coffee generates spent coffee grounds (CG), an insoluble waste material rich in organic content. Ground granulated blast furnace slag (S), is a waste by-product derived from steel production. The combustion of coal in power plants produces fly ash (FA) as a waste by-product. The reuse of CG, S and FA as green and sustainable construction materials is of global concern nowadays. The objective of this study was to evaluate the possibility of combining a highly organic waste (CG) with industrial wastes (S and FA) into a sustainable subgrade construction material by a geopolymerization process. A geopolymeric material was synthesized using CG as the base material, and a controlled ratio of S and FA as precursors. A mixture of sodium silicate solution (Na_2SiO_3) and sodium hydroxide solution (NaOH) was used as the alkaline liquid activator (L). Strength development of these geopolymers was assessed using the unconfined compressive strength (UCS) test. Particle bonding and geopolymer matrix pattern of the geopolymers were observed with scanning electron microscopy (SEM). With the base material-to-precursor ratio fixed at a ratio of 70:30, the following factors are found to influence strength development in the geopolymer: (1) ratio of S:FA, (2) ratio of Na_2SiO_3:NaOH, (3) curing time, and (4) curing temperature. When compacted under optimum liquid content (OLC), all the material combinations investigated meet the structural strength requirement for subgrade materials in road embankments specified by various road authorities. It was found that the mixture with CG:S:FA = 70:30:0, Na_2SiO_3:NaOH = 70:30, and L = 55% was the optimum geopolymer blend recommended, as it produces a relatively high UCS with a relatively low L content. This green geopolymer comprising essentially of waste materials was found to be viable as a stabilized subgrade material. The research findings have the potential to transform the construction industry in the sustainable usage of waste by-products in future road subgrades.

1. Introduction

Recent advancements in sustainability and innovation have increasingly stimulated research and development of novel green construction materials by recycling waste materials traditionally destined for landfills. By processing industrial wastes, with practically no commercial value [1], into usable materials for construction applications, the demand for virgin quarry materials and

* Corresponding authors at: Department of Civil and Construction Engineering, Swinburne University of Technology, P.O. Box 218, VIC 3122, Australia (A. Arulrajah). School of Civil Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand (S. Horpibulsuk).

E-mail addresses: aarulrajah@swin.edu.au (A. Arulrajah), suksun@g.sut.ac.th (S. Horpibulsuk), slshen@sjtu.edu.cn (S.-L. Shen).

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landfill space will decline substantially [2]. Substituting raw materials with recycled wastes, which require low capital cost to procure, would result in significant economical and environmental benefits. In recent years, construction and demolition materials such as recycled concrete aggregate [3], recycled glass [4], crushed brick [5], reclaimed asphalt [6], and other wastes such as calcium carbide residue [7] and waste-water biosolids [8] have been extensively evaluated for their suitability as recycled construction materials, particularly in the field of civil engineering.

An estimation done in 2008 reports that the world produces 7.4 million tonnes [9] of insoluble and highly organic [10] spent coffee grounds (CG) annually as a resultant waste product from coffee brewing. This figure is expected to rise, especially in developing nations, due to rising worldwide popularity of the beverage [11]. This waste material has been used as domestic agricultural fertilizer [12] or landfill leachate absorbent [13]. Nevertheless, large-scale harvesting of CG for recycling or commercial purposes has yet to be reported. Therefore, developing a derivative construction material, which heavily utilizes recycled CG may be a way to divert this insoluble solid from landfills.

In its natural state, CG has low shear strength and high compressibility, limiting its usage to non-structural construction applications [14]. Australia is not a major coffee producer and has only a few minor coffee plantations. Coffee is imported into Australia from various regions and countries to satisfy the increasingly high domestic consumption needs. Cafes in Australia source coffee beans from various African, South American and Asian coffee plantations. Earlier studies by the authors [14] indicated that from an engineering perspective, the properties are consistent regardless of the region of origin.

Conventionally, weak soil strata or aggregates are stabilized chemically by mixing the soil with Portland cement or lime [15]. However, these stabilizing agents are manufactured at a high cost, and the process furthermore results in a large carbon footprint [16]. Therefore, it is desirable to seek an alternative stabilizing method to create a green material with low negative environmental impact. Geopolymerization is a chemical bonding process, which uses highly alkaline solutions such as NaOH to dissolve aluminosilicate-rich materials (precursor) to form polymers of alumina and silica. While creating a cementitious compound similar to Portland cement, the geopolymerization process, comprising an inorganic polymeric material, leaves almost no carbon footprint compared to Portland cement [17]. With the right ratio of precursor and alkaline liquid activator, geopolymers cured at elevated temperatures can substitute Portland cement in producing concrete mixes with satisfactory compressive strengths [18]. Consequently, geopolymerization can also be applied to greatly improve the unconfined compressive strength of unfavorable geo-materials [16,19]. Fly ash and slag, both rich in alumina and silica, are commonly used as the precursors for geopolymerization [20,21]. On the other hand, mixing NaOH and Na_2SiO_3 to form a compound activator liquid is reported to augment the strength of geopolymers [22,23] due to a gel-like substance resulting from the aluminosilicate-sodium silicate reaction [24].

Coal combustion is a common method in many countries to generate energy. Incidentally, the ignition of coal produces aluminosilicate-rich FA as a residue, which has been reused extensively as a material in civil engineering applications. In Australia alone, 75% of the nation's energy was reported to be drawn from coal power plants and 12 million tonnes of FA was accumulated as a by-product [25]. Statistics gathered in 2008 show that industries worldwide generated 900 million tonnes of FA in that year alone, and this figure is expected to increase up to a staggering 2000 million tonnes by 2020 [26]. FA is commonly used to limit heat development during concrete hydration to prevent cracking associated with thermal expansion [27]. In the geotechnical engineering sub-discipline, FA is used to stabilize problematic soils and to reduce the moisture content of in-situ soil strata [28]. FA can also partially replace natural soils as a load bearing material in pavement design [29]. FA is a precursor that has been used to produce geopolymers [19,30], which are chemically bound soils with elevated unconfined compressive strength.

Ground granulated blast furnace slag (S) is an industrial by product from the blast-furnaces produced during the manufacturing of iron [31]. Manufacturing 1 tonne of steel produces 340–421 kg of blast furnace slag [32]. The ever increasing demand for steel has generated a proportional amount of slag [33], but only a small fraction of this waste is reused while the remainder is destined for the landfill [34]. Air cooled slag can be used as an aggregate in pavements [35], while grinding this material into fine particles enables it to be used as a stabilizing agent for soils [36].

There is a current waste reduction initiative in Melbourne, Australia that has organized the collecting, sorting and transportation of CG from various cafes, with the intention to divert the stockpiles of CG, from landfills and into sustainable practices. It has been estimated that up to 5 km of road can be constructed per year in the city of Melbourne with the usage of CG [14]. This research has been undertaken to evaluate the usage of geopolymer stabilized CG as a road subgrade material, a current interest of road construction companies.

CG, FA, and S are waste materials that are abundantly generated, have great potential to be recycled, but are often disposed to landfills. This study aims to determine the optimum composition of a novel CG:S:FA geopolymer where maximum unconfined compressive strength can be achieved. The effects of liquid content, curing duration, and curing temperature on the unconfined compressive strength (UCS) development were also studied. Additionally, observations were made on the microscale level to study and understand the formation of geopolymers under the aforementioned factors. This new material, derived from three major sources of waste products (CG, S, FA), would significantly reduce landfill demand and carbon footprint as a novel solution in subgrade applications.

2. Materials and methods

Raw CG collected from coffee roasters has a very high natural moisture content of 115% [37]. The acquired material is usually mixed with other wastes such as paper towel, milk bottle caps, and serviettes used by the café operators, which have to be removed. CG was collected daily from a roaster cafe in Melbourne, Australia. After the undesirable wastes inside the CG were removed by hand, the remaining CG was oven-dried in a controlled environment of 50 °C to ensure that the organic materials are not lost by ignition [14]. The drying process requires up to 5 days mainly due to the high natural moisture content in CG, and the relatively low oven temperature used. Large coagulations of CG are commonly observed because as part of the brewing process, ground coffee powder is always compacted into tablets in coffee machines. However, when fully dried, these lumps can be easily fragmented with light abrasion by hand, indicating no chemical bonding. Hence, before being used as test specimens, dried CG was passed through a 2.36 mm sieve to filter out coagulated CG particles. Scanning electron microscopy (SEM) was used to observe the physical features of dried and sieved CG particles. Particle size distribution analysis was undertaken on the dried CG in accordance with ASTM D442-63 [38].

Table 1
Chemical constituents and properties of CG, FA, and S.

Major chemical constituent (%)	CG	FA	S
Al_2O_3	–	23.8–24.0%	13%
CaO	–	0.31–1.59%	40%
SiO_2	–	65.9–67.0%	35%
D_{50} (mm)	0.349	0.036	0.021
Specific gravity	1.37	2.4	3.2