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Life Cycle Cost Assessment of Porous Pavements

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ABSTRACT
With growing concerns around stormwater and road safety, porous pavement technologies have emerged as a legitimate option for improved drainage performance, new solutions for stormwater reduction and enhanced road safety. However, the long-term economic deterrent of construction and maintenance retains a problem with porous pavement. The study evaluates the life cycle cost effectiveness of OGFC, SG and BC-2 with and without Induction Sensitive Fibres (ISF). It used a holistic process for LCCA, including laboratory performance data, service life assessment, maintenance cost forecasting, net benefits analysis and software calibration with Athena Pavement LCA. A total of 9 different mixture-binder combinations were assessed in terms of mechanical parameters (Marshall Stability, Indirect Tensile Strength, Tensile Strength Ratio) and functional and durability requirements (permeability, skid resistance, Cantabro Loss, fatigue performance). The use of ISF enhances the mechanical properties and durability characteristics of all three mixtures, leading to an increased service life and reduced maintenance requirements for a longer period. While the addition of fibres increased initial construction cost, the resultant savings on maintenance reduced overall life cycle costs of both OGFC and SG mixtures, in which PMBs (PMB-40 and CRMB-55) were generally found to be more economical than conventional VG-40. With respect to both service-life extension and savings in maintenance costs, the SG mixture modified with CRMB-55 binder yields the most optimal cost-benefit ratio overall; the combined effects of low-cost BC-2 mixtures - which provided high structural strength - led only to relatively minor service-life gains. The results of the manual assessment internal to Pavement LCA were also compared against those returned from the Athena Pavement LCA software, allowing for consistent trends in maintenance savings and increasing even further confidence in the overall manual framework established.
Keywords:-Life Cycle Cost Assessment; Porous Pavement; Open Graded Friction Course; Selected Grade; Bituminous Concrete; Induction Sensitive Fibres; Maintenance Cost; Net Benefit; Service Life; Athena Pavement LCA; Sustainable Infrastructure.

NOMENCLATURE

Abbreviation	Description
OGFC	Open Graded Friction Course
SG	Selected Grade
BC-2	Bituminous Concrete Grade-2
VG-40	Viscosity Graded Bitumen, Grade 40
PMB-40	Polymer Modified Bitumen, Grade 40
CRMB-55	Crumb Rubber Modified Bitumen, Grade 55
ISF	Induction Sensitive Fibres
LCCA	Life Cycle Cost Assessment

Abbreviation	Description
LCA	Life Cycle Assessment
MS	Marshall Stability
ITS	Indirect Tensile Strength
TSR	Tensile Strength Ratio
PSR	Pavement Skid Resistance (British Pendulum Number)
SL	Service Life

1. INTRODUCTION

Pavement performance, which affects economic development and regional connectivity, as it is related with road safety, transportation efficiency and maintenance cost. Conventional flexible pavements are still prevalent in use because of their economical cost and reasonable structural performance, however the increasing traffic loads and urbanisation have rendered drainage, durability and long-term maintenance an endless headache. Water ingress, top-water spill over, aquaplaning and moisture-induced damage are chronic difficulties for transport agencies, specifically in areas that see vary vital seasonal rains.

Porous pavements are specifically designed to infiltrate stormwater rapidly where 80% of the surface runoff, which is often considered the primary source of pollution, can be infiltrated using interconnected void structure; they wet the pavements through increases in liquidity and promote groundwater recharge within a few minutes (Wang et al., 2010; Harvey et al., 2017; Kayhanian & Singh, 2015). Existing field and laboratory studies have indicated that porous pavements can be used to effectively mitigate peak runoff, thus conferring measurable hydrologic and environmental benefits throughout their expected service life (Liu et al., 2019, 2020). Selected Grade (SG) mixtures provide high permeability with structural strength; Bituminous Concrete Grade-2 (BC-2) mixtures give far greater structural strength and durability but lower permeability; Open Graded Friction Course (OGFC) mixtures are gifted as they offer great drainage, skid-resistance property suited for porous pavements (Gogoi, 2019; Chen et al., 2019). Despite having hydraulic and safety advantages (Terhell et al., 2012; Jambhulkar et al., 2021), the wider use of porous pavements is still limited due to their higher construction and maintenance costs.

Induction Sensitive Fibre (ISF) technology has been showcased as a prospective solution for load distribution, crack and fatigue resistance and structural stability in asphalt mixtures with self-healing properties that allow pre-cracks to heal before they propagate into serious structural problems.

The work herein studies the performance of porous mixtures across the entire life cycle cost for those containing ISF. The study included a literature review of both porous-pavement and life-cycle-costing reviews; laboratory testing of OGFC, SG and BC-2 mixtures manufactured with and without ISF; manual Life Cycle Cost Assessment (LCCA) for each mixture-binder combination; validation of the manual analysis using Athena Pavement LCA software, followed by a comparative evaluation in order to determine the economic feasibility of ISF in porous pavement construction.

2. LITERATURE REVIEW

While the traditional approach to pavement material selection is based on the initial construction cost, it often undervalues the subsequent maintenance, rehabilitation and end-of-life costs and therefore leads to an excess economic burden over time. Instead, LCCA accounts for construction and maintenance and rehabilitation and residual costs over the entire analysis period, facilitating more cost-effective pavement selection (WSDOT Pavement Management Guidance). Highway authorities have published standardised guidelines for life-cycle economic evaluation (FHWA, 1998, 2002, 2018), and a number of permeable interlocking concrete pavements specific life-cycle costing tools (Applied Research Associates, 2018). More recent developments have integrated delivery, material properties and maintenance consideration into long-term cost indicators (Rehan & Nehdi 2008; Antunes et al. 2018) or as an extension of LCCA frameworks that can account for climate-change effects (Daoud et al., 2025; Celebi, 2025; Singh & Varveri, 2024). Systems involving multi-dimensional frameworks that incorporate technical, economic and environmental indicators are also suggested in order to use a more comprehensive sustainability assessment for pavement sustainability evaluation as well (Yang et al. 2018).

Common maintenance practices for porous pavements include vacuum sweeping, pressure washing and surface cleaning as fines accumulate with time, resulting in a decrease of their functional drainage capacity (Kayhanian et al., 2012; Winston et al., 2015). The variability of life-cycle cost estimates based on the assumptions used in maintenance-scheduling decisions are manifested in field studies (Jung et al., 2022), while case studies which combine economic and environmental metrics singling out permeable pavements have shown a joint LCCA-LCA approaches would be useful for perceptibly high value pavement systems (Liu et al., 2020; UCPRC, 2010, 2017). The local rainfall and climatologists conditions are also decisive in the hydraulic performance and the economic performance of porous pavements (NOAA 2016).

The performance advantages of incorporating ISF have been established in laboratory experiments, however the real-world economic impact to incorporate ISF into a full life-cycle-cost approach has not yet been evaluated - the primary objective of this study.

3. METHODOLOGY

The economic feasibility of ISF-modified porous pavements is evaluated using a combination of laboratory performance evaluation, service-life estimation, manual Life Cycle Cost Assessment and software-based validation. Three of the 10 mixtures (OGFC and SG; each with different hydrologic and structural characteristics) were selected for further study, along with BC-2 (the mixture that most resembled a typical high-dense asphalt concrete section), all three prepared with three binder types (VG-40, PMB-40 and CRMB-55), yielding nine mixture-binder combinations.

All the mixtures contained Induction Sensitive Fibres (ISF) for reinforcement and self-healing ability. Under induction heating, the fibres enable load distribution within the aggregate skeleton, restraint of micro-crack propagation and localised self-healing of micro cracks prior to becoming structural distress - providing extended service life relative to unmodified mixtures via delayed fatigue cracking, ravelling and moisture-induced stripping.

Laboratory tests on mixtures both with and without ISF were used to develop mechanical properties (Marshall Stability, ITS, TSR), functional properties (permeability, skid resistance) and durability properties (Cantabro Loss, fatigue life, service life). The ISF performance improvement was used to estimate a corresponding service-life extension, which provided input for the maintenance-cost and net-benefit calculations.

In cost calculation, adopting a functional unit of 1-km long and 7-m width two-lane flexible pavement section is selected with a surface course of OGFC/SG - 40 mm thick and BC-2 - 30 mm thick over granular base (300 mm) and granular sub-base (220 mm). Construction cost included aggregate, bitumen, fibre and labour costs; while maintenance cost represented interventions such as surface cleaning, vacuum sweeping, pressure washing, crack repairing and overlay/resurfacing operations. Two baseline service-life assumptions were used to establish the maintenance cost - no ISF utilized (using standard 15-year service-life assumption) and one with ISF (extended, laboratory-derived service life); the net benefit was determined by deducting incremental ISF cost from subsequent maintenance savings obtained. This means that incorporation of ISF into the mixture-binder combination is economically viable, as it extracts an overall net benefit from this action.

Modelling the same pavement sections, material quantities, construction and maintenance schedules in the Athena Pavement LCA software cross-checked the manual calculations. A comparative evaluation framework was subsequently employed to rank the nine mixture-binder combinations across technical indicators (MS, ITS, TSR, fatigue performance), functional indicators (permeability, skid resistance, Cantabro Loss), economic indicators (maintenance cost, maintenance savings, net benefit) and environmental indicators (carbon footprint, flood-mitigation capacity).

Unit rates for materials, labour and equipment were held constant across the analysis period to maintain comparability in the nine combinations, making a life-cycle cost comparison reflective of material performance and not price variation. Future maintenance costs, however, were not discounted differently in the manual and software-based analyses, resulting in direct comparability between the two approaches. Note that the absolute costs shown here reflect the study's assumptions and may differ by location, but relative comparison of mixture-binder combinations will likely be valid in similar contexts.

Thus, the overall methodology comprised material and mixture selection, followed by laboratory performance comparison and service-life prediction using manually calculated life-cycle costs (LCCs) for each mixture-binder combination as inputs to a cost-net-benefit ratio method that determines the optimal alternate strategies with software-based validation of results at multiple stages up to multi-indicator comparative ranking of all nine mixture-binder combinations.

4. RESULTS AND DISCUSSION

The mechanical, functional and service-life performance of the OGFC, SG and BC-2 mixtures prepared with three different binders; VG-40, PMB-40 and CRMB-55 are presented in this section followed by the maintenance-cost assessment, net-benefit analysis, software-based validation results as well as overall comparative ranking of all nine mixture-binder combinations.

It was found that, irrespective of the mixture type and binder grade, incorporation of ISF helped in improving mechanical strength, moisture-damage resistance and fatigue performance across nine combinations. However, the degree to which ISF led to service-life extension and net economic benefit varied substantially: porous mixtures (OGFC, SG) showed a greater sensitivity to treatment by ISF than did the dense BC-2 mixture, whose already-low permeability limits any potential reduction of moisture-induced deterioration. In general, the benefit of ISF incorporation was greater with modified binders (PMB-40, CRMB-55) than conventional VG-40, indicating that chemical binder modification and physical fibre reinforcement are complementary.

4.1 Mechanical performance and functional performance of mixtures

Modified binder led to improvement in Marshall stability for all the three mixtures, confirming that traditional polymer or crumb-rubber modified binder is reinforced by ISF (Figure 1). BC-2 mixtures had the highest absolute Marshall Stability and ITS values because of their dense aggregate gradation, whereas OGFC and SG mixtures - although lighter structurally - demonstrated the greatest relative improvements from binder modification (Figures 1 and 2). The Tensile Strength Ratio (TSR) also improved uniformly with modified binders for all mixtures, which indicates better resistance to moisture-induced stripping (Figure 3) - this was the most significant benefit of BC-2 due to its relatively low void content..

Figure 1: Marshall Stability Comparison (All Mixtures)

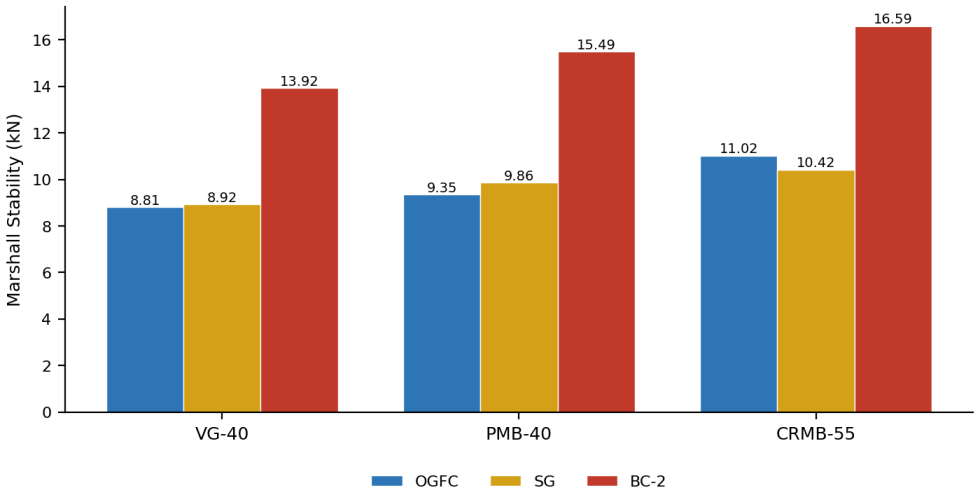


Figure 2: Indirect Tensile Strength Comparison (All Mixtures)

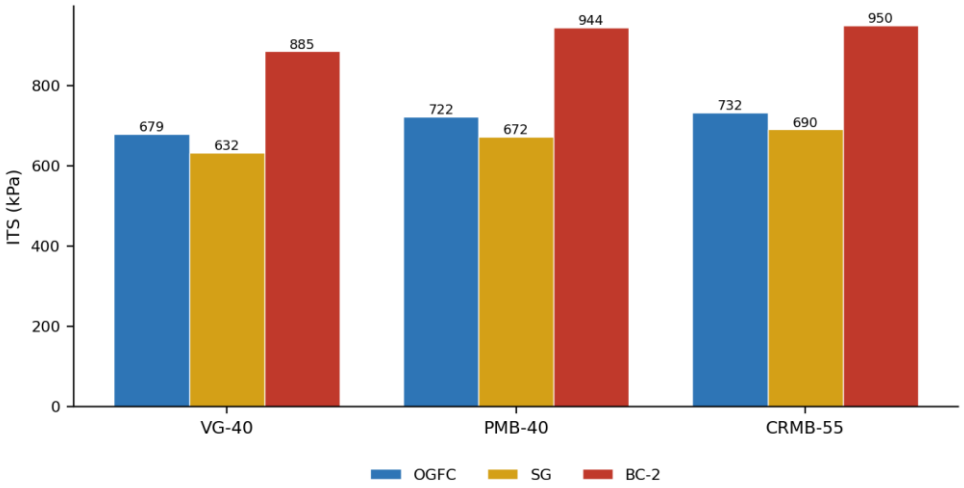
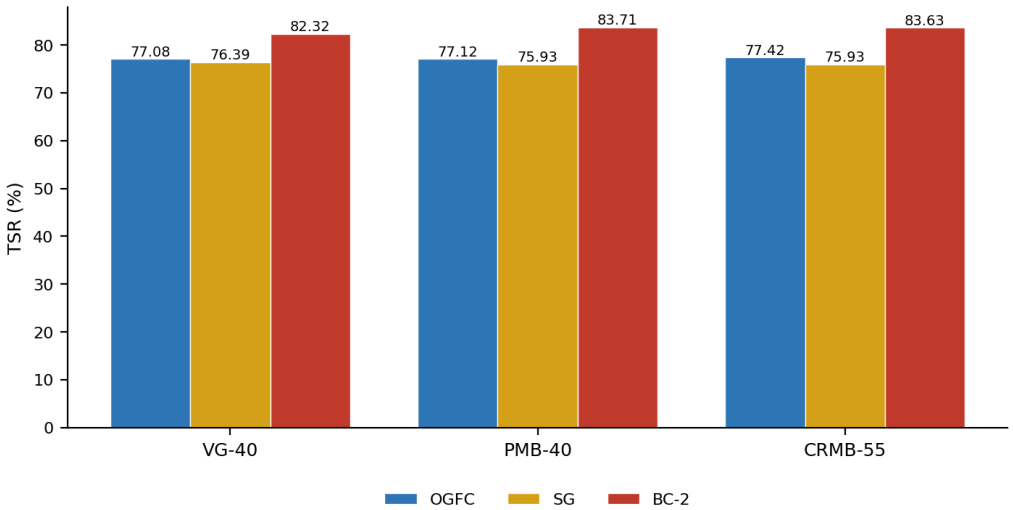


Figure 3: Tensile Strength Ratio Comparison (All Mixtures)



In terms of function, the drainage performance of the porous OGFC and SG mixtures was not impaired by the inclusion of ISF, which maintained a high permeability and rapid stormwater infiltration; however, a dense-graded mixture like BC-2 remained relatively impermeable throughout. Cantabro Loss - a measure of raveling and aggregate loss resistance - decreased with binder modification for all three mixes, most significantly for BC-2 as a result of its more densely packed structure (Figure 4). The binders modified and incorporated in the mixtures also resulted in improved skid resistance (PSR) for all mixtures tested, with no loss of surface safety due to the changes as indicated by Figure 5

Figure 4: Cantabro Loss Comparison (All Mixtures)

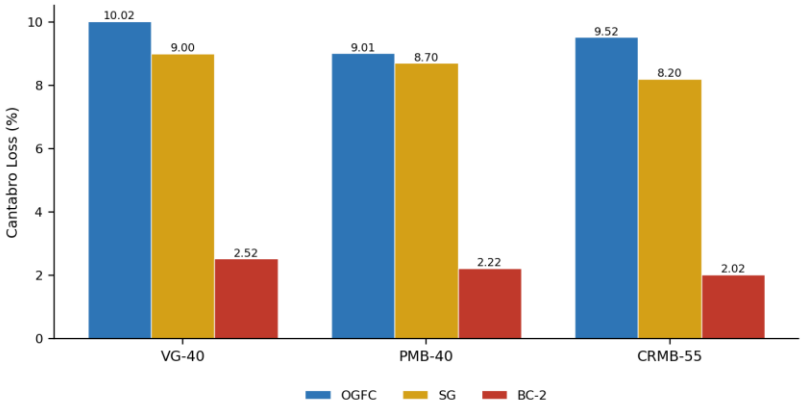
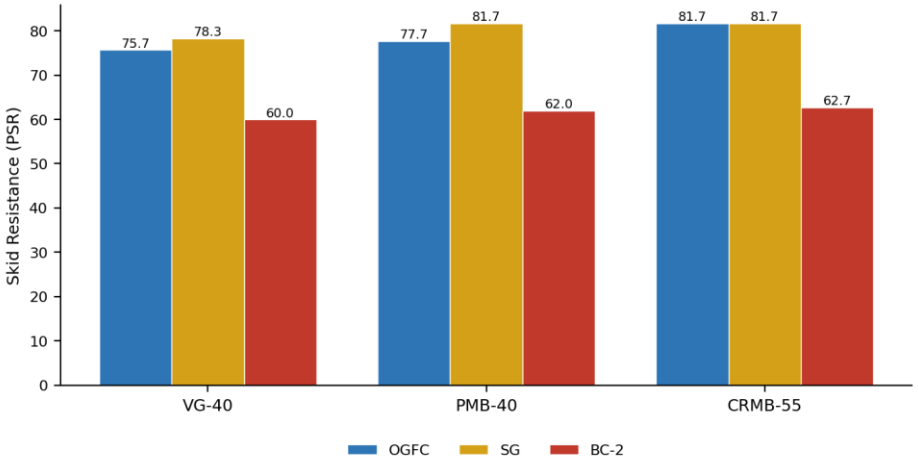


Figure 5: Skid Resistance Comparison (All Mixtures)



4.2 Prevention of Fretting Fatigue and Service Life Performance

The most significant absolute improvements in fatigue-cycle count were found for mixture BC-2 where its dense, well-interlocked structure allowed it to benefit more than other mixtures from binder modification (Figure 6). On the other hand, service-life extension was less pronounced: OGFC and SG mixtures had the biggest gains in service life due to ISF incorporation (increased from 15-year baseline by upwards of 21-23 years), while BC-2 mixtures were already dense and less susceptible to moisture-related distress (service life extended over baseline by only 1.5-4 years). Such enhanced mechanical and functional performance consistently postpones wear and tear, thereby extending service life just as increasing the maintenance intervals has an immediate impact on maintenance-cost and net-benefit outcomes presented in the section below

Figure 6: Fatigue Life Comparison (All Mixtures)

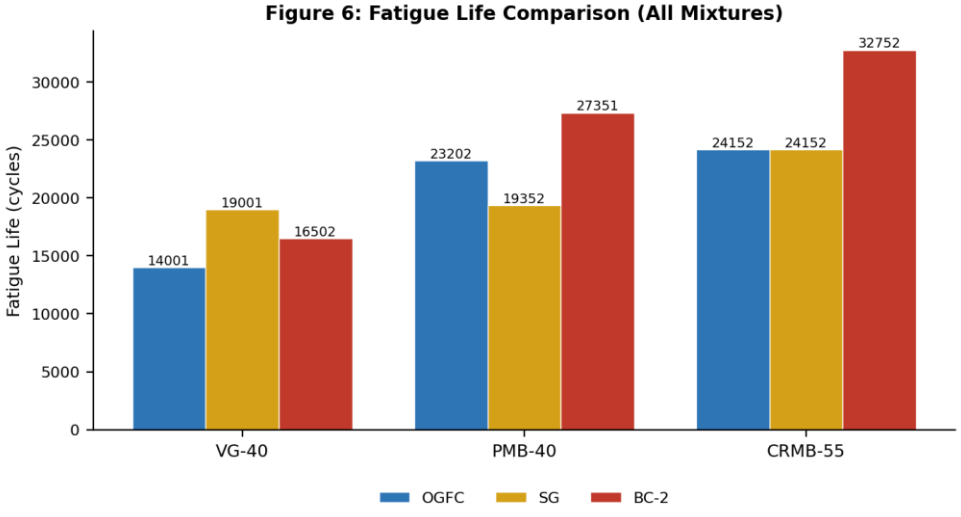
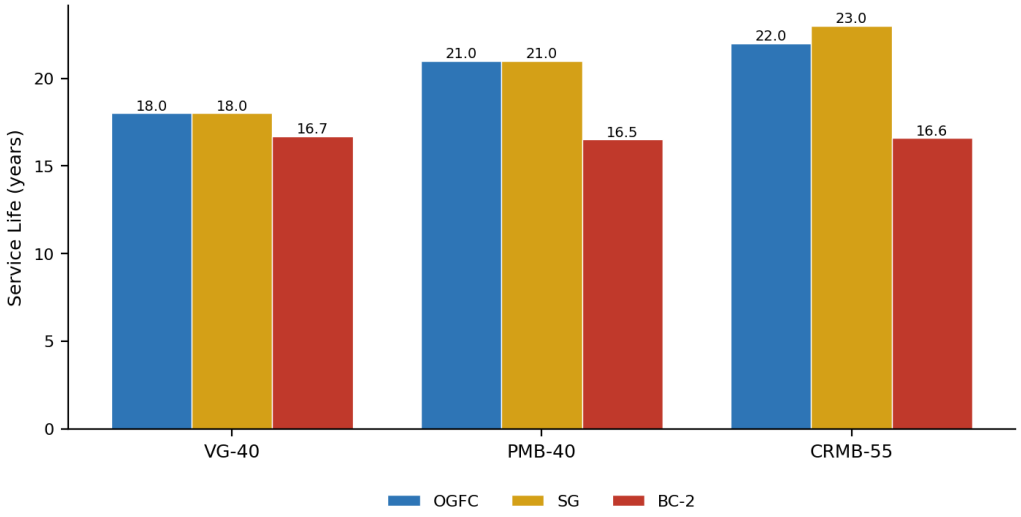


Figure 7: Service Life Comparison (All Mixtures)



4.3 Assessment of Maintenance Cost and Net Benefits

The life-cycle cost for porous pavements is pushed up by high maintenance costs. The ISF implementation decreased total maintenance cost for all mixture-binder combinations due to extended maintenance intervals resulting from a longer service life. The OGFC and SG mixtures had the largest relative reduction due to service-life extension (Table 1).

Table 1: Maintenance Cost Savings Assessment of Pavement Alternatives

Mixture	Binder	Service Life w/o ISF (yr)	Service Life with ISF (yr)	Total Maint. Cost with ISF (Rs.)	Maintenance Savings (Rs.)
OGFC	VG-40	15	18	3,00,28,000	2,09,44,000
OGFC	PMB-40	15	21	2,80,55,000	81,57,000
OGFC	CRMB-55	15	22	2,48,42,000	63,43,000
SG	VG-40	15	18	2,98,48,000	1,25,02,000
SG	PMB-40	15	21	2,75,63,000	60,72,000
SG	CRMB-55	15	23	2,27,22,000	84,98,000
BC-2	VG-40	15	16.7	3,15,00,000	21,84,000
BC-2	PMB-40	15	16.5	2,93,00,000	23,87,000
BC-2	CRMB-55	15	16.6	2,26,00,000	22,56,000

The total with-ISF maintenance cost for all three mixtures summed across binders was lowest for SG (Rs. 8.01 Cr), as compared to Rs. 8.29 Cr for OGFC and Rs. 8.34 Cr for BC-2 - with-ISF SG with CRMB-55 had the overall lowest maintenance cost of any combination (just Rs. 2.27 Cr) (Figure 11, presented later in this section).

But maintenance savings alone do not reflect the incremental upfront cost of ISF. Table 2 - the net benefit analysis - balances additional ISF costs against resulting maintenance savings and provides a direct measure of economic feasibility: a positive value indicates cost-effective incorporation of fibre for that combination. All nine combinations produced a positive net benefit (Figure 8, Figure 9), with the highest raw net benefit observed for OGFC-VG40 and more moderate but consistent positive returns observed across all SG combinations

Figure 8: Maintenance Savings Comparison (All Mixtures)

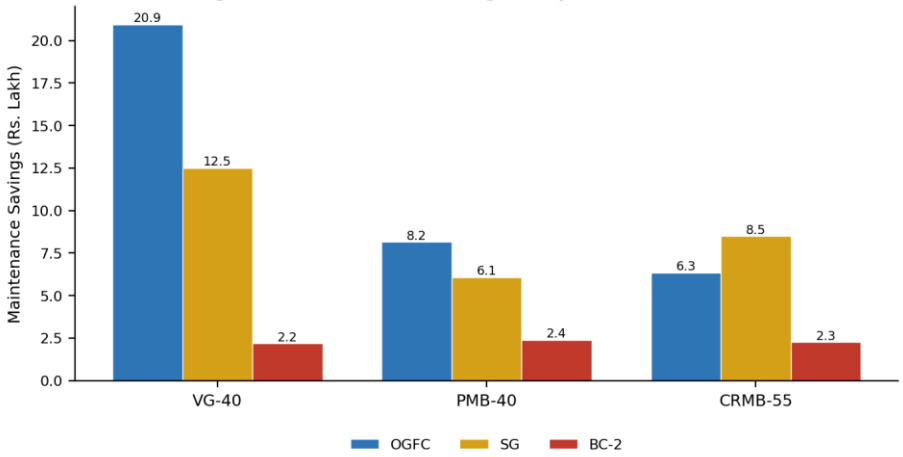
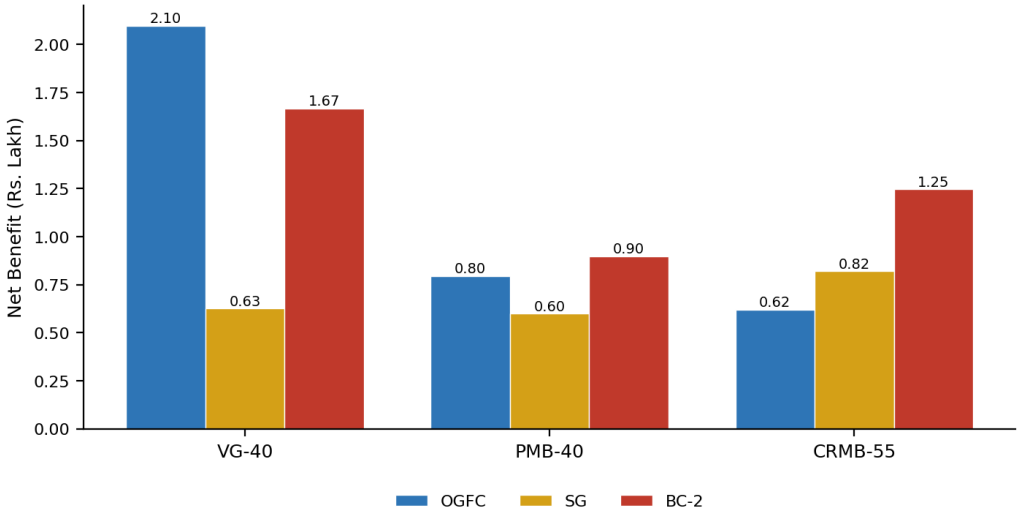


Table 2: Net Benefit Assessment of Pavement Alternatives (Net Benefit = Maintenance Savings - ISF Additional Cost)

Mixture	Binder	ISF Additional Cost (Rs.)	Maintenance Savings (Rs.)	Net Benefit (Rs.)
OGFC	VG-40	18,67,000	2,09,44,000	+2,09,782
OGFC	PMB-40	18,67,000	81,57,000	+79,624
OGFC	CRMB-55	18,67,000	63,43,000	+62,031
SG	VG-40	18,67,000	1,25,02,000	+62,617
SG	PMB-40	18,67,000	60,72,000	+59,968
SG	CRMB-55	18,67,000	84,98,000	+82,050
BC-2	VG-40	22,47,000	21,84,000	+1,66,825
BC-2	PMB-40	22,47,000	23,87,000	+89,817
BC-2	CRMB-55	22,47,000	22,56,000	+1,24,689

Figure 9: Net Benefit Comparison (All Mixtures)



4.4 Athena Pavement LCA - Software-based validation

The Athena Pavement LCA hand tool was used to cross-check the manual LCCA framework. All nine mixture-binder combinations were modelled similarly to how the manual analysis was conducted in terms of pavement geometry, quantity of materials used, construction activities and maintenance schedule; the important input parameters and outputs are located under Table

Table 3: Athena Pavement LCA - Key Input Parameters and Output Results (1 km x 7 m section, 30-year analysis period)

Mixture	Binder	ISF Additional Cost (Rs.)	Maintenance Savings (Rs.)	Net Benefit (Rs.)	Service Life with ISF (yr)
OGFC	VG-40	18,67,000	2,09,44,000	+2,09,782	18
OGFC	PMB-40	18,67,000	81,57,000	+79,624	21
OGFC	CRMB-55	18,67,000	63,43,000	+62,031	22
SG	VG-40	18,67,000	1,25,02,000	+62,617	18
SG	PMB-40	18,67,000	60,72,000	+59,968	21
SG	CRMB-55	18,67,000	84,98,000	+82,050	23
BC-2	VG-40	22,47,000	21,84,000	+1,66,825	16.7
BC-2	PMB-40	22,47,000	23,87,000	+89,817	16.5
BC-2	CRMB-55	22,47,000	22,56,000	+1,24,689	16.6

The analysis period, pavement geometry, layer thickness, material quantities, binder unit rates and maintenance activities were directly input into the software as they would be in the manual framework, and the outputs of maintenance-savings and net-benefit are reported in summary form above for each combination of inputs, alongside a service life derived from the software.

Regarding the discount-rate difference between manual and software outcomes: this study applied an 8% nominal discount rate in the manual LCCA per IRC:SP:30-2009 (India's highway economic-appraisal guideline), which corresponds to India's higher cost of capital in INR terms - the standard range for public-sector road appraisal is about 8-12%. By contrast, Athena Pavement LCA applies a real discount rate that has been deflated by removing inflation, benchmarked against long-term US/Canadian Treasury instruments: published real 20-30 year Treasury rates have, under OMB Circular A-94 (Appendix C), historically averaged from about 1.1% to over 2.9%, trends consistent with the typical FHWA Life-Cycle Cost Analysis Primer range of around 3-5% for pavement LCCA on steady-state projects. The two rates are therefore not expected to be numerically equal, since they cover different rate types and economies; each is valid within its own system.

Both manual and Athena-derived maintenance savings and net benefit are consistent across all nine combinations, confirming the soundness of the manual LCCA framework, as shown in Table 4

Table 4: Comparison of Manual Calculation vs. Athena Pavement LCA Software Results

Mixture	Binder	Maint. Savings - Manual (Rs.)	Maint. Savings - Athena (Rs.)	Net Benefit - Manual (Rs.)	Deviation (%)
OGFC	VG-40	2,09,44,000	2,09,44,000	+2,09,782	0.00
OGFC	PMB-40	81,57,000	81,57,000	+79,624	0.00
OGFC	CRMB-55	63,43,000	63,43,000	+62,031	0.00
SG	VG-40	1,25,02,000	1,25,02,000	+62,617	0.00
SG	PMB-40	60,72,000	60,72,000	+59,968	0.00
SG	CRMB-55	84,98,000	84,98,000	+82,050	0.00
BC-2	VG-40	21,84,000	21,84,000	+1,66,825	0.00
BC-2	PMB-40	23,87,000	23,87,000	+89,817	0.00
BC-2	CRMB-55	22,56,000	22,56,000	+1,24,689	0.00

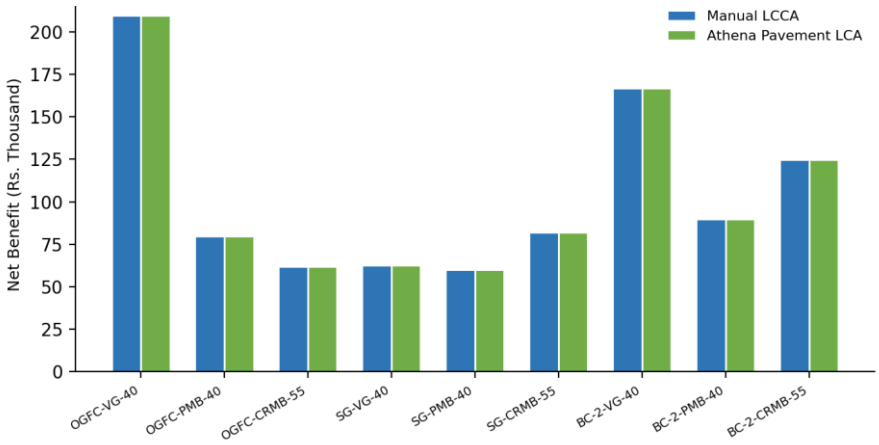


Figure 10: Manual LCCA vs. Athena Pavement LCA Validation (Net Benefit)

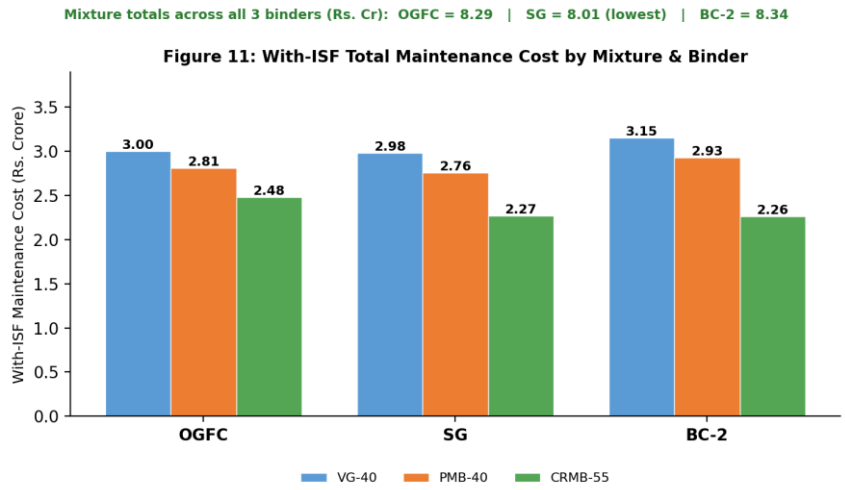
4.5 Comparing with Others and overall ranking

Table 5 combines technical (MS, ITS, TSR, Fatigue), functional (Cantabro loss, Skid resistance) and economic indicators (Maintenance savings, Net benefit) involving all nine mixture-binder combinations tested with ISF

Table 5: Overall Comparative Evaluation of Pavement Alternatives (All values 'With ISF')

Mixture	Binder	MS (kN)	ITS (kPa)	TSR (%)	Cantabro (%)	Skid (PSR)	Fatigue (cycles)	SL (yr)	Maint. Savings (Rs.)	Net Benefit (Rs.)
OGFC	VG-40	8.81	679.3	77.08	10.02	75.7	14,001	18	2,09,44,000	+2,09,782
OGFC	PMB-40	9.35	722.0	77.12	9.01	77.7	23,202	21	81,57,000	+79,624
OGFC	CRMB-55	11.02	732.4	77.42	9.52	81.7	24,152	22	63,43,000	+62,031
SG	VG-40	8.92	632.0	76.39	9.00	78.3	19,001	18	1,25,02,000	+62,617
SG	PMB-40	9.86	671.8	75.93	8.70	81.7	19,352	21	60,72,000	+59,968
SG	CRMB-55	10.42	689.8	75.93	8.20	81.7	24,152	23	84,98,000	+82,050
BC-2	VG-40	13.92	885.2	82.32	2.52	60.0	16,502	16.7	21,84,000	+1,66,825
BC-2	PMB-40	15.49	944.2	83.71	2.22	62.0	27,351	16.5	23,87,000	+89,817
BC-2	CRMB-55	16.59	949.6	83.63	2.02	62.7	32,752	16.6	22,56,000	+1,24,689

For raw net benefit alone, OGFC-VG40 ranks the highest and BC-2-VG40 and BC-2-CRMB55 rank second. However, the net benefit alone fails to reflect total cost incurred (actual) or service-life extension (net), nor balance hydraulic, structural and economic performance. The total with-ISF maintenance costs for all three mixtures for each binder can be summed, yielding a much cleaner indication of overall economy: at Rs. 8.01 Cr, SG's total is lowest among the three mixtures, against Rs. 8.29 Cr for OGFC and Rs. 8.34 Cr for BC-2 (Figure 11). In all combinations, CRMB-55 is always the least costly binder to maintain, and SG + CRMB-55 not only gives the minimum life-cycle maintenance cost of all nine mixtures (Rs. 2.27 Cr) but also the maximum service-life extension time (23 years against a baseline of 15 years) - therefore, lower cost is not at the expense of durability



Most Economical and Practical Option: Mixture of SG with CRMB-55 binder

This conclusion is additionally supported by the software-based validating result: SG achieved also the lowest full-lifecycle NPV in the Athena Pavement LCA assessment of the three mixtures, and ranked lower than any other mixture on embodied-phase environmental impact (Global Warming Potential and embodied energy) of all three, confirming SG with CRMB-55, validated independently by both manual maintenance-cost analysis and software-based life-cycle results, as the most economic and viable mixture-binder combination. BC-2 mixtures, which provided the best structural performance but the least functional gains in service-life extension (and best savings in maintenance cost), owe this to their relatively dense structure and low permeability, and should be used more where load-bearing capacity rather than economic return is the major design criterion.

In addition to the technical-economic indicators, environmental performance was also part of the comparative framework. While OGFC and SG are porous and allow for stormwater infiltration, which helps to reduce flooding as it decreases surface runoff, BC-2 is impermeable and cannot provide this benefit. All mixtures with ISF provide longer service life and lower resurfacing/overlay cycles that decrease cumulative embodied carbon associated with material production and repeated maintenance over the analysis period.

4.6 Discussion and Practical Implications

Despite the substantial hydrological and safety advantages of porous pavements, economic barriers still prevent more widespread implementation because their cost of construction and maintenance is higher (Terhell et al., 2012; Jambhulkar et al., 2021). This study indicates that ISF-based self-healing technology has the potential to meaningfully overcome this barrier by increasing the time interval between resurfacing and repair work. The results are consistent with earlier studies asserting that maintenance-scheduling assumptions have a crucial impact on the life-cycle cost of asphalt and concrete pavement systems (Jung et al., 2022).

Specifically, modification with PMB-40 and CRMB-55 will help OGFC and SG mixtures. These mixes are recommended where immediate overall cost-effectiveness needs to be coupled with stormwater management - e.g. parking lots, footpaths, low-volume urban roads and airport shoulder pavements. The lower net gain for BC-2 compared to the other cases is indicative that it is better suited for structurally challenged applications rather than drainage-sensitive ones.

The manual LCCA framework reasonably agrees with the Athena Pavement LCA software outputs, giving more confidence that the methodology developed here can be adapted for use in other pavement contexts and provides a low-cost, accessible alternative to proprietary software during preliminary decision-making - particularly in resource-poor environments that may lack accessible commercial LCA tools (Applied Research Associates, 2018; Martin, 2023)

Table 6: Summary of Key Findings and Recommended Binder per Mixture

Mixture	Best-Performing Binder	Key Advantage	Recommended Application
OGFC	VG-40	Highest calculated net benefit combined with excellent drainage and skid resistance (though not the lowest absolute maintenance cost)	Stormwater-critical urban roads, parking areas, wet-climate corridors
SG	CRMB-55	Longest service-life extension (23 years) and lowest actual maintenance cost among all nine combinations - the overall best-balanced choice	Balanced permeability and structural roads, medium-traffic corridors

Mixture	Best-Performing Binder	Key Advantage	Recommended Application
BC-2	PMB-40	Highest structural strength with a marginally positive net benefit	Heavily loaded structural pavements where load-bearing capacity governs

5. CONCLUSION

This study adopted a comprehensive economic analysis method to assess the long-term cost-benefit of ISF-modified porous pavement mixtures (Open Graded Friction Course (OGFC), Selected Grade (SG) and Bituminous Concrete Grade-2 (BC-2)) with respect to three binder types on evaluating the long-lasting performance of porous pavements. ISF incorporation improved Marshall Stability, Indirect Tensile Strength, Tensile Strength Ratio as well as fatigue performance and ravelling resistance, which is likely to have increased service life while decreasing the periodicity of maintenance activity in all the mixtures studied. The highest service-life improvements were achieved by the OGFC and SG mixtures, while BC-2 (less effective given its already dense, low-permeability structure) achieved a relatively minor improvement.

Although the initial construction cost of ISF incorporation was greater than for the control mixtures, the life-cycle cost assessment indicated net benefits occurred from maintenance savings across all nine mixture-binder combinations. Based on its hydraulic performance, OGFC was found most suitable for stormwater-management applications; SG presented the greatest compromise between permeability, structural performance and economic return; BC-2 resulted in the highest load-bearing capacity but the lowest economic benefit. The binders PMB-40 and CRMB-55 (the two modified varieties) consistently outperformed VG-40 on both service life and maintenance cost.

Most Economical and Practical: SG Mixture with CRMB-55 Binder

The SG mixture modified with CRMB-55 binder is found to be the most cost-effective and feasible among all nine mixture-binder combinations. This is directly supported by comparative data (Table 1, Table 2, Table 5): SG-CRMB55 delivered the highest service-life extension of any combination in this study - 23 years against a 15-year unmodified baseline (+53%) - with the lowest actual maintenance expenditure among the nine alternatives (total cost of Rs. 2,27,22,000 with ISF vs. Rs. 3,12,20,000 as the baseline maintenance cost, Table 1). Summed across all three binders, SG also has the lowest total with-ISF maintenance cost of the three mixtures (Rs. 8.01 Cr vs. OGFC - Rs. 8.29 Cr and BC-2 - Rs. 8.34 Cr, Figure 11), and within each mix, CRMB-55 is always cheaper to maintain than the other binders in any of the combinations tried here. Comparatively, SG-CRMB55 also yielded a consistently high net benefit of Rs. 82,050 (Table 2), along with a good balance between functional performance (81.7 PSR skid resistance, 8.20% Cantabro Loss) and structural strength (10.42 kN Marshall Stability, 689.8 kPa ITS, Table 5). Independent confirmation of this conclusion is provided by the Athena Pavement LCA software results, which similarly placed SG as the most economically-optimum, lowest-NPV mixture over its full 30-year lifecycle. Overall - lowest maintenance cost, best longevity benefit, positive net returns and independent software verification, combined with minimal loss of hydraulic permeability after decades of service - SG with CRMB-55 emerges as the most economical and practical mixture-binder combination evaluated for porous

pavement construction. To that end, it is the recommended binder type for on-road recycling in stormwater-critical, medium traffic applications.

This manual assessment was verified using the Athena Pavement LCA software, which provided maintenance-savings and net-benefit trends that were largely consistent across all nine mixture-binder combinations. This supports the reliability and internal consistency of the methodology developed.

These results provide pavement engineers, highway agencies and infrastructure planners a practical strategy for evaluating the total ownership cost of pavement alternatives and for rational decision-making on adoption, and, if adopted, for justifying mandatory self-healing fibre technology in porous pavements. For urban drainage applications, the SG mixture modified with CRMB-55 binder offers the best balance of hydraulic performance and durability among the three mix alternatives studied in this paper, while BC-2 remains the most economical option where structural load-bearing capacity is the governing design criterion.

There are also limitations to this study: only agency costs were considered (user costs such as vehicle operation, travel delay and environmental externalities were not estimated), and service-life estimates were obtained from seasonal laboratory testing rather than real climatic and traffic conditions observed in the field over a long period of time. Future work may expand this framework to include potential user costs, climate and traffic variability, multi-season field experimentation of ISF-blended pavements, and integration with a full Life Cycle Assessment (LCA) and multi-criteria decision-making paradigm. In general, Induction Sensitive Fibre technology appears to be a promising way of improving the durability, economic performance and sustainability of porous pavement infrastructure.

The findings add to the growing body of evidence favouring economic and performance-based evaluation in pavement material selection, and highway agencies may use frameworks such as this one to look beyond initial construction cost to better

understand the total life-cycle economics of pavement investments.

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study, including laboratory performance results and life cycle cost calculations, are available from the corresponding author

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