International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 11 | Nov 2026 www.irjet.net p-ISSN: 2395-0072

Sustainable Geopolymer and Alkali-Activated Materials Incorporating Industrial, Agricultural, and Construction and Demolition Wastes for Pavement Applications: A Critical Review

Deepjyoti Nath[1], Dibyajyoti Saikia[2], Risha Agnibaishya[3], Nishita Das[4], Mayur Jyoti Das[5]

[12]Assistant Professor, Department of Civil Engineering, Bineswar Brahma Engineering College, Assam, India
[345]Undergraduate Student, Department of Civil Engineering, Bineswar Brahma Engineering College, Assam, India

---

Abstract - *The need for transportation infrastructure development has created a heavy dependency on conventional cementitious binders and aggregates, leading to many environmental problems including natural resource exhaustion and large carbon footprints. Geopolymers and alkali activated materials serve as potential substitutes through the utilization of industrial, agricultural, and construction and demolition (C&D) waste streams in pavements. In this important review, a thorough discussion on fly ash, GGBS, RHA, and recycled C&D waste used as subgrade, subbase, and pavement base stabilization material has been presented. It should be noted that much emphasis has been made on the distinction between chemically reactive precursors and recycled aggregates. Literature synthesis is carried out on compaction characteristics, UCS, CBR, resilient modulus, moisture resistance, durability, and environmental sustainability. Based on the current literature, there appears to be considerable potential in Geopolymer stabilization through fly ash and alkali-activated construction and demolition wastes; however, variation in precursor composition, activators, curing process, and test procedures hampers the ability to draw a comparison between studies. In addition, the overall environmental benefit also depends largely on material production, transportation, curing process, and service life. The future research areas that need to be explored further include ambient curing, cyclic load resistance, moisture resistance, leachability of contaminants, and field tests.*

Key Words: Geopolymer; Alkali-activated materials; Construction and demolition waste; Pavement stabilization; California Bearing Ratio.

1. INTRODUCTION

Construction of transportation infrastructures needs huge amounts of aggregates, soil stabilizers, and cementing agents. Traditional road construction can result in the exhaustion of natural resources, high energy usage, greenhouse gas emissions, and generation of construction and industrial waste. Natural aggregates need is especially significant in granular roadbeds since the cost and environmental performance of the construction can be affected by the material availability, transport distance, and quality of the aggregates.

Ordinary Portland cement (OPC) is used in concrete and ground improvement due to its reliable properties and accessibility. But cement production is energy intensive due to the formation of clinker and emissions caused by limestone calcination. Thus, alternative binder technologies have become of interest as the part of the general trend in decreasing the environmental footprint of building materials [1]. found out that the greenhouse gas emissions of Geopolymer and OPC concrete can vary depending on the materials and technologies used in the comparison.

Geopolymerization and alkali-activation can serve as possible ways for using aluminosilicate containing materials as binders. Fly ash, GGBS and certain mineral wastes are able to form hardenable binding systems under alkaline conditions. The final reaction products and their properties are a function of the raw material compositions, the activating agent, the presence of water and curing [2, 3]. While the terms Geopolymer and alkali-activated materials are often applied together, they are not always interchangeable. Geopolymers usually denote specific aluminosilicate network-forming systems while alkali-activated materials include a wider range of reaction products, which can contain calcium compounds as well [4].

The use of industrial and agricultural waste will not only cut down the requirement of raw materials but also help in finding applications for such wastes. Fly ash has already gained attention as a precursor for Geopolymer production whereas rice husk ash can act as a possible source of reactive silica if synthesized properly [3, 5]. Waste from quarries may help as a mineral source, fillers or granular materials depending on their mineral content and properties [6]. C&D waste can be converted into recycled aggregates or used as binders when their composition is favorable for it [6, 7].

These materials are particularly important for pavement engineering because stabilization would help increase the strength and stiffness of poor subgrade soils and granular pavement bases. [8] studied the Geopolymer stabilization of black cotton soil based on fly ash, whereas [9] studied the mechanical behavior of fly ash-based Geopolymer as a road base stabilizer. [10] studied one-part fly ash-slag Geopolymer for the stabilization of demolition wastes in pavement bases. The importance of alkali-activated materials for pavement engineering is shown in these

studies; however, the performance of every material is application-specific.

One problem is that results obtained for Geopolymer concrete and mortar cannot be easily extended to stabilized soils or geosynthetic materials. The performance of concrete is primarily determined by the characteristics of its binder matrix and aggregates' bonding. On the other hand, pavement base performance depends on not only these factors but also on compaction, moisture sensitivity, stiffness, stress distribution, and repeated loadings. Recycled-aggregate Geopolymer concrete investigations showed that sometimes deterioration in terms of water absorption and sorptivity was observed despite improved fresh and hardened properties [7].

Whereas [11] have comprehensively covered pavement applications of Geopolymer materials, this review will focus specifically on the differences between precursors, recycled aggregates and fillers, and link material properties to pavements' engineering and environmental considerations.

The key aims of the review include:

1. To study the contribution of industrial wastes, agricultural waste, construction and demolition wastes and quarry wastes to Geopolymeric and alkali activated pavement materials.
2. To synthesize knowledge on compaction, strength, stiffness, shrinkage, moisture resistance and durability.
3. To recognize gaps in the research, especially related to extrapolating the findings from concrete and mortars to pavement layers.
4. To determine research priorities for mixture development, environmental assessment and field application.

2. RESEARCH METHODOLOGY

2.1 Literature identification

This study utilizes a critical literature review methodology which is more specific. The literature was sourced from searches carried out by the scholar using scholarly sources and journal databases. More weight was put on journal articles and review papers focusing on Geopolymerization, alkali activation, recycled aggregates, quarry wastes, pavement stabilization, durability, and life cycle environmental impact.

The selected literature has been grouped under the following broad categories: Binder Chemistry and Precursors; Recycled Aggregates and Mineral Wastes; Geotechnical and Mechanical Performance; Durability and Environmental Impact Assessment.

2.2 Inclusion Criteria and Scope

A publication was regarded as relevant in case it covered any of the following topics:

- Binding and precursor reactions of Geopolymers or alkali activated binders.
- Recycling of fly ash, GGBS, RHA, quarry dust or C&D wastes.
- Stabilization of soils, granular materials, sub-grades or pavement base layers.
- Mechanical performance, durability, environmental safety or lifecycle assessment.

Articles on Geopolymer concrete and mortars were reviewed when they added information on the chemistry of the binder or performance of aggregates in terms of environment. Results of the studies were not regarded as conclusive evidence for suitability of pavements-sub-grades or pavement bases.

2.3 Evidence Synthesis

Selected papers were qualitatively analyzed based on the nature of materials used, application of the materials, experimental conditions, and limitations described by each research. Specifically, emphasis was made on differentiating the obtained measurements from the suggested mechanism and future applications.

Since there are differences in precursor chemistry, mixing ratios, curing process, and measurement methods, no meta-analysis is done in this paper and hence there is no average improvement in strength and optimum mixture ratio. This paper employs a critical review technique rather than systematic review.

3. MATERIALS AND REACTION MECHANISMS

3.1 Industrial By-Products

Fly Ash

Fly ash is an extremely fine particulate matter produced by the burning of coal. Depending on the type of the coal, combustion, and fly ash recovery process, the composition may vary and include silica, alumina, iron compounds, calcium materials, and crystalline materials having varying roles in the formation of alkalis.

[12] conducted research on the effect of fly ash reactivity on Geopolymerization process. It was shown that fly ash reactivity influences the formation of binding products and compressive strength. The results indicate that the selection of fly ash is based not only on its type and size but also on the chemical and mineralogical composition.

Fly ash could act as the main precursor in alkali activation for soil stabilization and pavement construction. For instance, [8] examined its performance in black cotton soil stabilization and [9] explored the role of Geopolymer made from fly ash in road base stabilization. In this way, it becomes evident that fly ash-based binder materials could be studied based on pavement-related criteria.

However, fly ash sources may vary significantly in terms of glass content, grain size, calcium availability, and reactivity. Thus, material analysis and tests are necessary before selecting a formula to apply in the field.

Ground Granulated Blast-Furnace Slag

GGBS is a manufactured by-product of steel production and it is frequently used as a source of calcium in the alkali-activated binders. Its addition may affect the kinetics of reaction, setting behavior, strength at an early age and the formation of binding phases.

Fly ash and slag were combined as potential additives in alkali-activated materials. [10] studied the properties of one-component fly ash-slag Geopolymer for the stabilization of demolition wastes in pavement bases. This study is especially important since it considers the relation between the composition of the binder and the properties of reclaimed pavement material.

The effect of slag depends on its proportion in the blend of precursors, activators, moisture and curing regime. Reaction products with calcium may provide strength gain and microstructure compaction, although slag addition does not necessarily result in better performance of the material under all conditions [4, 13].

3.2 Agricultural Residues: Rice Husk Ash

Ash from Rice Husk is derived through the burning of rice husk and may be a potential source of reactive silica for alkali-activated materials. The content and reactivity of silica in rice husk ash is dependent on the temperature of burning, burning time, cooling process, and processing of ash, hence the performance of the materials will greatly differ among the sources.

A review of the use of waste Rice Husk Ash in Geopolymer system was carried out by [5], discussing the effect of the material on the performance of the system. The production, characterization, and application of RHA in alkali-activated materials were studied by [14].

Silica provided by RHA could potentially lead to the development of aluminosilicate or calcium-containing reaction products, depending on the chemical nature of other components. In high-calcium mixes, calcium silicate or aluminosilicate hydrates, among other reaction products, may develop; in low-calcium mixes, alkali aluminosilicate gels may predominate.

It is clear that the possible application of RHA for road building purposes would depend on its reactivity, preparation needs, water consumption, and compatibility with other ingredients. Even though RHA contributes to binder formation, it does not mean that all mixtures will be improved in strength or porosity by adding it.

3.3 Construction and Demolition Waste

C&D waste is waste resulting from construction, renovation, and demolition processes of buildings and infrastructure. This waste could include items like crushed concrete, mortar, masonry, ceramics, and other construction wastes. Once processed to meet specified quality requirements, such waste can be used in construction products.

Three roles must be distinguished:

1. Reactive precursor: The waste contributes chemically to the formation of binding products.
2. Recycled aggregate: The processed material provides the granular skeleton of a mixture.
3. Filler: The material modifies particle-size distribution and packing, with its chemical contribution depending on composition and reactivity.

These roles are not interchangeable because they influence mixture design and performance differently.

Recycled aggregate inclusion was found by [7] to have the ability to improve some fresh properties but increase water absorption and sorptivity. This clearly indicates the need to appreciate the pros and cons of using recycled materials.

C&D waste-based Geopolymer concrete parameters and sustainability were determined by [6]. This study is important because it sheds light on the use of C&D materials as Geopolymer components; however, concrete behavior cannot always be transferred to stabilized soil and granular pavements.

The application of one-part fly ash–slag Geopolymer stabilization of demolition wastes as a pavement base was studied by [10]. This study is more pertinent to pavement applications and stresses the need to assess the fully stabilized material rather than only the binder.

Recycled C&D material suitability is based on the source composition, particle size distribution, water absorption, contamination, and mechanical properties of the material. These factors must be determined before using the recycled material in the pavement layer.

3.4 Quarry Waste and Mineral Fillers

Quarry waste comprises fine mineral particles generated during the processes of quarrying of rocks, crushing, screening, and aggregation processing. Quarry waste may act as a precursor, filler, or granular material based on its composition and physical properties.

[15] conducted a review of quarry waste as a precursor material for Geopolymer synthesis and application in civil engineering projects. The review points out the role of mineralogy, processing, curing, and chemical stability. The results of the review indicate that quarry waste derived from various geological formations do not have similar reactivity. The use of quarry dust can facilitate particle packing when it is compatible with other constituents of the mixture. Its impact on the density, moisture requirements, and mechanical properties is dependent on the nature of the material and the amount used. The use of quarry waste as a filler should not be confused with its use as a chemically reactive precursor.

The researchers [16] conducted a study on Class C fly ash and quarry dust as the sub-base material for a flexible pavement. The research can be cited as an example of an applied approach to the evaluation of industrial residues and quarry wastes. However, the results obtained with a certain mixture of fly ash and quarry dust cannot be extended to all alkali-activated mixes.

3.5 Activators and Curing Conditions

The alkali activation process is based on the dissolution of active compounds from the precursor and their further reaction to create bonding products. According to the formulation, an activator can be sodium hydroxide, sodium silicate or some other type of alkaline substance. The chemistry and dosage of the activators determine the dissolution process, reaction kinetics, setting behaviour and strength growth [2, 17].

Significant parameters are activator dosage, activator-to-precursor ratio, water amount, precursor mixture composition and curing conditions. Those parameters interact and altering one of the variables impacts the others at once.

[12] have shown the significance of the precursor reactivity, and [9] and [10] have studied alkali-activated materials specifically for pavement use.

One-part Geopolymers could make construction easier as they use solid activator materials instead of having to prepare an alkaline solution separately. Even though solid activators are easier to handle, they do influence the material's ecological and economical aspects.

The curing of the material is especially significant in pavement engineering. If the system provides good mechanical properties under laboratory curing conditions but not ambient curing conditions, then its use in conventional paving becomes questionable.

4. PAVEMENT ENGINEERING PERFORMANCE

4.1 Compaction and Density Characteristics

The compaction process will define both the density and the structure of the soil or granular pavement materials. Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) are often utilized to specify the correct compaction parameters for stabilized subgrades and granular materials.

The use of binders or recycled fines can affect the particle size distribution, water requirements, inter-particle friction, and the formation of binding compounds. Such an effect on the OMC and MDD will vary depending on the initial soil or aggregate, binder quantity, material porosity, and mixture characteristics.

As an example, the use of fine materials can help improve particle packing where there are initial voids within the particle size distribution of the material. On the other hand, porous or highly absorptive materials may raise the water requirement of the mixture.

[15] addressed the issue of the significance of quarry waste properties in Geopolymer applications, while [16] evaluated fly ash and quarry dust mixtures for sub-base pavements application. This clearly demonstrates the significance of considering the whole granular aggregate rather than assuming the compaction behavior from only the binder.

Further studies must consider reporting the compaction technique, moisture density relationship, precursor quantity, activator quantity, and curing process. The comparisons must include untreated control samples and ordinary stabilizers under identical conditions.

4.2 Unconfined Compressive Strength and California Bearing Ratio

UCS and CBR are important criteria for assessing subgrade materials after stabilization. UCS indicates compressive strength in an unconfined state, whereas CBR offers an index of penetration resistance under specific testing conditions. [8] studied Geopolymer stabilization of black cotton soil by fly ash as a subgrade material. [9] evaluated fly ash-based Geopolymer as a stabilizer for the road base, while [18] evaluated strength, durability, and toxicity aspects of Geopolymers based on water treatment sludge used as subgrade material. All these studies illustrate the importance

of strength and bearing capacity testing for alkali-activated waste materials.

[10] conducted research on the stabilization of demolition wastes with a one-part fly ash-slag Geopolymer system. This study expands the scope of alkali activation technology from traditional soil stabilization to recycled pavement base materials.

Nevertheless, high UCS alone does not guarantee acceptable performance of pavements. Other parameters like CBR, stiffness, shrinkage, moisture susceptibility, and repeated load behaviour should also be considered. Moreover, acceptance criteria may depend on the pavement layer, testing conditions, and road design criteria.

The reported strengths may only be compared if there is sufficient similarity between the materials used, sample preparation, curing process, and testing methodology. There is no way to come up with a general strength enhancement or percentage replacement value without a systematic evaluation of the original experimental data.

4.3 Stiffness, Tensile Behaviour, and Repeated Loading

The layers of pavements experience repeated traffic loads and no single or monotonic loading cycles. The behaviour of the layers depends on stiffness, magnitude of the stresses, cumulative strains, moisture content, and interaction with the adjoining layers.

[9] evaluated several mechanical properties of Geopolymer pavement materials made from fly ash including unconfined compressive strength, flexural strength, indirect tensile strength, resilient modulus, and shrinkage. The above properties give complementary data regarding the behaviour of the materials in relation to mechanical responses and cracking.

[10] studied the Geopolymer stabilization of demolition wastes for road base applications. It is important to note that performance evaluation of the stabilized material under pavement-relevant conditions was considered essential.

For proper pavement design, it is important to distinguish the static strength from stiffness and resistance to accumulation of strains under repeated loadings. More testing of resilient modulus, permanent strains, and moisture sensitivity is necessary to evaluate the laboratory strength values.

4.4 Comparative Synthesis of Published Evidence

Table 1 summarizes selected verified publications relevant to Geopolymer and alkali-activated pavement materials.

Study	Material system or scope	Principal contribution	Important limitation
[12]	Fly ash Geopolymerization	Examines precursor reactivity and strength development.	Does not directly establish complete pavement-layer performance.
[3]	Fly ash-based Geopolymer review	Reviews preparation, properties, applications, and environmental considerations.	Covers multiple applications, not exclusively pavement materials.
[15]	Quarry and mining waste Geopolymer review	Examines waste suitability, processing, and chemical stability.	Results vary with mineralogy and source characteristics.
[5]	RHA-based Geopolymer review	Synthesizes RHA utilization and its influence on material properties.	Does not establish pavement suitability for every RHA formulation.
[14]	RHA in alkali-activated materials	Reviews production, characteristics, and fresh and hardened properties.	Most findings concern binder and construction-material behaviour rather than road-layer validation.
[7]	Recycled aggregates in Geopolymer concrete	Reviews fresh and hardened properties of recycled-aggregate Geopolymer concrete.	Concrete findings cannot be directly transferred to stabilized soils.
[8]	Fly ash Geopolymer stabilization of black cotton soil	Directly investigates subgrade-related performance.	Findings apply to the investigated soil and formulation.
[9]	Fly ash-based Geopolymer road-base stabilizer	Examines strength, stiffness, and shrinkage-	Long-term field validation remains important.

		related properties.	
[10]	One-part fly ash–slag Geopolymer for demolition wastes	Investigates chemical stabilization of pavement-base materials.	Performance depends on waste characteristics and construction conditions.
[18]	Water-treatment-sludge-based Geopolymer for subgrade	Examines strength, durability, and environmental safety.	Conclusions apply to the investigated waste and formulations.
[16]	Class C fly ash and quarry dust	Evaluates potential use as a flexible-pavement sub-base material.	Findings should not be generalized to all alkali-activated mixtures.
[11]	Geopolymers for pavement stabilization	Reviews the application of Geopolymer materials in road pavement construction.	Further application-specific comparison and field validation remain necessary.

Note. The table summarizes the scope and relevance of the selected publications; it does not rank their performance or imply that all studies tested the same properties.

The literature review shows the potential use of alkali activated materials in the field of pavement construction, although the data may vary depending on the particular usage of the material. Stabilized soil, granular base course, and recycled aggregate Geopolymer concrete have their own specific requirements.

5. DURABILITY AND ENVIRONMENTAL ASSESSMENT

5.1 Moisture Resistance and Water Absorption

Pavement foundation materials will be subjected to environmental factors such as precipitation, seepage, variations in groundwater levels, and variations in moisture content. Moisture can affect the strength, stiffness, deformation, and durability of stabilized materials.

For Geopolymer concrete and mortars, water absorption and sorptivity give information regarding water movement through the hardened product. According to [7], water absorption and sorptivity properties could be influenced by the addition of recycled aggregates in Geopolymer concrete. This example shows that recycling materials can cause additional moisture issues.

For stabilized soils and granular pavement materials, soaked CBR, moisture-conditioned UCS, permeability, erosion resistance, and wet–dry cycling tests could be conducted. The choice of tests would depend on the material and its role in the pavement structure.

[3] analyzed strength and durability of alkali-activated RHA Geopolymer mortar, which is an example of relevant literature on RHA Geopolymer binder systems. Nevertheless, testing mortar only is not enough to show the moisture resistance of the stabilized pavement subgrade.

The durability of each proposed mixture needs to be shown using appropriate exposure tests and not the presence of RHA, slag, or recycled fines.

5.2 Chemical Durability and Environmental Safety

By-product industrial wastes and recycled waste materials may have chemical components that need environmental analysis before reuse. Not only is the mechanical behavior an important factor in deciding about the suitability of alkali-activated binder, but also the stability of reaction products and the release of any unwanted chemicals needs to be taken into account.

[4] conducted a review on the durability of alkali-activated materials under aggressive exposures, including sulfate and chloride environment. [13] studied durability in comparison with the OPC-based materials. This review shows that the durability is dependent on the interaction between material, microstructure, and exposure conditions.

The environmental safety can be determined by conducting proper leaching tests. The concentration can be evaluated based on the regulations, considering the method used and pH of exposure.

[18] studied the strength, durability, and environmental safety of Geopolymers made from water treatment sludge. This is a good example for the study of mechanical properties and environmental aspects together. However, contamination immobilization cannot be considered for all waste-based binders: it needs to be verified for the specific case of interest.

5.3 Life-cycle Environmental Performance

The application of industrial wastes and recycled aggregates can lower the need for primary raw materials and waste disposal. Nevertheless, the environmental characteristics of alkali-activated materials should be considered within the whole production cycle.

[1] made a comparison of greenhouse gases in Geopolymer and OPC concrete to demonstrate the significance of taking into account the process of material production, transportation, and construction. [20] carried out an analysis of life cycle assessments of alkali-activated materials and found the significance of functional unit, system boundary, life-cycle inventory, and impact assessment.

An environmentally sound comparison for pavement materials should consider:

- Precursor processing and transportation.
- Production of alkaline activators.
- Mixing and curing energy.
- Construction and maintenance requirements.
- Service life and potential rehabilitation.
- Waste diversion and the allocation of environmental burdens to industrial by-products.

The evaluation done based only on the mass of the binder may not adequately reflect the pavement performance. A more meaningful evaluation will involve comparing the two materials which provide the same function within the correct period of service life.

Therefore, it is scientifically unjustified to state that all Geopolymer mixes have less environmental effect than their OPC counterparts. It all depends on the mixture composition, manufacturing process, functional unit, and system boundary considered [1, 19].

6. RESEARCH GAPS AND FUTURE PERSPECTIVES

The future direction for research needs to be towards solving material variability issues, optimal mixture design, and the long-term fitness for purpose of Geopolymer materials using waste as the binder material in pavements. Industrial, agricultural, and C&D wastes vary in terms of their chemistry, mineralogy, particle size distribution, and reactivity. Thus, characterizing these source materials and devising suitable mixture-design procedures is key. Formulations that perform well under ambient curing conditions and realistic moisture contents as well as construction timelines need to be prioritized.

Future research needs to assess pavement behavior under long-term cyclic loads including resilient modulus, permanent deformation, shrinkage cracking, and fatigue resistance among others. Durability of these materials needs to be assessed in terms of behavior under wet–dry cycling, long-term saturation, erosion, and chemical exposures among others in terms of retained strength and stiffness. The findings from laboratory investigations must be corroborated by field tests and long-term pavement monitoring studies where possible.

Also, the safety and sustainability of the environment should be assessed thoroughly. Suitable tests should be carried out for evaluating the leaching potential of the hazardous contents of the materials derived from waste. Environmental lifecycle assessment should take into account the impact of alkali activator, production of material, transport, and curing, as it cannot be assumed automatically that the use of waste will always cause less impact on the environment [20]. Comparisons of the pavement material should follow consistent assumptions and performance requirements.

Finally, standardized methods should be developed for characterization of the material, mixture proportion, curing process, quality control, and performance based acceptance criteria. By carrying out laboratory studies, environmental assessment, life cycle assessment, and field validations in future researches, appropriate guidelines for the use of Geopolymer materials in pavement subgrade, sub-base, and base materials can be established.

7. CONCLUSIONS

Geopolymers and alkali-activated materials produced from wastes generated from industries, agriculture, and construction/demolition processes provide promising alternatives to traditional pavement materials through improved use of wastes and potential reduction in the use of Portland cement and natural aggregates. The suitability of Geopolymers as pavements materials will depend on the compositions of precursors, amount of the activator used, curing process, and engineering demands of the pavement layer. While there are promising reports about the strength, bearing capacity, and durability of Geopolymers as pavements, there is a lot of variability in terms of the combinations and testing conditions of Geopolymers. Future research should focus on standard testing, field verification, environmental leaching tests, and life cycle cost/carbon analysis.

REFERENCES

1) Turner LK, Collins FG (2013) Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. Constr Build Mater 43:125–130. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2013.01.023

2) Duxson P, Provis JL, Lukey GC, van Deventer JSJ (2007) The role of inorganic polymer technology in the development of 'green concrete.' Cem Concr Res 37:1590–1597. https://doi.org/https://doi.org/10.1016/j.cemconres.2007.08.018

3) Zhuang XY, Chen L, Komarneni S, et al (2016) Fly ash-based geopolymer: clean production, properties

and applications. J Clean Prod 125:253–267. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.03.019

4) Bernal SA, Provis JL (2014) Durability of Alkali-Activated Materials: Progress and Perspectives. J Am Ceram Soc 97:997–1008. https://doi.org/https://doi.org/10.1111/jace.12831

5) Hossain SS, Roy PK, Bae C-J (2021) Utilization of waste rice husk ash for sustainable geopolymer: A review. Constr Build Mater 310:125218. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.125218

6) Alhawat M, Yildirim G, Ashour A, et al (2024) A study on the influencing parameters in developing construction and demolition waste-based geopolymer concretes and their sustainability assessment. Constr Build Mater 426:136143. https://doi.org/10.1016/j.conbuildmat.2024.136143

7) Skariah B, Yang J, Bahurudeen A, et al (2022) Geopolymer concrete incorporating recycled aggregates : A comprehensive review Ordinary Portland cement. Clean Mater 3:100056. https://doi.org/10.1016/j.clema.2022.100056

8) Murmu AL, Dhole N, Patel A (2020) Stabilisation of black cotton soil for subgrade application using fly ash geopolymer. Road Mater Pavement Des 21:867–885. https://doi.org/10.1080/14680629.2018.1530131

9) Sofri LA, Mustafa M, Bakri A, et al (2022) Mechanical Performance of Fly Ash Based Geopolymer (FAG) as Road Base Stabilizer. Materials (Basel) 1–14

10) Doan T, Arulrajah A, Lin Y, et al (2024) Transportation Geotechnics Chemical stabilization of demolition wastes in pavement bases using one – part fly ash and slag based geopolymers. Transp Geotech 45:101192. https://doi.org/10.1016/j.trgeo.2024.101192

11) Nanda RP, Priya N (2024) Geopolymer as stabilising materials in pavement constructions : A review. Clean Waste Syst 7:100134. https://doi.org/10.1016/j.clwas.2024.100134

12) Kumar S, Kumar R, Alex TC, et al (2007) Influence of reactivity of fly ash on geopolymerisation. Adv Appl Ceram 106:120–127. https://doi.org/10.1179/174367607X159293

13) Wang A, Zheng Y, Zhang Z, et al (2020) The Durability of Alkali-Activated Materials in Comparison with Ordinary Portland Cements and Concretes : A Review. Engineering 6:695–706. https://doi.org/10.1016/j.eng.2019.08.019

14) Kumar S, Adediran A, Rodrigue C, et al (2022) Production , characteristics , and utilization of rice husk ash in alkali activated materials : An overview of fresh and hardened state properties. Constr Build Mater 345:128341. https://doi.org/10.1016/j.conbuildmat.2022.128341

15) Solouki A, Viscomi G, Lamperti R, Tataranni P (2020) Quarry Waste as Precursors in Geopolymers for Civil Engineering Applications : A Decade in Review. Materials (Basel) 13(14):1–29. https://doi.org/https://doi.org/10.3390/ma13143146

16) Joshi AR, Patel S (2023) Application of Class C Fly Ash and Quarry Dust Mix for Utilization as Subbase Material in Flexible Pavement. Int J Eng 36:1597–1604

17) Elahi MMA, Hossain MM, Karim MR, et al (2020) A review on alkali-activated binders: Materials composition and fresh properties of concrete. Constr Build Mater 260:119788. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.119788

18) Bijalwan A, Mishra AK, Sonowal B (2024) Strength, durability, and toxicity characteristics of water treatment sludge based geopolymers for subgrade application. Constr Build Mater 447:138162. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2024.138162

19) Nikravan M, Firdous R, Stephan D (2023) Life cycle assessment of alkali ‐ activated materials : a systematic literature review. Low-carbon Mater Green Constr 6:1–24. https://doi.org/10.1007/s44242-023-00014-6