Environmental Impact Assessment of fly ash and GGBS based Geopolymer Concrete in Road Construction

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Abstract – Geopolymer concrete is an effective alternative to reduce adverse impacts of cement manufacturing on environment and achieving sustainable development. Road construction is a major sector, which utilizes concrete in large volume, having significant effect on environment. The present work is presented in two parts. In the first part, evaluation of CO₂ emission for 1m³ of geopolymer and ordinary Portland cement concrete has been carried out and further compared. In the second part the results of first part are used to evaluate the CO₂ emission for various types of road construction, National highway, State highway, Major District Road, Other District Road, Village Road for 1km of road. About 18% of reduction in CO₂ emission can be obtained by using geopolymer concrete instead of ordinary Portland cement concrete in road construction, just in 1km of stretch. Significant reduction in CO₂ emission can be obtained in road sector by utilising geopolymer concrete leading to sustainability.

1. Introduction

India stands second in production of cement globally. The demand for cement in roads, urban infrastructure, and commercial real estate is expected to grow at a compound annual growth rate (CAGR) of 5.65% between FY16 and FY22[1]. India produced 329 million tonnes of cement in FY20, but 294.4 million tonnes (MT) of cement in FY21. It is estimated that cement industry will reach 419.9 million tons per annum by FY2027[2]. Regarding specific energy consumption, the cement industry in the nation is among the most energy-efficient in the globe.

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The consumption and production of cement for each year from 2016 to 2022 is shown in Fig. 1 region wise. From the figure, it is observed that cement production is increasing day by day with increase in cement consumption. Cement industry releases CO$_2$ in the atmosphere, which contributes to global warming. Every 1 ton of cement manufacturing process emits up to 1 ton of CO$_2$\cite{4}. Emission of CO$_2$ from cement industry is 50% from the calcination process of limestone, 40% from combustion of fuels in kiln, 5% from transportation and the remaining 5% from electricity used in manufacturing operations\cite{5}. Type of fuel used for cement manufacturing affects CO$_2$ emission. To reduce the air pollution and global warming efforts should be taken. Using cement substitutes to make concrete is a fair starting point to reduce the CO$_2$ emissions of concrete. There are many different types of cement substitutes, including fly ash, GGBS, rice husk ash, metakaolin, etc. However, it is important to take into account cement alternatives made from waste products from different industries.

Fig. 1. Cement consumption and cement production in India.

Fig. 2. CO$_2$ Emission over years\cite{3}.
For instance, industrial wastes, such as fly ash and Ground Granulated blast furnace slag (GGBS) are waste by products from the thermal power plant and iron and steel industry, respectively. The quantity of fly ash and GGBS waste from industries are increasing day by day. The disposal is covering several hectares of valuable land. Thus, these large volumes of fly ash and GGBS which are considered as waste can be used as a substitute for cement in the production of concrete.

Total fly ash generation is increasing in every year from 2014-15 to 2019-20 and it is highly anticipated to increase in the following years. Substituting 100% of the cement with these industrial by products will help to utilize the growing waste streams and reach the carbon reduction goal faster.

French Professor Davidovits introduced the term Geopolymer concrete (GPC) in 1978. The geopolymer concrete is an emerging class of cementitious materials that can be produced with industrial waste/by products like fly ash, GGBS as a substitute for Portland cement. Alkaline solution can be prepared from sodium hydroxide and sodium silicate or by potassium hydroxide and potassium silicate in proper proportion. Geopolymer cement, high alkali (K-Ca)-Poly(sialate-siloxo) cement, results from inorganic polycondensation reaction, called geopolymerisation yielding three dimensional zeolitic frameworks. The behavior of geopolymer concrete is similar to that of zeolites and feldspathoids, they immobilize hazardous materials within the geopolymeric matrix, and act as binder to convert semi-solids into adhesive solids.

Fig. 3. Advantages of Geopolymer Concrete

Geopolymer Concrete

Reduction of CO2 Emission
Minimise Dumping issue of Industrial Waste
High Fire Resistance
Less Water Consumption
Waste Consumption
2 Environmental Impact of Geopolymer Concrete

G.Habert et al. concluded the results of the environmental impact of different geopolymer materials. The impact assessment method known as CML 2001, developed by the Institute of Environmental Sciences (CML) of Leiden University, was used for the impact evaluation to evaluate 10 environmental impacts, including abiotic depletion, global warming, ozone layer depletion, fresh and marine water ecotoxicity, terrestrial ecotoxicity, human toxicity, eutrophication, acidification, and photochemical oxidation.

G.Habert et al. and Zain et al. reported that, in the case of geopolymer concrete, it is clear that using a sodium silicate solution has the greatest effect on the environment. It is evident that this new type of binder enables a significant decrease in the global warming potential when this type of geopolymer concrete is compared with conventional cement concrete. Geopolymer concrete emits only 169 kg of equivalent CO$_2$ per m$^3$, which is a 45% reduction from the 306 kg of equivalent CO$_2$ per m$^3$ released by OPC-based concrete.

Interesting to note that, this amount is not significantly different from the carbon dioxide (CO$_2$) reduction obtained with an increase in cement technology efficiency, where a 50% reduction can be attained by using current geopolymer concrete technologies. Because of this, even though this new technology greatly reduces CO$_2$ emissions, it is not significantly different from solutions that only promote for technological improvements and clinker replacement rather than requiring drastic changes in existing technology. In the building industry, where a conservative approach to new products is understandable, these eco-efficiency solutions are usually preferred over revolutionary options. Because of this, fly ash-based geopolymer concrete, as it is presently developed, does not include the innovative technology which could help the concrete industry to reduce CO$_2$ emissions by a factor around 4.

Due to the use of sodium silicate solution, geopolymer concrete consistently exhibits greater impacts on the environment than OPC concrete in the other environmental impact categories. When sodium silicate solution is used in place of OPC in concrete, pollution from global warming issues will become secondary to all other environmental effects.

3. System Boundary and Life Cycle Assessment of Geopolymer Concrete

Life cycle assessment of any product or service is potential impact assessment during their full life. For production of cement concrete, energy is consumed from very first stage of raw material extraction or production. System boundaries include raw materials extraction and production, alkali activators production, and GPC production.
Fig. 4. System Boundary and Life Cycle Assessment of Geopolymer Concrete

Above figure shows system boundary analysis of OPC concrete and Geopolymer concrete which includes:

Quarrying: In this process, raw material is extracted from quarry. This process involves foul gas emission from combustion of fuel, electricity usage for mining, drilling, crushing etc.

Cement Raw material Production: Blending and grinding of raw material like Lime stone and GGBS requires large amount of electricity.

Cement Pyro processing: Heating of raw materials at about 800°C for production of clinkers emits large number of foul gases. Heavy use of electricity impacts largely on environment.

Clinker cooling process: consists of emissions produced by the instant cooling of clinkers with electricity.

Cement Grinding and Milling: Emission caused by heavy usage of electricity for grinding and milling of cement.

Cement conveying and Packing: This process includes conveying of cement in process and final cement product within the plan. Along with conveying, packing of cement also has emission produced by usage of electricity.

Transportation: Transporting the raw materials to mixing plant from manufacturing plant and concrete from mixing plant to site requires use of heavy vehicles. Vehicular movement consumes fuel and produces foil gases leading to huge environmental impact.

Demolition: After useful life of concrete, it is demolished and dumped at site. For demolition of harden concrete breakers and other heavy equipment’s are used which consumes fuel and
4 Comparison of Environmental Impact between Geopolymer concrete and OPC Concrete

Comparison of Environmental Impact of GPC and OPC concrete has been carried out by considering the major parameters as quantities of raw materials required to produce 1m$^3$ of concrete and other operations like batching, transportation and site placement. The calculations are divided into two parts, first from raw materials and second by considering the operations.

Quantities of raw materials required for 1m$^3$ of GPC and OPC concrete has been calculated by carrying out mix design. Table 1. Provides the raw material quantities required for 1m$^3$ of GPC and OPC Concrete.

Table 1. Quantities of Raw Materials for 1m$^3$ of GPC and OPC Concrete.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Raw Material</th>
<th>Quantity of Material required for 1m$^3$ of concrete (kg)</th>
<th>GPC</th>
<th>OPC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>NaOH</td>
<td>64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Na$_2$SiO$_3$</td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Fly Ash</td>
<td>448</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>GGBS</td>
<td>112</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Fine Aggregate</td>
<td>564</td>
<td></td>
<td>711</td>
</tr>
<tr>
<td>6</td>
<td>Coarse Aggregate</td>
<td>1048</td>
<td></td>
<td>1283</td>
</tr>
<tr>
<td>7</td>
<td>Cement</td>
<td></td>
<td>380</td>
<td></td>
</tr>
</tbody>
</table>

After calculating the quantities required for 1m$^3$ of GPC and OPC concrete, the CO$_2$ emission has been calculated to assess the environmental impact. For calculation of CO$_2$ emission, basic values of each raw material have been considered from literature. Table 2. Presents the CO$_2$ emission by each raw materials for 1m$^3$ of GPC and OPC concrete.

Table 2. CO$_2$ Emission by Raw Materials for 1m$^3$ of GPC and OPC concrete.

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Material</th>
<th>CO$_2$ Emission for unit quantity (kg CO$_2$/kg)</th>
<th>Actual CO$_2$ Emission from 1 m$^3$ concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>GPC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OPC</td>
</tr>
<tr>
<td>1</td>
<td>NaOH</td>
<td>0.603</td>
<td>38.592</td>
</tr>
<tr>
<td>2</td>
<td>Na$_2$SiO$_3$</td>
<td>1.26</td>
<td>201.6</td>
</tr>
<tr>
<td>3</td>
<td>Fly Ash</td>
<td>0.027</td>
<td>12.096</td>
</tr>
<tr>
<td>4</td>
<td>GGBS</td>
<td>0.035</td>
<td>3.92</td>
</tr>
<tr>
<td>5</td>
<td>Fine Aggregate</td>
<td>0.0139</td>
<td>7.84</td>
</tr>
<tr>
<td>6</td>
<td>Coarse Aggregate</td>
<td>0.0408</td>
<td>42.759</td>
</tr>
<tr>
<td>7</td>
<td>Cement</td>
<td>0.82</td>
<td>311.6</td>
</tr>
</tbody>
</table>

Total 306.807 373.83
As discussed in section 3 of this work, system boundary plays an important role in the assessment of environmental impact of any product. In the present work, along with the raw materials, few other important operations are considered and an attempt has been made to arrive at more realistic results.

The operations considered are Batching, Transportation, and site placement. For the calculation of CO$_2$ emission, basic values are considered from available literature. The CO$_2$ emission values are presented in Table 3.

Table 3. CO$_2$ emission for various operations of concreting

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Material</th>
<th>CO$_2$ Emission</th>
<th>Unit</th>
<th>Actual CO$_2$ Emission from 1 m$^3$ concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Batching</td>
<td>0.0033 kg CO$_2$</td>
<td>m$^3$</td>
<td>GPC and OPC</td>
</tr>
<tr>
<td>2</td>
<td>Transportation</td>
<td>0.0094 kg CO$_2$</td>
<td>m$^3$</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Site Placement</td>
<td>0.009 kg CO$_2$</td>
<td>m$^3$</td>
<td></td>
</tr>
</tbody>
</table>

The cumulative values of CO$_2$ emission for 1 m$^3$ of GPC and OPC concrete by considering raw materials and few important operations are 306.830 kg CO$_2$-e/m$^3$ for GPC and 373.853 kg CO$_2$-e/m$^3$ for OPC concrete. The calculation shows nearly about 18% of reduction in CO$_2$ emission can be obtained just in 1 m$^3$ of concrete, if GPC concrete is utilized instead of OPC concrete. These calculations and results obtained clearly demonstrate that the utilization of GPC concrete is an effective alternative to achieve sustainability.

Major utilization of concrete is in the field of infrastructure. In order to evaluate the effect of GPC as compared to OPC concrete in road construction, further calculations are carried out and are presented in the next section.

5. Road Construction: CO$_2$ Emission comparison between GPC and OPC Concrete -

Roads are the most used mode of transportation. As pavement construction helps in employment, health, education, and other services which ultimately aim to develop the nation. Roads are classified in two types according to the method of construction and materials used. Flexible and rigid pavements are the two types of pavements. Rigid pavement is concrete pavement which is more durable and requires less maintenance than flexible pavement. From research, it is proven that about 35% of the cost is reduced over the full life cycle when rigid pavement is constructed and compared with flexible pavement [16]. Rigid pavement reduces fuel consumption of passenger vehicles and heavy weight vehicles.

In India, for improving socio-economic growth and enabling it to overcome the impact of COVID-19 pandemic, the Ministry placed the highest ever target of 12,000 kms for award and 12,000 kms for construction for the year 2021-22 [17]. Overall road projects exceed 64,000 km in length, costing more than Rs. 11 lakh crores. Out of which work in respect of projects of more than 40,000 km length has been completed and in balance length of more than 24,000 km is in progress [17].

From above statistics, we can observe that a large amount of concrete is used in road construction. Generally, ordinary Portland cement concrete is widely used in this construction, which emits a large amount of CO$_2$. This CO$_2$ emission can be reduced to some extent by using Geopolymer concrete.
Table 4. CO₂ Emission in road construction for various road classes

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Road Classes</th>
<th>Roadway width in meters (Plain Terrain)</th>
<th>Volume of Concrete Required for 1.0 km Length (Cum)</th>
<th>CO₂ Emission (MT) using Ordinary Portland Cement Concrete</th>
<th>CO₂ Emission (MT) using Geopolymer Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>National and State highway</td>
<td>12.0 (Single Lane) 12.0 (Two lanes)</td>
<td>3000 3000</td>
<td>1122 1122</td>
<td>921 921</td>
</tr>
<tr>
<td>2</td>
<td>Major District Roads</td>
<td>9.0 (Single Lane) 9.0 (Two lanes)</td>
<td>2250 2250</td>
<td>841.5 841.5</td>
<td>690.75 690.75</td>
</tr>
<tr>
<td>3</td>
<td>Other District Single Lane Roads</td>
<td>7.5</td>
<td>1875 2250</td>
<td>701.25 841.5</td>
<td>575.62 690.75</td>
</tr>
<tr>
<td>4</td>
<td>Village Road Single Lane</td>
<td>7.5</td>
<td>1875</td>
<td>701.25</td>
<td>575.62</td>
</tr>
</tbody>
</table>

CO₂ emission calculated for 1m³ of concrete in part 1 of this work are used for these calculations. Table 4 shows the CO₂ emission for various types of roads of 1km. For calculation of concrete volume, nominal thickness of 250 mm is considered as per IRC 118-2015. For the stretch of 1km of rigid pavement nearly 201 MT CO₂ emission can be reduced in case of National and State highway by adopting geopolymer concrete over Ordinary Portland cement concrete.

Fig. 5. CO₂ Emission in road construction for various road classes

![CO₂ Emission in road construction for various road classes](image)
6. Conclusion

The present work has been carried out in two parts. In the first part CO\textsubscript{2} emissions for 1m\textsuperscript{3} of GPC and OPC concrete has been evaluated by considering the CO\textsubscript{2} emissions by raw materials and considering few operations of concreting. In the second part of work the results of part one is used to assess the CO\textsubscript{2} emission for 1km of various types of roads construction for GPC and OPC concrete. On the basis of above work, following major conclusions are derived:

1. Portland cement contributed 83.34% of the CO\textsubscript{2}-e in OPC concrete. Geopolymer binders (fly ash + GGBS + NaOH + Na\textsubscript{2}SiO\textsubscript{3}) contributes 256.208 kg CO\textsubscript{2}-e/m\textsuperscript{3} compared to OPC 311.6 kg CO\textsubscript{2}-e/m\textsuperscript{3}.

2. For 1 km of road stretch about 18% of CO\textsubscript{2} emission reduction can be obtained by utilizing GPC instead of OPC concrete.

On the basis of pretend work, it can be concluded that, the utilization of GPC instead of OPC, reduces the CO\textsubscript{2} emission significantly and further considering the huge utilization of concrete in the field of transportation, the utilization of GPC is the most sustainable solution as it resolves the problems of managing the waste by products and reducing the adverse impacts on the environment.

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