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Experimental investigation of using a recycled glass powder-based geopolymer to improve the mechanical behavior of clay soils

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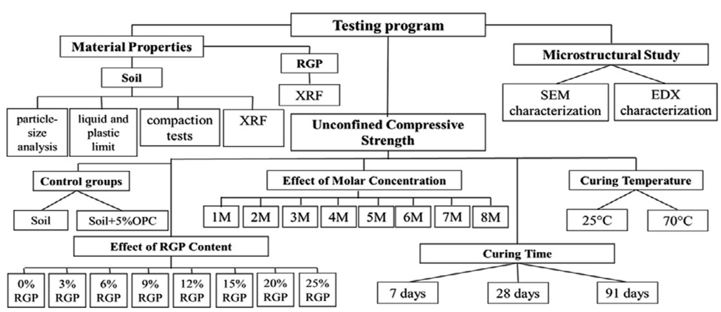
HIGHLIGHTS

- Recycle glass powder geopolymer was investigated to improve the clay soil behavior.
- The ductility and strength of soil were increased by using geopolymer.
- SEM-EDX analysis verified the formation of geopolymeric gel in the stabilized soil.
- Recycle glass powder-based geopolymer can be used as an effective soil stabilizer.

GRAPHICAL ABSTRACT



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ABSTRACT

This research investigated the feasibility of using a geopolymer based on recycled glass powder (RGP) to improve the mechanical behavior of clay soils. The chemical elements of soil and RGP were determined by XRF. Unconfined compressive strength (UCS) testing was used to investigate the mechanical behavior of specimens. The effects of different parameters, such as the RGP content, molar concentrations, curing time and temperature, were investigated. The results revealed that the UCS and (ε_f) of specimens that were stabilized using a geopolymer were increased in comparison to the unstabilized specimens. SEM-EDX was analyzed to investigate the microstructure of stabilized specimens.

1. Introduction

The modification of soil improves mechanical characteristics and durability of the structure; however, it can have a harmful environmental impact and increase the energy consumption. Growth in energy request causes an increase in the consumption of fossil fuels [1]. One of the most traditional methods of soil modification is to use Portland cement. Currently, the cement-manufacturing industry causes destructive environmental effects via the excessive consumption of fossil fuels and high emission of greenhouse gases especially carbon dioxide (CO_2). The emission of CO_2 is the main cause of global warming [2]. Research has shown that approximately one ton of CO_2 is emitted in the manufacturing of one ton of cement. This means that the cement-manufacturing industry produces approximately 5%-8% of global pollution caused by emission of CO_2 [3]. Additionally, a large amount of natural minerals is used during the cement-manufacturing process. Therefore, researchers are always searching for more environment-friendly and appropriate methods to replace ordinary Portland cement (OPC) as a soil stabilizer. One of the most appropriate alternatives for replacing cement is to use geopolymers. The acceptable temperature range for geopolymeric compositions is usually 25–80 °C [4]. Therefore, energy consumption and CO_2 emission are very

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low during geopolymerization [5]. Any pozzolanic material that has a rich source of silica and alumina in an amorphous phase and is soluble in an alkaline activator can be the base of a geopolymer for geopolymerization [6]. Geopolymers are a group of inorganic minerals including alkaline activated aluminosilicates [7,8]. The chemical structure of geopolymers is defined as follows [9]:

$$Mn[-(SiO_2)z - AlO_2-]_n wH_2O$$

where w is the amount of structural water; n is the polymerization degree; *M+* is the alkaline cation [k+ or Na+] and z is the molar ratio of Si/Al, which is commonly z = 1–15 and can be even greater [9]. Variation in the Si/Al ratio results in different physicochemical properties of geopolymers [10–12]. The strength of a geopolymeric cement depends on geopolymerization, which depends on different factors, such as the type of base material, the amount of base material, the structure and type of alkaline activator, the time for which the elevated temperature is applied, the curing time, the water/solid ratio, the mixture pH and the initial synthesis temperature [13,14]. A wide range of recycled waste materials such as fly ash, volcanic ash, rice husk ash, the slag and tailing of iron/steel furnaces and meta-kaolin have the potential to use as a base for geopolymers [15–17]. The application of these waste materials as a precursor for geopolymers in civil engineering applications is evaluated by several geotechnical researchers. Fly ash (FA) based geopolymer as an eco-friendly additive were used to increase the strength of recycled asphalt pavement [18,19]. The effect of wetting-drying (w-d) cycles on microstructure and compressive strength of recycled asphalt pavement – Fly ash geopolymer was performed by Hoy et al (2017) [20].

Non-recycled glass constitutes one of the most wastes produced in some countries [21]. Using glass waste in manufacturing geopolymers is a new technology that has recently been considered in construction projects [21]. Cyr et al (2012) conducted research on a geopolymeric mixture with glass pieces. The results showed that there is no need for a high synthesis temperature to produce a geopolymer with glass pieces [22]. Some research on the capability of glass powder to be used in mortars as a precursor for geopolymers showed that a glass powder can be productively used for preparing an alkaline solvent and as a base for a geopolymer due to its alkaline properties and silicate contents [23–27]. Commonly, a combination of NaOH and Na_2SiO_3 has been used as an alkaline activator in the manufacturing process of geopolymers. As a rich source of silica, glass powder can be an appropriate replacement for sodium silicate in manufacturing geopolymers [28]. Using geopolymeric cements to improve and stabilize soils is another important application of geopolymers, which is a field with little background or conducted research. Zhang et al (2013) investigated the possibility of using a meta-kaolin geopolymer to stabilize a clay soil with a high plasticity. The results of their research showed that geopolymers were appropriate for stabilizing clay soils [29]. Cistelo et al (2013) investigated the stabilization of soft soils by alkaline activation of fly ash. They concluded that activated fly ash could be used as a replacement for cement in soil stabilization [30]. Singhi et al (2016) investigated a geopolymer made of fly ash and slag. Their results showed that the specimens stabilized by a slag geopolymer with less than 8% slag do not obtain a remarkable strength [31]. Mozumder and Laskar (2015) conducted a numerical study for predicting the UCS of the soils that had been modified by a geopolymer [32]. Phummiphan et al (2016) conducted research on the improvement of lateritic soils using a fly ash-based geopolymer and alkaline activator composed of different combinations of Na_2SiO_3 and NaOH [33]. Literature reviews illustrate that there is little research on soil modification by geopolymers [32,34]. Thus, based on the existing gap and the importance of environmental impacts, the possibility of using an RGP-based geopolymer as a soil stabilizer was studied in the presented research. NaOH was used as an alkaline activator due to its high pH and ease of access. This research emphasized basic tests of soil mechanics to identify the used soil characteristics, such as gradation, Atterberg limits and standard compaction (Proctor) test behavior. The chemical compositions of soils and RGP are identified using X-ray fluorescence (XRF) tests. Additionally, the effect of stabilizers on the soil mechanical behavior was investigated by a UCS test conducted on unstabilized specimens (control1), specimens stabilized by 5% cement (control2) and specimens stabilized by a geopolymer based on RGP. Then, the values of the UCS and ε_f were measured. The parameters studied in this research are the effect of the RGP content, the concentration of NaOH, the curing time and the initial synthesis temperature. Considering the low bearing capacity of clay soils in wet conditions, all of the specimens were kept in OWC conditions (from manufacture until the testing time). The SEM images and EDX analyses of some specific specimens were prepared and investigated to study the microstructural properties of the specimens.

2. Materials and methods

2.1. Soil

The soil used in this research was collected from a 5-m depth in Shahid Bahonar University of Kerman, Iran (30.2522°L 57.1055°E; 1800 m AMSL). The gradation test was conducted on this soil according to ASTM-D422 and ASTM-D2487 standards [35–36]. Fig. 1 shows the gradation chart of the soil. According to the Atterberg limits test (ASTM D4318-00) that was conducted on the soil passing the No. 40 sieve (particles finer than 425 μm) [37], the soil plasticity index (PI) was 10% and the liquid limit (LL) was 30%. According to the Unified Soil Classification System (USCS), this soil is categorized as a low-plasticity clay soil or CL [36]. Such soil has a low bearing capacity for upper loads due to the structure weight. Therefore, this type of soil was selected for investigating the effect of stabilization by an RGP-based geopolymer. The standard compaction (Proctor) test was conducted according to the ASTM D698 standard to determine the OWC and the maximum dry density (γdmax) [38]. According to the standard compaction test, γ_{dmax} = 1.78 gr/cm3 and OWC = 20%. Based on previous research and experimental observations, the OWC and γdmax should remain relatively constant when adding geopolymer base materials [29,39]. Thus, the compaction conditions for stabilized and unstabilized specimens were selected equally.

2.2. Glass powder

The recycled glass powder (RGP) was provided from glass waste. To do so, glass waste was crushed by a crusher (Fig. 2(a))

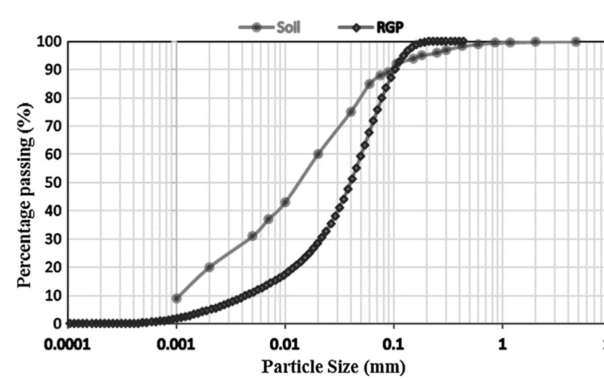

Fig. 1. The particle size distribution curve of glass powder and soil.