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Sustainable Road and Bridge Construction Materials for Saudi Arabia: Balancing Durability, Carbon Reduction, and Cost

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Abstract- Saudi Arabia's road and bridge programme is expanding under national mobility, logistics and urban-development agendas, yet the material base of this expansion remains carbon-intensive, cost-sensitive and exposed to demanding service conditions. This review examines sustainable construction materials for Saudi road and bridge assets by integrating durability, embodied-carbon reduction and whole-life cost considerations. The aim is to develop a review-based decision framework that helps owners, designers and contractors select concrete, steel, asphalt and recycled-material options that remain technically reliable under hot-arid, coastal and high-traffic conditions. A structured evidence mapping methodology was applied to peer-reviewed and institutional literature published between 2020 and 2025, with emphasis on Saudi studies, life cycle assessment, life cycle cost assessment, pavement decarbonisation and durability evidence. The review finds that material sustainability cannot be reduced to cement replacement or recycled content alone. High-strength and optimised concrete can reduce quantities of concrete and reinforcement when design is not over-conservative; supplementary cementitious materials and alkali-activated binders can reduce clinker demand but require local qualification; recycled aggregates and construction waste can support circularity when processing quality is controlled; warm mix asphalt and reclaimed asphalt pavement can lower production impacts while maintaining pavement performance if mix design, binder ageing and rutting resistance are verified. For Saudi Arabia, the decisive issue is not the absence of sustainable materials, but the limited integration of performance specifications, environmental product declarations, local exposure testing and cost-risk allocation in procurement. The paper proposes a staged material-selection framework linking exposure classification, mechanical performance, carbon benchmarks, supply-chain readiness and maintenance scenarios. It concludes that the most defensible path for road and bridge projects is a portfolio approach: deploy proven low-carbon concrete and asphalt immediately, qualify higher-risk alternatives through pilot sections, and institutionalise carbon-informed procurement without weakening safety or durability.

Keywords: Sustainable Materials, Road Infrastructure, Bridges, Saudi Arabia, Low-Carbon Concrete, Asphalt, Life Cycle Assessment, Durability.

I. INTRODUCTION

Roads and bridges are central to Saudi Arabia's economic diversification because they connect ports, industrial zones, tourism destinations, logistics corridors and expanding metropolitan areas. Their material requirements are large, repetitive and long-lived. Consequently, even marginal improvements in cement content, steel quantity, asphalt temperature, aggregate sourcing or maintenance frequency can generate meaningful carbon and cost savings across a national portfolio. This point is particularly important because the construction sector remains strongly dependent on cement, aggregates, asphalt binder and reinforcing steel, all of which carry significant embodied impacts before an asset opens to traffic [7, 8]. Sustainable infrastructure therefore needs to move beyond symbolic material substitution and toward technically verifiable reductions in whole-life impact. The Saudi context makes this task demanding. Road pavements are exposed to high pavement temperatures, heavy axle loads, dust contamination and substantial thermal cycling. Bridges, especially in coastal or industrial areas, face chloride ingress, carbonation, sulphate attack, humidity fluctuations and corrosion risk. Inland structures face heat, shrinkage, abrasion and fatigue under rapidly growing traffic. Materials that perform acceptably in temperate climates may not deliver equivalent service lives in the Kingdom without adaptation. Therefore, low carbon content is valuable only when it is accompanied by durability, maintainability and predictable construction behaviour. A pavement mix that reduces production emissions but rutts early under summer traffic can increase total emissions through premature maintenance. Likewise, a bridge concrete with lower clinker content is not sustainable if it increases permeability or delays strength gain beyond project constraints.

Recent Saudi evidence shows why early-stage design decisions matter. A study of concrete grades for a Saudi hotel structure found that higher concrete strength could reduce concrete and steel quantities and that a C70 option achieved lower embodied carbon and cost than a C40 base case under the assessed conditions [1]. A related Saudi study found that reducing the steel-to-concrete ratio in columns lowered embodied carbon, embodied energy and cost, reinforcing the argument that material sustainability is as much about structural optimisation as about alternative binders [2]. Although building columns are not road bridges, the principle is transferable: material selection should be assessed at the element and system level, not only by the carbon intensity of one cubic metre or one tonne.

The problem is also urgent because Saudi Arabia has committed to reduce emissions and pursue net-zero pathways [6] while Vision 2030 continues to stimulate major infrastructure investment [10, 11]. International analyses of building materials emphasise three connected strategies: avoid unnecessary material demand, shift to lower-impact material systems, and improve conventional material production [7]. For road and bridge construction, these strategies translate into lean structural design, optimised concrete and asphalt mixes, recycled aggregates, reclaimed asphalt pavement, longer service lives and carbon-aware procurement. However, each option has different implications for technical risk, cost uncertainty and supplier readiness.

This review therefore addresses the following question: how can Saudi road and bridge projects balance durability, carbon reduction and cost when selecting construction materials? The paper contributes by synthesising recent evidence from 2020 to 2025 and by proposing a practical selection framework for Saudi infrastructure. It does not argue that one material is universally superior. Instead, it positions sustainability as a performance-weighted decision in which exposure environment, design life, maintenance access, supply availability and carbon accounting boundaries are explicitly considered.

II. AIM, OBJECTIVES AND RESEARCH QUESTIONS

The aim of this review is to develop a material-selection framework for Saudi road and bridge infrastructure that aligns durability requirements with carbon reduction and cost control. Four objectives guide the analysis. The first objective is to classify sustainable material families relevant to Saudi road and bridge projects, including low-carbon concrete, supplementary cementitious materials, alkali-activated binders, recycled aggregates, recycled steel, warm mix asphalt and reclaimed asphalt pavement. The second objective is to evaluate the durability implications of these options under hot-arid, coastal, high-traffic and maintenance-constrained conditions. The third objective is to compare carbon-reduction pathways with cost and constructability implications so that environmental gains are not achieved through hidden service-life penalties. The fourth objective is to propose a procurement and supplier-qualification logic that can convert research evidence into project delivery.

The review is organised around three research questions. RQ1 asks which material strategies from the 2020-2025 literature show the strongest potential for road and bridge applications in Saudi Arabia. RQ2 asks how carbon reduction interacts with durability and cost when material decisions are evaluated over the life cycle rather than at purchase price alone. RQ3 asks what governance, testing and procurement mechanisms are needed to scale sustainable materials without reducing safety, reliability or compliance.

III. METHODOLOGY

Table 1. Evidence-mapping protocol used for the review.

Review component	Operational treatment	Quality control logic
Time window	2020-2025 peer-reviewed and	Older material rules used only

	institutional sources	as background, not as cited evidence.
Material families	Concrete, reinforcement, asphalt, recycled aggregate, recycled base and alternative binders	Options screened by road or bridge function before carbon ranking.
Appraisal dimensions	Durability, embodied carbon, cost, constructability and supplier readiness	No material is treated as sustainable without performance evidence.
Saudi relevance	Hot-arid climate, coastal exposure, heavy logistics traffic and local supply capability	Evidence closest to Saudi production and testing conditions receives higher weight.

This paper uses a structured evidence-mapping review method. The approach was selected because the topic spans concrete technology, pavement engineering, bridge durability, life cycle assessment, supply-chain management and Saudi policy. The review focused on publications and institutional reports from 2020 to 2025. Search strings combined terms for Saudi Arabia, roads, bridges, concrete, asphalt, sustainable materials, embodied carbon, life cycle assessment, life cycle cost, durability, reclaimed asphalt pavement, warm mix asphalt, supplementary cementitious materials, recycled aggregate, alkali-activated binders and structural optimisation. Sources were screened for relevance to three decision dimensions: technical performance, environmental impact and economic feasibility.

The review placed greater weight on studies with clear material boundaries, quantified life cycle data, durability testing or Saudi-specific evidence. Saudi studies on concrete grade optimisation, steel-to-concrete ratios and asphalt mixture decarbonisation were treated as high-context sources because they connect environmental assessment to local design and production conditions [1-5]. Global reports and roadmaps were used to frame decarbonisation pathways where Saudi-specific data were limited [7-9, 12, 13]. Pavement life cycle studies and reviews were used to interpret asphalt-related trade-offs, including RAP, warm-mix production, binder dominance and maintenance timing [14-20]. Concrete and bridge-material studies were used to interpret clinker reduction, recycled aggregate, geopolymer and durability concerns [21-30].

The method intentionally avoids treating all evidence as equal. Laboratory results were considered useful for material feasibility but insufficient for immediate network-level adoption without pilot sections. Life cycle studies were examined for system boundary, functional unit, transport assumptions, allocation method and maintenance scenario. Cost evidence was interpreted cautiously because Saudi material prices, haul distances, contractor capability and project-risk allocation can change rapidly. The analysis therefore reports directional implications rather than universal numerical rules.

IV. SAUDI OPERATING CONTEXT FOR SUSTAINABLE MATERIALS

Saudi Arabia's infrastructure environment is characterised by high thermal stress, material transport distances, coastal exposure zones, dust, heavy logistics traffic and programme delivery pressures. These factors increase the value of durable materials because maintenance closures can impose large user costs and network disruption. They also complicate carbon accounting because local production emissions, transport distances and maintenance cycles can dominate the result depending on the project boundary. In asphalt pavements, binder and aggregate transport can strongly influence greenhouse gas results, while warm-mix technologies and RAP provide benefits only if performance is not compromised [4, 5].

The Kingdom's climate policy context adds another layer. Saudi Arabia's emission-reduction commitments and long-term net-zero ambition create pressure to reduce the carbon intensity of infrastructure materials [10]. Vision 2030 also prioritises mobility, logistics, local industry and quality of life, which makes roads and bridges not merely construction assets but economic enablers [11]. Sustainable materials must therefore support reliability, local supply development and cost discipline. A material that depends on scarce imported additives may score well in laboratory carbon terms but fail procurement resilience. Conversely, locally available recycled aggregates or RAP may offer strong circularity benefits but require stricter processing, stockpile control and quality assurance.

Saudi road and bridge projects also need to distinguish between initial cost and whole-life cost. The lowest tendered material price can be misleading when a pavement mix increases rutting, when concrete permeability accelerates reinforcement corrosion, or when quality variability leads to rework. International studies of embodied carbon increasingly emphasise early decisions, environmental product declarations and life cycle thinking rather than product price alone [7, 12, 13]. For Saudi clients, this means specifications should allow carbon reduction but require performance evidence, especially where traffic loads, exposure classes and asset criticality are high.

V. CONCRETE FOR BRIDGES, CULVERTS AND RIGID PAVEMENTS

Concrete remains essential for bridge decks, piers, abutments, culverts, barriers and selected rigid pavements. Its sustainability challenge is dominated by cement production, reinforcement demand and durability. The Saudi concrete-grade study is important because it demonstrates that a higher strength class can reduce total concrete and steel quantities in a designed element, producing lower embodied carbon and cost under the tested scenario [1]. This finding does not mean that all bridge elements should use high-strength concrete. Rather, it shows that decision makers should compare designed alternatives at element level. A C70 mix with more cement per cubic metre may still reduce total impact if it enables smaller sections, lower steel demand and longer service life. Conversely, for mass concrete, high cement content may raise heat, shrinkage and cost without proportional structural benefit.

Supplementary cementitious materials remain a central pathway for lowering clinker content. Slag, fly ash, silica fume, natural pozzolans and calcined clay can improve later-age strength, permeability and chemical resistance when proportioned correctly. In bridge environments, the main durability value is reduced permeability and improved chloride resistance, which can delay reinforcement corrosion. Yet availability is a strategic issue. As power and steel industries decarbonise, traditional fly ash and slag supplies may become less predictable [9]. Saudi projects should therefore treat SCMs as qualified performance materials rather than generic green substitutes. Specifications should require mix-specific evidence for strength development, heat, shrinkage, chloride migration, sulphate resistance and curing sensitivity.

Alkali-activated and geopolymer concretes offer larger potential reductions because they can reduce or eliminate Portland cement. Recent reviews identify improved chemical resistance and durability potential, including applications for bridge structures, but they also report adoption barriers involving activator handling, curing, standardisation, long-term field evidence and quality control [23, 24]. For Saudi Arabia, these materials may be suitable for controlled precast elements, drainage units, barriers or pilot bridge components before full deck or pier adoption. The rational route is staged implementation: laboratory qualification, plant trials, pilot sections, monitored field performance, and eventual specification inclusion.

Recycled aggregate concrete is attractive because it reduces quarrying demand and construction waste. Saudi Arabia already faces large construction and demolition waste streams, and life cycle work indicates that recycling can reduce avoided impacts when well managed [30]. However, recycled aggregates vary in water absorption, adhered mortar, chloride content and strength. Bridge concrete should therefore use recycled aggregates cautiously, prioritising non-critical elements, lean concrete, sub-base, approach slabs or components with controlled exposure. Carbonated recycled aggregates and pre-treatment can improve quality, but procurement must require traceability and grading consistency [25].

Steel also matters. Reinforcement contributes significant embodied carbon, and corrosion drives bridge maintenance. Saudi evidence on steel-to-concrete ratios indicates that over-reinforcement can increase embodied carbon and cost without proportional sustainability benefit [2]. Bridge design should therefore combine crack-width control, durability modelling, corrosion protection and material efficiency. Stainless steel, epoxy-coated bars, galvanised reinforcement or fibre-reinforced polymer bars may be justified in severe chloride zones, but only when whole-life cost demonstrates that higher initial cost is offset by reduced maintenance and longer life.

VI. ASPHALT AND PAVEMENT MATERIALS

Flexible pavements dominate road networks, making asphalt decarbonisation a high-impact opportunity. Recent Saudi asphalt LCA work shows that reclaimed asphalt pavement and warm mix asphalt can reduce environmental impacts, with larger gains when RAP, lower mixing temperatures, cleaner fuels and local logistics are combined [3-5]. The most immediate opportunity for Saudi road projects is therefore not a single novel material, but the systematic use of RAP and warm-mix technologies through performance-based mix design.

RAP reduces demand for virgin aggregate and binder, both of which carry environmental and cost burdens. Reviews show that RAP can produce cost and environmental benefits, but performance depends on aged binder stiffness, blending efficiency, rejuvenator selection and plant control [18, 19]. In Saudi Arabia, high pavement temperatures make rutting resistance particularly important, while older binder can increase cracking risk if not balanced. High-RAP mixtures should therefore be evaluated through balanced mix design, including rutting, fatigue, moisture susceptibility and ageing tests. Agencies should avoid simple percentage targets that reward recycled content without confirming performance.

Warm mix asphalt reduces production and compaction temperature. This can cut fuel use, extend haul distance, improve compaction windows and reduce plant emissions. However, benefits depend on additive type, aggregate moisture, compaction density and field workmanship. Combining WMA and RAP can be particularly promising because lower temperatures reduce additional ageing of reclaimed binder [3, 18]. For Saudi Arabia, WMA can also support night paving and long-distance supply, but specifications should verify moisture damage resistance and density under local aggregate conditions.

Cold recycling, foam bitumen, emulsion recycling and stabilised base layers can also reduce material and transport impacts. These methods are especially relevant for rehabilitation because they reuse in-place material and reduce hauling. Yet they should be matched to traffic level, drainage condition and expected structural capacity. For high-volume corridors, recycled layers may be best used in base or binder courses with engineered overlays. For lower-volume roads, they can provide substantial cost and carbon reductions if quality control is disciplined.

VII. CARBON ACCOUNTING, COST AND FUNCTIONAL PERFORMANCE

Sustainable-material decisions require a functional unit. For a bridge, the relevant comparison may be one deck square metre over 75 or 100 years, including maintenance. For a pavement, it may be one lane-kilometre carrying a defined traffic load over a defined analysis period. Product-level carbon intensity alone can mislead because a low-carbon material that reduces service life may increase total impact. Equally, a higher-carbon product can be rational when it extends life in a severe exposure zone.

Life cycle assessment should therefore include at least material production, transport, construction and maintenance scenarios. For early design, cradle-to-gate assessment is useful because it identifies material hotspots, but road and bridge decisions also need maintenance and use-stage sensitivity. Pavement smoothness, work-zone congestion and rehabilitation frequency can influence total emissions, particularly on high-traffic corridors [14, 16]. Bridge material durability similarly affects inspection, repair, traffic disruption and replacement impacts.

Cost assessment should follow the same logic. Initial bid price should be separated from whole-life cost, risk allowance and maintenance access. Some low-carbon materials may cost more initially because of admixtures, qualification testing or supplier learning. Others, such as RAP, can reduce cost if processing and stockpile management are mature. The Saudi concrete-grade study is instructive because it shows a case where the lower-carbon option was also cheaper, but such alignment should be verified rather than assumed [1].

VIII. PROPOSED SAUDI MATERIAL-SELECTION FRAMEWORK

Figure 1 presents a proposed material-selection pathway. The process begins with the asset function: highway pavement, urban road, bridge deck, culvert, barrier, retaining element or temporary works. The second step defines exposure and loading, including chloride zone, sulphate risk, temperature, flood risk, traffic loading, maintenance access and design life. The third step screens material options using minimum mechanical and durability requirements. Only materials that pass performance thresholds move to carbon and cost comparison. This sequence prevents carbon targets from displacing safety.

Figure 1. Performance-led material selection pathway for Saudi road and bridge projects.

The fourth step requires carbon evidence. Suppliers should provide environmental product declarations, plant-specific data or verified calculation sheets. Where such evidence is unavailable, conservative default factors should be used until better data are provided. The fifth step assesses supply-chain readiness, including local production capacity, quality management, stockpile control, admixture availability, curing requirements and contractor experience. The final step assigns an adoption route: approved for standard use, approved with project-specific verification, pilot only, or not recommended.

This framework supports procurement reform. Instead of prescribing only cement type, binder grade or recycled percentage, Saudi infrastructure clients can specify performance classes, carbon disclosure, durability tests and whole-life cost evaluation. Supplier qualification should reward verified performance and transparent data, not claims. Pilot projects should include monitoring plans, not merely construction acceptance. Results should be fed into national material databases so that future tenders can use Saudi-specific carbon and durability evidence.

IX. DISCUSSION

The review indicates that the strongest near-term options for Saudi roads and bridges are not speculative. Concrete optimisation, SCM-based mixes, efficient reinforcement, RAP, WMA, recycled base materials and improved maintenance planning are ready for broader use when supported by performance specifications. More transformative options, such as alkali-activated bridge concrete, carbonated recycled aggregates and high-volume recycled mixes, should be advanced through monitored pilots. This two-speed strategy protects reliability while avoiding unnecessary delay in carbon reduction.

A major risk is fragmented decision making. Designers may optimise structural sections without access to plant carbon data; contractors may propose recycled materials without long-term performance evidence; owners may focus on initial price because carbon and maintenance impacts are not priced in tender evaluation. Integration is therefore essential. Material decisions should be made through a triad of durability, carbon and cost. If one side is missing, the decision is incomplete.

Another implication concerns local content. Sustainable materials can strengthen Saudi industry if local suppliers develop EPD capability, recycled-material processing, low-carbon cement blends, asphalt plant controls and testing laboratories. Local content should not mean accepting lower performance. It should mean building domestic capacity to meet high-performance, low-carbon specifications. This aligns sustainability with industrial development rather than treating it as an imported compliance requirement.

X. APPLICATION-SPECIFIC MATERIAL PRIORITIES

For bridge decks, the first priority should be permeability control rather than compressive strength alone. Decks receive chlorides from coastal air, de-icing is not the dominant Saudi mechanism, and cracking can create a direct path to reinforcement. Low-carbon concrete for decks should therefore be specified with limits on rapid chloride penetration or migration, water absorption, shrinkage, modulus and curing sensitivity. SCM replacement should be increased only where early strength, finishing and curing can be managed. For piers and substructures in marine or sabkha-influenced locations, sulphate resistance and chloride diffusion should be evaluated together, because a mix that performs well for one mechanism may not be best for the other. Protective surface treatments and corrosion-resistant reinforcement should be assessed through whole-life cost.

Table 2. Sustainable material options and adoption guidance for Saudi road and bridge assets.

Material option	Typical Saudi application	Durability gate	Carbon/cost logic	Adoption route
SCM concrete	Bridge decks, piers, culverts and barriers	Chloride, sulphate, shrinkage and curing verification	Lower clinker; possible longer life	Standard use after local mix approval
RAP + WMA	Asphalt surface, binder and base courses	Rutting, moisture damage, fatigue and ageing	Lower virgin binder and plant energy	Use through balanced mix design
Recycled aggregate	Base layers, lean concrete, non-critical concrete	Gradation, absorption, salts and abrasion	Reduced quarrying and haul impacts	Project-specific qualification
Geopolymer or alkali-activated binders	Precast units and pilot bridge components	Activator safety, curing, carbonation and field monitoring	High carbon potential but higher delivery risk	Pilot and monitored deployment
Corrosion-resistant reinforcement	Marine bridge decks and inaccessible repairs	Service-life modelling and crack control	Higher initial cost; lower repair risk	Whole-life cost justification

For bridge foundations and mass elements, thermal cracking is a central sustainability issue. A low-carbon binder with lower heat of hydration may improve both carbon and durability, but only when setting time and strength gain are compatible with construction sequencing. Blended cements, limestone calcined clay systems and slag-rich concretes can be promising in such elements because they can reduce clinker demand and temperature rise. However, material acceptance should require local temperature-matched trials. For precast beams, barriers and culverts, controlled plant conditions create a safer pathway for innovative materials. Precast production allows better curing, quality assurance, repeatability and carbon-data collection, so it should be a priority platform for scaling low-carbon mixes.

For asphalt wearing courses, durability under heat and traffic governs adoption. Any lower-carbon mix should be checked for rutting resistance, moisture susceptibility, fatigue cracking, skid resistance and ageing. RAP content should be linked to binder grade, rejuvenator design and blending evidence. In heavy-traffic freight corridors, conservative RAP levels with strong performance testing may provide better life-cycle outcomes than aggressive recycled content without field confidence. For base and binder courses, higher recycled content may be feasible because functional requirements differ. This differentiated approach prevents rejection of recycled materials.

For unbound and hydraulically bound layers, construction and demolition waste, recycled concrete aggregate and reclaimed asphalt aggregate can reduce virgin aggregate demand. Saudi projects should prioritise these materials where drainage, contamination and gradation are controlled. Specifications should include limits for sulphates, chlorides, plasticity, abrasion, soundness and fines. In desert regions, aggregate hauling can be a significant cost and carbon component, so locally processed recycled aggregate may have strong advantages when quality is verified. In coastal or high-groundwater settings, recycled aggregate should be assessed for leaching and salt content before use.

XI. PROCUREMENT AND SUPPLIER QUALIFICATION

The transition to sustainable materials will fail if procurement continues to reward only minimum compliant price. Saudi owners can shift the market by using two-stage material approval. The first stage should define non-negotiable performance requirements: code compliance, design strength, exposure-class durability, constructability and testing frequency. The second stage should compare eligible options by embodied carbon, whole-life cost, maintenance implications and local supply resilience. This protects safety while encouraging innovation among compliant alternatives.

Supplier qualification should include four components. First, suppliers should demonstrate process control, including batching records, plant calibration, temperature control, curing procedures and traceable raw materials. Second, they should submit environmental data, preferably EPDs or life cycle calculations. Third, they should provide durability evidence relevant to Saudi conditions, including heat exposure, chloride or sulphate tests where applicable, and field trial results for asphalt mixtures. Fourth, suppliers should show capacity to deliver consistently at project scale. A low-carbon mix that is available only in small batches may be unsuitable for a major highway unless scaling risks are allocated.

Contract forms also matter. If a contractor carries all performance risk, rational bidders may avoid innovation or price it heavily. Conversely, if an owner mandates new materials without clear test methods, disputes are likely. Shared innovation pilots, early contractor involvement and performance warranties can distribute risk fairly. For routine projects, approved-material lists should be updated when pilots demonstrate reliable performance. For strategic projects, tender evaluation can assign a modest carbon score among technically compliant bids, while maintaining life-cycle cost and durability as controlling factors.

Digital material passports can strengthen governance. Each major material batch could record source, mix design, recycled content, EPD reference, transport distance, test results and installed location. This information would support maintenance planning, future recycling and carbon reporting. It would also help Saudi agencies move from generic assumptions to asset-specific data. Over time, a national road and bridge materials database could support benchmark carbon factors, approved recycled-material sources, supplier performance histories and region-specific durability models.

XII. SYNTHESIS OF TRADE-OFFS

The core trade-off is not carbon versus durability; it is poorly specified carbon reduction versus performance-verified carbon reduction. Many sustainable materials can improve durability when used properly. SCMs can reduce permeability, RAP can reduce virgin binder demand, WMA can improve compaction, and recycled aggregates can conserve natural resources. The challenge is matching each material to the right application, exposure class and quality-control regime. Saudi Arabia should therefore avoid both extremes: rejecting innovative materials because they differ from conventional practice, or accepting them because they carry a green label. The defensible middle ground is performance-based approval with transparent carbon accounting.

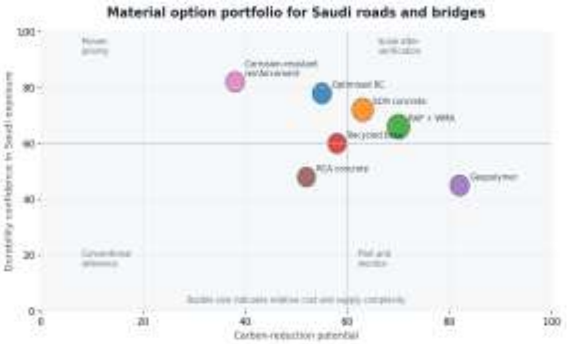

Figure 2. Comparative portfolio of sustainable material options by carbon potential and durability confidence.

Cost follows a similar logic. Some sustainable materials will reduce initial cost, especially where they replace expensive virgin binder, reduce steel quantities or use local recycled aggregate. Others may require higher initial investment but reduce maintenance, closures and replacement. A Saudi bridge deck in a corrosive coastal environment, for example, may justify a more expensive low-permeability concrete or corrosion-resistant reinforcement because premature repair would be costly and disruptive. A low-volume rural road may justify recycled base materials because the performance demand is lower and local material savings are high. Thus, cost evaluation must be asset-specific.

The review also suggests that the first procurement reforms should be simple. Require carbon disclosure for concrete, asphalt and steel; permit alternative mixes that meet performance criteria; allow RAP and WMA through balanced mix design; create pilot pathways for geopolymer and high-recycled materials; and require life-cycle comparison for major bridges. These measures can produce progress. As Saudi evidence improves, thresholds can become more ambitious and regionally differentiated.

XIII. LIMITATIONS AND FUTURE RESEARCH

This review is limited by the uneven availability of Saudi road and bridge material data. Building-focused studies provide useful design lessons but do not fully represent bridge exposure and pavement loading. Asphalt LCA evidence is improving, yet long-term field data for high-RAP and WMA mixtures under Saudi traffic and climate conditions remain limited. Cost comparisons are also sensitive to local prices, plant technology, haul distance and contract structure.

Future research should develop Saudi exposure-calibrated databases for concrete, reinforcement, asphalt and recycled aggregates. Bridge studies should compare SCM, geopolymer, corrosion-resistant reinforcement and protective systems using service-life modelling and monitored field sections. Pavement studies should evaluate RAP, rejuvenators, WMA and recycled base layers through balanced mix design and accelerated pavement testing. Policy research should examine how tender scoring can incorporate carbon and durability without producing disputes or excessive administrative burden.

XIV. CONCLUSION

Sustainable road and bridge materials for Saudi Arabia must be selected through performance-weighted judgement rather than product labels. The evidence from 2020 to 2025 shows that carbon reduction, durability and cost are interdependent. High-strength concrete, SCMs, efficient reinforcement, RAP and WMA can reduce impacts, but the outcome depends on design ptimization, exposure conditions, supplier quality and maintenance planning. For Saudi Arabia, the most credible pathway is a staged portfolio: use proven low-carbon options now, qualify advanced materials through pilots, and institutionalise transparent carbon and whole-life cost assessment in procurement. Such an approach supports Vision 2030 infrastructure delivery while reducing embodied emissions, protecting asset life and controlling public expenditure.

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