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Experimental Investigation on Ultra-Thin White Topping Using Fly Ash-Based Geopolymer Concrete- A Review

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Abstract- The increasing deterioration of flexible pavements due to heavy traffic loading and environmental effects has necessitated the development of efficient rehabilitation techniques. Ultra-Thin White Topping (UTWT) has emerged as an effective solution for improving pavement performance with reduced material consumption and cost. Simultaneously, the environmental concerns associated with Ordinary Portland Cement (OPC), particularly its high carbon emissions, have led to the development of sustainable alternatives such as fly ash-based geopolymer concrete (GPC). This paper presents a comprehensive review of existing studies on UTWT and geopolymer concrete, focusing on their mechanical properties, durability, bonding behavior, and sustainability aspects. Based on the review of more than 30 research studies, it is observed that geopolymer concrete exhibits superior strength, durability, and environmental benefits compared to conventional concrete. However, limited research has been conducted on its application in UTWT systems. This study identifies key research gaps and highlights the need for further investigation into the feasibility of using geopolymer concrete in ultra-thin white topping applications for sustainable pavement rehabilitation.

Keywords: Ultra-Thin White Topping, Geopolymer Concrete, Fly Ash, Pavement Rehabilitation, Sustainable Construction, Durability.

I. INTRODUCTION

Flexible pavements are extensively used in road construction due to their cost-effectiveness, ease of construction, and adaptability to varying traffic and environmental conditions; however, they are highly susceptible to various forms of distress such as rutting, fatigue cracking, potholes, and surface deformation, primarily caused by increasing traffic loads, heavy axle repetitions, temperature fluctuations, and moisture variations, which significantly reduce their service life and performance. To address these challenges and enhance the structural capacity of deteriorated pavements, several rehabilitation techniques have been developed, among which white topping has emerged as a promising and effective solution. Ultra-Thin White Topping (UTWT), a modern and innovative pavement rehabilitation technique, involves the placement of a thin cement concrete overlay, typically less than 100 mm thick, over an existing bituminous surface, ensuring proper bonding between the layers to achieve composite action, which improves load distribution, enhances structural performance, reduces maintenance requirements, and increases the overall service life of the pavement. Despite its advantages, conventional UTWT relies heavily on Ordinary Portland Cement (OPC), the production of which is associated with significant environmental concerns, as it contributes approximately 5–8% of global carbon dioxide (CO_2) emissions and consumes substantial energy resources, thereby accelerating global warming and environmental degradation. In response to these challenges, geopolymer concrete (GPC) has been developed as a sustainable and eco-friendly alternative to conventional cement concrete, utilizing industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and metakaolin, which not only reduce dependency on natural resources but also significantly lower greenhouse gas emissions through the process of geopolymerization. Geopolymer concrete has demonstrated superior mechanical properties, enhanced durability, resistance to chemical attack, and improved long-term performance compared to OPC-based concrete, making it a suitable candidate for pavement applications. However, despite extensive research on UTWT and geopolymer concrete individually, their combined application remains relatively unexplored, particularly in the context of thin and ultra-thin pavement overlays.

Therefore, this review paper aims to comprehensively analyze the potential of using fly ash-based geopolymer concrete in Ultra-Thin White Topping applications by evaluating its mechanical performance, durability characteristics, bonding behavior, and sustainability aspects, while also identifying critical research gaps and future directions for the development of high-performance, cost-effective, and environmentally sustainable pavement rehabilitation systems.

II. LITERATURE REVIEW

A comprehensive review of existing studies indicates that Ultra-Thin White Topping (UTWT) is an effective pavement rehabilitation technique that enhances load distribution, durability, and service life of distressed bituminous pavements. Simultaneously, geopolymer concrete (GPC) has emerged as a sustainable alternative to conventional concrete, offering superior strength, durability, and reduced environmental impact through the utilization of industrial by-products such as fly ash and GGBS. Although both UTWT and GPC have been extensively studied individually, limited research has been conducted on their combined application, particularly in terms of bonding behavior, fatigue performance, and field implementation in pavement systems.

[1] Karmakar et al. (2026) conducted an experimental study on fly ash-based rubberized geopolymer concrete under elevated temperature curing. The study incorporated crumb rubber as a partial replacement of fine aggregates to address waste management issues. It was observed that an optimum mix with 6% rubber and 16M NaOH provided improved strength and durability. However, higher rubber content reduced strength due to lower stiffness of rubber particles.
[2] Tank et al. (2026) investigated the effect of mix proportions and curing conditions on geopolymer mortar. The study varied binder ratios and curing temperatures to optimize strength. Results showed that heat curing at 60°C significantly enhanced compressive and tensile strength. The study also highlighted good chloride resistance but moderate resistance to sulphate attack.
[3] Ilayarsi et al. (2025) studied the effect of ultrafine slag on self-compacting geopolymer concrete. The results indicated that ultrafine slag improved compressive and tensile strength by up to 45%. Durability properties were also enhanced due to a denser matrix formation. However, workability decreased with increasing slag content.
[4] Rayapudi and Rao (2025) evaluated ultra-thin geopolymer concrete overlays using finite element analysis. The study showed that geopolymer overlays reduce stress concentration at edges and corners. Increased overlay thickness improved load distribution and performance. The study concluded that geopolymer UTWT is structurally efficient and sustainable.
[5] Ashfaq et al. (2024) investigated the combined effect of fly ash and metakaolin in geopolymer concrete. The study found that a 70:30 ratio improved compressive, tensile, and flexural strength. Microstructural analysis showed a denser geopolymer matrix. The research confirmed improved durability and reduced water absorption.
[6] Kiran et al. (2023) studied the effect of oven curing on geopolymer concrete strength. The study showed that heat curing accelerates geopolymerization reactions. This results in higher early-age compressive strength. The use of silica fume and GGBS further enhanced strength.
[7] Eisa et al. (2023) analyzed geopolymer concrete beams strengthened with CFRP sheets. The results showed significant improvement in flexural and shear strength. Crack load and ultimate load increased considerably. The study confirmed CFRP as an effective strengthening technique.
[8] Sahil et al. (2023) investigated geopolymer concrete using fly ash, GGBS, and metakaolin. The results showed improved strength, durability, and faster curing compared to OPC concrete. The study also highlighted reduced shrinkage and better resistance to fire and corrosion. It concluded that GPC is a sustainable construction material.
[9] Sathvik et al. (2023) evaluated geopolymer concrete for thin white topping applications. The study analyzed strength, fatigue behavior, and workability. Results showed high resistance and improved performance under traffic loading. The study concluded that GPC is suitable for pavement overlays.
[10] Sathvik et al. (2023) further emphasized that higher alkaline molarity enhances strength and fatigue resistance. The study highlighted the environmental benefits of GPC with reduced CO_2 emissions. It also reported cost savings compared to conventional concrete. The research supported GPC for sustainable pavements.
[11] Zhang et al. (2023) conducted a bibliometric analysis of geopolymer composites. The study highlighted global research trends and performance characteristics. It was found that GPC exhibits superior durability and strength. However, lack of standardization remains a challenge.
[12] Birkur et al. (2023) performed an experimental analysis on UTWT. The study used alternative materials like Alccofine and recycled aggregates. Results showed improved strength and sustainability. UTWT was found effective for pavement rehabilitation.

[13] Eisa et al. (2022) studied reinforced geopolymer concrete members such as beams and slabs. The results indicated similar structural performance to conventional RCC. Load carrying capacity and deformation behavior were satisfactory. The study confirmed GPC suitability for structural applications.
[14] Yazid et al. (2022) investigated fiber-reinforced geopolymer concrete. The addition of Nylon66 fibers improved compressive and flexural strength. It also enhanced ductility and crack resistance. However, higher fiber content reduced workability.
[15] Youssf et al. (2022) studied geopolymer concrete with lightweight aggregates. The results showed improved ductility and impact resistance. However, strength decreased with higher replacement levels. The study highlighted the need for optimized mix design.
[16] Szabó et al. (2022) developed lightweight geopolymer composites using expanded perlite. The study achieved very low density materials. Mechanical strength was moderate but suitable for insulation purposes. It confirmed potential for lightweight applications.
[17] Tahir et al. (2022) evaluated geopolymer concrete for rigid pavement applications. The results showed higher durability and acid resistance compared to OPC. The optimum mix achieved 47 MPa compressive strength. The study recommended GPC for pavements.
[18] Subash et al. (2021) studied geopolymer concrete using alternative fine aggregates. M-sand showed the best performance in strength and durability. Other materials like copper slag showed limited improvement. The study supported sustainable materials in GPC.
[19] Galande et al. (2021) reviewed fly ash-based geopolymer concrete. The study highlighted its eco-friendly nature and reduced CO_2 emissions. It also showed better resistance to chemical attacks. The research emphasized its future potential.
[20] Lavanya and Suhas (2019) studied geopolymer concrete in TWT and UTWT. The results showed adequate strength for pavement applications. It reduced environmental impact and lifecycle cost. The study recommended GPC for sustainable roads.
[21] Sutama et al. (2019) investigated lightweight geopolymer concrete with kaolin. Higher NaOH concentration improved strength and density. However, excess kaolin reduced performance. The study highlighted microstructural improvements.
[22] Bharadiya et al. (2019) studied fly ash-based geopolymer concrete. The results showed comparable strength to conventional concrete. It also reduced carbon emissions significantly. The study confirmed GPC as sustainable.
[23] Kanesan et al. (2018) developed geopolymer cement for oil well applications. The study showed superior performance under high pressure and temperature. It also had better durability than OPC. However, lack of standardization was noted.
[24] Lokhande et al. (2018) developed translucent geopolymer concrete. Optical fibers were used to transmit light through concrete. The material reduced energy consumption in buildings. It was found suitable for green construction.
[25] Emmanuel (2018) studied slag and fly ash-based geopolymer concrete. Strength increased with higher molarity of NaOH. However, durability was affected due to surface cracking. The study emphasized proper mix design.
[26] Kambale et al. (2018) studied UTWT for rural roads. The study showed improved durability and reduced maintenance cost. UTWT was found suitable for village roads. It also improved riding quality.
[27] Roy et al. (2018) developed geopolymer bricks using fly ash. The bricks showed good strength and durability. They reduced environmental impact significantly. The study promoted waste utilization.
[28] Dar and Azam (2017) developed fly ash-based geopolymer concrete. The study showed high strength and durability. It also reduced CO_2 emissions by up to 80%. The material was found suitable for construction.
[29] Alapure et al. (2015) studied UTWT as a rehabilitation technique. The study highlighted its performance in Indian conditions. It improved pavement life and reduced maintenance. UTWT was found cost-effective.
[30] Saravanan et al. (2013) reviewed geopolymer concrete technology. The study highlighted its superior strength and durability. It also emphasized environmental benefits. However, lack of mix design standards was noted.

III. RESEARCH GAP

Based on the comprehensive review of existing literature on Ultra-Thin White Topping (UTWT) and geopolymer concrete (GPC), it is evident that significant advancements have been made in both pavement rehabilitation techniques and sustainable construction materials; however, several critical research gaps still exist, particularly in their combined application. Most of the studies on UTWT have primarily focused on conventional cement concrete overlays, emphasizing parameters such as overlay thickness, joint spacing, bonding characteristics, and structural performance under traffic loading, whereas very limited research has explored the use of geopolymer concrete in UTWT systems, thereby creating a gap in understanding its structural behavior under real field conditions.

Although geopolymer concrete has been extensively studied for its mechanical properties, durability, and environmental benefits, these investigations are largely confined to laboratory-scale studies and structural elements, with insufficient attention given to its application in pavement overlays where factors such as bonding with existing bituminous layers and fatigue performance under repeated loading are crucial. Furthermore, the bonding behavior between geopolymer concrete and existing asphalt surfaces, which is essential for composite action in UTWT, has not been adequately investigated, and there is a lack of standardized surface preparation techniques and evaluation methods for such systems. Another major gap lies in the absence of design guidelines and codal provisions for geopolymer-based white topping, as current design methods are based on the properties of conventional concrete and do not account for the unique characteristics of geopolymer materials, such as different modulus of elasticity, shrinkage, and thermal behavior. In addition, there is limited research on the long-term durability and fatigue performance of geopolymer concrete in thin overlay applications under varying traffic and environmental conditions, which is essential for assessing its suitability for real-world pavement systems. The lack of field implementation and large-scale case studies further restricts the validation of laboratory findings and hinders practical adoption. Moreover, the complexity of geopolymer mix design, influenced by factors such as alkaline activator concentration, curing conditions, and precursor materials, necessitates the development of optimized and simplified mix design procedures specifically tailored for thin and ultra-thin overlays. There is also a need for research on ambient curing geopolymer systems suitable for field applications, as many existing studies rely on heat curing, which is not always feasible in practice.

CONCLUSION

The present review highlights the significant potential of integrating Ultra-Thin White Topping (UTWT) technology with fly ash-based geopolymer concrete (GPC) as a sustainable and high-performance solution for pavement rehabilitation. From the extensive analysis of more than 30 research studies, it is evident that UTWT is an effective method for restoring deteriorated flexible pavements by improving load distribution, reducing maintenance requirements, and enhancing service life, while geopolymer concrete offers remarkable advantages such as reduced carbon emissions, utilization of industrial waste materials, superior mechanical strength, and enhanced durability compared to conventional Ordinary Portland Cement (OPC) concrete. The review also reveals that advancements in geopolymer technology, including the use of supplementary materials such as GGBS, metakaolin, fibers, and ultrafine slag, have further improved its performance characteristics, making it a viable alternative for structural and pavement applications. However, despite the proven benefits of both technologies individually, their combined application in UTWT systems remains largely unexplored, particularly in terms of bonding behavior with existing bituminous layers, fatigue performance under repeated traffic loading, and long-term durability under varying environmental conditions. The absence of standardized design guidelines, limited field implementation, and challenges related to mix design optimization and curing conditions further restrict the practical adoption of geopolymer-based UTWT systems. Therefore, it can be concluded that fly ash-based geopolymer concrete has strong potential to replace conventional concrete in Ultra-Thin White Topping applications, contributing to sustainable infrastructure development and environmental conservation; however, comprehensive experimental and field-based studies are required to validate its performance, develop design standards, and ensure its large-scale implementation in real-world pavement systems.

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