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A review of the influence of source material's oxide composition on the compressive strength of geopolymer concrete

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A B S T R A C T

Off late, geopolymer concrete has gained significant attention in the construction industry because of the benefits that it brings via, by-product waste utilization, reduction in greenhouse gas emission. Studies reveal that the chemical oxide composition of the raw material (viz., fly ash) strongly influences the mechanical behavior and durability properties of geopolymer concrete. However, not many studies have paid attention towards the influence of an oxide percentage in the raw material on the compressive strength of the geopolymer concrete. In this paper, an attempt has been made to study the compressive strength behavior against the percentage of oxides (viz., SiO_2, Al_2O_3, Fe_2O_3, CaO etc.) present in the raw material which were employed in the production of geopolymer concrete. In this extensive data has been collected from various earlier research publications. Trends for 7 & 28 day compressive strengths against individual oxide component percentages were developed, and it was observed that the strength of geopolymer concrete differs greatly with the variation in percentage of the individual oxide component. Also, each oxide has shown distinct influence on the compressive strength of geopolymer concrete. Further, it has been noticed that the compressive strength of a sample has been predominantly influenced by the percentage of alumina-silicate oxides, and whereas oxides like CaO and Fe_2O_3 even though lesser in amount compared to alumina-silicate oxides have shown a distinctive effect on the strength built-up. Also, the oxide molar ratios influence on the compressive strengths has been analysed and it was noticed that compared to individual oxide composition its influence is not major on the compressive strength development. Therefore, knowing the typical range of the major oxides percentage required for achieving superior compressive strength will be beneficial in developing concrete mix proportion.

1. Introduction

Over the last few decades, rapid industrialization and urbanization is taking place all across the world. This rapid industrialization has a direct influence on the cement usage, which has been tremendously increasing and in turn has led to the emission of large amounts of CO_2 into the atmosphere. Production of one ton cement lead to emission of approximately 1 ton of CO_2 from the reaction of materials and also through fuel consumption for producing cement [1]. Current cement production across the globe is 4.0 billion tonnes per annum and growing at 4% annually [2]. But the usage of cement cannot be completely avoided in the construction because of aestheticism that it gives to the structure compared to the other building materials. So, the ideal thing could be to look at the other alternative. In this regards "geopolymer concrete" holds good, not only in reducing the carbon footprint, but also in utilizing waste materials like fly ash, red mud, slag etc., which helps in reducing the environmental pollution due to their disposal activities. The research on the geopolymer concrete started in 1979 by a French scientist Joseph Davidovits. But, it was not substantial in the first two decades, from the last decade or so, considerable research efforts have been directed mainly because the geopolymer concrete performance is at par or even superior to conventional concretes. Also geopolymer concrete has an added advantage of significant reduction of greenhouse gas emissions; it gives an answer to the peoples increasing emphasis on global warming and energy conservation [3].

Geopolymer concrete is a green concrete, which is synthesized by alkali activation of source material rich in aluminosilicates, using strong alkali solutions like NaOH or KOH and soluble

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silicates (mostly) such as sodium silicate in gel, under appropriate curing conditions [4]. A very wide range of industrial by-product waste materials and natural raw materials, such as fly ash [5–7], slag [8,9], palm oil fuel ash [10,11], rice husk ash [5,12], from the rice milling units, red mud a waste by-product of alumina refining industry [12,13], copper and hematite mine tailings [14,15], metakaolin [16,17], silica fume [18], which are rich in aluminosilicates can be used as source materials. The source material in the presence of alkaline medium undergoes geopolymerization to form an amorphous to semi-crystalline structure with strength similar to or higher than the conventional concrete.

The reaction between the source material (which basically is of geological origin) and the alkaline activator represents an inorganic polymerization process, and hence its mechanism is termed as "geopolymerization". The geopolymerization mechanism basically involves the following three steps: 1) Dissolution of Al and Si species from the source material under the influence of alkali media. Dissolution starts immediately once the alkaline solution gets in contact with the source material rich in aluminosilicates and allows for an ionic interface between species followed by the breaking of covalent bonds between silicon, aluminum and oxygen atoms. The dissolution of Al and Si species depends on the amount and composition of the source material, and the pH of the activator [19,20]. 2) Dissolution is followed by the transportation or orientation or condensation of precursor ions into monomers, and 3) Polycondensation of monomers take place to form a rigid three-dimensional network of silica-aluminates.

In geopolymerization process, the Si–Al species undergoes a substantially fast chemical reaction in the presence of suitable alkaline conditions yielding an amorphous to semi-crystalline polymers chain and ring structure consisting of Si–O–Al and Si–O–Si bonds [21]. In fact, the geopolymerization depends on the ability of the aluminum ions either in four-fold or six-fold coordination to induce crystal structure, chemical changes in silica backbone [22].

With the geopolymer concrete, the use of ordinary Portland cement can be completely avoided and subsequently CO_2 emissions can be reduced. Even though the utilization of waste materials and reduction of CO_2 emissions is very much essential, one has to look into the mechanical properties of the final product, since the mechanical properties are the governing factors for any concrete to decide its suitability and superiority over others.

Till now the various research studies have revealed that the following factors affect the compressive strength properties of geopolymer concrete: the nature and the type of alkaline activator [8,23], concentration of alkaline activator [13,24], temperature and time of curing [5,18,25,26], chemical composition and type of source material [27], ratio of Si to Al in the geopolymer system [16], mass ratio of alkaline activator solution to source material [28], sodium silicate to sodium hydroxide mass ratio [29], water to geopolymer solids ratio [30,31], sodium silicate form i.e. liquid or powder form [32], ratio of SiO_2 to Na_2O in the geopolymer system [33,34], mixing time and rest period prior to curing [31], effect of molar ratio of Na_2O to H_2O in the geopolymer system [35], concentration of CaO, K_2O, and Si-to-Al molar ratio in the source material [36], etc.

As such, not many studies have been directed towards finding the influence of the individual oxides percentage present in the source material employed for geopolymer concrete on its compressive strength properties. Having an idea of the typical range of the oxide components in the source material will help in choosing the material that has to be employed and it will also help when two or more materials are employed for making geopolymer concrete. The primary aim of this paper is to evaluate the influence of the percentage of major oxides such as SiO_2, Al_2O_3, CaO, and Fe_2O_3 on the compressive strength of low calcium fly ash based geopolymer concretes. As the other factors are controllable in the laboratory like the type and concentration of solution, curing temperature and methods, mixing time, etc., it is the oxides percentages presence in the source material which is not controllable, and therefore the present study is of utmost important. Secondly, an attempt has been made to validate the findings from the primary study with the geopolymer concretes made with different raw materials. And finally, the study is extended to validate the findings with the geopolymer concretes made by using two or more raw materials mixed together.

1.1. Basis for data points

Vast data points relating to the compressive strength of geopolymer concrete have been collected from the past research reports of various researchers all across the world. In the present study, firstly major emphasis has been kept on studying the influence of composition of oxides on the compressive strength of geopolymer concrete made with low calcium based fly ash alone; and later the study is extended to correlate the findings from the former study with the geopolymer concretes made purely using different source materials like high calcium fly ash, metakaolin, Ground Granulated Blast furnace Slag (GGBS), red mud, and as well as with the geopolymer concretes made using the mixture of two or more source materials. Also, in order to judge the findings from the study, proper experimental investigation was also conducted on the geopolymer concrete cubes cast in the laboratory by using low calcium fly ash (NALCO Plant, Angul, India), GGBS (Orissa, India) and red mud (NALCO Plant, Damanjodi, India) as source material. The data points obtained from literature survey have been tabulated in Table 1.

2. Literature review and experimental validation

2.1. Role of various oxides in geopolymer concrete

Materials which are rich in aluminosilicates like fly ash, slag, metakaolin, rice husk ash, granulated blast furnace slag etc., act as efficient binder materials in geopolymer concrete preparation. More importantly, the starting binder material plays a significant role in the geopolymeric reaction and affects the mechanical properties of the final hardened product [36,59]. The source material mainly comprises of SiO_2, Al_2O_3, Fe_2O_3, Na_2O, K_2O, and CaO. Of this, 90% is contributed by SiO_2, Al_2O_3, CaO, and Fe_2O_3, with the other oxides presence being relatively low. Therefore, the role of these oxides seems to be of major influence on the compressive strength of the geopolymer concrete.

The geopolymerization reaction primarily involves the chemical reaction between the dissolved species of silicates and aluminates(Al^{3+} in four– fold coordination, mostly) in the presence of highly alkaline activator solution, yielding any one of the -Si-O-Al-O- poly(sialate) (Si/Al = 1), –Si–O–Al–O–Si–O– poly(sialate-siloxo) (Si/Al = 2), and –Si–O–Al–O–Si–O–Si–O– poly(sialate-disiloxo) (Si/Al = 3) molecular units or chemical groups based on their Si/Al ratio. The resulting polymeric Si–O–Al–O bond formation can be presented schematically as follows [60];