Divya S Nair, et. al. International Journal of Engineering Research and Applications
www.ijera.com
ISSN: 2248-9622, Vol. 14, Issue 4, April, 2024, pp: 93-99

RESEARCH ARTICLE OPEN ACCESS

Geopolymer Paver Blocks Using Fly Ash, Rice husk Ash & Coconut fiber: A Sustainable Construction Material

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ABSTRACT
This project investigates the synthesis of geopolymer paver blocks using Rice husk ash (RHA) and Coconut fiber (CF) as eco- friendly alternatives in construction materials. Geopolymers, recognized for their reduced carbon footprint compared to traditional cement, are explored for their potential to enhance sustainability in paving applications. RHA, derived from agricultural waste, serves as a pozzolanic material to augment the geopolymer's strength, while CF is introduced to improve tensile strength and crack resistance. This study involves a systematic examination of varying proportions of RHA and CF in geopolymer mixes, focusing on material characterization, compressive strength, water absorption and tensile strength. The aim is to optimize the composition for achieving both environmental benefits and structural integrity in paver block applications. The research contributes to the growing field of sustainable construction practices by repurposing waste materials and incorporating natural fibers to enhance the overall performance of geopolymer paver blocks. The outcomes seek to offer a viable and environmentally conscious solution for paving applications, aligning with the global pursuit of greener alternatives in the construction industry.

Key words: Geopolymer, Sustainability, alternatives, applications

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Date of Submission: 05-04-2024 Date of acceptance: 17-04-2024

I. INTRODUCTION

Conventional concrete paver blocks, while widely used for paving applications, have significant environmental drawbacks due to the energy-intensive production of Portland cement, a key ingredient in concrete. Geopolymer paver blocks, emerging as a sustainable alternative, offer a promising solution to address these environmental concerns. Geopolymer concrete, the foundation of geopolymer paver blocks, is synthesized using aluminosilicate source materials and alkali activators, bypassing the need for Portland cement. These source materials can be industrial byproducts or natural resources, reducing the environmental footprint of the production process. Geopolymer technology, at the core of this evolution, represents a departure from the conventional reliance on Portland cement. This departure is not merely a technological choice; it embodies a commitment to sustainability and responsible resource utilization. The advantages of geopolymer paver blocks are manifold. These blocks exhibit superior compressive strength and durability, often surpassing the performance of their cement-based counterparts. Furthermore, the production of geopolymer binders involves significantly lower carbon emissions, aligning with global efforts to mitigate the environmental impact of construction activities. Paver bricks are utilized to enhance paved areas' visual appeal. All places are ideal for these pavers. Pavers are more aesthetically pleasing when they have colored blocks. The paver bricks are cast in various thicknesses and widths. These paver blocks are utilized in a wide range of locations, including toll plazas, city streets, bus depots, intersections, high altitude road repairs, car parks, truck parking lots, sidewalks, residential streets, level crossings, petroleum bunks, parks, and cycle tracks. In low, medium, and high traffic, blocks are utilized. The inclusion of fly ash (FA), a by-product of coal combustion, and Rice husk ash (RHA), an agricultural residue, serves a dual purpose. It not only diverts these materials from landfills but also imparts unique properties to the paver blocks. Fly ash contributes to the geopolymer binder, enhancing strength and durability, while Rice husk ash adds a sustainable and lightweight aspect to the mix. One of the newly popular concretes that contains no cement is geopolymer concrete. Researchers' interest in geopolymer concrete is growing daily as a result of the 100% and 0% use of pozzolanic material as a source material. Researchers, academics, and environmentalists are becoming more interested in using geopolymer concrete due to its ability to reduce carbon emissions from the environment while using less cement. Instead of using cement, the primary raw material of geopolymer concrete is heavily embedded with silica and alumina. Na2Si03, NaOH, and stimulator solution are used to process and initiate the polymerization process. Chain links and bonding of silicon, oxygen, and aluminum are created as a result of the polymerization process, enhancing the strength characteristics of concrete. Every thermal power station produces enormous amounts of fly ash, which are discarded into the ground. Fly ash, which has been an unusual substitute for cement in recent years, has hampered research efforts in the last few decades. And the need for an environmentally friendly environment fuels a great deal of GPC research. Its low cost, eco-friendliness, and exceptional strength and durability attributes are driving up demand for it daily. Since CO2 is not released into the atmosphere, it has no environmental effects in contrast to Portland cement. Rice husk ash (RHA) can serve as a partial substitute for other materials like fly ash or slag in geopolymer mixtures. It can enhance the properties of paver blocks by contributing to their strength, durability, and reducing the environmental impact by utilizing a waste product replace cement in concrete, depending on the specific requirements. [1] Coconut fibre is a natural fiber, when it added to the concrete it increases the many properties of concrete like compressive strength, flexural strength, split tensile strength of concrete and also reduce the cracking. Coconut fibers are easily available with large amount and also very cheap. Hence, they are also used to enhance the overall performance of geopolymer paver blocks.

1.1 Geopolymer concrete

Davidovits introduced the concept of geopolymer in 1978. Geopolymer is formed by activating an alkaline solution, which consists of sodium or potassium silicate and sodium or potassium hydroxide, with high alumina silica-rich materials. It resembles ceramic composites that establish a bond between alumina and silica. Geopolymer-based concrete, using fly ash, has the potential to replace ordinary Portland Cement (OPC)- based concrete in the construction industry due to its comparable structural properties [2]. Geopolymerisation is a reaction where the formation of the alumino-silicate gel structure utilizes silica and alumina content derived from pozzolan binding materials such as fly ash and slag, activated by an alkaline solution (NaOH and Na2SiO3). The microstructure of the interconnected geopolymer exhibits greater resistance to external environmental conditions. In the process of geopolymerisation, alkali metal plays a crucial role in determining the reaction rate and final products. It is a type of polymer that lacks a definite crystalline structure when exposed to elevated temperatures. The process of heat-curing accelerates the rate of geopolymerisation in comparison to curing at ambient-temperatures [3].

1.2 Cement replacement

Concrete is the second most commonly used building material. One of its main ingredients is cement; Its production, which uses large amounts of fossil fuels, produces about 7% of globalCO2 emissions, contributing negatively to the increase in pollution [4]. For this reason, cement production and consumption must be reduced, as it emits large amounts of greenhouse gases. Failure to reduce cement production leads to an overexploitation of the materials used for the manufacture of concrete, causing a negative impact on the environment, since the current production of 25 billion tons of concrete already generates sustainability problems. This is why the construction industry seeks policies to avoid the scarcity of these resources, proposing using fly ash as a supplementary cementing input to reduce pollution due to cement production and uncontrolled decomposition of agro-industrial wastes [5]. Because of this, solutions are sought to reduce this type of problem, making it feasible to partially replace cement with fly ash (FA), which, as studied, reduces carbon dioxide emissions. Numerous endeavors have been undertaken to select an alternative substance to Portland cement that serves as a waste material. Identifying a material that mitigates the aforementioned challenges represents one of the most efficacious solutions. This entails substituting regular cement entirely with a composition consisting of zero percent cement and a hundred percent utilization of fly ash or a substance rich in silica and alumina. In this sense, the use of FA, associated with the disposal of industrial waste, is one of the main alternatives to mitigate environmental pollution [5]. FA, or amorphous aluminosilicate materials, have the potential to be non-cementitious in their natural state. However, when they come into contact with calcium hydroxide and water, they undergo a reaction that results in the formation of cementitious compounds. This characteristic makes them a highly sustainable alternative to traditional Portland cement concrete. FA offers numerous benefits, including a decrease in heat of hydration [6], improved resistance to frost, potential energy savings [7], reduced CO2 emissions, minimized use of natural resources, and improved management of hazardous waste [8]. Paver blocks, also referred to as concrete pavers, are robust and versatile construction materials employed in outdoor flooring applications. These interconnected concrete elements are available in a variety of shapes, sizes, and hues, enabling innovative and personalized designs in driveways, walkways, patios, and landscaping endeavors. The strength, stability, and resilience to deterioration exhibited by paver blocks render them well-suited for enduring heavy loads and inclement weather conditions. Their interlocking mechanism facilitates effortless installation, and in case of damage, they can be readily replaced. Furthermore, paver blocks offer permeability, enabling water to permeate, thereby diminishing surface runoff and contributing to sustainable urban drainage. Paver blocks are also used in light traffic, medium traffic and heavy traffic areas. The blocks are cast into various colours, shape and sizes to suit to the requirement to satisfy the norms of IS: 15658-2006.

II. MATERIALS USED

2.1 Fly ash

It is a by-product from combustion of coal in large power plants. Fly ash is collected in electrostatic precipitators or bag houses, then transferred to substantial silos for shipment. FA produced from anthracite and bituminous coals are Class F, while sub-bituminous and lignite coals produce Class C FA [9]. The short summary of these two types of fly ash is given in Fig.1

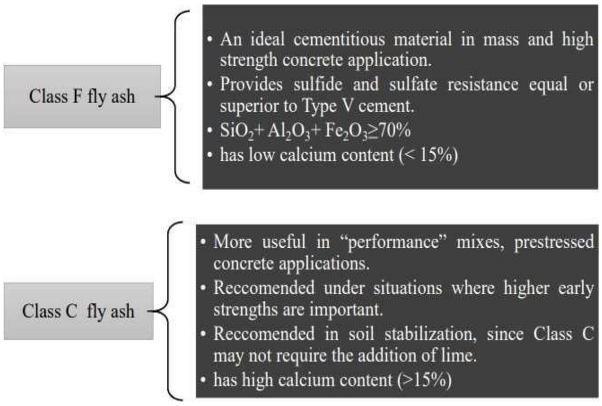

Figure 1. Summary of fly ash classification, use and composition [10]

Fly ash can be mixed with other materials such as volcanic materials, husk ash and clay to produce light weight geopolymer paste [11].

2.2 Rice Husk Ash

Rice husk ash is a byproduct of the cultivation and processing of rice as a foodstuff. Between 20% and 25% of the rice paddy is an indigestible outer husk, which is removed and usually burnt (either in a local power plant, to create steam with which to parboil the rice itself, or in household stoves). Approximately 18% of these husks, when burnt, will become ash, therefore, the production of 1 ton of rice will result in roughly 45 kg (70 lbs) of RHA, which is rich in silica (95%), with a high surface area and substantial pozzolanic properties [12]. The chemical composition of RHA has been identified to have high SiO2 content in which this component could help in forming a good binder for the geopolymer.

2.3 Coconut fiber

Among all natural fibers (jute fiber, cotton fiber, coir, flax fiber, sisal fiber, banana fiber, etc.), coir is widely studied as fiber reinforcement in cementitious materials. This is because coconut fibers are cheap, environment-friendly, and have the highest tensile toughness among natural fibers. Coir shows a prominent ductile response before failure and experiences longer deflections. It is worth noting that coir has the highest toughness compared to other natural fibers [13].

2.4 Alkali activator solution

The most used alkaline activators are a mixture of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate and potassium silicate. The alkaline activated slag reporting an increase in mechanical strength when the concentration of the activator increases. Furthermore, after a study of the geo-polymerisation of sixteen natural Al-Si minerals, they found that generally the NaOH solution caused a higher extent of dissolution of minerals than the KOH solution [14]. Fig.2 clearly shows how the compressive strength of geopolymer concrete increase with increase in molarity of alkaline solution.

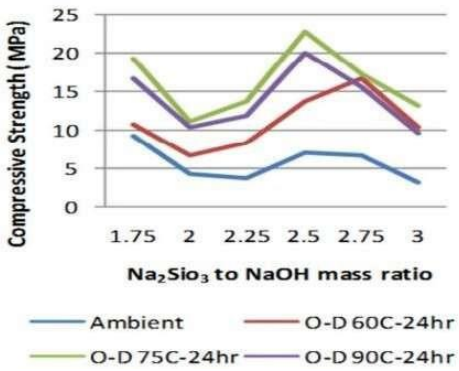

Figure 2. Effect of mass ratio of sodium silicate to sodium hydroxide for Ambient and oven dry curing [15].

2.5 Fine Aggregate

M-sand is mostly used as an alternate material for fine aggregate. M-sand particles are passing through 4.75mm sieve and retained on 75µm sieve are classified into fine aggregates. The aggregate material should satisfy the code book conditions mentioned in IS 383–2016 [16].

2.6 Coarse Aggregate

Coarse aggregates shall comply with the requirements of IS 383. As far as possible crushed semi-crushed aggregates shall be used. For ensuring adequate durability, the aggregate used for production of blocks shall be sound and free of soft or honeycombed particles. The nominal maximum size of coarse aggregates used in production of paver blocks shall be 12 mm [17].

III. MECHANICAL PROPERTIES

Investigated the mechanical properties of fly ash based geopolymer concrete, like the compressive strength, flexural strength, and Elastic Modulus. The test samples were made with varying concentration of sodium hydroxide solution from4 M up to 12 M. The compressive strength of the concrete varied from normal to high strength, encompassing a wide range. The results of this study produced 3 values of concrete mechanical properties which are very much needed on structural reinforced geopolymer concrete design, namely compressive strength, flexural strength and shear strength [18].Compared the physical and mechanical properties of fly ash (FA)-based geopolymer concrete (GC), compared to those of Portland cement concrete (CC). GC exhibits competitive compressive strength compared to CC. GC achieved its maximum compressive strength at three days, which remained constant even after two years [19]. Investigated the effects of chemical changes of alkaline activators on the compressive strength of mortar and to analyze the microstructure of the mortar through SEM, EDS, XRD, FT- IR and by porosity assessments. The results showed that chemical changes of the alkaline activators had a significant effect on the early strength with higher molarity [20]. Examined the effects of particle size distribution and fly ash source on the mechanical and microstructural properties of fly ash-based geopolymer concrete. The utilization of a fly ash with a smaller average particle size distribution resulted in an increase in the bulk density, absorption after immersion, and the ratio of volume of permeable pore space. Furthermore, the finer particle size distribution contributed to the enhancement of the compressive strength [21]. Investigated Effect of Na2O content, SiO2/Na2O molar ratio, and curing conditions on the compressive strength of FA-based geopolymer. The results reveal that higher compressive strength can be obtained with higher Na2O content, higher curing temperatures, and longer pre-curing periods at the relatively low temperature (23 C). On the other hand, an extension of curing period at high temperatures leads to strength reduction due to increasing macro-pores over 50 nm[22]. The present study outlines the experimental inquiry conducted to formulate geopolymer concrete utilizing alkali- activated rice husk ash (RHA) through the combination of sodium hydroxide and sodium silicate. The impact of curing technique and NaOH concentration on the compressive strength, along with the optimal blend ratio of geopolymer mortar, was examined. It is possible to achieve compressive strengths of 31 N/mm2 and 45 N/mm2 , respectively for the 10 M alkali-activated geopolymer mortar after 7 and 28 days of casting when cured for 24 hours at

60◦ C. Results indicated that the increase in curing period and concentration of alkali activator increased the compressive strength [23]. It is noted that RHA blended concrete can decrease the temperature effect that occurs during the cement hydration. RHA blended concrete has the potential to enhance the workability of concrete in comparison to OPC. It can also increase the initial and also final setting time of cement pastes. Additionally, RHA blended concrete can decrease the total porosity of concrete and modifies the pore structure of the cement, mortar and concrete, and significantly reduce the permeability which allows the influence of harmful ions leading to the deterioration of the concrete matrix. RHA blended concrete can improve the compressive strength and helps in enhancing the early age mechanical properties as well as long-term strength properties of cement concrete [24]. Investigated the use of natural fibres such as coconut fibre as an alternative material in geopolymer mortar composites. This research carried out compressive strength and flexural strength test by doing several variations such as the length of coconut fibres 10 mm, 20 mm,and 30 mm and the percentage of fibre used was 0, 0.25% and 0.50% of the weight of the mortar. This study indicated that the fibre length of 30 mm with a percentage of 0.50% fibre at a concentration of 16 M NaOH solution gives the maximum compressive strength and flexural strength [25].

2.7 Benefits of FA-RHA-CF based Geopolymer paver blocks

Geopolymer technology, which involves the use of fly ash and rice husk ash, typically results in lower carbon emissions compared to traditional concrete production methods. This contributes to the reduction of greenhouse gas emissions [26]. Geopolymer pavers tend to have higher resistance to chemical attacks compared to conventional concrete. This makes them suitable for areas exposed to corrosive substances, such as industrial zones or areas with high chemical concentrations [27]. Depending on the availability of raw materials in a specific region, geopolymer pavers can be cost-effective due to the utilization of industrial and agricultural waste products. Fly ash, rice husk ash, and coconut fiber-based geopolymer paver blocks offer several benefits compared to traditional concrete or clay pavers. Utilizing fly ash in geopolymer paver blocks helps in recycling industrial waste. This byproduct of coal combustion reduces the need for traditional cement, which is a significant source of carbon dioxide emissions [28]. Rice husk ash, which is an agricultural waste product, the environmental impact is minimized. It promotes the utilization of agricultural byproducts, reducing the need for their disposal. Coconut fiber can be used as a reinforcing material in geopolymer concrete to enhance its mechanical properties, particularly its tensile strength and toughness. Increased compressive strength, flexural strength and resistance to crack are some of the benefits of adding coconut fibre to geopolymer concrete. When incorporated into the mix, coconut fiber adds reinforcement and can contribute to the overall sustainability of the geopolymer paver blocks [29].

IV. CONCLUSION

The following conclusions can be drawn based on the above studies. Research on geopolymer concrete paver blocks is definitely the answer to the need of greener concrete for sustainable development. Fly ash can be used to produce geopolymeric binder phase which can bind the aggregate to form geopolymer concrete. For different mixes of geopolymer concrete increase in alkaline solution increases the compressive strength. The compressive strength of geopolymer paver block increases with $Na_2SiO_3/NaOH$ ratio. RHA can be used as a partial replacement of cement in OPC concrete and as a source material in Geopolymer concrete. So instead of dumping it into ground it should be used to enhance the properties of geopolymer concrete. RHA is rich in silica so it's a pozzolanic material and can be used as a source material in Geopolymer concrete in addition with other source materials. Coconut fiber, when added to geopolymer concrete increases the many properties of concrete like compressive strength, flexural strength, split tensile strength and also reduce the cracking. Coconut fibers are easily available with large amount and also very cheap. Fly ash in concrete enhances its strength, durability, mechanical properties. Hence the use of cement in concrete decreases which ultimately reduces cost, as well as carbon footprints of structure. So production of pavers with flyash and fibres is an economical and sustainable approach.

While geopolymer paver blocks have numerous benefits, it's essential to consider local conditions, availability of raw materials, and the specific requirements of the project before choosing this technology for pavement construction. Additionally, ongoing research and development in this field may lead to further improvements and innovations**.**

ACKNOWLEDGEMENTS

We take this opportunity to express our deep sense of gratitude and sincere thanks to all who helped us to complete this work successfully. We would like to acknowledge the support and guidance of our external research advisor, Dr. T Meena Associate Professor, School of Civil Engineering, VIT Vellore. We express our sincere gratitude to our Principal and HOD for providing all the facilities needed for the completion of this work. We are greatly thankful and deeply indebted to our Project Guide Ms. Divya S Nair for her excellent guidance, Positive criticism, Valuable comments and support Finally we would like to thank for all the institution facilities provided by the Civil Engineering Department of College of Engineering Kidangoor.

REFERENCES

[1]. Bang. C., Study on Fly Ash Based Interlocking Concrete Paver Block Using Chopped Fibers, 2020: p. 2

[2]. Albitar, M.; Visintin, P.; Ali, M.S.M.; Drechsler, M. Assessing Behaviour of Fresh and Hardened Geopolymer Concrete Mixed with Class-F Fly Ash,. KSCE J. Civ. Eng.2015, 19, p. 1445–1455

[3]. Verma, M.; Dev, N.; Rahman, I.; Nigam, M.; Ahmed, M.; Mallick, J. Geopolymer Concrete: A Material for Sustainable Development in Indian Construction Industries, Crystals 2022, 12, 514

[4]. B. Thomas, C. K S, H. A, A. Raj Kunnath and D. Mohan, A Study on Strength Properties of Fly Ash and Ground Granulated Blast Furnace Slag based Geopolymer Concrete, Grenze International Journal of Engineering & Technology, vol. 6, no. 2, pp. 186-190, 2020.

[5]. J. . A. Lizcano Cabeza, L. F. Ávila Ascanio, C. A. Ríos Reyes and L. Y. V.-F. Y. Vargas Fiallo, Effect of the fusion and aging process in the synthesis of zeotypes from fly ash, Revista Facultad de Ingeniería, Universidad de Antioquia, no.74, pp. 213-225, 2015.

[6]. P. R. de Matos, R. Junckes and L. R. Prudêncio Jr, Influênciado uso de cinza volante na elevação adiabática de temperatura e resistência à compressão de concretos, Matéria, vol. 24, no. 2, pp. 1-16, 2019.

[7]. S. Zhang, B. B. Chen, b. tian, X. Lu and B. Xiong, Effectof Fly Ash Content on the Microstructure and Strength of Concrete under Freeze–Thaw Condition, Buildings, vol. 12,no. 12, p. 2113, 2022

[8]. M. Czop, B. Łaźniewska-Piekarczyk and M. Kajda- Szcześniak, Evaluation of the Immobilization of Fly Ash from the Incineration of Municipal Waste in Cement Mortar Incorporating Nanomaterials—A Case Study, Energies, vol.15, no. 23, p. 9050, 2022.

[9]. Headwaters resources, “Fly Ash Types & Benefits,” p. 84095

[10]. Zerfu, Kefiyalew & Ekaputri, Januarti. (2016). Review on Alkali-Activated Fly Ash Based Geopolymer Concrete, Materials Science Forum. 841. 162-169. 10.4028/www.scientific.net/MSF.841.162.

[11]. Gonçalves, Mayra & Bergmann, Carlos. (2007). Thermal insulators made with rice husk ashes: Production and correlation between properties and microstructure, Construction and Building Materials. 21. 2059-2065. 10.1016/j.conbuildmat.2006.05.057.

[12]. Babar Ali, A. Hawreen, Nabil Ben Kahla, Muhammad Talha Amir, Marc Azab, Ali Raza, A critical review on the utilization of coir (coconut fiber) in cementitious materials, Construction and Building Materials, Volume 351, 2022, 128957

[13]. Baskar, Prabu & Shalini, A. & Kumar, J.K.. (2014). Rice husk ash based geopolymer concrete - A Review. Chem Sci Rev Lett. 3. 288-294.

[14]. Joshi, S. & Kadu, Mahendra. (2012). Role of Alkaline Activator in Development of Eco-friendly Fly Ash Based Geo Polymer Concrete, International Journal of Environmental Science and Development. 3. 417-421. 10.7763/IJESD.2012.V3.258.

[15]. V, Arulpandian & S, Venkatramana & R, Jegankumar &G, Balaji. (2023), Sustainable Development of Geopolymer Concrete Paver Blocks Blended With Boiler Sand, 10.21203/rs.3.rs-3202401/v1.

[16]. IS 15658 : 2006 Precast concrete blocks for paving.

[17]. Hardjasaputra, Harianto & Cornelia, Melanie & Gunawan, Y & Surjaputra, I & Lie, H & Rachmansyah, Rachmansyah & Ng, G. (2019). Study of mechanical properties of fly ash-based geopolymer concrete, IOP

[18]. Conference Series: Materials Science and Engineering. 615. 012009. 10.1088/1757-899X/615/1/012009.

[19]. Nikoloutsopoulos, N.; Sotiropoulou, A.; Kakali, G.; Tsivilis, S. Physical and Mechanical Properties of Fly Ash Based Geopolymer Concrete Compared to Conventional Concrete Buildings, 2021, 11, 178.
[20]. Gum Sung Ryu, Young Bok Lee, Kyung Taek Koh, Young Soo Chung, The mechanical properties of fly ash-based geopolymer concrete with alkaline activators, Construction and Building Materials, Volume 47, 2013, Pages 409-418, ISSN 0950-0618,
[21]. Lateef N. Assi, Edward Eddie Deaver, Paul Ziehl, Effectof source and particle size distribution on the mechanical and microstructural properties of fly Ash-Based geopolymer concrete, Construction and Building Materials, Volume 167, 2018, Pages 372-380, ISSN 0950-0618
[22]. Young-Keun Cho, Sung-Won Yoo, Sang-Hwa Jung, Kwang-Myong Lee, Seung-Jun Kwon, Effect of Na2O content, SiO2/Na2O molar ratio, and curing conditions on the compressive strength of FA-based geopolymer, Construction and Building Materials, Volume 145, 2017, Pages 253-260, ISSN 0950-0618
[23]. Kim YY, Lee BJ, Saraswathy V, Kwon SJ. Strength and durability performance of alkali-activated rice husk ash geopolymer mortar, Scientific World Journal. 2014;2014:209584. doi: 10.1155/2014/209584. Epub 2014 Nov 23. PMID: 25506063; PMCID: PMC4258323.
[24]. Baskar, Prabu & Shalini, A. & Kumar, J.K.. (2014). Rice husk ash based geopolymer concrete - A Review, Chem Sci Rev Lett. 3. 288-294.
[25]. Zulfiati, Ria & Saloma, & Idris, Yakni. (2020). The Nature of Coconut Fibre Fly Ash-Based Mechanical Geopolymer, IOP Conference Series: Materials Science and Engineering. 807. 012041. 10.1088/1757-899X/807/1/012041.
[26]. Agustinus Agus Setiawan et al., Embodied carbon dioxide of fly ash based geopolymer concrete, 2023 IOP Conf. Ser.: Earth Environ. Sci. 1195 012031
[27]. Srinivas*, Dr. T., Vundi (2019). Resistance of Acid Attack on Geopolymer Concrete Developed With Partial Replacement of Course Aggregate by Recycled Aggregate, In International Journal of Recent Technology and Engineering (IJRTE) (Vol. 8, Issue 4, pp. 12142–12146).
[28]. Kalombe RM, Ojumu VT, Eze CP, Nyale SM, Kevern J, Petrik LF. Fly Ash-Based Geopolymer Building Materials for Green and Sustainable Development. Materials (Basel). 2020 Dec 14;13(24):5699.
[29]. Mahyuddin Ramli, Wai Hoe Kwan, Noor Faisal Abas, Strength and durability of coconut-fiber-reinforced concrete in aggressive environments, Construction and Building Materials, Volume 38, 2013, Pages 554-566