Comparative Study of Strength Properties of Conventional and One-Part Geopolymer Binder

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Abstract: The production of ordinary Portland cement (OPC) is a carbon-intensive process that generates significant amounts of carbon dioxide gas from the combustion of fossil fuels and the thermal decomposition of limestone. Overall, the cement industry is responsible for around 7% of global carbon dioxide emissions, which poses a considerable threat to the global climate due to its greenhouse effect. The recent advent of geopolymer shows great potential to reduce carbon footprints by utilising industrial by-products, such as fly ash and ground granulated blast-furnace slag (GGBS), and converting them into a binding material. Generally, geopolymer binders are made using alumina silicate compounds (fly ash and/or GGBS) and an alkali activator (combination of sodium silicate and sodium hydroxide solution) called "two-part geopolymer". Despite having superior engineering properties to conventional OPC concrete, geopolymer concrete has not been widely adopted in the concrete industry so far. The safety hazards in mixing and handling geopolymer concrete possessed by sodium hydroxide are one of the barriers to the adoption of geopolymer concrete. Replacing liquid sodium hydroxide with less hazardous alkali materials, such as sodium carbonate powder, makes the geopolymer binder less hazardous and easier to mix and handle than with liquid sodium hydroxide. Geopolymer binders made using alumina silicate compounds and alkali activator (combination of sodium silicate and sodium carbonate), all in powdered form, are called "one-part geopolymer". This paper investigates a comparison of fresh and hardened properties between OPC concrete and geopolymer concrete samples of M30 grade. Also compares the environmental and social impacts that may occur due to construction using ordinary concrete and geopolymer concrete, and their impacts by calculating the amount of ingredients required for the construction of the building.

Keywords: One-part Geopolymer binder, Ordinary Portland cement.

1. INTRODUCTION

The construction industry is a major consumer of natural resources and energy, and its continued expansion has intensified concerns regarding resource depletion, industrial waste generation, and greenhouse gas emissions. Among the materials used in construction, concrete occupies a dominant position owing to its versatility, availability, and favourable mechanical properties. However, the environmental impacts associated with the production of conventional ordinary Portland cement (OPC), the principal binding material in concrete, have created a need for alternative binder systems with improved sustainability characteristics. The manufacture of OPC involves the extraction and processing of limestone and other mineral raw materials, followed by high-temperature clinker production. During this process, substantial quantities of carbon dioxide (CO_2) are released through both the calcination of limestone and the combustion of fuels required to maintain the elevated kiln temperatures. In addition, electricity consumption, raw-material transportation, and associated industrial operations contribute to the overall environmental burden of cement production. The cement industry is consequently recognised as a significant anthropogenic source of CO_2 emissions, contributing approximately 7% of global CO_2 emissions according to the background presented in the original manuscript. The reduction of cement-related emissions is therefore an important component of strategies aimed at mitigating global warming and promoting sustainable construction.

Global warming is primarily associated with the accumulation of greenhouse gases in the atmosphere, particularly CO_2, which alters the Earth's radiative balance and contributes to an increase in global mean temperature. The construction sector contributes to this problem through both the production of energy-intensive materials and the consumption of resources throughout the life cycle of buildings and infrastructure. Although improvements in kiln efficiency, fuel substitution, and process optimisation have reduced the environmental intensity of cement manufacture, the inherent CO_2 release associated with limestone calcination remains a fundamental challenge. Consequently, the development of alternative cementitious binders that reduce dependence on clinker and utilise industrial by-products has received considerable attention in the field of sustainable construction materials. In this context, geopolymer technology has emerged as a promising approach for producing concrete with reduced reliance on conventional OPC while incorporating aluminosilicate-rich industrial by-products.

Geopolymer binders are inorganic aluminosilicate-based materials formed through the alkaline activation of reactive silicon- and

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aluminium-bearing precursors. Industrial by-products such as fly ash and ground granulated blast-furnace slag (GGBS) can serve as precursor materials in geopolymer systems. Unlike conventional OPC hydration, in which calcium silicate hydrate (C–S–H) is a principal strength-contributing phase, geopolymerisation involves the dissolution of reactive aluminosilicate species in an alkaline environment, followed by the formation of a three-dimensional aluminosilicate reaction network. Depending on the chemical composition of the precursors and the activating system, the resulting binder may contain geopolymeric gels, calcium-rich reaction products, or other associated phases. The utilisation of fly ash and GGBS in geopolymer concrete provides an opportunity to divert industrial by-products from disposal, reduce the consumption of virgin raw materials, and replace a substantial proportion of OPC in concrete production. Nevertheless, the environmental advantage of geopolymer concrete is dependent on precursor characteristics, activator manufacture, curing requirements, transportation, and the overall composition of the concrete mixture.

Conventional geopolymer concrete is generally produced using a two-part alkaline activation system, in which the aluminosilicate precursor is activated by a combination of liquid sodium silicate and sodium hydroxide (NaOH) solutions. The sodium hydroxide provides a highly alkaline environment that promotes the dissolution of reactive silica and alumina from the precursor materials, while sodium silicate contributes soluble silicate species and influences the development of the geopolymer binding network. The resulting reaction products contribute to the strength and durability of the hardened concrete. Previous research has demonstrated the potential of two-part geopolymer systems to achieve satisfactory mechanical properties and reduce OPC consumption. However, the practical application of these systems is associated with several limitations. The preparation, transportation, storage, and handling of concentrated NaOH solutions require appropriate safety precautions because of their highly caustic nature. The use of liquid activators also introduces additional requirements for batching, handling equipment, storage facilities, and quality control at construction sites. Furthermore, the preparation of alkaline solutions in advance and the separate transportation of liquid activator components can complicate field application and large-scale construction. These practical limitations have contributed to the search for alternative geopolymer binder systems that are safer, simpler, and more convenient to handle.

One-part geopolymer concrete, also referred to as a just-add-water geopolymer system, has emerged as a promising development intended to address some of the practical limitations associated with conventional two-part geopolymer concrete. In a one-part system, the aluminosilicate precursors and alkaline activating components are supplied in a dry, powdered form. The binder may incorporate materials such as fly ash, GGBS, powdered sodium silicate, and sodium carbonate. Water is added during concrete mixing to initiate the dissolution of the reactive components and the subsequent geopolymerisation process. The replacement of liquid NaOH with powdered alkaline activating materials, particularly sodium carbonate in the system investigated in the present study, can reduce direct handling of highly caustic liquid solutions and simplify the preparation and transportation of the binder. This dry-mix approach offers potential advantages in terms of handling convenience, batching, storage, and field application. However, one-part geopolymer concrete should not be regarded as inherently environmentally superior to every two-part system. The manufacture of powdered activators, the energy required for their processing, the water demand, and the resulting mechanical and fresh properties must be considered when evaluating its overall sustainability.

Recent investigations have examined the development and performance of one-part geopolymer binders using different precursor materials and powdered alkaline activators. Neupane and Hadigheh (2021) investigated a sodium-hydroxide-free geopolymer binder for prestressed concrete applications, while Neupane (2022) evaluated the environmental sustainability of one-part geopolymer binder concrete. Ooi *et al*. (2020) examined the influence of sodium carbonate on the fresh and hardened properties of fly ash-based one-part geopolymer concrete. These studies demonstrate the potential of dry alkaline activation as an alternative to conventional two-part geopolymer systems. However, the performance of one-part geopolymer concrete is strongly influenced by the proportions and reactivity of the precursor materials, the type and dosage of powdered activators, water availability, and the resulting reaction kinetics. Differences in binder composition can significantly affect setting time, workability, strength development, and the suitability of the material for structural applications. Therefore, further comparative investigations are necessary to establish the relationship between one-part binder composition and concrete performance, particularly when evaluated against conventional OPC concrete under comparable mix-design and curing conditions.

In this context, the present study investigates the fresh and hardened properties of M30-grade one-part geopolymer concrete and compares its performance with that of conventional OPC concrete. The one-part geopolymer binder comprises fly ash, GGBS, powdered sodium silicate, and sodium carbonate, with three different binder compositions considered to evaluate the influence of precursor-to-activator proportions on concrete behaviour. The experimental programme includes the assessment of consistency, initial setting time, workability, compressive strength, split tensile strength, and flexural strength. In addition to the mechanical and fresh-property investigation, the study examines the environmental and social implications associated with the use of conventional and one-part geopolymer concrete in building construction. The specific contribution of this research is therefore the integrated comparison of binder properties, fresh concrete behaviour, hardened mechanical performance, and construction-related environmental implications for the investigated M30 concrete mixtures. This assessment provides a basis for understanding the potential and limitations of one-part geopolymer concrete as an alternative binder system for more sustainable construction.

2. EXPERIMENTAL PROGRAMME

2.1. Materials

The present study involved the development of both conventional concrete and one-part geopolymer concrete (GPC) suitable for ambient curing. For conventional concrete, 43-grade Ordinary Portland Cement (OPC) was used as the binder. In the case of geopolymer concrete, the binder was considered as a combination of fly ash, ground granulated blast-furnace slag (GGBS), sodium silicate powder, and sodium carbonate powder**.** Fly ash and GGBS served as the primary aluminosilicate precursor materials, while sodium silicate and sodium carbonate acted as the powdered alkaline activating components.

M-sand having a specific gravity of 2.52 was used as fine aggregate, while coarse aggregate with a specific gravity of 2.88 was used as coarse aggregate. The physical properties of the fine and coarse aggregates are presented in Table **1**, and their particle-size distribution curves are shown in Figs. (**1** and **2**).

Table 1: Properties of Coarse and Fine Aggregate

No.	Property	Values	
		Coarse Aggregate	Fine Aggregate
1	Bulk density	1.62g/cc	1.72g/cc
2	Porosity	43.6%	32.0%
3	Void ratio	0.77	0.47
4	Specific gravity	2.88	2.52
5	Fineness modulus	4.89	2.84

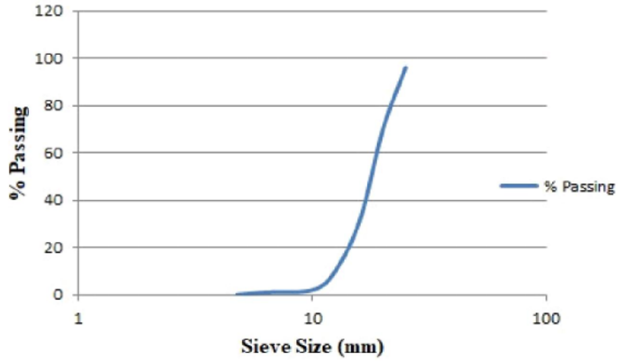

Figure 1: Graph of grading of coarse aggregate.

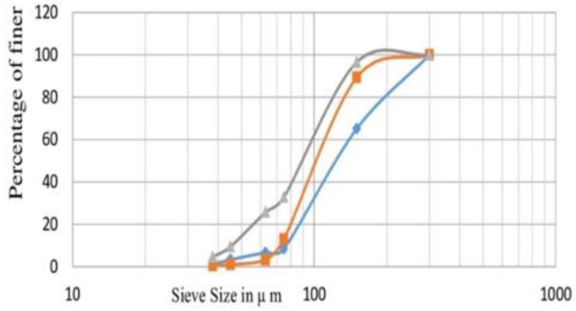

Figure 1: Graph of grading of fine aggregate.

2.2. Mix Design and Preparation of Specimens

Conventional concrete was designed based on IS 10262: 2019. The mix design of the one-part geopolymer concrete was developed by considering four binder constituents, namely fly ash, ground granulated blast-furnace slag (GGBS), sodium silicate powder, and sodium carbonate powder. The selection of the precursor materials and powdered alkaline activators was guided by previous studies on one-part geopolymer systems and ambient-cured fly ash–GGBS geopolymer concrete. Previous investigations have reported that the proportions of fly ash and GGBS significantly influence the reaction kinetics, setting characteristics, workability, and strength development of geopolymer binders. The incorporation of GGBS can promote strength development under ambient curing conditions, while the type and quantity of powdered alkaline activators influence the geopolymerisation process and the resulting mechanical properties [1-3]. Furthermore, the selection of suitable activator proportions is important for achieving an appropriate balance between workability, setting time, and strength development [1,2]. Table **2** shows the quantity of materials for different mixes.

Based on the findings reported in the literature, three geopolymer binder compositions were selected for the present experimental investigation. The total binder was defined as the combined mass of fly ash, GGBS, sodium silicate powder, and sodium carbonate powder.

The proportions of the four constituents were expressed as percentages by mass of the total binder. GPC01 was formulated with a relatively high fly ash content of 60%, together with 25% GGBS, 6% sodium silicate, and 9% sodium carbonate. This composition was intended to investigate a fly ash-dominant binder with a moderate GGBS contribution and a selected combination of powdered alkaline activators. GPC02 consisted of 40% fly ash, 40% GGBS, 10% sodium silicate, and 10% sodium carbonate. This composition was developed to examine the influence of an increased GGBS proportion and higher combined activator content on the fresh and hardened properties of the geopolymer concrete. GPC03 comprised 50% fly ash, 37% GGBS, 5% sodium silicate, and 8% sodium carbonate. This composition was selected to investigate the performance of an intermediate fly ash–GGBS blend with a comparatively lower powdered activator content. The selected proportion of GGBS was intended to support strength development under ambient curing, while the activator contents were adjusted to provide a suitable balance between reaction, workability, and strength.

Table 2: Quantity of Constituent Materials of CVC and GPC

Materials(kg/m^3)	CVC	GPC01	GPC02	GPC03
OPC	373.00	0	0	0
Fly ash	0	223.80	149.20	186.50
GGBS	0	93.25	149.20	138.01
Na_2CO_3	0	33.57	37.30	29.84
Na_2SiO_3	0	22.38	37.30	18.65
Fine aggregate	790	790	790	790
Coarse aggregate	1159	1159	1159	1159
Water	149	149	149	149

2.3. Mixing, Casting, Curing and Testing of Specimens

The conventional concrete was prepared using standard concrete mixing procedures. For the geopolymer concrete (GPC), a pan mixer was used for mixing the constituent materials. The geopolymer binder consisted of fly ash, ground granulated blast-furnace slag (GGBS), sodium silicate powder, and sodium carbonate powder. A water-to-binder ratio of 0.40 was adopted for all the geopolymer concrete mixtures, where the binder represents the combined mass of fly ash, GGBS, sodium silicate, and sodium carbonate.

The dry constituents, comprising fly ash, GGBS, sodium silicate powder, sodium carbonate powder, and fine aggregate, were initially mixed thoroughly to ensure uniform distribution. The required quantity of coarse aggregate was subsequently added, and mixing was continued until it was uniformly distributed throughout the mixture.

The total mixing water corresponding to a water-to-binder ratio of 0.40 was divided into two portions. Approximately 70% of the required water was initially added to the dry mixture and thoroughly mixed to obtain a uniform and homogeneous concrete. The remaining 30% of the mixing water was used to prepare a suspension with the required quantity of superplasticiser. This suspension was then gradually added to the mixture, and mixing was continued until a homogeneous and workable concrete was obtained.

The fresh concrete was immediately placed into the respective moulds and compacted using uniform vibration to eliminate entrapped air and ensure adequate compaction. The top surface was finished using a trowel to obtain a smooth and level surface. The specimens were kept undisturbed for 24 h, after which they were demoulded and allowed to cure at room temperature under ambient curing conditions.

The fresh properties were evaluated through binder consistency and concrete slump tests. The consistency test was conducted on the binder compositions to assess their water requirement and fresh-state characteristics. The workability of the concrete mixtures was determined using the slump test. The hardened properties were evaluated at an age of 28 days through compressive strength, split tensile strength, and flexural strength tests. Compressive strength was determined using cube specimens measuring 150 × 150 × 150 mm. Split tensile strength was determined using cylindrical specimens measuring 150 mm in diameter and 300 mm in length. Flexural strength was determined using beam specimens measuring 100 × 100 × 500 mm. For each concrete mixture, six cube specimens were prepared for compressive-strength testing, three cylindrical specimens were prepared for split tensile-strength testing, and three beam specimens were prepared for flexural-strength testing. Individual experimental results were recorded and are available for reporting. The mean values shall be presented as results.

2.4. Properties of Binder

The consistency and initial setting time of the binder in conventional concrete and one-part geopolymer concrete were tested. In conventional concrete, cement serves as the binder, while in one-part geopolymer concrete, a combination of fly ash, GGBS, sodium silicate, and sodium carbonate was used. The results are presented in Table **3**. The findings indicate that the initial setting time of one-part geopolymer concrete is longer compared to that of conventional concrete.

Table 3: Properties of Binder

Item	Consistency(%)	Initial Setting Time (Minutes)
CVC	30	120
GPC01	38	480
GPC02	32	360
GPC03	26	200

2.5. Fresh Properties

The workability of the conventional and one-part geopolymer concrete mixtures was evaluated using the slump test. Workability is an important fresh-state property because it influences the transportation, placement, compaction, vibration, and finishing of concrete. The slump values of the conventional concrete and geopolymer concrete mixtures were 40 mm, 17 mm, 22 mm, and 30 mm for CVC, GPC01, GPC02, and GPC03, respectively. GPC01 and GPC02 exhibited lower slump values than conventional concrete, indicating comparatively low workability. GPC03 exhibited a higher slump than GPC01 and GPC02 and approached the workability of the conventional concrete mixture. The lower workability of GPC01 and GPC02 may be associated with the combined effects of the powdered alkaline activators, precursor proportions, particle packing, water demand, and paste viscosity. Since the proportions of more than one binder constituent were varied simultaneously, the reduction in slump cannot be attributed to a single constituent based on the present results alone. Table **4** shows the workability of different mixes.

Table 4: Slump Value of Mixes

Item	Slump	Remarks
CVC	40	Medium
GPC01	17	Low
GPC02	22	Low
GPC03	30	Medium

2.6. Hardened Properties

The compressive strength, split tensile strength, and flexural strength of the conventional and one-part geopolymer concrete mixtures were determined at 28 days. The measured compressive strengths of CVC, GPC01, GPC02, and GPC03 were 39.75 MPa, 24.30 MPa, 27.56 MPa, and 36.21 MPa, respectively. Among the geopolymer mixtures, GPC03 exhibited the highest compressive strength. Its compressive strength was approximately 91.1% of the conventional concrete value. The split tensile strength of GPC03 was 3.02 MPa, compared with 3.12 MPa for conventional concrete. The flexural strength of GPC03 was 4.20 MPa, compared with 3.69 MPa for conventional concrete. These results indicate that GPC03 exhibited comparable performance to conventional concrete in selected hardened properties. However, the results should not be interpreted as demonstrating complete equivalence between the two concrete systems. The lower compressive strength of GPC03 compared with conventional concrete should also be acknowledged. The results indicate that the proportions of fly ash, GGBS, sodium silicate powder, and sodium carbonate powder influence the fresh and hardened properties of the one-part geopolymer concrete. Since the present study investigated complete binder compositions rather than varying one constituent at a time, the independent contribution of each constituent cannot be isolated from the current experimental results. Table **5** shows the properties of hardened concrete.

Table 5: Hardened Properties

Tests	OPC	GPC0I	GPC02	GPC03
Compressive strength (N/mm^2)	39.75	24.30	27.56	36.21
Split tensile strength (N/mm^2)	3.12	0.97	1.51	3.02
Flexural strength (N/mm^2)	3.69	1.76	2.88	4.2

3. STUDY OF ENVIRONMENTAL AND SOCIAL IMPACTS OF OPC AND GPC CONCRETE

3.1. Study on CO_2 Emissions

Anthropogenic emissions of greenhouse gases, particularly carbon dioxide, are the primary cause of global warming. These emissions come from five major economic sectors: electricity and heat production, agriculture, forestry and other land use, industry, transportation, and buildings. Within the industrial sector, the cement industry is a significant contributor to carbon dioxide emissions. CO_2 emissions in the cement industry primarily result from the combustion of fossil fuels and the calcination of limestone into calcium oxide. Additionally, a portion of carbon dioxide is produced indirectly through the electricity consumed in cement production, which is generated by burning fossil fuels. Approximately half of the CO_2 emissions stem from fuel combustion, while the other half comes from the limestone calcination process.

The cement sector accounts for about 12-15% of total industrial energy use, primarily due to the energy required for the calcination of raw materials and the fuels needed to maintain the high temperatures in a kiln. As urbanisation and infrastructure development continue to rise, especially in developing countries, cement production is expected to increase. Globally, about one-third of carbon dioxide emissions released into the atmosphere are associated with energy use in various industrial sectors. It has been reported that the industrial sector emits around 2,370 Tg of carbon dioxide, which constitutes about 43% of total global CO_2 emissions. The cement industry alone contributes approximately 7% of these emissions. It is estimated that 0.9 to 1.0 tons of carbon dioxide are produced per ton of clinker. Depending on the type of fuel used, approximately 0.65 to 0.92 kg of carbon dioxide is produced per kg of cement in modern facilities.

A preliminary comparison of the potential CO_2 emissions of conventional concrete and GPC03 was conducted based on the quantities of constituent materials required to produce 1 m³ of concrete. The assessment considered the production of the constituent materials only. Transportation, mixing energy, casting, curing, maintenance, demolition, and end-of-life processes were excluded from the initial calculation.

The CO_2 emissions associated with each mixture were estimated using the following equation:

$$Ematerial = \sum mi \times EFi$$

here:

- mi = quantity of material in kg/m³;
- EFi = emission factor of material in kg CO_2-eq/kg.

The total estimated material-related emissions of CVC and GPC03 were calculated as 326.84 kg CO_2-eq/m³ and 78.83 kg CO_2-eq/m³, respectively, using the emission factors from LCA literature or Environmental Product Declarations. The corresponding estimated reduction was calculated as 75.9%. This value should be interpreted only as an indicative material-based estimate. It is not a complete life-cycle assessment because the calculation does not include transportation, energy consumption, processing requirements, or allocation of environmental burdens associated with industrial by-products such as fly ash and GGBS. A preliminary material-based calculation indicated a potential reduction in CO_2 emissions for GPC03 compared with CVC. However, the result is dependent on the emission factors and allocation assumptions adopted and should not be considered a complete life-cycle assessment

3.2. Study on Amount of Fly Ash and GGBS Generation and their Utilisation and Disposal

The use of fly ash and GGBS as constituents of the geopolymer binder provides an opportunity to utilise industrial by-products in concrete production and reduce dependence on conventional OPC. In the present study, fly ash and GGBS were incorporated into the geopolymer binder together with powdered sodium silicate and sodium carbonate. The environmental implications of this approach are therefore related to both the replacement of OPC and the production of the powdered alkaline activators.

The environmental benefits of using industrial by-products cannot be assumed to be zero in all circumstances. The impacts associated with processing, transportation, storage, and the allocation of burdens to fly ash and GGBS depend on the adopted assessment methodology. Accordingly, the present study reports the environmental comparison based on the defined system boundary and the emission factors listed in the environmental assessment section.

The one-part geopolymer system may also provide practical advantages over two-part geopolymer systems by eliminating the direct preparation and handling of concentrated liquid sodium hydroxide solutions. The use of powdered activators can simplify dry-material storage and batching. Nevertheless, the handling of powdered alkaline materials requires suitable precautions, and the actual social and occupational benefits would require a separate assessment.

The environmental and social implications of the present study are therefore interpreted in relation to the specific binder compositions and concrete quantities investigated. The results should not be generalised to all geopolymer concrete systems without considering differences in precursor materials, activator manufacture, curing conditions, transportation, and mix proportions.

4. CONCLUSIONS

The present study compared the fresh and hardened properties of conventional concrete (CVC) and one-part geopolymer concrete mixtures prepared using fly ash, GGBS, sodium carbonate, and powdered sodium silicate. The geopolymer mixtures were produced by a dry-mixing procedure and cured under ambient conditions, demonstrating the practical feasibility of developing a one-part geopolymer binder without the direct handling of a concentrated liquid alkaline activator.

- One-part geopolymer concrete was successfully developed using fly ash, GGBS, sodium carbonate, and powdered sodium silicate and cured under ambient conditions, demonstrating its feasibility as an alternative binder system to conventional concrete.

- The one-part geopolymer mixtures exhibited lower slump values than conventional concrete. The slump values were 40 mm for CVC, 17 mm for GPC01, 22 mm for GPC02, and 30 mm for GPC03. Among the geopolymer mixtures, GPC03 showed the best workability.
- The geopolymer mixtures showed longer initial setting times than CVC. GPC03 exhibited the most favourable setting behaviour among the geopolymer mixtures, with an initial setting time of 200 min, compared with 120 min for CVC.
- The hardened properties were strongly influenced by the proportions of fly ash, GGBS, sodium carbonate, and sodium silicate. Among the geopolymer mixtures, GPC03 exhibited the highest overall mechanical performance.
- GPC03 achieved a compressive strength of 36.21 MPa at 28 days, compared with 39.75 MPa for CVC, corresponding to approximately 91% of the compressive strength of conventional concrete.
- GPC03 recorded a split tensile strength of 3.02 MPa, which was close to the 3.12 MPa obtained for CVC, indicating comparable tensile performance.
- GPC03 achieved a flexural strength of 4.20 MPa, which was higher than the 3.69 MPa obtained for CVC, demonstrating favourable flexural performance under the investigated conditions.
- Among the investigated mixtures, GPC03 provided the most balanced performance in terms of workability, setting time, compressive strength, split tensile strength, and flexural strength.
- The results indicate that one-part geopolymer concrete has potential as an alternative to conventional concrete, particularly because it can be prepared using powdered activators and ambient curing, thereby simplifying the handling of alkaline activators compared with conventional two-part geopolymer systems.

However, the present study was limited to the investigated mix proportions and test conditions. Further studies on durability, long-term strength development, shrinkage, microstructure, and life-cycle environmental performance are recommended to establish its suitability for wider structural applications.

CONFLICT OF INTEREST

The author declare that there is no conflict of interest.

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