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Evaluation of the mechanical properties of sea sand-based geopolymer concrete and the corrosion of embedded steel bar

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HIGHLIGHTS

- The compressive strength of geopolymer concrete using sea sand as fine aggregate reaches the highest value at an alkaline to fly ash ratio of 0.35–0.45.
- For sea sand based geopolymer concrete, when the ratio of aggregate to fly ash is low, the compressive strength enhances high value.
- The difference in strength between specimens using river sand and sea sand is not significant.
- It takes more time for steel bar in geopolymer concrete using sea sand to be attacked and corroded, compared with the steel bar in normal concrete.

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ABSTRACT

Portland cement concrete is a major construction and building material used all over the world. It is a composite material comprising Portland cement, coarse aggregate, fine aggregate, and water. But its increased use in construction is exhausting natural resources used in its production, making it necessary to find alternative materials. One potential method is to use sea sand as fine aggregate to produce fly ash based geopolymer concrete. In this paper, the mechanical properties of geopolymer concrete prepared with sea sand as the fine aggregate, and the corrosion of steel bar embedded in the concrete subjected to accelerated corrosion tests, were investigated. The test data revealed that for sea sand based geopolymer concrete, the compressive strength reached high values at an alkaline to fly ash ratio of 0.35–0.45. The geopolymer concrete exhibited highcompressive strength with a low aggregate to fly ash ratio. Also, there was an increase in compressive strength when the Si/Al ratio changed from 1.16 to 1.67. Furthermore, very little difference was observed between the mechanical properties of geopolymer concrete using sea sand, and river sand. Measurements of the corrosion of steel bar using a half-cell potential survey indicated that the steel in geopolymer concrete with sea sand was attacked and corroded like normal concrete. However, the potential of steel bar in geopolymer concrete was higher than in Portland cement concrete.

1. Introduction

Concrete is the key building material used for construction activities and development projects throughout the world. Portland cement is ordinarily used as the main binder to produce concrete, however, it is not an enviro-friendly material. The production of Portland cement depletes natural resources and results in the emission of a large amount of greenhouse gases [1–5]. In addition to Portland cement, fine aggregate is also a principal component of concrete. The typical fine aggregate used is river sand. With the high current demands for concrete from new construction, natural resources like limestone and river sand become are being rapidly exhausted [27]. Therefore, to preserve the global environment, it is imperative to search for and explore new possibilities to develop a concrete material that is more environmentally friendly, and yet remains an efficient construction material, to partially or completely replace conventional Portland concrete [6].

In recent years, geopolymers have received considerable attention because of their environmental benefits. Geopolymer concrete utilizes solid industrial aluminosilicate based waste materials fly ash, rice husk ash or granulated blast furnace slag to produce a low-cost and environmentally friendly material as an alternative

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to Portland cement [28,29]. Unlike ordinary Portland cement (OPC), which requires high temperature calcining, the production of raw materials for geopolymer cement does not need a high level of energy consumption. The production of one ton of kaolin based geopolymeric cement generates 0.180 tons of carbon dioxide (CO_2), from the combustion of carbon-fuel, compared with one ton of CO_2 for OPC, six times more [7].

The sustainable development of construction materials with more eco-friendly characteristics in both the manufacturing and operational phases of the material lifecycle is an increasingly important consideration in construction all over the world. In this regard, geopolymer concrete is one of the revolutionary developments that can reduce emissions of CO_2 and provide operational energy savings through the use of waste materials. In addition, the use of alternative materials can conserve declining natural resources. There is also a need to research ways to partially or completely replace current materials. For example, sea sand is one of the potential materials which might be used in concrete instead of the river sand.

In many countries, sea sand has been used for making concrete for a very long time, although the particular technology depends on the research achievements and specific conditions of each country. However, previous studies have consistently reported that while concrete using sea sand exhibits strength early on, its strength later declines due to the chloride content [8,9]. Moreover, sea sand contains sulfate factors. Sulfate and chloride are the two main factors that cause damage in concrete structures. The sulfate factors react with the C_3A, hydrated aluminates, or mono-sulfate ($C_3A.CaSO_4{\cdot}12H_2O$) and $Ca(OH)_2$ from the Portland cement to create expansive gypsum and ettringite. Also, thaumasite ($CaSiO_3.CaCO_3.CaSO_4{\cdot}15H_2O$) can form in concrete from the reaction of calcium-silicate hydrates (C–S–H) with sulfates in the presence of carbonate ions. Thaumasite formation leads to gradual softening, spalling and significant loss of strength [10,11]. Cement known as sulfate-resisting Portland cement or type V according to ASTM C150 [12], is used to overcome the above problems. However, previous research has noted that the use of sulfate-resisting cement can be disadvantageous when there is a risk of the presence of chloride ions in concrete containing steel reinforcement or the other embedded steel. The reason for this is that C_3A binds chloride ions, forming calcium chloroaluminate ($3CaO.Al_2O_3.CaCl_2{\cdot}10H_2O$). And, under some circumstances, it may become dissociated, releasing chloride ions to replenish those removed from the pore water after transport to the surface of the steel [13]. To avoid this, washing the sea sand to remove the chloride content and salt is performed in some cases. However, this increases the cost of construction.

On the other hand, geopolymer concrete has a different hardening process from Portland cement concrete. The main product of geopolymerization generally includes no portlandite or C–S–H formation. As a result, there is only a small possibility that sulfate factors will attack geopolymer concrete. For this reason, using sea sand as fine aggregate for geopolymer concrete is a potentially advantageous method. This study evaluated the mechanical properties of geopolymer concrete using sea sand as the fine aggregate, based on alkaline liquid to fly ash ratios, aggregate to fly ash ratios, and the ratio of Si to Al inside the source material. Also, the mechanical properties of geopolymer concrete made with sea sand and river sand were compared using compressive, splitting tensile strength, Scanning Electron Microscope (SEM) imaging and X-ray diffraction (XRD) analyses. In addition, the corrosion of steel bar embedded in the sea sand geopolymer concrete was examined. The natural electric potential was measured during 252 wet/dry cyclic tests using the half-cell potential method.

2. Materials and methods

2.1. Materials

Fly ash 'Class F' based on ASTM 618 [14], with a specific gravity of 2500 kg/m^3, was used for this research. This fly ash came from a power station and the chemical compositions of the fly ash are shown in Table 1.

The alkaline liquid was a combination of sodium silicates (Na_2SiO_3) and sodium hydroxide (NaOH). The components of the sodium silicates solution were Na_2O and SiO_2 (approximately 36–38% by mass). Water glass and sodium hydroxide were mixed in the ratio 2.5 by mass. Besides this, the ratios of alkali solutions (including water glass and sodium hydroxide) to fly ash were 0.35, 0.4, 0.45, 0.5, 0.55, 0.6 and 0.65.

Aggregates comprising 20 mm coarse aggregates (CA) and fine aggregates (FA) were used. The ratio of coarse to fine aggregates was 64.4% and 35.6%. The specific gravity was 2700 kg/m^3 and 2650 kg/m^3 for the coarse and fine aggregates, respectively. In this research, two types of fine aggregate were used, river sand and sea sand. The chemical and physical properties of two types of sand are given in Table 2.

Ordinary Portland cement (OPC, type I) was used to manufacture conventional concrete for the durability test. The physical and chemical compositions are listed in Tables 3 and 1, respectively. Also, micro-silica with a particle size of 0.5 ± 0.1 μm was used in the present study. Enlarged particles of micro-silica are shown in the SEM image in Fig. 1.

Steel bar was used to evaluate the durability of the reinforced geopolymer concrete under accelerated corrosion conditions. Smooth steel bar with a diameter of 8 mm was employed. Before being embedded in concrete, the bar was brushed with sandpaper and cleaned with acetone.

Details of the mix proportions per cubic meter used in this study are shown in Table 4. For all mix proportions, the concentration of sodium hydroxide solution was 12 M. In Table 4, the name of the mixtures are GSXa (where GS = geopolymer concrete using sea sand as fine aggregate, X = name of series, a = number of series), GR = geopolymer concrete using river sand as fine aggregate, PCCb = Portland cement concrete grade b.

2.2. Specimen preparation and curing condition

For the experiments, two kinds of concrete, geopolymer concrete and Portland cement concrete, were mixed. The geopolymer concrete included coarse aggregate, fine aggregate, alkaline liquid, fly ash and water. The two aggregates and the fly ash were quantified before mixing. Alkaline liquid is a combination of water glass and sodium hydroxide solution. To make the sodium liquid solution, sodium hydroxide solids were mixed with the water. Then, the sodium hydroxide solution was mixed with the water glass. This liquid was prepared one day before mixing day. According to Davidovits [15], the alkaline liquid should be mixed first, which makes the polymerization easier. The mixing procedure followed that of a previous researcher [16]. Firstly, all solids are mixed together about three minutes after quantifying by mixer machine or by hand. The amount used is determined by the amount required for the number of specimens needed. Secondly, the alkali liquid, which is prepared one day before, is poured over the solids. Then they are mixed together for about four minutes. After casting the specimens, they were sent to an oven and cured. Curing conditions, such as time and temperature, depended on the needs of the tests used. The Portland cement concrete included CA, FA, cement,