DEVELOPMENT AND PERFORMANCE EVALUATION OF SUSTAINABLE GEOPOLYMER CONCRETE FOR RIGID PAVEMENTS USING RICE HUSK ASH AS A CEMENT REPLACEMENT

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ABSTRACT: *In modern construction, cement was the main binder of the concrete although the boundless use of cement puts a lot of burden on the cement industry causing high costs, raising greenhouse gas emissions. In particular, the emission of one tonne of carbon dioxide (CO_2) for the production of just one tonne of cement is very notable. Over the decades, researchers have been driven by the environmental cause to look for sustainable and cost-effective alternatives. This study investigates the incorporation of rice husk ash (RHA) in geopolymer concrete for rigid pavement applications. Tests to assess workability, compressive strength, flexural strength and split tensile strength were conducted to evaluate performance. Curing at ambient, 45°C, 80°C, and 100°C was performed, and OPCC water cured for 3, 7, 14, and 28 days was served as a benchmark. The highest compressive strength of 27.44 MPa was found at 100°C. In addition, 100°C curing produced the highest results in flexural strength and split tensile strength at 5.17 MPa and 3.24 MPa, respectively. Consistently, specimens attained a target slump of 3 inches, independent of specimen size. Moreover, these CO_2 emissions were compared to those of conventional cement, showing a reduction in excess of 90%. These outcomes form the basis for strong recommendation for using RHA based geopolymer concrete as a potential viable and sustainable material for construction of rigid pavement.*

Keywords: Ambient curing, Carbon dioxide emissions, Environmental impact, Geopolymer concrete, Greenhouse gas emissions, Rice husk ash (RHA), Rigid pavements, Sustainable construction.

1. INTRODUCTION

Concrete is an important material used in the construction industry; however, its production has a large price in environmental cost. Cement, due to its importance as one of the most common of concrete ingredients, is manufactured through the burning of fossil fuels and heating of limestone, which releases large quantities of carbon dioxide (CO_2) and other harmful gases. It causes global warming and air pollution due to which causes various environmental and health issues. Rising construction costs and the adverse environmental effects of cement production necessitate alternative materials. 1 metric ton of CO_2 is emitted from the production of 1 metric ton of cement [12]. Moreover, cement carbonation during hydration further contributes to CO_2 emissions during construction, especially in rigid pavements, thus raising the financial burden on those projects. Concrete is responsible for large amounts of greenhouse gas emissions, biodiversity loss and resource depletion, and as such, greater attention is being paid to how it affects this environment. For instance, some studies point out that the process of manufacturing cement, which is energy-intensive and involves copious use of fossil fuels, accounts for about 7% of the global greenhouse gas emissions [4, 18]. Beyond CO_2 emissions, the extraction of both raw materials, such as limestone, sand, and gravel, also entails habitat destruction and biodiversity loss [3].

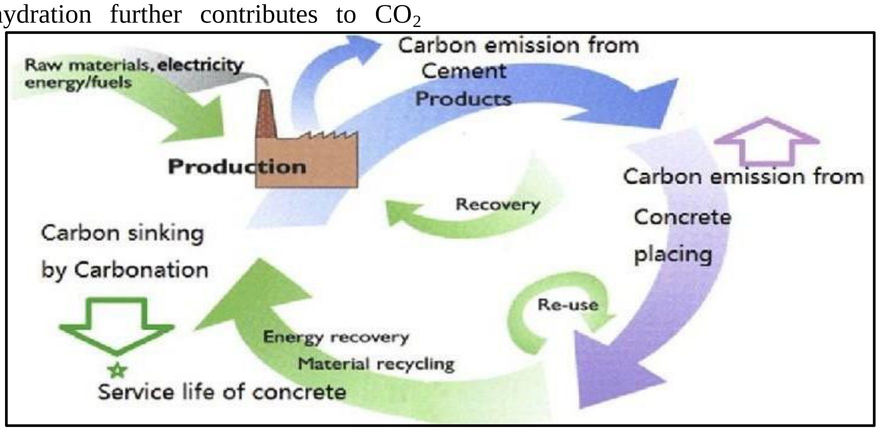

Figure 1: Environmental Impact of Cement Production and Utilization [24].

Scientists have been looking for sustainable alternatives to these environmental concerns. Some of them found that green concrete or the use of materials such as fly ash and slag can reduce dependence on traditional cement [27]. In addition to this, old construction materials are recycled and wonderful substitutes for cement are found, as these processes make the concrete industry much more environmentally friendly and pave the way for a better future of construction. Researchers are also looking at alternative materials to combat these concerns as they look to minimize the environmental impact of concrete production. Rice Husk Ash (RHA) is one such alternative, being a by-product of burning rice husks. Unlike traditional cement, RHA-strengthened concrete reduces CO_2 emissions and leads to more eco-friendly material [1]. Because RHA is abundant, particularly in regions where rice is a major staple food, its use in concrete mixtures is likely to result in a strong, durable concrete with a lower environmental impact. The outer shell of rice grains, known as rice husk, is accessible and frequently thrown away. Burned or used in small-scale non-technical applications. Nevertheless, rice husks are also a valuable natural resource in many parts of the world [10]. Frequently burned to produce electricity via steam generators, the associated ash is then used as a raw material for making self-compacting concrete (SCC). The ash that results when the compound is burned under controlled conditions, if amorphous, is a beneficial supplementary cementitious material (SRM). In SCC, RHA is a pozzolanic material improving concrete properties via its physical packing/filler effect and a chemical pozzolanic effect. These improvements include better strength and durability [21], enhanced resistance to chloride ion penetration [16], improved performance in freeze-thaw conditions, reduced effect of salt coating and a reduction in Alkali silica reaction (ASR) expansion [30]. Furthermore, due to the reduction of unit weight of concrete, RHA increases the resistance of concrete to chemical attack [7, 22]. Thus, RHA has great potential as a desirable alternative to develop sustainable concrete in areas with plentiful rice production. In line with this, geopolymer concrete has become a viable option to be used in place of Portland cement-based concrete due to its sustainability, durability and environmental footprint [14]. Unlike traditional concrete, geopolymer concrete does not depend on cement as its binding agent, which makes the production process a lot less CO_2-intensive. Activated aluminosilicate materials, such as fly ash or slag, with alkali activators can initiate a geopolymerization reaction and form a solid binder matrix through geopolymer binders [15]. On the surface, this process offers benefits in terms of reducing CO_2 emissions since it runs at lower temperatures and avoids the calcination of limestone, a significant CO_2 emitter in conventional cement production [6]. Additionally, the use of industrial by-products such as fly ash, slag or inexpensive materials like rice husk ash (RHA) as supplementary cementitious materials is useful so that the waste can be utilized and the environmental impact of concrete manufacturing minimized. The geopolymer concrete incorporating RHA was developed in this study to mitigate the ever-increasing cement cost and the environmentally unfriendly aspect of cement-based materials. Geopolymer concrete research has shown that geopolymer concrete can achieve or better mechanical properties than conventional concrete. Research has shown that geopolymer concretes may have higher compressive strengths, lower permeability and better resistance to chemical attack and fire when compared to Portland cement-based concrete [20]. The effects of these advancements place geopolymer concrete as a viable and sustainable alternative for the construction industry of the future. Curing of geopolymer concrete is a key aspect of geopolymer concrete production and is very different from curing ordinary Portland cement (OPC) [5]. Curing at OPC is done by water to ensure supply of enough moisture for hydration to allow the formation of CSH gel and CH crystals that provide strength development. It will normally take 7 to 28 days in order for the mixture to achieve full strength. Unlike geopolymer concrete, the geopolymerization process in geopolymer concrete is different. Unlike hydration of the above-mentioned material, geopolymerization requires an external water for the hydration of a polymer, which then forms a geopolymeric binder by geopolymerization. To accelerate this process, thermal or heat curing is used and optimal temperatures are between 40°C and 80°C, for up to 6 to 24 hours [8]. However, too high the temperatures can lead to thermal cracking and decrease long term durability [20]. Consequently, in geopolymer concrete development, alkaline liquids (e.g., sodium or potassium hydroxide and sodium or potassium silicate) especially take an important role. Potassium carbonate, sodium carbonate and others are other alkaline activators that can be used but are not often used due to availability and cost issues [9]. The geopolymerization process, the final concrete properties, as well as the choice and ratio of the alkaline activators depend on the selection and ratio of these alkaline activators. A study concluded that by combining sodium silicate solution with sodium hydroxide, the reaction between the binder material and the activator is improved [28]. Furthermore, research showed that accelerated polymerization is obtained using sodium or potassium silicate other than several alkaline hydroxides [19].In OPC, curing is achieved by water in such a way that the needed moisture for hydration is maintained to form CSH gel and CH crystals, which provide strength development. It normally takes 7–28 days to reach full strength in this hydration process. However, geopolymer concrete is a different process in which a chemical process known as geopolymerization takes place. Geopolymerization instead relies on an alkaline solution to activate polymeric chain and the resulting geopolymeric binder [13]. This process is accelerated by heat curing (or thermal curing) with optimum temperatures between 40°C and 80°C and time varying from 6 to 24 hours [8]. However, excessively high temperatures exacerbate thermal cracking and reduce long term durability [20]. There is a fundamental role for alkaline liquids, consisting of sodium or potassium hydroxide mixed with sodium or potassium silicate, in geopolymer concrete development. There are other alkaline activators like potassium carbonate, sodium carbonate, etc. which are also available but not commonly used when due to their availability and cost issues. A great variety of alkaline activators are available for geopolymerization, with a clear impact on final concrete properties due to the choice and ratio of these alkaline activators. With the various combinations of metals activated by sodium hydroxide, researchers noted that adding sodium silicate solution improved the reaction between the binder material and the activator [28]. Moreover, sodium or potassium silicate accelerates the polymerisation in comparison with other alkaline hydroxides [19].

2. METHODOLOGY

Results from previous research have shown that the method used in the calculation of mix proportions in geopolymer concrete has not been universally accepted compared to the method used for the calculation of mix proportions of Ordinary Portland Cement Concrete. Established practices used in the production and testing of Ordinary Portland Cement Concrete were adopted to streamline the testing and manufacturing process. The reason it was done was to make Rice Husk Ash-based geopolymer concrete compatible with present-day building practices in Pakistan to encourage its use in the construction industry in future. Among the various available materials for making geopolymer concrete, Rice Husk Ash was selected because it is abundant in Pakistan. To improve the feasibility and sustainability of the project, cement and other necessary materials were sourced locally. Moreover, strict quality control measures, including the use of aggregates from a single source, were implemented to minimize the impact of different aggregate properties on the performance of the Rice Husk Ash-based geopolymer concrete.

2.1. MATERIALS USED

2.1.1. RICE HUSK ASH

Initially, Rice Husk Ash was procured online from Lahore Gardening Shop, which was later found to be partially burnt. Though the material was thoroughly analyzed after sieving it through a No. 200 sieve, to assess the mechanical properties of Partially Burnt RHA and its performance. After encountering some problems with GPC made with partially burnt RHA, raw Rice Husk was obtained from Narowal. Subsequently, it was sent to the PCSIR laboratory in Peshawar, which is already producing fully burnt RHA for research purposes. There, it went through high-temperature combustion and was ground to a fineness comparable to OPC.

Figure 3: Fine Aggregate

2.1.2. FINE AGGREGATE

Fine aggregates that were available in the concrete laboratory were used, having a loose bulk density of about 1600 kg/m^3.

Table 1 provides the sieve analysis of the fine aggregate available in the concrete laboratory.

Table 1: Sieve Analysis of Fine Aggregate

Sieve No.		Weight retained	% Retained	Cumulative % Retained	% Passing
No.	**mm**	**(g)**	**(%)**	**(%)**	**(%)**
#4	4.75	3	0.57	0.57	99.43
#8	2.36	5	0.94	1.51	98.49
#16	1.18	57	10.75	12.26	87.74
#30	0.6	132	24.91	37.17	62.83
#50	0.3	249	46.98	84.15	15.85
#100	0.15	58	10.94	95.09	4.91
#200	0.75	12	2.26	97.35	3.02
Pan	0	14	2.64	0.99	0

2.1.3. COARSE AGGREGATE

Coarse aggregate was purchased from a local vendor in Risalpur, with a bulk density of 1550 kg/m3 and an aggregate size range of 13 mm to 25 mm. Table 3.2 provides the sieve analysis for coarse aggregate.

.**Table 2: Sieve Analysis For Coarse Aggregate**

Sieve No.	Weight retained	% Retained	Cumulative % Retained	% Passing
No.	(kg)	(%)	(%)	(%)
3/8	1.2	0.84	0.84	99.16
½	2.3	1.61	2.45	97.55
¾	5.1	3.56	6.01	93.99
1	9.7	6.78	12.79	87.21
11/2	15.2	10.63	23.42	76.58
2	21.17	14.80	38.22	61.78
21/2	25.70	17.97	56.19	43.81
3	30.13	21.07	77.26	22.74
31/2	35.76	22.57	99.83	0.17
Pan	0.24	0.17	100	0

2.1.4. ALKALINE LIQUIDS

Sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were employed as alkaline liquids for activation of geopolymer concrete. The selection of these liquids was based on an extensive literature review and their easy accessibility in the local market. Both the liquids were locally procured from Haq Chemicals, Peshawar and were already in solution form. The molarity of sodium hydroxide (NaOH) was determined to be 12M, which was consistent with the values reported in the literature. These solutions were readily available and met the required specifications for our research purposes.

Figure 1: Alkaline Liquids

2.1.5. SUPERPLASTICIZER

Ultra Superplast 675, a high-performance water-reducing and plasticizing admixture, was incorporated to enhance the workability of RHA-based geopolymer concrete.

2.2. MIXTURE PROPORTIONS

A consistent 1:1.5:3 proportion was used for all of our moulds. This allowed us to directly compare the test strengths to concrete made with the same proportion. In addition, several research studies were reviewed to investigate alternative alkaline activator-to-binder ratios. Specimens were created using these ratios, and after analyzing the data, a ratio of 0.6 looked most appropriate. The same approach was used for the Na_2SiO_3 to NaOH ratio, with a final value of 2.5 determined after thorough analysis of the data. Table 3.3 displays the mix proportions for several samples.

Table 3: Mix Proportions of Various Samples in kg/m^3

Materials	OPCC	RHA-GPC	RHA-GPC	RHA-GPC	RHA-GPC	RHA-GPC	RHA-GPC	RHA-GPC	RHA-GPC
Cement	403.2	-	-	-	-	-	-	-	-
Rice Husk Ash	-	238	238	238	238	238	238	238	238
Coarse Aggregate	1365	1365	1365	1365	1365	1365	1365	1365	1365
Fine Aggregate	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0	672.0
Sodium Silicate Solution	-	180.85	180.85	180.85	180.85	180.85	180.85	180.85	180.85
Sodium Hydroxide Solution	-	72.34	72.34	72.34	72.34	72.34	72.34	72.34	72.34
Water	241.92	22.5	22.5	22.5	22.5	22.5	35	50	70
Super Plasticizer	-	8.925 (3.75%)	5.95 (2.5%)	4.76 (2%)	2.38 (1%)	10.7 (4.5%)	-	-	-

The amount of RHA in GPC was found by using the volume of the cement to be used, and thus using the exact volume of RHA.

2.3. MANUFACTURING PROCESS

The production method for ordinary Portland cement concrete (OPCC) is widely recognized, and considering that this research adhered to standard practices to create a control batch for comparative analysis. It was found that while the manufacturing process for geopolymer concrete (GPC) shares similarities with OPCC, there are a few differences. The steps involved in producing GPC include:

- Mixingofmaterialsandcasting
- Curing

2.3.1. MIXING OF MATERIALS AND CASTING

First, the solid components of the mixture were mixed by hand for 2-3 minutes. Then, the alkaline liquids were mixed separately in the required amounts and added to the mixture. This mixture was then stirred for an additional 5 minutes.
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After mixing, the concrete was poured into various moulds, including 100 mm x 100 mm x 100 mm Cubical Moulds and 100 mm x 200 mm cylinders. Each mould was filled in three layers and compacted manually with a rod for 25 blows per layer. To ensure stability, each layer was placed on a vibrating table for 10 seconds. Similarly, 100 mm x 100 mm x 400 mm prisms were also cast in two layers, with each layer compacted by tamping for 25 blows and then stabilised on a vibrating table for 10 seconds.

2.3.2. Curing

Two types of curing were employed to investigate their effects on the properties of RHA-based GPC. The first type involved dry curing in an oven, as shown in Figure 3.5. After the specimens were cast, they were left in their moulds for a day in an oven located in the structural dynamics lab of MCE. Some of the samples were cured at 100°C while others were cured at 45°C. Subsequently, the samples were left for ambient curing

Figure 5: Curing of Moulds

The second curing method involved curing at ambient temperature without the use of water. This was implemented to assess the effect of temperature variation during curing on the compressive strength of RHA-based GPC and to evaluate its suitability as a binder material under typical daily temperature conditions.

2.3.3. Test Matrix

Table 3. 4 shows the number of specimens made for tests

.Table 4: No. of Specimens

	TYPE OF TEST									
	COMPRESSIVE STRENGTH TEST				FLEXURAL STRENGTH TEST			SPLIT TENSILE STRENGTH TEST		
	Cubical mold				Prism Beam			Cylindrical mold		
SAMPLE	3 DAYS	7 DAYS	14 DAYS	28 DAYS	7 DAYS	14 DAYS	28 DAYS	7 DAYS	14 DAYS	28 DAYS
OPCC	3	3	3	3	3	3	3	3	3	3
RHA GPC 3.75%SP 100C	3	3	3	3	3	3	3	3	3	3
RHA GPC 3.75% SP 80C	3	3	3	3						
RHA GPC 3.75%SP 45C	3	3	3	3						
RHA GPC 3.75%SP Ambient	3	3	3	3						
RHA GPC 1% SP		2	2	2						
RHA GPC 2% SP		2	2	2						
RHA GPC 2.5% SP		2	2	2						

RHA GPC 4.5%SP		2	2	2						
RHA GPC 0.14 W/B		2	2	2						
RHA GPC 0.21 W/B		2	2	2						
RHA GPC 0.3 W/B		2	2	2						

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4. COMPRESSIVE STRENGTH TEST

The compressive strength test of specimens was performed on 3000 KN automatic servo plus machine available in structural dynamics lab, MCE as shown in figure 3.6. The tests were performed according to ASTM C39. In case of RHA based GPC specimens which were dry cured, they were taken for testing to check 7-, 14-, and 28-day strengths. The RHA-based GPC specimens, which underwent ambient curing conditions, were tested for 7-, 14- and 28-day strengths. The tests were performed at ambient temperature. Capping of Sulphur was carried out for RHA-GPC specimens because of the rough surface they have at the top and bottom. After application of Sulphur to the face of cylinders, the specimens were then cured for 5 hours, and then they were tested. The specimens were placed in the machine, and the relevant testing mode was selected from the menu in the machine. The test was stress-controlled with the load being applied at "0.25 MPa/s as per ASTM C39". The machine stopped the application of load automatically when the ultimate strength was achieved for the specimen at a stop load of 5%. Compressive strength test results were then recorded from the machine.

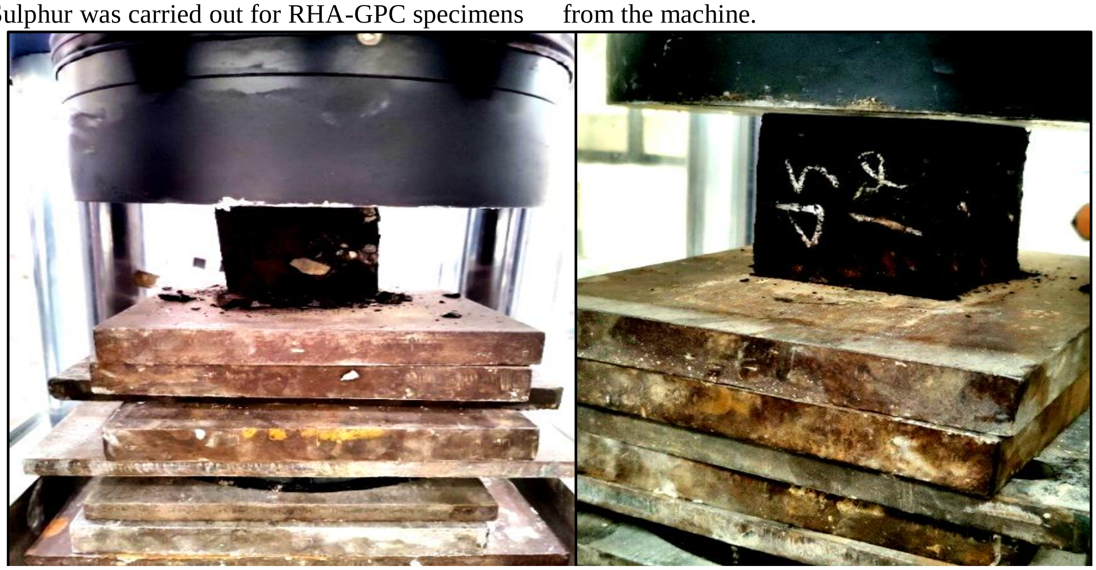


Figure 6: Compression Testing of Specimens

2.5. SPLIT TENSILE TEST

The Splitting tensile test of specimens was performed on the same (3000 KN automatic servoplus)machine that was used for compressive strength tests, as shown in Figure 3.8. The tests performed adhered to the standards outlined in ASTM 496. The test was performed on 100mm x 200mm cylindrical specimens. Before the testing specimens were adjusted in a steel jig to ensure proper alignment of the surface. The jig was then firmly placed within the machine, and the settings for the appropriate testing mode were adjusted. The test followed a stress-controlled protocol, and the load was applied at a rate of "0.7 – 1.4 MPa/min as per ASTM 496. The machine stopped applying the load automatically when the ultimate tensile strength of the cylinder was achieved. In the end, the results were then noted from the machine’sinterface.

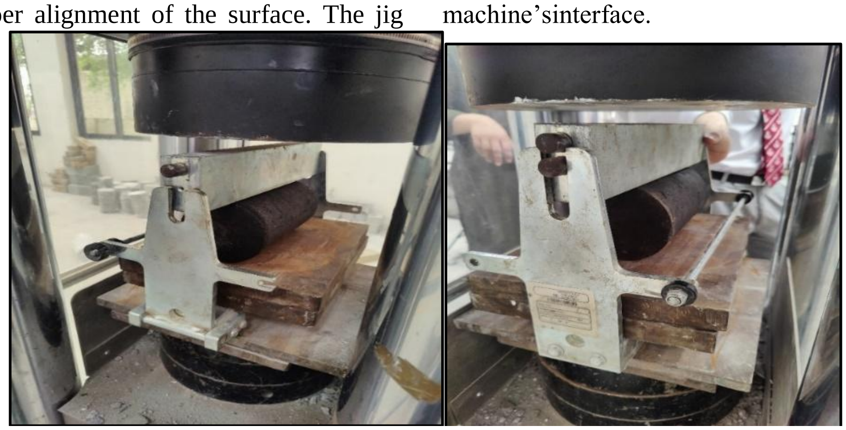


Figure 7: Split Tensile Test of Specimen

2.6. FLEXURAL STRENGTH TEST

The flexural test of specimens was conducted on prisms as shown in Figure 3.9. The tests were conducted according to ASTM C293. The size of the prisms was 100 mm x 100 mm x 400 mm. In case of based GPC, specimens which were dry cured at 100°C were tested for 7-, 14- and 28-day strengths. The supporting blocks, which would act as supports for the prism, were attached to the machine and the prism was then placed on the supporting blocks. A space of 25 mm was left between the point support and the end face of the prism as per the ASTM standard. The load applying block was then applied on the upper face of prism at centrepoint.Theloadwasappliedonthespecimenwithoutanyabruptchangesandtherateof loading was kept at 1 MPa/s which was well within the range mentioned in ASTM standards .

Figure 8: Flexural Testing of Specimen.

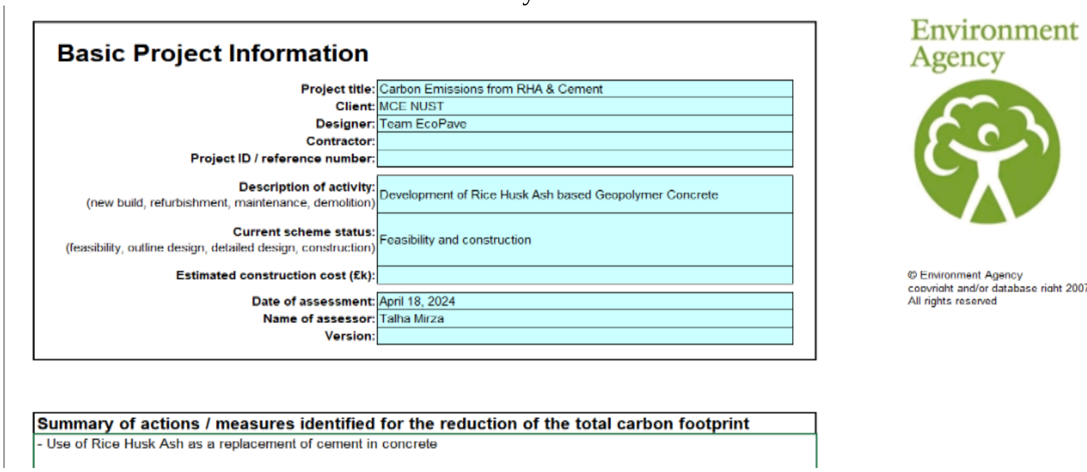
2.7. CARBON FOOTPRINT

To determine the carbon footprint, we did a thorough inspection of the carbon emissions related with the manufacturing of 100 cubic meters of both Ordinary Portland Cement (OPC) and Geopolymer Concrete (GPC). We used a carbon calculator given by the Environment Agency to properly calculate and compare the carbon emissions generated by each material, as shown in Figure 3.10. This evaluation gave us a useful understanding of the environmental impact of GPC over OPC. As RHA was not available in the carbon calculator, we used fly ash-based GPC as a substitute. This choice was made because RHA and fly ash have similar characteristics, allowing for a more realistic estimate of carbon emissions.

3. RESULTS AND DISCUSSIONS

3.1. Compressive Strength Test

Table 5 below shows the results of compressive strength tests performed by varying parameters like quantity of water, superplasticiser and temperature to check their effects on the compressive strength of Geopolymer Concrete incorporating Rice Husk Ash.



Basic Project Information

Project title:	Carbon Emissions from RHA & Cement
Client:	MCE NUST
Designer:	Team EcoPave
Contractor:	
Project ID / reference number:	
Description of activity: (new build, refurbishment, maintenance, demolition)	Development of Rice Husk Ash based Geopolymer Concrete
Current scheme status: (feasibility, outline design, detailed design, construction)	Feasibility and construction
Estimated construction cost (£k):	
Date of assessment:	April 18, 2024
Name of assessor:	Talha Mirza
Version:	

Environment Agency

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Summary of actions / measures identified for the reduction of the total carbon footprint

- Use of Rice Husk Ash as a replacement of cement in concrete

Construction material	Unit Conversion or Density	Embodied tCO_2e per tonne of material	Quantity (tonnes)	Distance between source of supply and site (km)	Mode of transport
Quarried aggregate	2.0 tonnes/m3	0.005	137		
Sand	1.2 tonnes/m3	0.005	67		
Fly Ash	1.5 tonnes/m3	0.01	24		

Construction material	Unit Conversion or Density	Embodied tCO_2e per tonne of material	Quantity (tonnes)	Distance between source of supply and site (km)	Mode of transport
Quarried aggregate	2.0 tonnes/m3	0.005	137		
Sand	1.2 tonnes/m3	0.005	67		
Cement: unknown type	1.5 tonnes/m3	0.88	40		

Figure 9: Carbon Emissions Calculator

Table 5: Compressive Strength Test Results of Various Specimens

COMPRESSIVE STRENGTH (PSI)					
SAMPLE	**3 DAYS**	**7 DAYS**	**14 DAYS**	**28 DAYS**	**REMARKS**
OPCC	890	1840	2660	2880	Water Cured
RHA-GPC 3.75% SP/B	1670	2710	3540	3980	Oven Cured at 100 C for 24 hours
RHA-GPC 3.75% SP/B	1550	2540	3250	3850	Oven Cured at 80 C for 24 hours
RHA-GPC 3.75% SP/B	1450	2330	3080	3630	Oven cured at 45 C for 24 hours
RHA-GPC 3.75% SP/B	1120	2170	2760	3250	Ambient Cured
RHA-GPC 1% SP/B		2470	3040	3550	Ambient Cured
RHA-GPC 2% SP/B		2350	2970	3430	Ambient Cured
RHA-GPC 2.5% SP/B		2220	2790	3320	Ambient Cured

RHA-GPC 4% SP/B		2060	2570	3050	Ambient Cured
RHA-GPC 0.14 W/B		2430	2935	3110	Ambient Cured
RHA-GPC 0.21 W/B		2130	2670	2950	Ambient Cured
RHA-GPC 0.30 W/B		1550	2325	2720	Ambient Cured

3.1.1. COMPARISON BETWEEN COMPRESSIVE STRENGTHS OF OPC AND GPC

When the compressive strength of Ordinary Portland Cement Concrete was compared with that of Geopolymer Concrete incorporating Rice Husk Ash which was thermally cured, interesting findings were revealed. Figure 10 below shows strength of different specimens which were cured at 3, 7, 14, and 28-days. It can be concluded that Geopolymer Concrete incorporating Rice Husk Ash gives better results than Ordinary Portland Cement Concrete, showing a considerable improvement ranging between 10% to 35%, depending on the curing temperature that was applied to Geopolymer Concrete incorporating Rice Husk Ash. Moreover, the steady gain in strength that was observed during the curing phase shows how maturing and developing Geopolymer Concrete incorporating Rice Husk Ash still is.

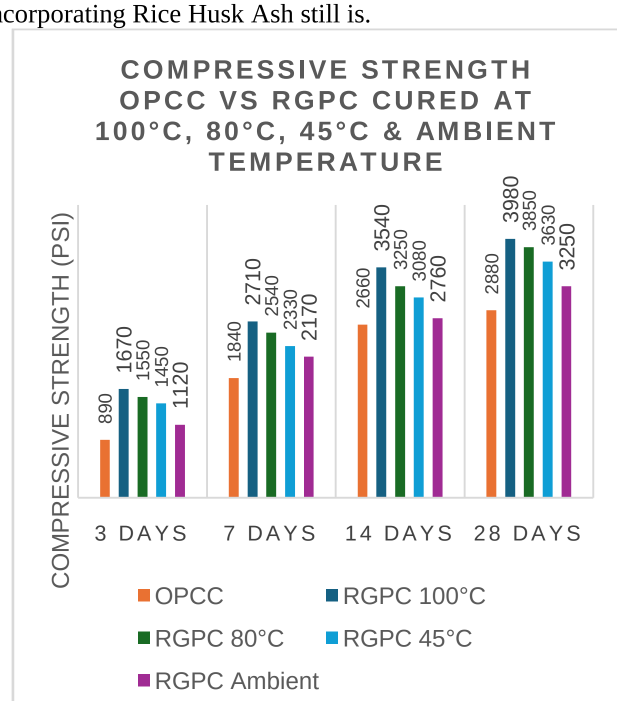

Figure 10: Comparison Between Compressive Strength of OPCC And Rice Husk Ash-Based Geopolymer Concrete Cured at Different Temperatures.

When the compressive strength of regular water-based concrete was compared with that of Geopolymer Concrete incorporating Rice Husk Ash, which was cured at ambient temperature and contained varied percentages of superplasticiser, like results were observed. Figure 11 shows a clear pattern throughout 7-, 14-, and 28- days. Geopolymer Concrete incorporating Rice Husk Ash continuously outperforms regular concrete in terms of compressive strength, with superplasticizer percentages ranging from 1% to 4%. Particularly, depending on the amount of superplasticizer used, the strength advantage varies from 5% to 20%.

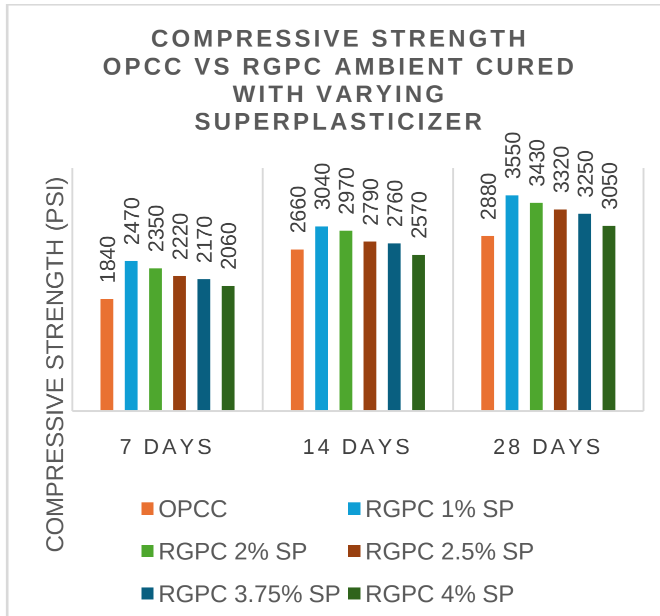

Figure 11: Comparison Between Compressive Strength of OPCC And Rice Husk Ash Based Geopolymer Concrete with Different Superplasticizer Percentages.

Figure 12 offers valuable information about the compressive strength comparison between Ordinary Portland Cement concrete (OPCC) and Geopolymer Concrete incorporating Rice Husk Ash made with different water-to-binder ratios and cured at ambient temperatures. The figure depicts distinct trends over 7-, 14-, and 28- days, where with a water-to-binder ratio of 0.14, Geopolymer Concrete incorporating Rice Husk Ash shows a significant strength advantage over OPCC, with a compressive strength that is around 5% higher. On the contrary, Geopolymer Concrete incorporating Rice Husk Ash mixtures with 0.21 water-to-binder ratios shows similar compressive strength to OPCC, suggesting similar performance when curing under ambient temperatures. It is interesting to note that Geopolymer Concrete incorporating Rice Husk Ash, having a water-to-binder ratio of 0.3 shows less strength than OPCC, indicating that there may be a trade-off between compressive strength and water content in Geopolymer Concrete incorporating Rice Husk Ash formulations. These results highlight how important the water-to-binder ratio is in determining the mechanical characteristics.

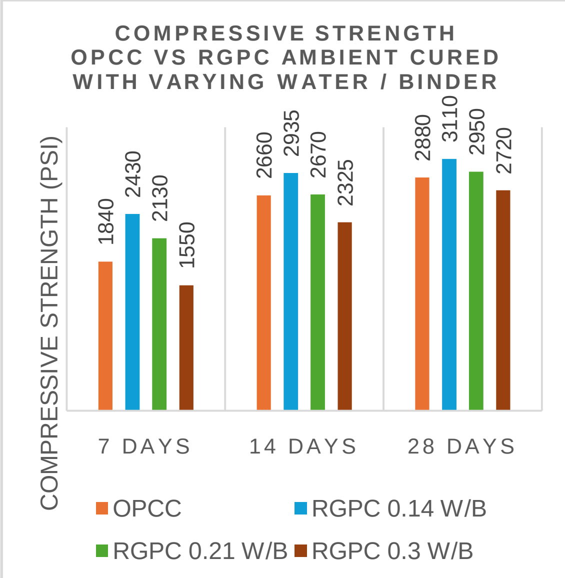

Figure 12: Comparison Between Compressive Strength of OPCC And Rice Husk Ash-Based Geopolymer Concrete with Different W/B Ratio.

3.1.2. EFFECTS OF CURING TEMPERATURE

Investigating how the temperature at which curing is done affects the compressive strength of geopolymer concrete (Geopolymer Concrete incorporating Rice Husk Ash) based on rice husk ash (RHA) uncovers interesting patterns. A consistent relationship can be seen from figures 13 to 7, 14, and 28-day compressive strength of RHA-based Geopolymer Concrete, which shows gradually higher compressive strength as the curing temperature rises from ambient levels to 100°C. But after a certain temperature, the further increment has not that much of an effect on the compressive strength of Geopolymer Concrete incorporating Rice Husk Ash. Geopolymer Concrete incorporating Rice Husk Ash that was cured at 100°C comes out on top, displaying the highest compressive strength of all the specimens that were examined.

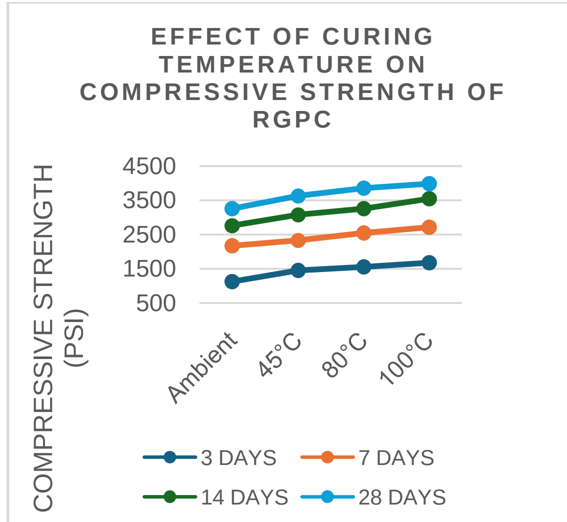

Figure 13: Effect of Curing Temperature on Compressive Strength of Rice Husk Ash-Based Geopolymer Concrete.

3.1.3. Effects of Superplasticizer

To increase the workability of Geopolymer Concrete incorporating Rice Husk Ash, superplasticizer was added to it. Table 6 below shows the compressive strength, slump, and workability of Geopolymer Concrete incorporating Rice Husk Ash made with varying percentages of superplasticizer, cured at ambient temperature.

Table 6: Compressive Strength, Slump and Workability of Various Specimens

SAMPLE	COMPRESSIVE STRENGTH (PSI)			SLUMP (in)	WORKABILITY	CURING
	7 DAYS	14 DAYS	28 DAYS			
RHA-GPC 1% SP/B	2470	3040	3550	0.75	Very Low	Ambient Cured
RHA-GPC 2% SP/B	2350	2970	3430	1.5	Low	Ambient Cured
RHA-GPC 2.5% SP/B	2220	2790	3320	2	Medium	Ambient Cured
RHA-GPC 3.75% SP/B	2170	2760	3250	3	Medium	Ambient Cured
RHA-GPC 4% SP/B	2060	2570	3050	3.5	Medium	Ambient Cured

The effect of the addition of varying percentages of superplasticizer by weight of the binder on the compressive strength of Geopolymer Concrete incorporating Rice Husk Ash is shown graphically in Figure 14 below. From Figure 4.3, as the amount of superplasticizer is increased, the compressive strength of Geopolymer Concrete incorporating

Rice Husk Ash starts to decrease. As a result, it can be deduced that the workability of the Geopolymer Concrete incorporating Rice Husk Ash increases, but the compressive strength decreases.

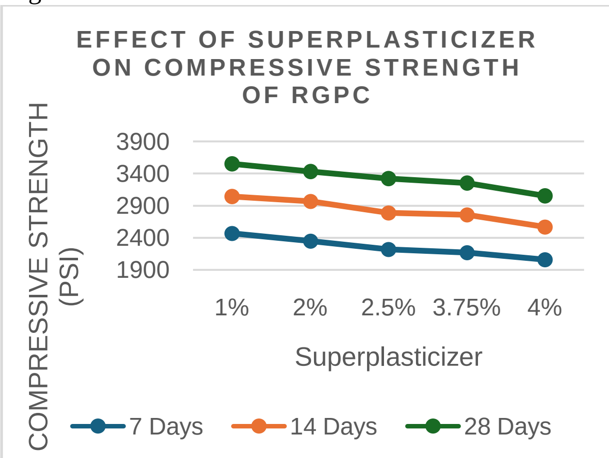

Figure 14: Effect of Superplasticizer on Compressive Strength of Rice Husk Ash-Based Geopolymer Concrete

3.1.4. EFFECT OF WATER BINDER RATIO

Water was added to RHA-based Geopolymer Concrete according to a specific water-to-binder ratio to increase its workability. Table 7 below gives the information about the compressive strength, slump and workability of RHA based Geopolymer Concrete made with different water to binder ratios and the curing of which was done at ambient temperature

The effect of addition of water according to different water to binder ratios on the compressive strength of Geopolymer Concrete incorporating Rice Husk Ash is shown graphically by figure 15 below. The compressive strength Geopolymer Concrete incorporating Rice Husk Ash decreases with increasing the quantity of superplasticizer and higher water-to-binder ratios.

The overall results indicate that the compressive strength of Geopolymer Concrete incorporating Rice Husk Ash is greater than that of Ordinary Portland Cement Concrete (OPCC) and shows the effectiveness of Rice Husk Ash (RHA) as a binding material.

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Table 7: Compressive Strength, Slump and Workability of Various Specimens

	COMPRESSIVE STRENGTH (PSI)			SLUMP (in)	WORKABILITY	CURING
SAMPLE	7 DAYS	14 DAYS	28 DAYS			
RGPC0.14 W/B	2430	2935	3110	1.5	Low	Ambient Cured
RGPC 0.21 W/B	2130	2670	2950	3	Medium	Ambient Cured
RGPC 0.30 W/B	1550	2325	2720	4.5	High	Ambient Cured

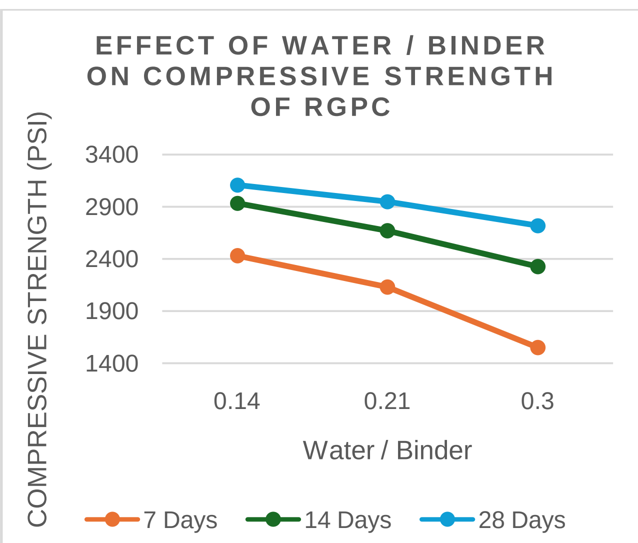

Figure 15: Effect of W/B on Compressive Strength of Rice Husk Ash-Based Geopolymer Concrete

3.2. FLEXURAL STRENGTH TEST

The results of the flexural strength test performed are shown in Table 8 given below.

Figure 16 shows the comparison of the flexural strength of Ordinary Portland Cement Concrete (OPCC) with Geopolymer Concrete incorporating Rice Husk Ash. From figure 11 flexural strength of Geopolymer Concrete incorporating Rice Husk Ash is about 40-45% greater than that of the Ordinary Portland Cement Concrete (OPCC).

Table 8: Flexural Strength of Various Specimens

FLEXURAL STRENGTH (PSI)				
SAMPLE	**7 DAYS**	**14 DAYS**	**28 DAYS**	**REMARKS**
OPCC	320	410	460	Water Cured
Rice Husk Ash-based Geopolymer Concrete 3.75% SP/B	460	640	750	Oven cured at 100 oC for 24 hours

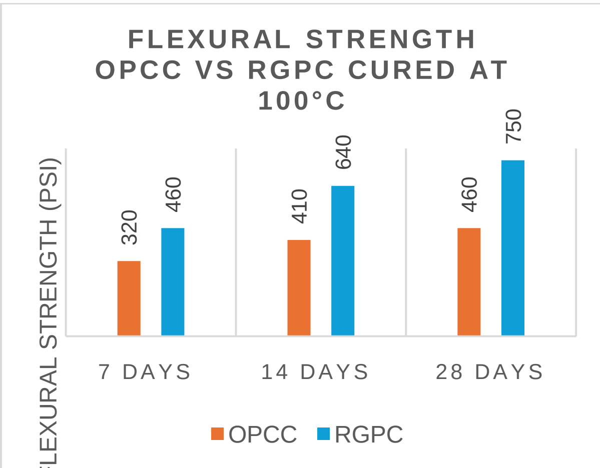

Figure 16: Comparison of Flexural Strength of OPCC And Rice Husk Ash-Based Geopolymer Concrete

3.3. SPLIT TENSILE STRENGTH TEST

The results of the split tensile strength test performed are shown by the table 9 given below

Figure 17 shows the comparison of the tensile strength of Ordinary Portland Cement Concrete (OPCC) with Geopolymer Concrete incorporating Rice Husk Ash. From figure 12 tensile strength of Geopolymer Concrete incorporating Rice Husk Ash is not much greater than that of Ordinary Portland Cement Concrete (OPCC) and is only about 5-10% greater than that of the Ordinary Portland Cement Concrete (OPCC).

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Table 9: Split Tensile Strength of Various Specimens

TENSILE STRENGTH (PSI)				
SAMPLE	**7 DAYS**	**14 DAYS**	**28 DAYS**	**REMARKS**
OPCC	290	370	420	Water Cured
Rice Husk Ash-based Geopolymer Concrete 3.75% SP/B	310	400	470	Oven cured at 100 oC for 24 hours

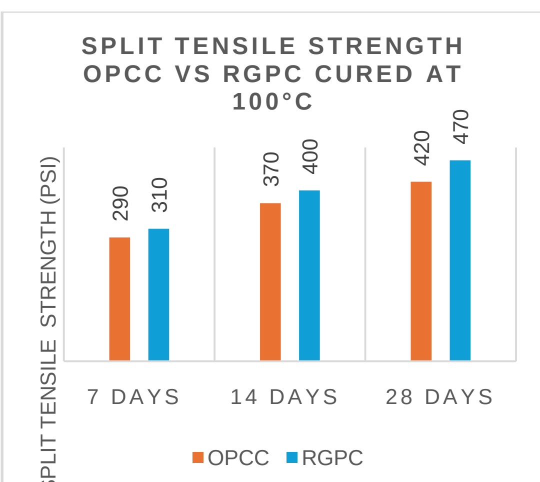

Figure 17: Comparison of Split Tensile Strength of OPCC and Rice Husk Ash-Based Geopolymer Concrete

3.4. CARBON FOOTPRINT

Figure 18 below shows the amount of carbon emitted using Fly Ash based geopolymer concrete (FGPC) and Ordinary Portland Cement Concrete OPCC. From the figures it can be seen that the carbon emissions of almost 36 tonnes made from $100m^3$ of Ordinary Portland Cement Concrete OPCC is 97% greater than the carbon emissions of 1 tonne made from Fly Ash-based geopolymer concrete (FGPC).

4. CONCLUSION

The development and mechanical properties of Rice Husk Ash (RHA)-based geopolymer concrete as a sustainable alternative to Ordinary Portland Cement Concrete (OPCC) in rigid pavements is investigated in this research. The relationship between curing temperature, superplasticizer dosage, water-to-binder ratio and compressive, flexural, and split tensile strength of RHA-GPC was investigated through

Sub-totals	tonnes CO_2e	%
Quarried Material	1.0	84%
Timber	0.0	0%
Concrete, Mortars & Cement	0.2	16%
Metals	0.0	0%
Plastics	0.0	0%
Glass	0.0	0%
Miscellaneous	0.0	0%
Finishings, coatings & adhesives	0.0	0%
Plant and equipment emissions	0.0	0%
Waste Removal	0.0	0%
Portable site accommodation	0.0	0%
Material transport	0.0	0%
Personnel travel	0.0	0%

Significant materials (figures include transport to site)	
Quarried aggregate	0.683 tonnes CO2e
Sand	0.343 tonnes CO2e
Fly Ash	0.190 tonnes CO2e

Total Carbon Footprint: 1 tonnes fossil CO_2e

Sub-totals	tonnes CO_2e	%
Quarried Material	1.0	3%
Timber	0.0	0%
Concrete, Mortars & Cement	35.5	97%
Metals	0.0	0%
Plastics	0.0	0%
Glass	0.0	0%
Miscellaneous	0.0	0%
Finishings, coatings & adhesives	0.0	0%
Plant and equipment emissions	0.0	0%
Waste Removal	0.0	0%
Portable site accommodation	0.0	0%
Material transport	0.0	0%
Personnel travel	0.0	0%

Significant materials (figures include transport to site)	
Cement: unknown type	35.464 tonnes CO2e
Quarried aggregate	0.683 tonnes CO2e
Sand	0.343 tonnes CO2e

Total Carbon Footprint: 36 tonnes fossil CO_2e

Figure 18: Carbon Emissions of FGPC and OPCC

systematic experimentation. Moreover, the environmental advantage of the use of RHA in reducing carbon emissions was also quantified. The results demonstrated that RHA-GPC exhibits superior mechanical performance compared to conventional OPCC. Oven cured at 100°C gave the highest compressive strength of 27.44 MPa, whereas the ambient cured samples had lower, but still acceptable, strength values. The flexural and split tensile strengths attained were 5.17 MPa and 3.24 MPa, respectively, exceeding the performance of OPCC. It was also observed that superplasticizer added in higher quantities improves workability but decreases compressive strength. Thus, like slump, the W/B ratio was improved, but strength performance did not improve, reinforcing the importance of optimizing these parameters for balanced performance. The carbon footprint analysis shows that the use of RHA in geopolymer concrete results in significantly more than 90% CO emissions reduction compared to OPC. This demonstrates the great environmental benefit from the adoption of geopolymer technology in developing large-scale infrastructure projects like Pakistan, in regions where RHA is plentiful, as in Pakistan. To conclude, this study demonstrates and proves that RHA-based geopolymer concrete can be used as a feasible, eco-friendly and technically sound material in rigid pavements. It not only offers improved strength properties under optimal curing conditions but also contributes to substantial reductions in greenhouse gas emissions, aligning with global sustainability goals in construction.

5. RECOMMENDATIONS

Several recommendations were made based on the promising findings of this study that can further promote the understanding and application of RHA-based geopolymer concrete in the construction industry:

- Long-term durability testing is future research that needs to be included, while compressive, flexural and tensile
- strengths were evaluated (Spelter et al., 2019). This test assesses resistance to penetration of the chloride anion, sulfate attack, freeze-thaw cycles, and acidic environment, which are all relevant to the rigid pavement subjected to very harsh conditions.
- Future work needs to be done to study other mechanical properties like modulus of elasticity, impact strength, fatigue strength and abrasion resistance in order to make RHA-GPC a fully reliable material[25]. For circumstances of varying loading on pavements with a need for durability, these properties are crucial.
- Chemical curing, although producing the highest mechanical results, may not be feasible to produce on-site for mass-scale projects. Consequently, alternative low-energy or ambient life curing formulations, which provide competitive strength levels, are sought. Steam curing or accelerated ambient curing methods can also be incorporated to save further energy consumption without sacrificing performance[11].
- Since there is no universally accepted mix design methodology for geopolymer concrete, it is suggested to develop standardized design procedures appropriate to RHA-based GPC[2]. It would assist engineers and contractors to replicate the material confidently in field conditions.
- Life Cycle Assessment (LCA) and cost-benefit analysis for RHA-GPC compared to OPCC will allow for direct comparison between the two in terms of the economic and environmental advantages of an RHA-GPC installation versus a conventional OPC[17]. It is especially important to encourage adoption by policymakers and industry stakeholders.
- RHA-GPC should be subjected to practical field trials in order to find out how it performs in rigid pavement applications (roads, runways, industrial floors) in the real world[23]. These projects can also be used to identify logistical aspects, refine the mix design for optimal performance in different climatic and operational conditions.

ACKNOWLEDGMENT
To no one.
CONFLICT OF INTEREST
The authors declare no conflict of interest.
FUNDING
None of the authors received any sort of funding from any source.

REFERENCES

1. Afrin, H., Huda, N., & Abbasi, R. (2021, November). An overview of eco-friendly alternatives as the replacement of cement in concrete. In *IOP Conference Series: Materials Science and Engineering* (Vol. 1200, No. 1, p. 012003). IOP Publishing. https://doi.org/10.1088/1757-899X/1200/1/012003
2. Ansari, M. A., Shariq, M., & Mahdi, F. (2023, September). Geopolymer concrete for clean and sustainable construction–A state-of-the-art review on the mix design approaches. In *Structures* (Vol. 55, pp. 1045-1070). Elsevier. https://doi.org/10.1016/j.istruc.2023.06.089
3. Babor, D., Plian, D., &Judele, L. (2009). "Environmental Impact of Concrete." Bulletin of the Polytechnic Institute of Jassy, CONSTRUCTIONS. ARCHITECTURE Section, Tomme LV (LIX), Fascicle 4, pp. 27-36.
4. Bakhtyar, B., Kacemi, T., & Nawaz, M. A. (2017). A review on carbon emissions in Malaysian cement industry. *International Journal of Energy Economics and Policy*, *7*(3), 282-286. https://www.econjournals.com/index.php/ijeep/article/view/4759.
5. Chowdhury, S., Mohapatra, S., Gaur, A., Dwivedi, G., & Soni, A. (2021). Study of various properties of geopolymer concrete–A review. *Materials Today: Proceedings*, *46*, 5687-5695. https://doi.org/10.1016/j.matpr.2020.09.835
6. Davidovits, J. (1991). Geopolymers: inorganic polymeric new materials. *Journal of Thermal Analysis and calorimetry*, *37*(8), 1633-1656. https://doi.org/10.1007/bf01912193
7. De Sensale, G. R. (2010). Effect of rice-husk ash on durability of cementitious materials. *Cement and Concrete Composites*, *32*(9), 718-725. https://doi.org/10.1016/j.cemconcomp.2010.07.008
8. Fernández-Jiménez, A., & Palomo, A. (2003). Characterisation of fly ashes. Potential reactivity as alkaline cements☆. *Fuel*, *82*(18), 2259-2265. https://doi.org/10.1016/S0016-2361(03)00194-7
9. Girawale, M. S. (2015). Effect's of alkaline solution on geopolymer concrete. *International Journal of Engineering research and general science*, *3*(4), 848-853. https://pnrsolution.org/Datacenter/Vol3/Issue4/109.pdf.
10. Glushankova, I., Ketov, A., Krasnovskikh, M., Rudakova, L., &Vaisman, I. (2018). Rice hulls as a renewable complex material resource. *Resources*, *7*(2), 31. https://doi.org/10.3390/resources7020031
11. Hamada, H., Alattar, A., Tayeh, B., Yahaya, F., &Almeshal, I. (2022). Influence of different curing methods on the compressive strength of ultra-high-performance concrete: A comprehensive review. *Case Studies in Construction Materials*, *17*, e01390. https://doi.org/10.1016/j.cscm.2022.e01390
12. Hardjito, D., & Rangan, B. V. (2005). Development and properties of low-calcium fly ash-based geopolymer concrete. http://hdl.handle.net/20.500.11937/5594
13. Hwang, C. L., & Huynh, T. P. (2015). Effect of alkali-activator and rice husk ash content on strength development of fly ash and residual rice husk ash-based geopolymers. *Construction and Building Materials*, *101*, 1-9. https://doi.org/10.1016/j.conbuildmat.2015.10.025
14. Ikotun, J. O., Aderinto, G. E., Madirisha, M. M., &Katte, V. Y. (2024). Geopolymer cement in pavement applications: bridging sustainability and performance. *Sustainability*, *16*(13), 5417. https://doi.org/10.3390/su16135417
15. Lavanya, G., &Jegan, J. (2015). Durability study on high calcium fly ash based geopolymer concrete. *Advances in Materials Science and Engineering*, *2015*(1), 731056. https://doi.org/10.1155/2015/731056
16. Maeda, N., Wada, I., Kawakami, M., Ueda, T., &Pushpalal, G. K. D. (2001). *Chloride diffusivity of concrete incorporating rice husk ash*. In Proceedings of the 5th CANMET/ACI International Conference on Recent Advances in Concrete Technology (pp. 291–308). Singapore.
17. Martínez, A., & Miller, S. A. (2025). Life cycle assessment and production cost of geopolymer concrete: A meta-analysis. *Resources, Conservation and Recycling*, *215*, 108018. https://doi.org/10.1016/j.resconrec.2024.108018
18. Mohamad, N., Muthusamy, K., Embong, R., Kusbiantoro, A., & Hashim, M. H. (2022). Environmental impact of cement production and Solutions: A review. *Materials Today: Proceedings*, *48*, 741-746. https://doi.org/10.1016/j.matpr.2021.02.212.
19. Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes: A cement for the future. *Cement and concrete research*, *29*(8), 1323-1329. https://doi.org/10.1016/S0008-8846(98)00243-9
20. Provis, J. L., & Van Deventer, J. S. J. (Eds.). (2009). *Geopolymers: structures, processing, properties and industrial applications*. Elsevier.
21. Ramasamy, V. W. (2012). Compressive strength and durability properties of rice husk ash concrete. *KSCE Journal of Civil Engineering*, *16*, 93-102. https://doi.org/10.1007/s12205-012-0779-2
22. Safiuddin, M., West, J. S., &Soudki, K. A. (2012). Properties of freshly mixed self-consolidating concretes incorporating rice husk ash as a supplementary cementing material. *Construction and Building Materials*, *30*, 833-842. https://doi.org/10.1016/j.conbuildmat.2011.12.066
23. Sbahieh, S., McKay, G., & Al-Ghamdi, S. G. (2023). Comprehensive analysis of geopolymer materials: Properties, environmental impacts, and applications. *Materials*, *16*(23), 7363. https://doi.org/10.3390/ma16237363

24. Shen, W., Cao, L., Li, Q., Wen, Z., Wang, J., Liu, Y., ... & Chen, R. (2016). Is magnesia cement low carbon? Life cycle carbon footprint comparing with Portland cement. *Journal of Cleaner Production*, *131*, 20-27. https://doi.org/10.1016/j.jclepro.2016.05.082
25. Singhal, D., & Jindal, B. B. (2017). Preparation of geopolymer concrete (GPC) using high-silica rice husk ash (RHA) incorporating alccofine. *Advanced Science, Engineering and Medicine*, *9*(5), 370-376. https://doi.org/10.1166/asem.2017.1993
26. Spelter, A., Bergmann, S., Bielak, J., &Hegger, J. (2019). Long-term durability of carbon-reinforced concrete: An overview and experimental investigations. *Applied Sciences*, *9*(8), 1651. https://doi.org/10.3390/app9081651
27. TANASH, A. O. A. A. R., & Muthusamy, K. (2022). Concrete industry, environment issue, and green concrete: a review. *Construction*, *2*(1), 01-09. https://doiorg/10.15282/construction.v2i1.7188.
28. Xu, H., & Van Deventer, J. S. J. (2000). The geopolymerisation of alumino-silicate minerals. *International journal of mineral processing*, *59*(3), 247-266. https://doi.org/10.1016/S0301-7516(99)00074-5
29. Yahya, Z., Kamarudin, H., Mohd Mustafa, A. B., Khairul Nizar, I., Rafiza, A. R., & Andrei Victor, S. (2015). The Influence of NaOH Concentration on Molar Ratios of Palm Oil Boiler. *Advanced Materials Engineering and Technology III*, 245. 10.4028/www.scientific.net/AMM.754-755.245
30. Zhang, M. H., & Malhotra, V. M. (1996). High-performance concrete incorporating rice husk ash as a supplementary cementing material. *ACI materials journal*, *93*, 629-636. https://doi.org/10.14359/9870

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