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Investigation on mechanical properties of fly ash-ground granulated blast furnace slag based self curing bio-geopolymer concrete

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HIGHLIGHTS

- Bio-additives + Geopolymer concrete = Bio-Geopolymer concrete.
- Bio-additives showed positive effects in self cured geopolymer concrete.
- Low molarity of NaOH (4 M) paved for safer manufacturing of geopolymer concrete.

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ABSTRACT

Heat cured geopolymer concrete (GPC) normally catalyze the geopolymerization reaction and thereby the mechanical properties of the geopolymer concrete were improved. Because of the practical challenges in applying steam curing/heat curing process, the applications of geopolymer concrete were limited to pre-cast elements alone. The objective of this research was to understand the positive impact of bio-additives such as Terminalia chebula and natural sugars (molasses/palm jaggery/honey) on the mechanical properties of the bio-geopolymer concrete under eco-friendly ambient curing conditions. In this study, both the bio-additives were added 0.8% by the weight of aluminosilicate minerals. Less concentrated alkaline solution (4 M sodium hydroxide) was employed. Experimental results confirmed that the bio-additives combination of Terminalia chebula and palm jaggery in fly ash-ground granulated blast furnace slag based self curing bio-geopolymer concrete improved 31.31% of compressive strength, 14.70% of splitting tensile strength, 27.59% of flexural strength when compared to control specimens cured at ambient condition for 28 days. Also the ultimate load of 83 kN and deflection of 11.99 mm was observed in load-deflection behaviour. Atomic force microscopy (AFM) studies confirmed that various surface roughness parameters were improved for bio-geopolymer concrete when compared to control specimens.

1. Introduction

The manufacturing process of ordinary portland cement (OPC) requires massive heat energy and it contributes 5–8% of world's greenhouse gas emissions. Analysis on the emission revealed a scary ratio of 1 between the production of cement and CO_2 emission (54% during calcinations and 46% during burning of fuels) [1]. The projections stated that annual worldwide production would rise to 4.38 billion tonnes in 2050 based on 5% growth per year [2]. In terms of CO_2 emission, significant environmental benefits could be achieved by less consumption of OPC. The above mentioned issues encouraged the development of environmental friendly materials. There is an alternative low carbon footprint option 'Geopolymers' for ordinary portland cement concrete. The testing of geopolymer cement showed the same or better results in accordance with the testing standard of OPC. Besides, geopolymers were made by using aluminosilicate waste as base material. Hence substituting OPC with aluminosilicate material reduced cost and CO_2 emission [3].

Geopolymers comprise of silicon and aluminium atoms bonded via oxygen atoms to form a polymer network. They were prepared by dissolution and polycondensation reactions between a reactive aluminosilicate material and an alkaline solution, such as a mixture of an alkali metal silicate and metal hydroxide. Different types of geopolymers had been made using fly ash, rice husk ash/rice husk bark ash, palm oil fuel ash, red mud, metakaolin and copper mine tailings at different curing conditions [4]. Also fly ash and

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ground granulated blast furnace slag (GGBS) were very effective starting materials for geopolymer concretes because of better geopolymerization that provided good strength and stability [5]. On the flip side, heat curing process led to high cost and in-situ practical issues thereby preventing the large scale application of geopolymer concrete. Therefore adopting self curing eliminated the need for externally applied heat source which was a major constraint in the ready mix applications of geopolymer concrete. In few studies OPC was used as an additive to make geopolymer concrete at room temperature. Partial replacement of OPC in the total binder with low calcium fly ash accelerated the curing of geopolymer concrete instead of using elevated heat [6] and setting and hardening of cotton fabric reinforced fly ash based geopolymer composite was achieved at room temperature [7]. Self cured geopolymer concrete could be produced by partially replacing OPC and also adopting the different manufacturing procedures [8]. Chemical additives such as calcium hydroxide, silica fume, nano SiO_2, nano Al_2O_3, synthetic resins and gypsum were used in the self curing geopolymer concrete. To improve the mechanical properties of metakaolin based geopolymer concrete at room temperature curing (20 °C), calcium hydroxide was used [9]. Chemical admixtures (3%) were added to decrease the setting time of geopolymer concrete cured at room temperature [10]. Geopolymer showed compact and denser microstructure that increased strength and durability properties at ambient temperature, when added silica fume [11]. Fly ash replacement of 30% by GGBS and 10% by silica fume improved the mechanical properties of self compacting geopolymer concrete under ambient curing [12]. To enhance the shear bond strength and decrease the setting time of geopolymers, nano particles such as nano SiO_2, nano Al_2O_3 were added in high calcium fly ash geopolymer cured at ambient temperature [13]. The mechanical performance was enhanced when metakaolin/granulated blast furnace slag based geopolymer composites was doped with different amount of acrylic resin emulsion and polyvinyl acetate resin fabricated at 20 °C with 99% relative humidity [14]. Combination of (20 wt% $Ca(OH)_2$, 5 wt% silica fume, and 10 wt% $Al(OH)_3$) additives enriched the efficiency of treated palm oil fly ash geopolymers [15]. Waste gypsum (5%) generated during the desulfurization reaction in thermal power plant (flue gas desulfurization gypsum) with fly ash improved the geopolymerization of bottom ash geopolymers [16]. Effects on properties of 'just adding water geopolymers' at ambient curing were also studied [17]. The above mentioned facts revealed the impact of good mechanical properties by adding chemical additives. Another important drawback of making heat cured geopolymer concrete was the need for elevated temperatures to initiate the geopolymerization process, which was important to increase the compressive strength of the geopolymer concrete. Furthermore, the need for excessive amounts of alkaline components created a risky work environment. Currently there were very limited researches had been conducted on safer manufacturing process and self curing geopolymers using bio-additives. Detailed literature review revealed the impact of various bio-additives in alkali activated geopolymer concrete/mortars. Addition of 1% and 2% glucose to the fly ash based geopolymer concrete improved the compressive strength by 18.79% and 12.75% respectively [18]. The setting time was delayed when 3% of glucose solution was added to microwave incinerated rice husk ash-fly ash based geopolymer concrete [19]. Inclusion of sucrose (1 wt% of fly ash) in fly ash based geopolymer mortar improved 16.67% of compressive strength and 16.54% of degree of reaction [20]. Addition of sucrose and citric acid (1.5%, 2.5% of fly ash) as additives made a significant change in rheological properties of fly ash based geopolymer paste and in particular the presence of sucrose prolonged the retardation effect and citric acid catalyzed stiffening process [21]. Xylitol (sugar alcohol) when added 0.3% by mass of fly ash enhanced the compressive strength of fly ash based geopolymer mortars at various curing temperatures [22]. Sugar cane straw ash when replaced 15–50% by mass of blast furnace slag improved the mechanical properties in blast furnace slag based alkali activated binders systems significantly [23]. Also the use of sugar as an additive in small quantities increased the compressive strength of OPC based concrete [24], OPC mortar mix [25,26], laterized concrete [27] and sandcrete blocks [28].

This provoked the investigation about adding bio-additives and less concentrated alkaline components that self cure which would eliminate the need of heat energy to cure the geopolymer concrete and improves user safe work environment. This experimental work outlined material properties, mix proportioning, casting procedure and testing methodology. Later in the report the results of the conducted experimental work, a detailed discussion on the influenced results of bio-additives content on the fresh properties, compressive strength, splitting tensile strength, flexural strength, load-deflection behaviour of the reinforced geopolymer concrete beams and microstructural properties were interpreted with the experimental facts.

2. Materials

The materials used for making self curing geopolymer concrete specimens were aluminosilicate materials (fly ash and GGBS), fine aggregate, coarse aggregate, alkaline liquids, superplasticizer and bio-additives (Terminalia chebula and natural sugars) in different combination.

2.1. Aluminosilicate materials

In this, both fly ash and GGBS were used as aluminosilicate materials. Fly ash has spherical particle and smooth surface [29] that led to more workability and reduced the water demand. It also increased the pozzolanic activity of geopolymers. Generally fly ash particles are 1 to 10 μm in diameter with average particle size of 5.33 μm and it makes geopolymer matrix more intact [30]. Low calcium Class F fly ash was obtained from the silos of thermal power station, Tuticorin, Tamil Nadu was used as one of the base aluminosilicate material. GGBS was obtained from local steel plant and it showed pozzolanic and binding properties in an alkaline medium [31]. The addition of GGBS lowered the total porosity of the hardened geopolymer concrete [32]. GGBS requires less sodium silicate solution for activation and hence lower environmental impact [33]. Chemical compositions of fly ash and GGBS had been identified in X-ray fluorescence spectrometry and were given in Table 1.

2.2. Aggregates

Locally resourced river sand and crushed granite were used as fine and coarse aggregates. The sieve analysis test results of the fine aggregate conformed to zone II as per IS 383-1970 (Reaffirmed on 1997). It had specific gravity of 2.63, bulk density of 1721 kg/m^3 and fineness modulus of 2.67. Similarly specific gravity of 2.84, bulk density of 1578 kg/m^3 and fineness modulus of 7.75 were obtained for differently sized 20 mm, 12 mm, 6 mm coarse aggregates. The final combined aggregate volume was a combination of 30% of fine aggregate, 21% of 20 mm, 29% of 12 mm and 20% of 6 mm coarse aggregates. The gradation curve for aggregates and aluminosilicate materials was shown in Fig. 1.

2.3. Alkaline liquid

A combination of commercially available 98% pure sodium hydroxide (flakes form) and sodium silicate (liquid gel form) was used as alkaline activators for geopolymerization. Here sodium hydroxide (NaOH) flakes was dissolved in water to make NaOH solution. In general, one molar (1 M) NaOH solution is prepared by dissolving 40 grams of NaOH flakes in one litre of water. Both 8 M and 4 M NaOH were taken in different geopolymer specimens for the present study. The chemical composition of sodium silicate was: Na_2O-14.7%, SiO_2-29.4% and Water- 55.9% by mass.

2.4. Superplasticizer

Naphthalene sulphonate based superplasticizer was used in this experiment to improve the workability of the fresh geopolymer mix while maintaining the strength [34].