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Theoretical and experimental study on mechanical properties and flexural strength of fly ash-geopolymer concrete

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HIGHLIGHTS

- Young's modulus of geopolymer concrete were affected by its microstructure.
- Stress–strain relation of geopolymer concrete is same as Portland cement concrete.
- The tensile strength of geopolymer concrete is greater than that of normal concrete.
- The actual geopolymer beam is stiffer than the theoretical analysis model.
- The deflections at mid-spans determined from FEM are matched well with the test data.

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ABSTRACT

In this paper, evaluation of the mechanical properties of heat-cured low-calcium fly-ash geopolymer concrete and the behavior of geopolymer concrete beams are reported in detail. The mechanical properties are evaluated using the modulus elasticity, Poisson's ratio, stress–strain relation, and indirect tensile strength. Behavior of the geopolymer beam is determined using a flexural test with four-point bending, elastic theory, and a finite element model (FEM). The measured modulus elasticity values of geopolymer concrete are lower than those calculated using current standards for normal concrete. The Poisson's ratio is from 0.16 to 0.21, which is similar to the values of conventional concrete. The stress–strain relation in compression matches well with the formulation designed for Portland cement concrete. The indirect tensile strength is a fraction of the compressive strength but it is higher than the calculated value using an expression designed for normal concrete. The deflections at mid-span, and the crack patterns of the geopolymer concrete beam determined from FEM, are better matched with the experimental results than with the elastic theory results.

1. Introduction

Global warming is caused by the emission of excessive greenhouse gases into the atmosphere by human activities, and carbon dioxide (CO_2) is responsible for about 65% of global warming. The global cement industry contributes around 6% of all CO_2 emissions because the production of one ton of Portland cement releases approximately one ton of CO_2 into the atmosphere [1,2]. Some researchers have stated that CO_2 emission could increase by 50% compared with the present scope [3,4]. Therefore, the impact of cement production on the environment issues a significant challenge to concrete industries in the future. As a result, it is necessary to find a new concrete material to replace traditional Portland cement concrete, which is environmentally stressful, yet provides an effective building material [5]. To this end, geopolymer concrete is a breakthrough development providing an essential alternative to conventional cement, using novel, low-cost, environmentally friendly materials [6]. Geopolymers are inorganic aluminosilicates produced by alkali activation solutions and source materials. Thus, geopolymer concrete is created using activated industrial waste materials such as fly ash in the presence of sodium hydroxide and sodium silicate solutions. It also has involves a geopolymerization process that is widely different from the hydration process of Portland cement [7].

Almost all research on geopolymers has determined that this new binder has great potential as an alternative to ordinary Portland cement (OPC). Geopolymers have received considerable attention because geopolymer materials may result in environmental benefits such as reduction in consumption of natural resources

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Nomenclature

Abbreviation

FEM	Finite element model
CO_2	carbon dioxide
OPC	ordinary Portland cement
RGPC	reinforced geopolymer concrete
CA	coarse aggregate
FA	fine aggregate
LVDT	Liner Variable Differential Transducer
l	length of specimen in splitting tensile strength
d	diameter of specimen in splitting tensile strength
a_o, b_o, L_o	Dimensions in the undeformed configuration
θ_A, θ_C	Bending angles at supports and at load application points in four bending
δ_C	Displacement of the load application points in a four-point bending test
I	Moment of inertia with respect to the middle plane
$Q = P/2$	Applied load at each node in four-point bending
b, h	Width and thickness of the specimen
E	Young's modulus
η_A, η_C	Terms related to support span and load span reduction in a four-point bending test
f_{ct}	splitting tensile strength
M_a	maximum moment in member at stage of deflection is computed
I_{cr}	moment of inertia of cracked, transformed section
I_g	moment of inertia of gross concrete section-neglect reinforcement
y_t	distance from neutral axis to tension face
f'_c, f_{cm}	the specified 28-day compressive strength of concrete
f_r	the tensile strength of concrete
ρ	density of concrete
v	Poisson's ratio
σ	Stress (MPa)
ε	Strain

and decrease in the net production of CO_2. Geopolymer concrete is an innovative binder material that could totally replace Portland cement. Geopolymer concrete utilizes solid industrial aluminosillicate-based waste materials such as fly ash, rice husk ash, and silica fume to produce an environmentally friendly and low-cost alternative to Portland cement.

Until recently, the understanding of structural geopolymer concrete was extremely limited. Some of the research carried out has been comparative study of experimental and analytical aspects of geopolymer concrete members. Broke et al. [8] reported that the behavior of geopolymer concrete beam–column joints was similar to that of members of Portland cement concrete. Uma [9] performed a flexural response of reinforced geopolymer concrete (RGPC) beams. The results from both ANSYS modeling and experimental data were compared, and revealed that the deflection obtained was low due to meshing of elements in the model. They also concluded that the comparative result gave a 20% difference between the experimental and ANSYS results. The results from the research by Curtin University on fly-ash-based geopolymer concrete is described in research report GC3 [10]. They concluded that the behavior of geopolymer concrete beams is similar to those of reinforced Portland cement concrete, and good correlation between the test and calculated values was found.

In order to have a deeper understanding of the characteristics and behavior of structural geopolymer concrete, this study was intended to evaluate the following properties of fly ash-geopolymer concrete: stress–strain relation in compression, Young's modulus, Poisson's ratio, and splitting tensile strength. The behavior of geopolymer concrete beams subjected to a four-point bending test was also investigated using experimental tests, theoretical-analysis-based elastic theory, and simulation software (ABAQUS).

2. Materials and methods

2.1. Materials

Low-calcium fly ash known as 'Class F' based on ASTM, with specific gravity 2500 kg/m^3, was used in this study. This fly ash came from a power station. Enlarged particles of it are shown in an SEM image (Fig. 1a) and dry bulk in Fig. 1b. Details of the chemical composition of the fly ash are presented in Table 1.

Solutions of sodium silicates and sodium hydroxide were mixed to create the combination called alkaline liquid. The components of the sodium silicate solution were Na_2O and SiO_2 (approximately 36–38% by mass). Coarse aggregates (20 mm and 10 mm, CA) and fine aggregates (FA) were used. The ratio between coarse aggregates and fine aggregates was 40% (20 mm), 30% (10 mm) and 30% (fine aggregate). The specific gravity of the coarse aggregates was 2700 kg/m^3 and 2650 kg/m^3 for the fine aggregates.

Details of the mix proportions used in this study are shown in Table 2. For all mix proportions, the concentration of sodium hydroxide solution was 8 M. Water glass and sodium hydroxide were mixed in the ratios 1, 2, and 2.5 by mass. Besides this, the ratios between alkali solutions (including water glass and sodium hydroxide) and fly ash were 0.4, 0.5 and 0.6. In Table 2, the name of the mixtures is GPCx, which stands for geopolymer concrete number x (where $x = 1$, 2, or 3). The ratio of alkali liquid to fly ash was 0.6 for GPC1, 0.5 for GPC2, and 0.4 for GPC3. The ratio of sodium silicate to sodium hydroxide was the same for all mix proportions and equaled 2.5. In the results and discussion section, the name of group data is GPCx – ab, (where ab is the curing temperature, ab = 60, 90, or 120 °C).

2.2. Specimen preparation and curing condition

Geopolymer concrete includes coarse aggregate, fine aggregate, alkaline liquid, fly ash and water. The two aggregates and the fly ash are quantified before mixing. Alkaline liquid is a combination of water glass and sodium hydroxide solution. To make 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 [5], the alkaline liquid should be mixed first, and it would make the polymerization easier.

The manufacturing process shown in Fig. 2, includes three steps:

- Step 1: 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.
- Step 2: The alkali liquid, which is prepared one day before, is poured over the solids. Then they are mixed together for about four minutes.
- Step 3: The fresh geopolymer concrete is cast and compacted into the molds. Right after finishing this step, the specimens are sent to an oven and cured. Time and temperature depend on the needs of the tests used.

2.3. Test methods

In this research, the test program was separated into two parts: one about the mechanical properties of the fly-ash-based geopolymer concrete, and one about the behavior of a geopolymer beam subjected to a four-point bending test. In Table 3, information about the testing procedure is summarized. The details of the tests are presented below.

2.3.1. Compressive strength

The standard ASTM C39/C 39M-99 [11], covers determination of the compressive strength of cylindrical concrete specimens, such as cylinders. This test method is used to apply a compressive axial load to molded cylinders at a rate from 0.15 to 0.35 MPa/s, until failure occurs. The compressive strength of geopolymer concrete specimens is determined by dividing the maximum load attained during the test, by the cross-sectional area of the concrete specimen. Concrete cylinders of 150 mm diameter and 300 mm height were cured in the oven and tested after aging for 7 d.