CARBON FOOTPRINT REDUCTION USING GEOPOLYMER CONCRETE

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The size and complex nature of today's construction project resulted in a global increase of the carbon footprint. Increased carbon dioxide emissions results in a severe deterioration to the environment and negative health implications. Recent studies showed that the production of 1 metric ton of portland cement results in the evolution of 0.9 metric tons of carbon dioxide. At this rate, the construction industry represents a significant threat on mankind. This paper presents geopolymer (cement-free) concrete applications in the United States local construction market. Geopolymer concrete production depends on the activation of a pozzolanic supplementary cementitious material (SCM) with a high alumino-silicate content using alkaline solution as sodium hydroxide (NaOH). The SCM activated material - known as precursor - forms a three-dimensional polymer that binds the aggregates instead of hydrated portland cement. The widespread of geopolymer concrete will significantly reduce the need to portland cement; hence, reduces the carbon emissions resulting from cement production. In addition to the environmental advantages, geopolymer concrete is highly durable due to the fine size of SCMs particles. Geopolymer concrete is more resistant to alkali-silica reactivity, and early age cracking. The widespread of geopolymer concrete in construction industry, especially in infrastructure projects, will result in significant improvement in projects condition, and lower the need to frequent maintenance, repair, and replacement of projects.

Keywords: Portland cement, Supplementary cementitious materials, Slag, Fly ash, Alkali activator, Precursor.

1 INTRODUCTION

The size and complex nature of today’s construction project resulted in a global increase of the carbon footprint. Increased carbon dioxide emissions results in a severe deterioration to the environment and negative health implications. To-date, several cities within the United States are classified as “non-attainment” areas where air-quality doesn’t meet the health standards set by the Environmental Protection Agency (EPA). Cement production is considered among the major pollutants to the environment due to the significant emission of carbon dioxide during cement manufacturing. Recent studies showed that 0.9 metric ton of carbon dioxide is emitted for every 1 metric ton of cement manufactured. As a result, several research programs have investigated the possible reduction of portland cement by incorporating supplementary cementitious materials (SCMs) as fly ash, silica fume, metakaolin, and blast furnace slag. According to Akhnoukh (2013, 2020a), SCMs are successfully incorporated in high strength concrete mixes resulting in a 30% reduction of cement consumption. According to Graybeal (2006), Akhnoukh and Soares (2018),
Akhnoukh and Elia (2019), Akhnoukh and Buckhalter (2021), Akhnoukh (2008, 2018a, 2018b, 2020b), and Akhnoukh et al. (2016) SCMs have positively impacted different concrete mechanical properties and improved its long-term performance through increased modulus of elasticity, modulus of rupture, and improved alkali-silica reactivity. This paper presents the applications of “cement-free” geopolymer concrete, its applications, and its possible utilization in reducing the carbon footprint of construction projects.

2 LITERATURE REVIEW

Geopolymer is the scientific term given by Davidovits in 1978 to hybrid materials characterized by chains and networks of organic materials. Recently, geopolymer was defined as “A term used to describe inorganic polymers based on aluminosilicates and can be produced by synthesizing pozzolanic compounds or aluminosilicate source materials with highly alkaline solution,” (Kong et al. 2007). The afore-mentioned theory of geopolymers is used to create a binding chemical that can be used in producing concrete mixes with superior characteristics. Opposite to ordinary portland cement (OPC) mixes, GPC uses different geopolymer cement materials as a binding material in lieu of portland cement (Davidovits 1991). Geopolymer cements include slag-based geopolymer cements (Mayhoub et al. 2021), rock-based geopolymer cements (Davidovits 2013), and fly-ash geopolymer cements (Adewuyi 2021).

Geopolymer concrete mix development depends on the creation of three-dimension geopolymer chain through the activation of a high alumina-silicate content in a byproduct material (example fly ash) using an alkaline solution as sodium or calcium hydroxide. Generated geopolymer chain would bind the aggregate content within the mix to form the required GPC mix. Mechanical properties of GPC depend on the type of geopolymer cement used and its alumina-silicate content, type and concentration of alkaline solution used in reaction action (polymerization), mixing regimen, and curing temperature. GPC basic mix constituents are shown in the following section.

3 GEOPOLYMER MIXES CONSTITUENTS

Geopolymer concrete production depends on the activation of a SCM with high aluminosilicate content as fly as, silica fume, blast furnace slag, and/or metakaolin using an alkali solution as sodium or potassium hydroxide combined with sodium or potassium silicates. The SCM is known as “precursor” and the alkaline solution is known as “activator”. GPC final characteristics is highly dependent on the individual properties of precursor material and the type/concentration of the alkaline activator.

3.1 Geopolymer Precursors

- **Class C fly ash**: derived from sub-bituminous coal and contains a high percentage of calcium oxide and a low carbon content. Class C fly ash is a pozzolanic material with self-cementing properties. Class C fly ash was initially used as a supplementary cementitious material in developing OPC concrete through stepwise replacement of Portland cement. Currently, Class C fly ash is used in producing cement-free GPC mixes.
- **Class F fly ash**: derived from bituminous coal and contains a higher percentage of silicon dioxide as compared with Class C fly ash. Class F fly ash is pozzolanic material without self-cementing properties. Class F fly ash developed mixes are highly resistant to alkali-silica reactivity, and very low void ratio. However, the average final strength of Class F fly ash mixes tends to be lower than mixes developed using Class C fly ash.
Class C and F fly ash are standardized using ASTM C618 and AASHTO M 295 specifications to set quality standards required for use in developing OPC and/or GPC mixes. Standard specifications are shown in Table 1 (AASHTO 2021, ASTM 2019a).

Table 1. Chemical requirements for fly ash in construction industry.

<table>
<thead>
<tr>
<th>Component</th>
<th>Class F FA</th>
<th>Class C FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide, aluminum oxide, and iron oxide, min %</td>
<td>70.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Sulfur trioxide, max %</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Moisture content, max %</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Loss on ignition, max %</td>
<td>6.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

- **Ground granulated blast-furnace slag**: is a self-cementing material and is a bi-product of blast furnaces used to make iron. Ground granulated blast furnace slag (GGBS) is used in producing GPC mixes due to its high aluminosilicate content. Flowing ability and mechanical properties of GGBS based geopolymers are highly dependent on the alkaline activator liquid to binder ratio (AAL/B) and water to binder ratio (W/B). Recent research showed that compressive strength in excess of 80 MPa are produced when 16M concentration of alkaline solution and 500 kg of binder was used, including 2% of nano-silica as per Saini and Vattipalli (2020). GGBS typical chemical composition is shown in Table 2.

Table 2. Chemical composition of GGBS.

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium oxide</td>
<td>40%</td>
</tr>
<tr>
<td>Silica</td>
<td>35%</td>
</tr>
<tr>
<td>Alumina</td>
<td>13%</td>
</tr>
<tr>
<td>Magnesia</td>
<td>8%</td>
</tr>
</tbody>
</table>

- **Silica fume**: also known as micro-silica is a byproduct of ferrosilicon industry. Typical silica fume particle size ranges from 0.5 – 1.0 µm. Traditionally, silica fume is used as a reactive pozzolan in partial replacement of cement in OPC mixes. The incorporation of micro-sized silica fume particles increases the compressive strength and durability of OPC mixes. Recently, silica fume is being used in GPC mix development. Silica fume is used in fly-ash based geopolymers to increase the mix density, compressive strength, and enhance its durability as per Okoye et al. (2016).

### 3.2 Alkaline Activators

Alkaline activators are used in the production of GPC mixes as they initiate and catalyze the geopolymerization process to form the concrete binder required to attain the required strength. Basic alkaline activators include sodium and potassium hydroxides. Alkaline activators are used in combination with sodium or potassium silicate solutions. The most common combination includes an activating solution composed of sodium hydroxide and sodium silicate solution. A recent study showed that 5 mol/dm³ of sodium hydroxide and 100 grams of sodium silicate results in increased compressive strength as compared to other mixes as per Prochon et al. (2020). In addition to the geopolymer cements and alkaline activators, GPC mix design includes coarse and fine aggregates used as an economic filler, and high range water reducers (HRWRs) to enhance GPC mix flowing ability at a lower water content.
4  FRESH AND HARDENED PROPERTIES OF GEOPOLYMER CONCRETE

GPC mixes provides a broad spectrum of fresh and hardened concrete properties. Variation in results attained is attributed to the type of pozzolan used as geo-polymer cement, pozzolan quantity, and the silica-to-aluminate ratio within the binder, the type of the alkaline solution, its molarity, temperature of mix production, and curing methods.

- Fresh GPC mix properties: as workability and set time decreases by increasing the molarity of the alkaline solution. In a recent study, the flow diameter of fresh GPC mix was reduced by 40% when sodium hydroxide molarity was increased from 8 (320 g per liter) to 12 (480 g per liter). Similarly, the increase in sodium silicate-to-sodium hydroxide ratio results in a significant decrease in GPC mix flowing ability (Malkawi et al. 2016). In GPC concrete mixes, final set time is short. On average a time span of 30 to 45 minutes were recorded between initial and final set time of GPC mixes. Thus, GPC could be beneficial in construction applications in need to high early strength as retrofitting of structural members, crack treatment, specific precast/prestressed applications, and additive manufacturing (3-D printing) of concrete (Akhnoukh 2021).

- Hardened GPC mix properties: in concrete is primarily judged by its compressive strength. In GPC mixes, strength is acquired at a faster pace compared to OPC. GPC mixes gained 75% of its final strength at 3-day compressive strength testing. GPC mixes of strength up to 90-100 MPa were attained when silica fume was used in addition to alkaline solutions with high molarity. In addition, GPC has low heat of hydration in comparison with OPC, higher fire resistance, and a chloride permeability rating of “low” to “very low” as per ASTM C1202 (ASTM 2019b).

5  GEOPOLYMER CONCRETE ADVANTAGES

GPC mixes market share has substantially increased in the recent decade (Akhnoukh 2022). The GPC mixes are used in petrochemical industry projects, mining applications, fire proofing, and structural applications, with emphasis on infrastructure projects, as follows:

- Petrochemical industry projects: including above ground and sub-surface storage tanks. GPC is highly utilized in petrochemical industry due to its durability and resistance to chemical attacks.

- Structural concrete: is being poured using GPC mixes due to the high strength attained and the increased project sustainability. GPC is extensively used in infrastructure projects including pouring bridge decks, highway hard pavement, water and sewer pipes, and retaining walls. GPC structural concrete includes high strength mixes, self-consolidating mixes, normal weight mixes, and light weight mixes using lightweight aggregates as expanded shales and clays.

- Fireproofing: applications are commonly used in structural applications, especially when steel sections are used. GPC mixes are successfully used in coating or covering steel sections susceptibly to fire to increase structural safety and integrity. Fireproofing uses GPC due to its higher resistivity to fire and very high temperature as compared to OPC mixes.

6  GEOPOLYMER APPLICATIONS IN THE UNITED STATES

Geopolymer concrete market share has expanded during the past decade (Akhnoukh 2022). Currently, GPC is used in multiple applications including 3-D printing of artificial reefs, construction of highway infrastructure by the FHWA and different State DOTs. GPC mixes are
used as a coating layer to protect reinforced concrete members against corrosion. Finally, GPC has been successfully used in the production of thermal-resistant tiles and in marine construction applications.

7 CONCLUSIONS

Geopolymer concrete is currently used in different construction applications to exploit its environmental advantages and superior mechanical properties. GPC binder is developed through the chemical reaction between geopolymer cement and alkaline solution to create a 3-D geopolymer chain that binds the aggregates within the mix. GPC mix properties are highly dependent on the type of geopolymer cement used, the type and molecular concentration of the alkaline solution, quality of aggregates used, the percentage of water and chemical used within the mix, and the temperature of the mix during mixing and curing.

The absence of portland cement in GPC mixes is favorable due to the reduction in carbon dioxide emissions that happens during cement manufacturing process. Thus, GPC construction projects are considered highly sustainable. In addition, the fineness of geopolymer cement used results in very low void ratio within GPC poured structural members, which increases its strength, and resistivity to alkali-aggregate reactions, and chloride attacks. Currently, GPC mixes are used in heavy construction projects including bridges, highways, and retaining structures. Additional research is required to expedite the introduction of GPC in different construction applications in the US and global markets.

References

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