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Strength Study on Geopolymer Concrete using Recycled Aggregate

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Abstract—*Geopolymer concrete (GPC) is a new class of building materials that has been emerged as an alternative to Ordinary Portland cement concrete (OPCC) and possess the potential to revolutionize the construction industry. The influence of alkaline activators on the strength characteristics of geopolymer has been studied. Fly ash used in this study was procured from a local thermal power station. Specimens are manufactured from low calcium fly ash by activation with a mixture of Sodium Hydroxide and Sodium Silicate solution. The concrete is prepared with a fly ash ratio of 0.5.Geopolymer specimens are cast using mix proportion with 12 Molar of sodium hydroxide solution. Compression strength test and Split tensile test are carried out for the specimens under elevated temperature. From the review of literatures, it indicates that the combination of the above constituents at 60o C has a positive impact on the strength characteristics of geopolymer concrete. The term recycled concrete aggregate (RCA) is used to define aggregate produced from crushed demolition and construction waste. Used together, geopolymer concrete and recycled concrete aggregate eliminate the need for Portland cement and makes use of waste materials. Since it utilizes the industrial waste such as flyash for producing the binding system in concrete it can be considered as eco-friendly materials.*

1. INTRODUCTION

1.1 General

Concrete usage around the world is second only to water. Ordinary Portland cement (OPC) is conventionally used as the primary binder to produce concrete. The environmental issues associated with the production of OPC are well known. The amount of the carbon dioxide released during the manufacture of OPC due to the calcination of limestone and combustion of fossil fuel is in the order of one ton for every ton of OPC produced. In addition, the extent of energy required to produce OPC is only next to steel and aluminium.

On the other hand, the abundant availability of fly ash worldwide creates opportunity to utilize this by-product of burning coal, as a substitute for OPC to manufacture concrete. When used as a partial replacement of OPC, in the presence of water and in ambient temperature, fly ash reacts with the calcium hydroxide during the hydration process of OPC to form the calcium silicate hydrate (C-S-H) gel. The development and application of high volume fly ash concrete, which enabled the replacement of OPC up to 60% by mass is a significant development.

In 1978, Davidovits (1999) proposed that binders could be produced by a polymeric reaction of alkaline liquids with the silicon and the aluminium in source materials of geological origin or by-product materials such as fly ash and rice husk ash. He termed these binders as geopolymers.

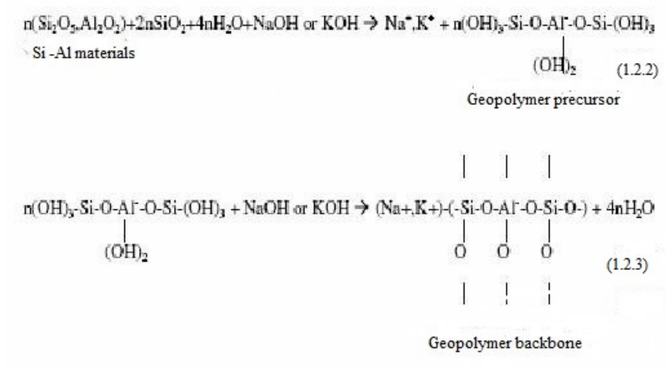
Palomo et al (1999) suggested that pozzolans such as blast furnace slag might be activated using alkaline liquids to form a binder and hence totally replace the use of OPC in concrete. In this scheme, the main contents to be activated are silicon and calcium in the blast furnace slag. The main binder produced is a C-S-H gel, as the result of the hydration process. This work was therefore dedicated to the development and the manufacture of fresh and hardened fly ash-based geopolymer concrete.

1.2 Geopolymers

Geopolymers are members of the family of inorganic polymers. The chemical composition of the geopolymer material is similar to natural zeolitic materials, but the microstructure is amorphous instead of crystalline. The polymerisation process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, those results in a three dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds, as follows (Davidovits 1999):

$$M_n [-(SiO_2)_z–AlO_2]_n.wH_2O \quad \text{(Equation 1.2.1)}$$

The equation 1.2.1 shows that M = the alkaline element or cation such as potassium, sodium or calcium; the symbol – indicates the presence of a bond, n is the degree of polycondensation or polymerisation; z is1, 2, 3, or higher, up to 32.



Equation 1.2.2 and 1.2.3

The last term in Equation 1.2.3 reveals that water is released during the chemical reaction that occurs in the formation of geopolymers.

This water, expelled from the geopolymer matrix during the curing and further drying periods, leaves behind discontinuous Nano-pores in the matrix, which provide benefits to the performance of geopolymers.

The water in a geopolymer mixture, therefore, plays no role in the chemical reaction that takes place; it merely provides the workability to the mixture during handling. This is in contrast to the chemical reaction of water in a Portland cement mixture during the hydration process.

1.2.1 Geopolymer Properties

The slump value of the fresh fly-ash-based geopolymer concrete increases with the increase of extra water added to the mixture .The Rest Period, defined as the time taken between casting of specimens and the commencement of curing, of up to 5 days increases the compressive strength of hardened fly ash-based geopolymer concrete. The increase in strength is substantial in the first 3 days of Rest Period. As the H2O-to-Na2O molar ratio increases, the compressive strength of fly ash-based geopolymer concrete decreases. The effect of the Na2O-to-Si2O molar ratio on the compressive strength of fly ash-based geopolymer concrete is not significant. The measured values of the modulus elasticity of fly ash-based geopolymer concrete with compressive strength in the range of 40 to 90 MPa were similar to those of OPC concrete. The Poisson's ratio of fly ash-based geopolymer concrete with compressive strength in the range of 40 to 90 MPa falls between 0.12 and 0.16. These values are similar to those of OPC concrete. Geopolymers possess high early strength, low shrinkage, freeze-thaw resistance, sulphate resistance, corrosion resistance, acid resistance, fire resistance, and no dangerous alkali-aggregate reaction.

Based on laboratory tests, geopolymer cement can harden rapidly at room temperature and gain the compressive strength in the range of 20 MPa after only 4 hours at 20oC and about 70-100 MPa after 28 days. Comfier et al, (1988) conducted tests on geopolymer mortars and reported that most of the 28-day strength was gained during the first 2 days of curing.

Geopolymeric cement was superior to Portland cement in terms of heat and fire resistance, as the Portland cement experienced a rapid deterioration in compressive strength at 300oC, whereas the geopolymeric cements were stable up to 600oC. It has also been shown that compared to Portland cement, geopolymeric cement has extremely low shrinkage. The presence of alkalis in the normal Portland cement or concrete could generate dangerous Alkali-Aggregate-Reaction. However the geopolymeric system is safe from that phenomenon even with higher alkali content. Geopolymer cement is also acid-resistant, because unlike the Portland cement, geopolymer cements do not rely on lime and are not dissolved by acidic solutions.

The heat-cured fly ash-based geopolymer concrete undergoes very little drying shrinkage in the order of about 100 micro strains after one year. This value is significantly smaller than the range of values of 500 to 800 micro strain for Portland cement concrete. The heat-cured fly ash-based geopolymer concrete has an excellent resistance to sulphate attack. There is no damage to the surface of test specimens after exposure to sodium sulphate solution up to one year. There are no significant changes in the mass and the compressive strength of test specimens after various periods of exposure up to one year. There is no mechanism to form gypsum from the main products of polymerisation in heat-cured low-calcium fly ash-based geopolymer concrete. Exposure to sulphuric acid solution damages the surface of heat-cured geopolymer concrete test specimens and causes a mass loss of about 3% after one year of exposure. The severity of the damage depends on the acid concentration.

1.2.2 Factors affecting the properties of geopolymers

Several factors have been identified as important parameters affecting the properties of geopolymers. The curing temperature was a reaction accelerator in fly ash-based geopolymers, and significantly affected the mechanical strength, together with the curing time and the type of alkaline liquid. Higher curing temperature and longer curing time were proved to result in higher compressive strength. Alkaline liquid that contained soluble silicates was proved to increase the rate of reaction compared to alkaline solutions that contained only hydroxide.

The water content and the curing and calcining condition of kaolin clay affected the properties of geopolymers. However, curing at too high temperature caused cracking and a negative effect on the properties of the material. Therefore, the use of mild curing improve the physical properties of the material. The source materials also determine the properties of geopolymers, especially the CaO content, and the water-to-fly ash ratio.

Based on the study of geopolymerisation of sixteen natural Si-Al minerals, the factors such as the percentage of CaO, K2O, and the molar Si-to-Al ratio in the source material, the type of alkali liquid, the extent of dissolution of Si, and the molar Si-to-Al ratio in solution significantly influences the compressive strength of geopolymers.

1.3 Geopolymer concrete products

Palomo et al (2004) reported the manufacture of fly ash-based geopolymer concrete railway sleepers. They found that the geopolymer concrete structural members could easily be produced using the existing current concrete technology without any significant changes. The engineering performances of the products were excellent and the drying shrinkage was small.

Earlier, Balaguru et al (1997; 1999) reported the use of geopolymer composites layers to strengthen concrete structures as well as geopolymer coating to protect the transportation infrastructures. They reported that geopolymer composites have been successfully applied to strengthen reinforced concrete beams. The performance of geopolymers was better than the organic polymer in terms of fire resistance, durability under ultra violet light, and did not involve any toxic.

1.4 Fly ash-based geopolymer concrete

In this project, fly ash-based geopolymer is used as the binder, instead of Portland cement paste, to produce concrete. The fly ash-based geopolymer paste binds the loose coarse aggregates, fine aggregates and other un-reacted materials together to form the geopolymer concrete, with or without the presence of admixtures. The manufacture of geopolymer concrete is carried out using the usual concrete technology methods.

As in the case of OPC concrete, the aggregates occupy about 75-80 % by mass, in geopolymer concrete. The silicon and the aluminium in the fly ash react with an alkaline liquid that is a combination of sodium silicate and sodium hydroxide solutions to form the geopolymer paste that binds the aggregates and other un-reacted materials.

1.5 Fly Ash

Fly ash is one of the residues generated in the combustion of coal. Fly ash is generally captured from the chimneys of power generation facilities. These ash particles consist of silica, alumina, oxides of iron, calcium, and magnesium and toxic heavy metals like lead, arsenic, cobalt, and copper. This poses problems in the form of land use, health hazards, and environmental dangers.

In addition to economic and ecological benefits, the use of fly ash in concrete improves its workability, reduces segregation, bleeding, heat evolution and permeability, inhibits alkali-aggregate reaction, and enhances sulphate resistance.

1.6 Recycled aggregate

When structures made of concrete are demolished or renovated, concrete recycling is an increasingly common method of utilizing the rubble. Concrete aggregate collected from demolition sites is put through a crushing machine. Crushing facilities accept only uncontaminated concrete, which must be free of trash, wood, paper and other such materials. Metals such as rebar are accepted, since they can be removed with magnets and other sorting devices and melted down for recycling elsewhere. The remaining aggregate chunks are sorted by size. Larger chunks may go through the crusher again. After crushing has taken place, other particulates are filtered out through a variety of methods including hand-picking and water flotation.

There are a variety of benefits in recycling concrete rather than dumping it or burying it in a landfill.

- Keeping concrete debris out of landfills saves landfill space.
- Using recycled material as gravel reduces the need for gravel mining.
- Using recycled concrete as the base material for roadways reduces the pollution involved in trucking material.

1.7 Economic benefits

Low-calcium fly ash-based geopolymer concrete offers several economic benefits over Portland cement concrete. Therefore, low-calcium fly ash-based geopolymer concrete is cheaper than Portland cement concrete.

One ton low-calcium fly ash can be utilised to manufacture approximately 2.5 cubic metres of good quality fly ash-based geopolymer concrete, and hence earn monetary benefits through carbon-credit trade. Furthermore, the very little drying shrinkage, the low creep, the excellent resistance to sulphate attack, and the good acid resistance offered by the low-calcium fly ash-based geopolymer concrete provides additional economic benefits when used in infrastructure applications.

1.8 Objective of the study

In this study, cement is completely replaced by Geopolymer binder which consists of fly ash and alkaline liquids. Our aim is to utilize the recycled aggregate instead of normal coarse aggregate in Geopolymer concrete and to compare the strength characteristics of Geopolymer concrete using recycled aggregate with Geopolymer concrete using normal aggregate.

2. METHODOLOGY

2.1 Mix Design

Concrete mixture design process is vast and generally based on performance criteria. Simple guidelines for the design of heat-cured low-calcium fly ash-based geopolymer concrete are proposed. The role and the influence of aggregates are considered to be the same as in the case of Portland cement concrete. The mass of combined aggregates may be taken to be between 75% and 80% of the mass of geopolymer concrete. The performance criteria of a geopolymer concrete mixture depend on the application. For simplicity, the compressive strength of hardened concrete and the workability of fresh concrete are selected as the performance criteria. In order to meet these performance criteria, the alkaline liquid-to-fly ash ratio by mass, water-to-geopolymer solids ratio by mass, the wet-mixing time, the heat-curing temperature, and the heat-curing time are selected as parameters. With regard to alkaline liquid-to-fly ash ratio by mass, values in the range of 0.30 and 0.45 are recommended. Based on the results obtained from numerous mixtures made in the laboratory over a period of four years, the data given in Table are proposed for the design of low-calcium fly ash-based geopolymer concrete. Note that wet-mixing time of 4 minutes, and steam-curing at 60oC for 24 hours after casting are proposed.

Sodium silicate solution is cheaper than sodium hydroxide solids. Commercially available sodium silicate solution A53 with SiO_2-to-Na_2O ratio by mass of approximately 2, i.e., Na_2O = 14.7%, SiO_2 = 29.4%, and water = 55.9% by mass, and sodium hydroxide solids (NaOH) with 97-98% purity are recommended. Laboratory experience suggests that the ratio of sodium silicate solution-to-sodium hydroxide solution by mass may be taken approximately as 2.5 (Hardjito and Rangan, 2005).

2.2 Specimen Details

Table 2.1 Specimen details

Specimens used	Specimen size	No. of Specimens casted
Cubes	150mmX150mmX150mm	6
Cylinder	300mm height,150mm dia	6

The following tests were carried out to study the strength behaviour of geopolymer concrete.

- Compression test

Compressive strength of Geopolymer Concrete is determined for G30 grade. It is tried for 12M molarity. Fly ash obtained from sub-bituminous coal is used with alkaline liquid. The cube mould of size 15cmx15cmx15cm is used. After curing, the cube is tested for compressive strength using compression testing machine. Compression testing machine is shown in the figure 2.1

Figure 2.1 Compression testing machine

- Split tensile test

This ASTM test method covers the determination of the splitting tensile strength of cylindrical concrete specimens. This method consists of applying a diametric compressive force along the length of a cylindrical specimen.

This loading induces tensile stresses on the plane containing the applied load. Tensile failure occurs rather than compressive failure. Plywood strips are used so that the load is applied uniformly along the length of the cylinder. The maximum load is divided by appropriate geometrical factors to obtain the splitting tensile strength.

Calculate the splitting tensile strength as follows:

$$f'_{st} = \frac{2P}{\pi l d}$$

Where,

P = Maximum load at failure

l = length of cylindrical specimen

d = diameter of cylindrical specimen

The split-tensile test is shown in the following figure 2.2

3. RESULTS AND DISCUSSIONS

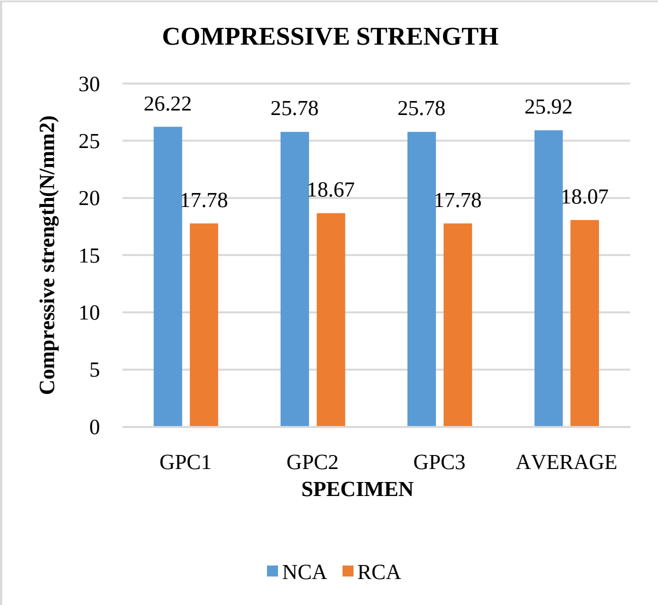


Fig. 3.1 Comparison of compressive strength

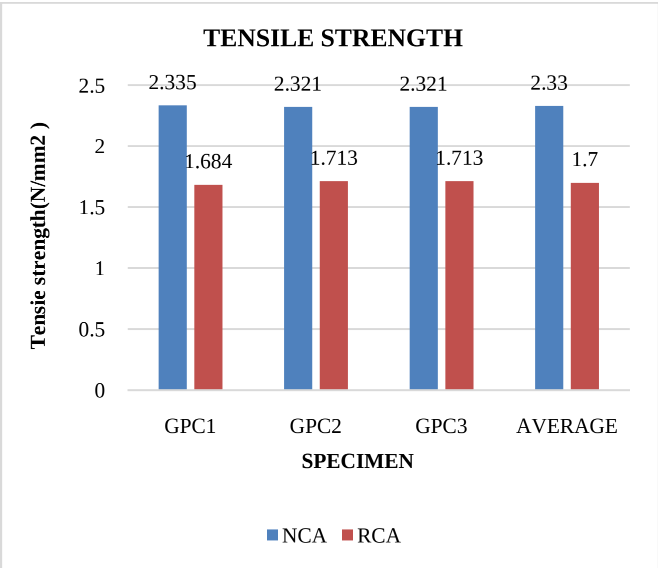


Fig. 3.2: Comparison of tensile strength

3.1 Discussion based on results

1. When normal coarse aggregate is replaced by the recycled aggregate there is a reduction in compressive strength.
2. Compared with the conventional geopolymer concrete there is 30% reduction in the compressive strength of the geopolymer concrete using recycled aggregate.
3. The relative compressive strength of conventional geopolymer and geo polymer with recycled aggregate is in the ratio of 1 : 0.697
4. Compared with the conventional geopolymer concrete there is a 27% reduction in the tensile strength of the geopolymer concrete using recycled aggregate.

3.2 Conclusion

Based on the experimental work reported in this study, the following conclusions are drawn:

1. The reduction in compressive strength of geopolymer concrete using recycled aggregate is allowed upto 10%-15%. Here the reduction in the strength is 30% and it can be reduced to lower percentage by partial replacement of normal coarse aggregate with recycled aggregate.
2. The compressive strength of heat cured fly ash based geo polymer concrete does not depend on age.
3. The increase in strength beyond 24 hours of heat curing is not significant.
4. The fresh fly ash-based geo polymer concrete is easily handled up to 120 minutes without any sign of setting and without any degradation in compressive strength
5. The addition of naphthalene sulphonate-based super plasticizer, approximately up to 4% of fly ash by mass, improves the workability of the fresh geopolymer concrete
6. In this study,the strength is low due to hand compaction and using only fly ash as a byproduct in a binder.So,the strength can be increased by machine compaction and replacing a fly ash by silica fume.

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