Study on Physical and Mechanical Properties of Fly ash Based Geopolymer Concrete

Pratiksha Dilip Gaikwad[1] **Prof. R. Mahadeva Swamy**[2] **Dr. M. S. Kuttimarks**[3]
Dr. Gyanendra Kumar Chaturvedy[4]
[1]M.E. Scholar [2,3]Associate Professor [4]Assistant Professor
[1,2,3,4]Department of Civil Engineering
[1,2,3,4]Shivajirao S. Jondhle College of Engineering & Technology, Asangaon, India

Abstract — The growing environmental concerns associated with the cement industry, particularly its high carbon dioxide emissions and energy-intensive production processes, have accelerated the search for sustainable construction materials. Simultaneously, the large-scale generation and disposal of fly ash from thermal power plants pose significant environmental challenges. Geopolymer concrete (GPC), produced using alumino-silicate materials such as fly ash, has emerged as a promising alternative to conventional Portland cement concrete due to its reduced carbon footprint and effective utilization of industrial by-products. However, the widespread application of GPC is constrained by its dependence on heat curing, which limits its suitability for cast-in-situ construction. This study investigates the development of ambient-cured geopolymer concrete composites (GPCC) and evaluates the influence of fly ash content on their physical and mechanical properties. An extensive experimental program was conducted, including the assessment of fresh and hardened concrete characteristics and the flexural behavior of reinforced GPCC beams. The results indicated that conventional ambient-cured GPC exhibited delayed setting, requiring nearly three days for hardening. To overcome this limitation, 10% fly ash was replaced with ordinary Portland cement (OPC), resulting in GPCC with improved setting characteristics and enhanced early-age strength without the need for heat curing. The findings demonstrate the feasibility of ambient-cured GPCC as a sustainable and practical construction material for structural applications.

Keywords: Compressive Strength, Flexural Strength, Fly ash, Geopolymer concrete, Split Tensile Strength, Sustainability

I. INTRODUCTION

Concrete is the most widely used construction material in the world owing to its versatility, durability, and economic advantages. Conventional concrete primarily relies on Ordinary Portland Cement (OPC) as its binding material. However, the production of cement is associated with significant environmental concerns due to its high energy consumption and greenhouse gas emissions. It is estimated that the manufacture of one ton of cement requires approximately 2.8 tons of raw materials and releases nearly one ton of carbon dioxide into the atmosphere as a result of limestone calcination and fuel combustion. In addition to contributing to global warming, cement production also leads to the depletion of natural resources. Consequently, the development of sustainable and environmentally friendly alternatives to Portland cement has become an important area of research in the construction industry [1-3].

To mitigate the environmental impact of cement production, several supplementary cementitious materials rich in silica and alumina have been incorporated into concrete. Materials such as fly ash, rice husk ash, silica fume, and ground granulated blast furnace slag (GGBS) have been widely used as partial replacements for cement. These materials participate in pozzolanic reactions with calcium hydroxide generated during cement hydration, thereby improving the mechanical and durability properties of concrete. Nevertheless, the replacement level of cement using these materials is generally limited. Although high-volume fly ash concrete introduced by Malhotra demonstrated the feasibility of replacing up to 60% of cement without significant loss of performance, further increases in replacement levels often result in reduced strength and delayed setting characteristics. This limitation has encouraged researchers to explore alternative binder systems that can completely eliminate the use of Portland cement [4-6].

One of the most promising alternatives is geopolymer technology, first introduced by Davidovits in 1978. Geopolymers are inorganic polymeric materials produced through the reaction of aluminosilicate-rich source materials with alkaline activating solutions. Unlike conventional cement hydration, geopolymerization involves the dissolution of silica and alumina in a highly alkaline medium followed by polycondensation into a three-dimensional aluminosilicate network. The resulting binder possesses an amorphous structure similar to natural zeolites and is characterized by a network of Si–O–Al bonds. Geopolymerization generally proceeds through four stages: dissolution of aluminosilicate species, formation of oligomeric structures, polycondensation into a continuous network, and integration of unreacted particles within the matrix. These reactions produce a dense and durable binder with excellent engineering properties [7-8].

Despite these advantages, the widespread application of geopolymer concrete is hindered by its dependence on elevated-temperature curing, which restricts its use in cast-in-situ construction. Most existing research has focused on precast elements cured under controlled heating conditions, while limited attention has been given to ambient-cured geopolymer systems. Furthermore, studies on fibre-reinforced geopolymer concrete remain relatively scarce, particularly with respect to impact resistance and the structural behavior of reinforced geopolymer concrete members. The incorporation of fibres is expected to enhance ductility, toughness, and energy absorption capacity, making geopolymer composites more suitable for structural applications [9-11].

In view of these research gaps, the present study aims to develop fly ash-based geopolymer concrete composites suitable for ambient curing and cast-in-situ applications. The investigation focuses on developing appropriate mix proportions, evaluating the physical and mechanical properties of fibre-reinforced geopolymer concrete, and examining its structural performance. Special emphasis is placed on assessing impact resistance and the flexural behavior of reinforced geopolymer concrete beams, thereby contributing to the advancement of sustainable and practical geopolymer technology for future construction applications.

II. MATERIALS AND METHODOLOGY

A. Materials

The present investigation focused on the development and evaluation of fly ash-based geopolymer concrete (GPC). Class F fly ash conforming to IS 3812:2003 was used as the primary binder material. The fly ash contained high proportions of silica (59.93%) and alumina (19.66%), making it suitable for geopolymerization. To study the influence of source variation, fly ash was procured from two thermal power stations locally available.

Locally available river sand conforming to Zone II grading as per IS 383:1970 was used as fine aggregate. The sand possessed a fineness modulus of 2.75 and a bulk density of 1693 kg/m³. Crushed granite with a maximum nominal size of 19 mm served as the coarse aggregate, having a fineness modulus of 6.64 and a bulk density of 1527 kg/m³.

The alkaline activator consisted of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. Sodium hydroxide flakes with 97% purity were used to prepare solutions of different molar concentrations. Sodium silicate solution containing 14.7% Na_2O, 29.4% SiO_2, and 55.9% water was used in combination with NaOH. To improve workability, a sulphonated naphthalene-based superplasticizer (Conplast SP430) was incorporated in all mixes. Distilled water was used for preparing the alkaline solutions and for additional water requirements.

B. Experimental Program

The experimental study was designed to evaluate the influence of four key parameters on the performance of geopolymer concrete: (i) source of fly ash (Mettur and Tuticorin), (ii) sodium hydroxide concentration (8 M, 12 M, and 16 M), (iii) curing condition (ambient curing and heat curing at 60°C for 24 h), and (iv) testing age (7 and 28 days).

The alkaline activator was prepared by mixing sodium hydroxide and sodium silicate solutions in a mass ratio of 1:2.5. Sodium hydroxide solutions of the required molarity were prepared at least 24 h before mixing to ensure thermal stabilization and uniformity. For geopolymer concrete production, the aggregate content was maintained at 77% of the total mix mass, with fine aggregate constituting 30% of the total aggregate fraction. An alkaline liquid-to-fly ash ratio of 0.4 was adopted based on previous studies. Additional water equivalent to 10% of the fly ash mass and superplasticizer dosage of 3% by mass of fly ash were used to achieve adequate workability.

The concrete was mixed in a horizontal pan mixer. Initially, fly ash and aggregates were dry mixed for three minutes. The alkaline activator was then added, followed by wet mixing for four minutes. Finally, extra water and superplasticizer were incorporated to obtain a homogeneous mixture.

A total of 72 cube specimens (150 × 150 × 150 mm), 72 cylindrical specimens (150 × 300 mm), and 36 prism specimens (100 × 100 × 500 mm) were cast for compressive, split tensile, and flexural strength tests, respectively. After casting, specimens were left in moulds for four days to allow initial hardening. Subsequently, half of the specimens were cured under ambient laboratory conditions, while the remaining specimens were heat-cured at 60°C for 24 h.

C. Testing Procedures

Fresh concrete properties were assessed through slump measurements. Hardened concrete properties were evaluated using compressive strength, split tensile strength, and flexural strength tests in accordance with relevant Indian Standards. Compressive strength was determined using a 3000 kN compression testing machine, while split tensile and flexural strengths were measured using standard cylindrical and prism specimens, respectively. The results obtained at 7 and 28 days were analyzed to assess the influence of fly ash source, alkaline concentration, and curing conditions on the performance of geopolymer concrete.

III. RESULTS AND DISCUSSION

A. Workability

The workability of freshly prepared geopolymer concrete composite (GPCC) was assessed using the standard slump cone test. The results indicated that the mix exhibited a cohesive, homogeneous, and highly workable consistency. A glossy appearance observed in the fresh concrete was attributed to the presence of sodium silicate in the alkaline activator, which enhanced lubrication among particles and improved flowability. These characteristics produce a ball-bearing effect that reduces internal friction and facilitates easier mixing, transportation, compaction, and placement of concrete. In addition, the fine particle size of fly ash improves particle packing by filling voids between aggregates, resulting in a denser matrix and reduced water demand. The partial replacement of fly ash with Ordinary Portland Cement (OPC) further enhanced the fresh properties of GPCC by improving particle grading and reaction kinetics. Consequently, GPCC exhibited higher slump values and better finishing characteristics, making it suitable for practical and large-scale construction applications. Result on workability is shown in Fig.1.

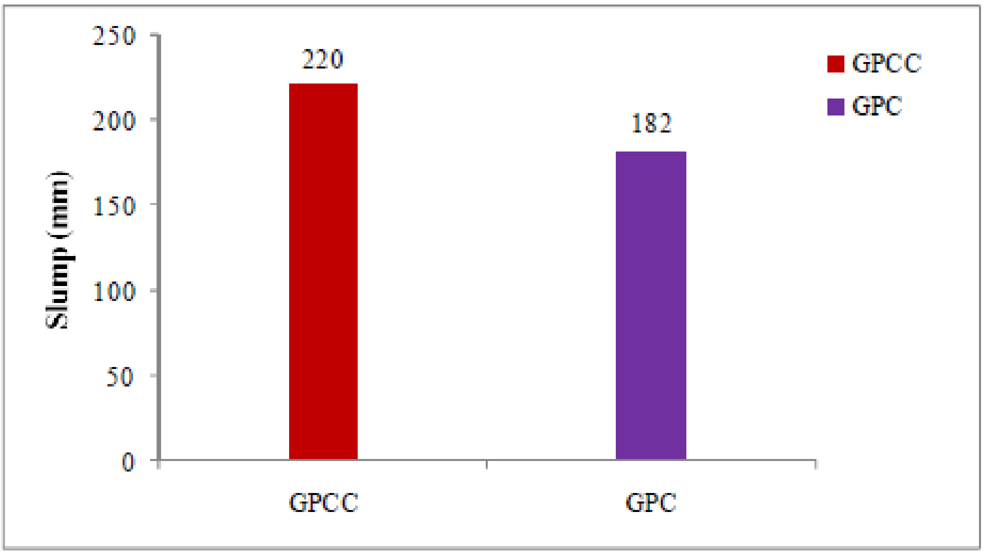

Fig. 1: Comparison of results on workability between GPC and GPCC

B. Compressive strength

The compressive strength behavior of geopolymer concrete composite (GPCC) was evaluated by considering the effects of 10% Ordinary Portland Cement (OPC) replacement, curing conditions, and testing age. The results demonstrated that the incorporation of OPC significantly enhanced the compressive strength of geopolymer concrete. This improvement is primarily attributed to the additional calcium supplied by OPC, which accelerates geopolymerization and promotes the formation of calcium–alumino–silicate–hydrate (C-A-S-H) gel, resulting in a denser microstructure and stronger inter-particle bonding.

Under ambient curing conditions, GPCC exhibited substantial strength gains compared to conventional geopolymer concrete (GPC), with increases of approximately 151% and 73% at 7 and 28 days, respectively. Similarly, heat-cured GPCC showed strength improvements of about 64% at 7 days and 39% at 28 days. These findings confirm the beneficial role of OPC in enhancing both early-age and long-term strength development. Result is shown in Fig.2.

The results further revealed that the percentage increase in compressive strength was greater under ambient curing than under heat curing. This can be attributed to the synergistic action of cement hydration and geopolymerization. The heat generated from OPC hydration, together with ambient temperature, facilitates the polymerization of fly ash, while the water released during geopolymerization supports continued cement hydration. This mutual interaction creates a favorable curing environment, leading to more effective strength development and improved overall performance of GPCC under ambient conditions.

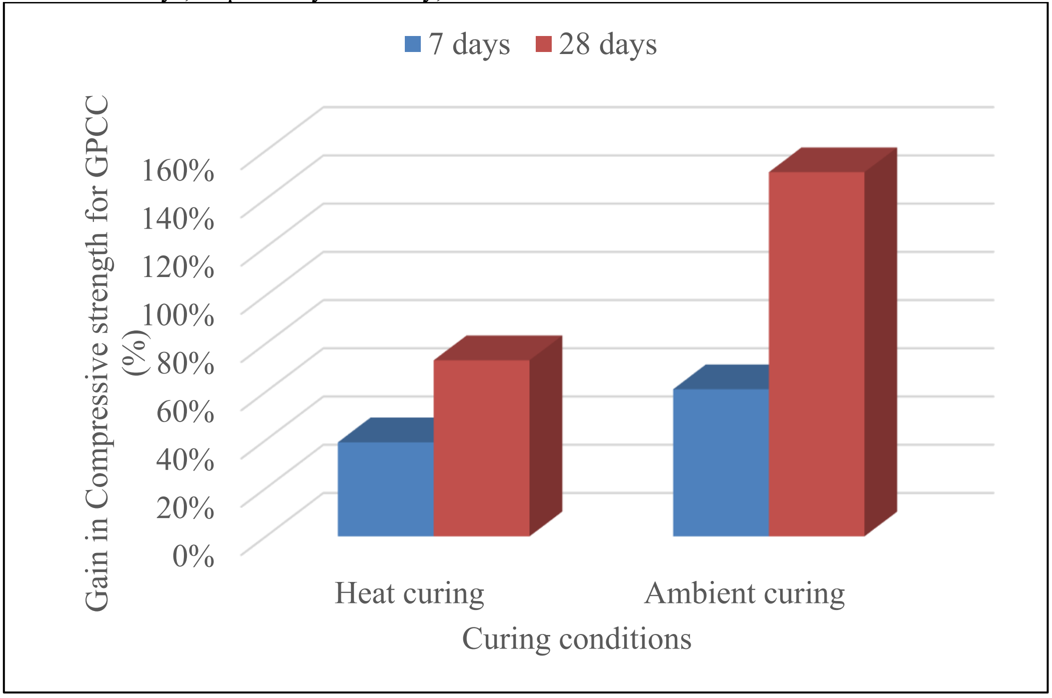

Fig. 2: Compressive strength gain of GPCC wrt. GPC at different curing periods

C. Split tensile strength

The split tensile strength behavior of geopolymer concrete composite (GPCC) was evaluated by considering the effects of 10% Ordinary Portland Cement (OPC) replacement, curing conditions, and testing age. The results showed that GPCC developed significantly higher tensile strength than conventional geopolymer concrete (GPC), particularly at early ages. Unlike traditional GPC, which generally depends on heat curing for effective strength development, GPCC exhibited rapid hardening and measurable split tensile strength within one day under ambient curing conditions. This improvement is mainly attributed to the hydration of OPC, which initiates early binding and strength gain immediately after mixing.

Under ambient curing, GPCC attained approximately 7% of its corresponding 28-day heat-cured tensile strength within the first day. The strength increased steadily with age, reaching about 41% and 88% at 7 and 28 days, respectively. These results demonstrate that substantial tensile strength can be achieved without the application of external heat.

The superior tensile performance of GPCC is attributed to the synergistic interaction between cement hydration and geopolymerization. The calcium-rich hydration products formed from OPC accelerate early-age strength development, while the geopolymerization of fly ash gradually creates a dense alumino-silicate network responsible for long-term strength. The gain in split tensile strength was found to be higher under ambient curing than heat curing, as the heat generated during OPC hydration and the moisture released during geopolymerization mutually support both reactions. This balanced curing mechanism promotes a denser microstructure and improved tensile resistance, making ambient-cured GPCC a practical and viable material for field applications. Result on tensile strength is shown in Fig.3.

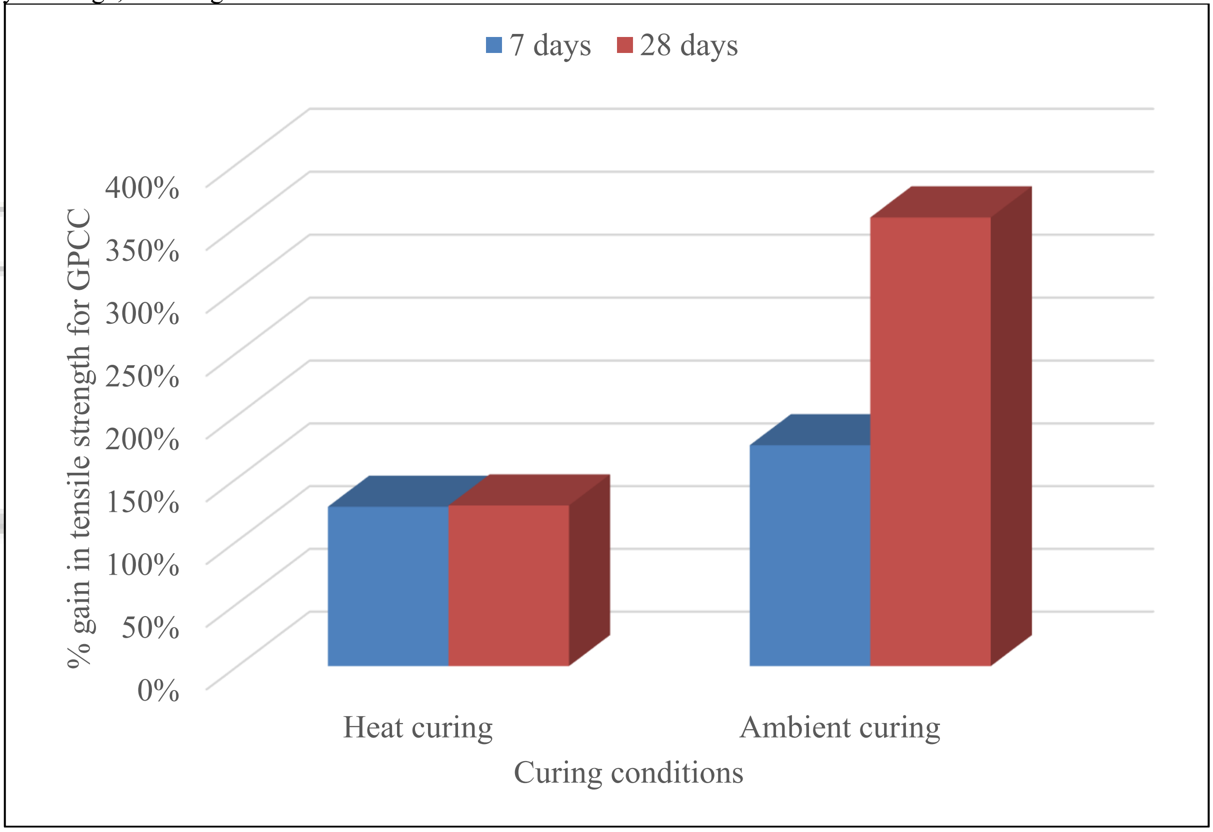

Fig. 3: Tensile strength gain of GPCC wrt. GPC at different curing periods

D. Flexural strength

The flexural strength characteristics of geopolymer concrete composite (GPCC) were evaluated by examining the effects of 10% Ordinary Portland Cement (OPC) replacement, curing conditions, and testing age. The results demonstrated that GPCC developed significant flexural strength under both ambient and heat-curing regimes. Under ambient curing conditions, the specimens attained nearly 66% of their corresponding 28-day heat-cured flexural strength within the first 7 days. With continued curing, strength increased steadily, and by 28 days, the ambient-cured specimens achieved approximately 98% of the flexural strength of heat-cured specimens. These findings indicate that ambient curing is sufficient for effective flexural strength development in GPCC.

The enhanced performance can be attributed to the combined effects of OPC hydration and fly ash geopolymerization. The hydration of OPC generates calcium-rich compounds that contribute to early-age strength, while the geopolymerization process forms a dense alumino-silicate gel network responsible for long-term strength gain. This synergistic interaction improves the bond between aggregates and the binder matrix, thereby increasing the flexural resistance of the concrete.

Compared with conventional geopolymer concrete (GPC), GPCC exhibited superior flexural strength. Under ambient curing, flexural strength increased by approximately

28% and 17% at 7 and 28 days, respectively. Similarly, under heat curing, improvements of about 20% and 11% were observed at 7 and 28 days. Overall, the results confirm that GPCC possesses enhanced flexural performance and can achieve the desired structural properties under normal ambient curing conditions, making it a practical and sustainable alternative for construction applications. Result on flexural strength is shown in Fig.4.

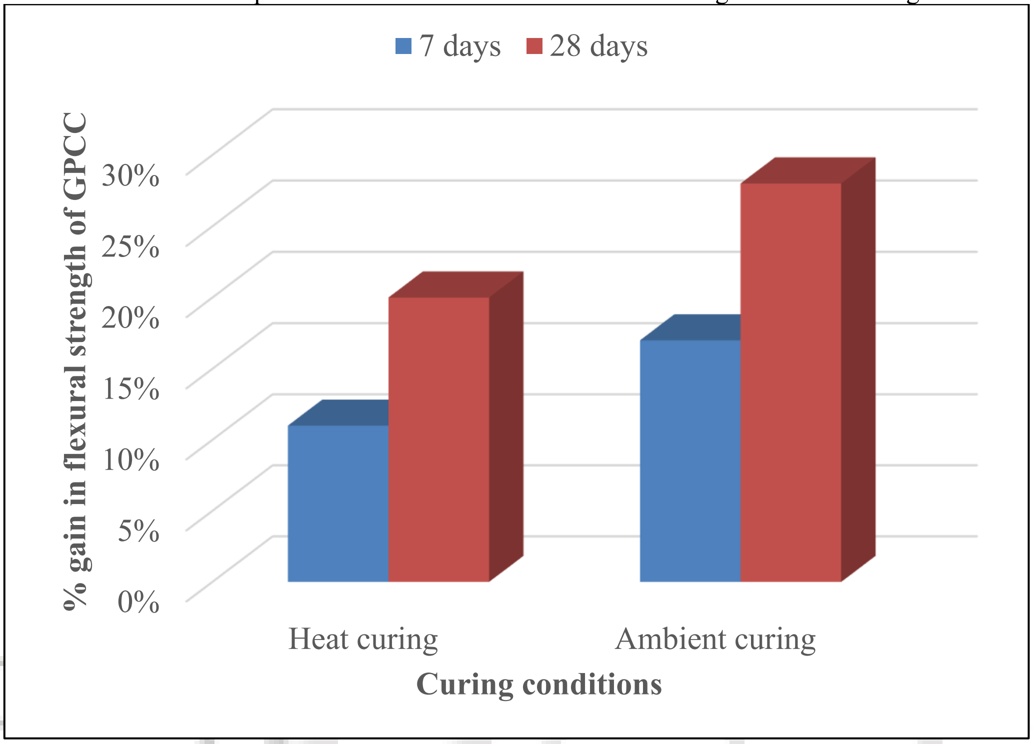

Fig. 4: Flexural strength gain of GPCC wrt. GPC at different curing periods

IV. CONCLUSION

Based on the experimental investigation conducted on geopolymer concrete composite (GPCC), the following conclusions can be drawn:

1) GPCC was successfully developed by partially replacing 10% of fly ash with Ordinary Portland Cement (OPC), effectively overcoming the major limitations of conventional geopolymer concrete (GPC), namely delayed setting and dependence on heat curing for early strength development.
2) The fresh properties of GPCC were superior to those of conventional GPC. The combined effect of OPC, fly ash, and sodium silicate improved the cohesiveness, consistency, and flowability of the mix, resulting in enhanced workability, ease of placement, and better finishing characteristics.
3) GPCC exhibited rapid strength development under ambient curing conditions. Unlike conventional GPC, measurable strength was achieved within one day without external heat curing. At 28 days, the compressive, split tensile, and flexural strengths increased by approximately 73%, 128%, and 17%, respectively, compared to conventional GPC.
4) Ambient curing was found to be sufficient for effective strength development in GPCC. At 28 days, ambient-cured specimens attained nearly 97% of compressive strength, 88% of split tensile strength, and 98% of flexural strength compared to corresponding heat-cured specimens.
5) The strength gain of GPCC was higher under ambient curing than under heat curing, owing to the synergistic interaction between OPC hydration and fly ash geopolymerization. The heat generated during cement hydration and the moisture released during geopolymerization mutually enhanced both reactions.
6) The marginal strength improvement obtained through heat curing (3% compressive, 13% split tensile, and 2% flexural strength) confirms that external heat curing is unnecessary. Ambient-cured GPCC even outperformed heat-cured GPC, demonstrating its practicality, sustainability, and suitability for cast-in-situ construction applications.

REFERENCES

[1] Adam, A.A., Molyneaux, T.C.K., Patnaikuni, I. and Law, D.W. “Strength, sorptivity and carbonation of geopolymer concrete”, Taylor & Francis Group, London, UK, pp. 563-568, 2010.
[2] Ali Behnood and Masouad Ghandehari. “Comparison of compressive and splitting tensile strength of high strength concrete with and without polypropylene fibres heated to high temperatures”, Fire Safety Journal, Vol. 44, pp. 1015-1022, 2009.
[3] Anthony J. Wolanski. “Flexural behavior of reinforced and prestressed concrete beams using finite element analysis”, M.S Thesis, Faculty of the Graduate School, Marquette University, Milwaukee, Wisconsin, 2004.
[4] Anuar, K.A., Ridzuan, A.R.M. and Ismail, S. “Strength characteristic of geopolymer concrete containing recycled concrete aggregate”, International Journal of

Civil and Environmental Engineering, Vol. 11, No. 1, pp. 81-85, 2011.

[5] CEB – FIP. "Diagnosis and assessment of concrete structures – State of art report", CEB Bulletin, pp. 83-85, 1989. 249

[6] Yeol Choi and Robert L. Yuan. "Experimental relationship between splitting tensile strength and compressive strength of GFRC and PFRC", Cement and Concrete Research, Vol. 35, pp. 1587-1591, 2005.

[7] Zhijian Li, Lijing Wang and Xungai Wang. "Compressive and Flexural Properties of Hemp Fiber Reinforced Concrete", Fibers and Polymers, Vol. 5, No. 3, pp. 187-197, 2004.

[8] Cengiz Duran Atis and Okan Karahan. "Properties of steel fiber reinforced fly ash concrete", Construction and Building Materials, Vol. 23, pp. 392-399, 2009.

[9] Chandramouli, K., Srinivasa Rao, P., Pannirselvam, N., Seshadri Sekhar, T. and Sravana, P. "Strength properties of glass fibre concrete", ARPN Journal of Engineering and Applied Sciences, Vol. 5, No. 4, pp. 1-6, 2010.

[10] Chin, C. S. and Xiao, R. Y. "Experimental and computational analysis of fibre reinforced concrete beams", Proceedings of the 11th International Conference on Non-conventional Materials and Technologies, Bath, UK, 2009.

[11] Dahmani, L., Khennane, A. and Kaci, S. "Crack identification in reinforced concrete beams using ANSYS software", Strength of Materials, Vol. 42, No. 2, pp. 232-240, 2010.