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LIFE CYCLE COST ANALYSIS OF ULTRA-THIN WHITE TOPPING OF GEOPOLYMER CONCRETE OVERLAY ON BITUMINOUS CONCRETE PAVEMENT

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ABSTRACT

The social and economic growth of nations greatly depends on effective pavement maintenance methods that adhere to sustainable principles, ensuring long-term durability and performance. Conventional methods for maintaining bituminous concrete pavements, such as using a bituminous concrete overlay, are not always the most efficient. In contrast, concrete overlays have consistently demonstrated superior performance globally. This paper focuses on the design, analysis of life cycle costs, and assessment of emissions of greenhouse gases associated with bituminous concrete pavement from a life cycle perspective. It evaluates two maintenance strategies: a bituminous concrete overlay and an ultra-thin geopolymer concrete overlay (often called "white topping"). The findings suggest that utilizing sustainable materials in an ultra- thin white topping (UTWT) geopolymer concrete overlay is a more favorable option when compared to a bituminous concrete overlay. The life cycle cost study, utilizing the net present value approach, demonstrates its superior economic viability in the long run. The study suggests that using a very thin layer of white topping geopolymer concrete as an overlay on bituminous concrete pavement improves its long term performance and provides economic and environmental advantages.

Keywords: geopolymer concrete, lifecycle cost analysis, ultra-thin White topping, bituminous concrete.

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1. INTRODUCTION

Road infrastructure projects are fundamental to economic and cultural progress, making informed pavement selection crucial for maximizing financial investments. The efficient maintenance of pavement systems is crucial for the social and economic development of nations. Crucial factors to think about include evaluating greenhouse gas emissions and conducting a life cycle cost study. Bituminous concrete pavements experience significant deterioration such as fatigue cracking, rutting, and potholes, necessitating frequent and costly maintenance. Pavement maintenance strategies must consider both economic and environmental impacts. Concrete overlays, specifically ultra-thin white topping (50-100 mm thick), provide a more durable and cost-effective solution with fewer failures compared to traditional bituminous concrete overlays. Portland cement manufacture emits 7-8% of world CO_2. GGBS and fly ash are industrial by-products that may be utilized during the manufacturing process of geopolymer concrete. By including these materials, GPC eliminates the need for Portland cement, which is a major source of CO_2 emissions. Davidovits (1994) pioneered the concept of geopolymers, highlighting their possibility of lowering CO_2 emissions by 80% in contrast to traditional Portland cement. GPC possesses superior qualities that can extend the lifespan of pavements and reduce maintenance costs when used for white topping, which involves overlaying concrete on existing bituminous pavements.

Furthermore, incorporating sustainable materials in geopolymer overlays enhances their economic viability and reduces greenhouse gas emissions, which is in line with international initiatives to address climate change. Thus, selecting the right overlay for bituminous concrete pavements is essential for achieving long-term economic and environmental sustainability in road infrastructure projects. There is a growing need for sustainable building materials, prompting the exploration of alternative binders like geopolymer concrete. Rayapudi & Rao (2020) stated comprehensive insights into the environmental and mechanical benefits of using GPC over traditional OPC. The review discusses the potential of GPC to reduce GHG emissions, which aligns with the global push towards sustainable development. Additionally, the superior mechanical properties of GPC make it a robust choice for pavement applications, offering immediate strength development and enhanced durability against chemical attacks.

Life cycle cost analysis (LCCA) is a critical tool for assessing the long-term financial viability of construction materials and making informed investment decisions by considering initial and future costs, such as maintenance and rehabilitation, for improving bituminous concrete pavements. LCCA selects cost-effective overlays by comparing construction and maintenance expenses over the pavement's design life and quantifies environmental impacts by estimating emissions during pavement production and installation stages. Previous studies on LCA have compared energy utilization and GHG emissions from different pavement materials and design parameters, providing insight into their sustainability (Wang *et al*. 2016). Santos and Ferreira (2012) developed the novel Life-Cycle Cost Analysis (LCCA) system for pavement management, incorporating a decision-making system by identifying cost-effective strategies and considering construction, maintenance, and residual values. It is validated through sensitivity analyses and provides a robust tool for selecting optimal pavement structures for national roads and highways.

Jundhare *et al*. (2013) examined white topping as a cost-effective solution for rehabilitating deteriorated asphalt pavements in India. They highlighted the benefits of using bituminous pavement with conventional white topping over hot mix asphalt overlays. They concluded that this method had a more cost effective life cycle compared to other rehabilitation methods. Flexible pavements can be repaired by applying a thin layer of rigid concrete, known as white topping. This method helps to minimize maintenance expenses and requires a lower upfront investment (Bellum, 2022). To minimize preliminary expenses, it is common practice to mix fly ash, which consists of aluminous and siliceous materials with pozzolanic properties, with ordinary Portland cement (OPC) and aggregates in small amounts (Sandanayake *et al*., 2018). Fly ash-based geopolymer concrete mix design by Assi *et al*. (2018), resulted in a 50% reduction in building costs. This strategy significantly reduces the life cycle cost of rigid bituminous concrete pavement in place with high levels of rain fall, such as in India, which has the second largest road network globally. With the constant flow of vehicles on India's growing highway network, the roads quickly wear down, causing significant concerns about the expenses associated with construction and upkeep. (Zhang *et al*., 2016; Chen *et al*., 2021). For grades ranging up to 30Mpa, geopolymer concrete also costs 1.7% more than traditional cement concrete. (Janardhan *et al.* 2016). Sathvik *et al*., (2023) explored the utilization of substitute components like fly ash, manufactured sand, and alkaline activators in geopolymer concrete for white-topping pavement. High-molarity activators enhance workability, strength, and fatigue resistance, making geopolymer concrete a sustainable and efficient option for road construction. Sambaiah *et al* (2021) developed blended fiber geopolymer concrete (GPC) for rigid pavements, revealing that a mix with equal proportions of fly ash and GGBS exhibits superior strength characteristics. Previous studies have stated that producing one m^3 of traditional concrete costs 7-8% more than geopolymer concrete (M. N. Lavanya *et al*. 2019). Rayapudi, S. *et al* (2024) studied the impact resistance on GPC slab elements with and without fibers. Previous research contributes to GPC sustainability and economic viability through reduced CO_2 emissions and long-term cost savings, with lifecycle cost analysis showcasing that GPC has superior durability, lower maintenance, and end-of-life costs, promoting its adoption of sustainable and cost-effective pavement maintenance solutions. This study aims to compare the lifecycle costs of bituminous concrete overlay and geopolymer concrete overlay and determine the long-term economic benefits of using geopolymer concrete for white topping. In addition, it comprehensively evaluates M45 grade geopolymer concrete for white topping on bituminous layers, emphasizing its sustainability and economic viability. The key contributions include its economic benefits, notably initial and maintenance costs from using fly ash and GGBS, and significant long-term cost savings. The innovative application of ultra-thin white topping GPC enhances the performance and sustainability of existing pavement, promoting infrastructure resilience.

2. METHODOLOGY

2.1 Life Cycle Cost Analysis (LCCA)

The life cycle cost analysis (LCCA) was performed in order to evaluate the economic feasibility of M45 grade Geopolymer concrete (GPC) compared to Bituminous overlay. The LCCA framework considered the overall cost throughout the pavement's 20-year design life.

2.2 Net Present Value (NPV)

The NPV method was employed to discount future expenses to their current value using a discount rate of 12%. The formula for NPV is shown in Equation 1.

$$\text{NPV} = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{1}$$

where:

- C_t represents the net amount of cash flow at a specified time t.
- The discount rate is represented by the variable r.
- The variable "n" represents the number of periods

Initial construction costs included materials and labor for the granular sub-base, base course, and GPC surface layer. Maintenance costs were estimated based on scheduled surface renewals and strengthening activities. By calculating the NPV, we could compare the overall economic impact of using GPC versus traditional cement concrete.

3. RESULTS

The bituminous concrete pavement mix design for urban area streets is carried out by the Indian standard code IRC 37-2001.

3.1 Bituminous Concrete Pavement Design

Duration of design life span: 20 years, Number of lanes: 2, and pavement width: 7 m wide.

Design traffic in million standard axles (MSA): 12, Vehicle damage factor: 4.5, Design California Bearing Ratio (CBR) of subgrade soil: 4%, Lane distribution factor: 0.75, Traffic growth rate: 7.5%

3.2 Design of Crust Thickness

Granular sub-base: 330 mm, Base course: 250 mm, Dense bituminous macadam: 90 mm, Bituminous concrete: 40 mm.

3.3 Design of Bituminous Concrete Overlay

Surface renewal of 40 mm bituminous concrete overlay was applied every 5 years. For strengthening, a 75 mm dense bituminous macadam layer and a 40 mm bituminous concrete overlay were periodically applied every 10 years, following the guidelines set by MoRTH (Ministry of Road Transport and Highways 2001).

3.4 Over Bituminous Concrete Pavement Design of an Ultra-Thin White Topping Geopolymer Concrete

Ultra-thin geopolymer concrete for 20 years of period life was designed according to IRC SP-76 2015. The percentage of axle load for the design of M45 grade geopolymer ultra-thin white topping is illustrated in given below Table-1.

Consider traffic growth rate: 7.5%, Traffic in commercial vehicles per day (CVPD): 400.

Design traffic in million standard axles (MSA): 12,

Design traffic is taken into account over the entire life span: 1,580,621.

Modulus of rupture in MPa: 6.56, Modified modulus of subgrade reaction: 0.06 MPa/mm, Modulus of elasticity of geopolymer concrete: 30,463 MPa.

Geopolymer Concrete overlay thickness: 100 mm with joint spacing of 60 mm.

Table-1. Axle load percentage adopted for Ultra-thin white topping geopolymer concrete overlay.

Axle Load (Tonnes)	Single Axle Load (%)	Tandem Axle Load (%)
26-30	-	2
22-26	-	5
18-22	-	1
14-18	-	3
<14	-	36
15-17	5	-
13-15	7	-
11-13	1	-
9-11	245	-
7-9	40	-
<8	25	-

3.5 Assumptions for Estimation of Quantities

Granular sub base layer density: 1602 kg/m^3
Granular sub-base Job mix formula: 40 mm-35%, 20 mm-20%, 10 mm-15%, 6 mm and dust-30%
Wet mix macadam layer density: 2350 kg/m^3
Wet Mix Macadam Job mix formula: 40 mm-32%, 20 mm-20%, 10 mm-20%, stone dust-28%
Ultra-thin geopolymer concrete mix density: 2435 kg/m^3

3.6 M45 Grade Geopolymer Concrete Mix Design with 50% FA + 50% GGBS (Per Cubic Meter)

The materials used in this study include fly ash (Class F fly ash sourced from a VTPS-Vijayawada, A.P), GGBS (obtained from a steel manufacturing plant, Vizag), alkaline activators (sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3)), locally available fine and coarse aggregates. The mix design proportions for M45 grade geopolymer concrete are illustrated below in Table-2 as:

Table-2. Geopolymer concrete mix design quantities in (kg/m^3).

Material		Quantity (kg/m^3)
Flyash		197.15
GGBS		197.15
NaOH		41 (12M)
Na2SiO3		102
Water		8%
Fine aggregates		605
Coarse aggregates	20 mm	776
	10mm	517

For the preparation of the NaOH solution, NaOH pellets were dissolved in water and then allowed to cool down. Considering, the ratio of Na_2SiO_3/NaOH by mass as 2.5. A solution with a concentration of 12M is created by mixing water with sodium hydroxide solids (NaOH), which consists of 40% NaOH solids and 60% water by mass.

The prepared geopolymer concrete was applied as an ultra-thin white topping on an existing bituminous pavement. The bituminous layer was cleaned and primed before the application of the concrete overlay.

3.7 Density and Binder Content

Dense bituminous concrete density: 2450 kg/m^3,
Lime content: 3% and Optimum binder content for dense bituminous macadam: 5%.

Aggregate composition: 20 mm-35%, 10 mm-20%, 6 mm-20%, stone dust-30%
Bituminous concrete mix density: 2500 kg/m^3,
Lime content: 2% and Optimum binder content for bituminous concrete: 6%.
Aggregate composition: 12 mm-26%, 6 mm-32%, fine dust-40%

4. LIFECYCLE COST ANALYSIS

The life cycle cost analysis was conducted to compare the total cost of overlays of bituminous concrete and geopolymer concrete over the design life period. The analysis took into consideration the cost of constructing and maintaining the bituminous concrete pavement at each stage throughout its life span, calculating them on a per-kilometer basis. The unit rate considered in the analysis of various layers was taken from National Highway 216 at Ponnuru, Andhra Pradesh, India shown in Table-3. The analysis period is considered for 20 years.

Table-3. Construction cost of considered for life cycle cost analysis.

Pavement Layer	Cost/km (Rs)	Rate (Rs)
Bituminous Concrete	2,475,800	8841 / Cum
Dense Bituminous Macadam (DBM)	4,985,800	7914 / Cum
Wet Mix Macadam	4,693,500	1750 / Cum
Granular Sub-base Macadam	5,313,000	2300 / Cum
Prime coat	2,17,000	31.00 / Sqm
Tack coat	77,000	11.00 / Sqm
Initial cost	17,762,100	
Construction of UTWT Geopolymer mix design M45 grade	4,584,181	6548/ Cum

The maintenance costs for bituminous pavement were determined by considering periodic renewal and reinforcement over its design lifespan, incorporating a 75 mm DBM layer and a 40 mm BC layer. The expenses of bituminous concrete overlay per kilometer are depicted in Figure-1. A layer of applying 25 mm BC layer every five years costs 1,145,900 lakhs/km.

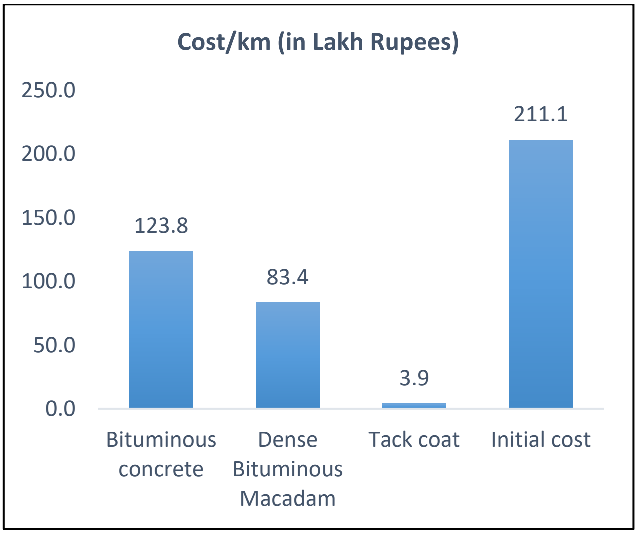

Figure-1. Maintenance Cost of Bituminous Overlay per kilometre.

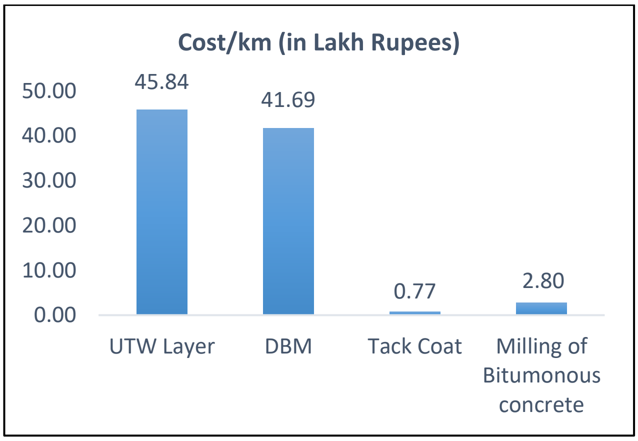

Figure-2. Maintenance Cost of Geopolymer concrete overlay per kilometer.

The analysis compares the initial and upkeep expenses of bituminous concrete pavement using bituminous concrete overlays and ultra-thin white topping overlays using sustainable materials. Initial construction and maintenance costs were derived from NH-216 data from Ponnuru, Andhra Pradesh. Figures 1 and 2 illustrate costs for initial construction, bituminous concrete overlay, and Ultra-thin white topping with sustainable materials. Findings show that maintenance with Ultra-thin white topping costs 90 lakh rupees per kilometer, significantly less than the 211 lakh rupees per kilometer for bituminous concrete overlay. UTWT is more cost-effective and sustainable, enhancing durability and reducing major failures. Utilizing double blended geopolymer concrete as a sustainable material, the UTWT mix cuts manufacturing costs by 50% and enhances concrete properties. The geopolymer concrete overlays maintain a consistent abrasion and roughness index, reducing vehicle operation costs over time compared to bituminous overlays. Hence, vehicle operation costs were not separately calculated in this study, underscoring the economic and durability advantages of the Ultra-thin white topping method. Malasani *et al* (2014) stated that geopolymer had on par abrasion resistance than cement concrete.

4.1 Net Present Value (NPV)

Tables 5 and 6 show the life cycle cost analysis for bituminous concrete pavement with bituminous overlay and UTWT geopolymer concrete overlay. The analysis utilized a 5.5% inflation rate and a 12% discount rate. The results reveal that the lifecycle cost of the bituminous overlay is 368.62 lakhs rupees, whereas the cost of UTWT geopolymer concrete is significantly lower at 279.10 lakh rupees, demonstrating its economic advantage.

Table-4. Life Cycle Cost of Bituminous Concrete Pavements with bituminous overlay by NPV.

Year	Stage	Current cost	Inflation Cost @ 5.5% P.a.		Discounted Cost @ 12% P.a.
			Overlay	Strengthening	
Initial cost		17,762,100	17,762,100	-	-
5	First Overlay	76,57,440	1,00,07,968	1,88,48,323	43,45,037
10	First Strengthening	1,34,43,010	1,30,80,014	2,76,94,370	89,16,846
15	Second Overlay	76,57,440	1,70,95,055	4,06,92,115	31,23,203
20	Second Strengthening	1,34,43,010	-	5,97,90,067	27,28,922
					3,68,76,108
Cost in Rupees					

Table-5. Life Cycle Cost of UTWT Geopolymer Concrete overlay by NPV.

Year	Present cost	Inflation Cost@5.5% P.a.	Discounted Cost @ 12% P.a.
Initial cost	26,515,281	26,515,281	-
5	1,00,000	1,46,933	83,374
10	1,00,000	2,15,892	69,512
15	1,00,000	3,17,217	57,954
20	1,00,000	4,66,096	48,319
			27,910,678
Cost in Rupees			

The inflation rate of UTWT with a geopolymer overlay significantly increases over its periodic design life, as illustrated in Figure-3. Furthermore, the initial cost is nearly twice the initial cost and three times after the design life period.

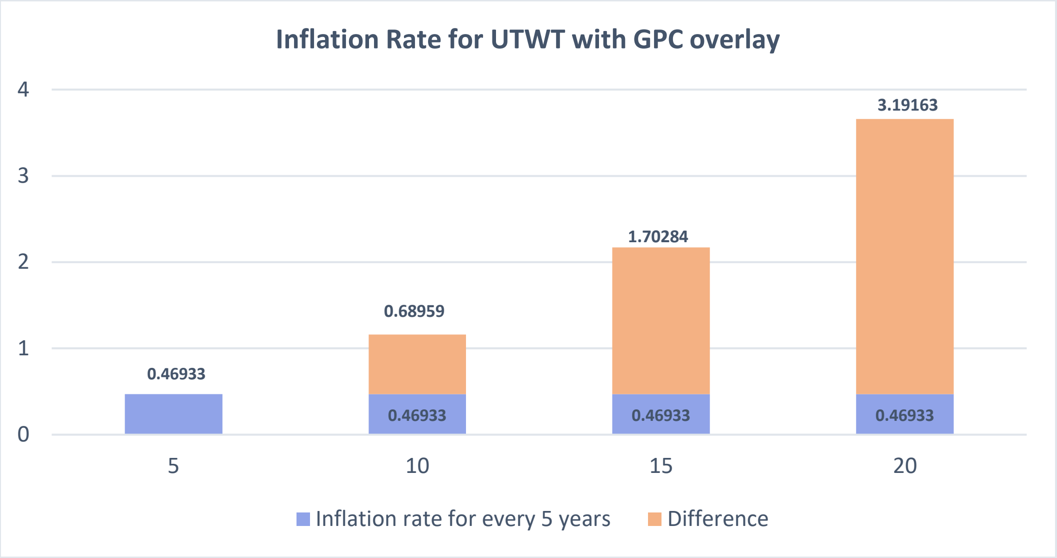

Figure-3. Inflation Rate of the Geopolymer overlay UTWT over 20-year periodic life.

5. DISCUSSIONS

The lifecycle cost analysis (LCCA) reveals that maintaining bituminous concrete pavement with an ultra-thin white topping geopolymer concrete overlay is 25.3% more cost-effective than using a traditional bituminous concrete overlay. This finding is consistent with prior research, indicating that conventional white topping is 14% less expensive than a 200 mm bituminous concrete overlay (Jundhare *et al*., 2013). Michael *et al*., (2010) also support that integrating sustainable materials into concrete overlays enhances sustainability, reduces the required thickness of the overlay, and lowers lifecycle costs. Further, thin white topping (TWT) has a thickness of 150mm - 200mm whereas UTWT has only a 100mm thick overlay, which shows economical benefits. The initial and maintenance costs of a geopolymer overlay over its design span of life are economical and reduce carbon emissions, as it uses only industrial waste byproducts as binders.

CONCLUSIONS

In comparison to bituminous concrete overlay, the life cycle cost of bituminous concrete pavement with UTWT geopolymer concrete overlay is 25.6% reduced. This reduces the cost and helps to save the economy on construction and maintenance. UTWT geopolymer concrete overlay helps bituminous concrete pavement to have durable and reliable performance over an extended period of time and permits a decrease in the thickness of the concrete overlay.

Further studies

Further research is focused on a detailed analysis of greenhouse gas emissions, especially in terms of material emissions throughout the lifecycle of the pavement. By employing the life cycle analysis using the cradle-to- grave approach, the estimated carbon footprint of bituminous concrete pavement is assessed. The lifecycle emissions from Bituminous and Geopolymer overlays will be examined to provide a comprehensive understanding of their environmental impacts.

REFERENCES

Assi L., Carter K., Deaver E. E., Anay R., and Ziehl P. 2018. Sustainable concrete: building a greener future. Journal of Cleaner Production. 198, 1641-1651, https://doi.org/10.1016/j.jclepro.2018.07.123

Bellum R. R. 2022. Investigation on the Accelerated Pavement Test Track (APTT) in the development of road network using geopolymer concrete. Clean. Mater 4, 100074. doi:10.1016/j.clema.2022.100074

Chen L., Gao X., Hua C., Gong S. and Yue A. 2021. The evolutionary process of promoting green building technologies adoption in China: A perspective of government. J. Clean. Prod. 279, 123607. doi:10.1016/j.jclepro.2020.123607

Davidovits. 1994. Pioneered the concept of geopolymers, highlighting their potential to reduce CO2 emissions by 80% compared to traditional Portland cement.

Farooq Furqan, Jin Xin, Javed Muhammad Faisal, Akbar Arslan, Shah Muhammad Izhar, Aslam Fahid, Alyousef Rayed. 2021. Geopolymer concrete as sustainable material: A state of the art review. Construction and Building Materials. 306. 124762. DOI: 10.1016/j.conbuildmat.2021.124762

Indian Road Congress. 2001. (IRC-37.2001). Tentative guidelines for the design of flexible pavements. New Delhi: Indian Road Congress.

IRC-SP-76 2015. Guidelines for conventional and thin white topping. New Delhi: Indian Road Congress.

Janardhanan T., Thaarrini J., Dhivya & S. and Dhivya S. 2016. Comparative study on the production cost of geopolymer and conventional concretes, International Journal of Civil Engineering Research. 7, 117-124.

Jundhare D. R., Khare K. C., Jain R. K. 2013. Life cycle cost analysis of conventional white topping v/s rigid pavement and flexible pavement. Int J Lifecycle Perform Eng. 1(3): 278-291.

M. N. Lavanya, R. Suhas. 2019. A Study on Thin and Ultra-Thin White Topping Using Geopolymer Concrete. IJRESM. 2(8): 2581-5792.

Malasani Potharaju & Ramujee Kolli. 2014. Abrasion Resistance of Geo - Polymer Composites. Procedia Materials Science. 6. 1961-1966. 10.1016/j.mspro.2014.07.230.

Michael D., Lepech Victor C. Li. 2010. Sustainable pavement overlays using engineered cementitious composites. Int. J. Pavement Res. Technol. 3(5): 241-250.

Ministry of Road Transport and Highways 2001. Specifications for road and bridge works. New Delhi: Indian Roads Congress.

Sambaiah Rayapudi & Rao T. 2021. Strength characteristics of fiber reinforced geopolymer concrete for rigid pavement applications. Technium: Romanian Journal of Applied Sciences and Technology. 3(1): 1-11.

Rayapudi S., Rao T. C. S. 2024. Strength Characteristics and Impact Resistance of Fiber-Reinforced Geopolymer Concrete Elements. In: Low Carbon Materials and Technologies for a Sustainable and Resilient Infrastructure. CBKR 2023. Lecture Notes in Civil Engineering, vol. 440. Springer, Singapore. https://doi.org/10.1007/978-981-99-7464-1_37

Sandanayake M., Gunasekara C., Law D., Zhang G. and Setunge S. 2018. Greenhouse gas emissions of different fly ash based geopolymer concrete in building construction. J. Clean. Prod. 204, 399-408. doi:10.1016/j.jclepro.2018.08.311

Santos J. & Ferreira A. 2012. Life-Cycle Cost Analysis System for Pavement Management. Procedia - Social and Behavioral Sciences. 48, 331-340.

Sathvik S., Shakor P., Hasan S., Awuzie B. O., Singh A. K., Rauniyar A., *et al*. 2023. Evaluating the potential of geopolymer concrete as a sustainable alternative for thin white-topping pavement. Front. Mater. 10, 1181474. doi:10.3389/fmats.2023.1181474.

Wang H., Thakkar C., Chen X., Murrel S. 2016. Life-cycle assessment of airport pavement design alternatives for energy and environmental impacts. J Cleaner Prod. 133: 163-171.

Zhang Z., Li L., Ma X. and Wang H. 2016. Compositional, microstructural, and mechanical properties of ambient condition cured alkali-activated cement. Constr. Build. Mater. 113, 237-245. doi:10.1016/j.conbuildmat.2016.03.043