

Hybrid Multi-Criteria Selection of Sustainable Materials for Two-Lift Concrete Pavement Construction

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Abstract

Road transportation infrastructure requires rigid pavement systems that can provide high load-carrying capacity, durability, economical construction and reduced environmental impact. This study investigates an innovative Two-Lift Concrete Pavement (TLCP) system in which Roller Compacted Concrete (RCC) and Geopolymer Concrete (GPC) are used as economical and sustainable bottom-lift materials, while Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) and Engineered Cementitious Composite (ECC) are used as high-performance top-lift materials. The research began with an M40 Pavement Quality Concrete (PQC) designed to achieve a target 28-day flexural strength of 4.5 MPa in accordance with IRC:44-2017. The baseline mix was systematically modified to develop RCC, GPC, UHPFRC and ECC, followed by multi-criteria selection using a hybrid Analytic Hierarchy Process–Technique for Order Preference by Similarity to Ideal Solution (AHP–TOPSIS) framework. The experimental programme covered fresh properties, compressive strength, split tensile strength, flexural strength, modulus of elasticity, abrasion resistance, shrinkage, fatigue behaviour, interlayer bond, microstructural characteristics, full-scale plate loading and finite-element validation. For the two-lift specimens, RCC or GPC occupied approximately two-thirds of the thickness and UHPFRC or ECC approximately one-third, with the top layer placed within about one hour of the bottom layer to promote composite action. At 28 days, the R+U and G+U configurations reached compressive strengths of 69.67 and 78.12 MPa, respectively. Pull-off and bi-surface shear observations showed that failure generally occurred within the bottom lift rather than at the interface, indicating strong interlayer bonding. SEM observations confirmed development of a dense Overlay Transition Zone (OTZ) and increasing C–S–H formation with curing. Weibull-based fatigue analysis further showed that UHPFRC-top configurations possessed the most favourable fatigue performance among the two-lift systems. The combined evidence demonstrates that the proposed TLCP concept can integrate economical structural support with high-performance crack-resistant surfacing, offering a technically feasible and sustainable approach for modern rigid pavements.

Keywords: Two-Lift Concrete Pavement; Roller Compacted Concrete; Geopolymer Concrete; UHPFRC; Engineered Cementitious Composite; AHP–TOPSIS; Interlayer Bond; Weibull Fatigue Analysis; Sustainable Pavement.

1. INTRODUCTION

Rigid pavements are widely adopted where high structural stiffness, long service life and resistance to repeated wheel loading are required. Conventional cement-concrete pavements can distribute traffic loads over a relatively broad area and generally require less routine maintenance than flexible pavements. However, their construction is associated with substantial consumption of Portland cement and natural aggregates, while the brittle nature of ordinary concrete limits tensile and post-cracking performance. The supplied project report identifies these competing requirements as a central motivation for developing layered pavement systems in which each lift is designed for a specific function. □

Two-Lift Concrete Pavement (TLCP) separates the structural and surface functions of the slab. The lower layer provides the principal load-bearing capacity and can therefore be produced with economical, sustainable or rapidly compactable concrete. The upper layer is thinner but is exposed directly to traffic and environmental actions, so it can be designed with a high-performance concrete that offers improved abrasion resistance, crack control, ductility and durability. This functional separation can improve material efficiency without increasing the overall pavement thickness.

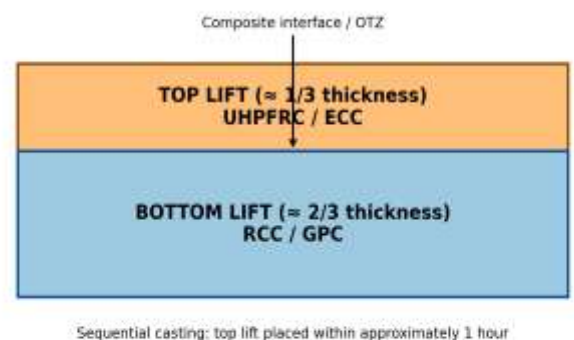


Figure 1. Conceptual configuration of the proposed Two-Lift Concrete Pavement system.

1.1 Problem Statement

In conventional single-layer rigid pavements, the entire slab must simultaneously satisfy structural, surface, durability and fatigue requirements. This can lead to conservative material selection and high cementitious-material consumption. The research problem addressed in the supplied report is therefore how to combine materials with different strengths, rheological characteristics and sustainability advantages into a reliable two-lift pavement

system while maintaining strong composite action between the layers.

1.2 Research Motivation and Gap

The literature reviewed in the source report shows that RCC, GPC, UHPFRC and ECC have each been investigated individually. RCC offers economical construction and efficient compaction; GPC can reduce dependence on Portland cement through industrial by-products; UHPFRC provides very high strength, dense microstructure and fibre-assisted crack bridging; and ECC provides exceptional tensile ductility and multiple micro-cracking. However, the report identifies limited research on their combined use within a two-lift pavement, especially on fatigue behaviour, bond performance, structural efficiency and the use of GPC as a sustainable bottom lift and UHPFRC as a top lift. The research gap is therefore the integrated experimental evaluation of these material combinations in a single TLCP framework.

1.3 Aim

The principal aim is to develop and evaluate a sustainable Two-Lift Concrete Pavement system by combining optimized RCC or GPC bottom layers with UHPFRC or ECC top layers and by examining their mechanical, interfacial, microstructural, fatigue and structural behaviour.

1.4 Objectives

1. Characterize the physical, mechanical and chemical properties of the constituent materials used for RCC, GPC, UHPFRC and ECC.
2. Design and optimize concrete mixtures suitable for the structural and surface functions of a Two-Lift Concrete Pavement.
3. Investigate the fresh and hardened properties of the developed concrete mixtures.
4. Evaluate the fatigue performance of the optimized mixtures under repeated loading.
5. Develop two-lift specimens using RCC or GPC as the bottom lift and UHPFRC or ECC as the top lift.
6. Determine compressive strength, flexural strength, bond strength and fatigue performance of the composite specimens.
7. Evaluate the structural behaviour of full-scale two-lift pavement slabs using plate-load testing.
8. Validate the experimental observations through finite-element analysis for stress distribution and pavement response.
9. Identify the most efficient pavement configuration considering structural performance, durability, sustainability and long-term service potential.

1.5 Scope of the Study

The investigation covers raw-material characterization, baseline M40 PQC mix design, development of four specialized concrete systems, laboratory optimization, multi-criteria material selection, fatigue evaluation, preparation of composite two-lift specimens, interlayer bond assessment, SEM-based microstructural investigation, full-scale plate

loading and finite-element validation. The source report uses a 1:2 top-to-bottom lift thickness ratio and focuses on combinations R+U, R+E, G+U and G+E.

2. LITERATURE REVIEW

The literature review in the supplied report establishes the technical basis for using different concretes in different pavement lifts. Conventional concrete remains effective in compression but is comparatively weak in tension and post-cracking behaviour. RCC addresses construction efficiency and density through low-slump mixtures and compaction. GPC offers a lower-Portland-cement binder route through alkali activation of aluminosilicate sources. UHPFRC combines dense particle packing, low water-to-binder ratio and fibre reinforcement, whereas ECC uses micromechanical design and polymeric fibres to achieve strain-hardening and multiple fine cracks.

2.1 Two-Lift Concrete Pavement

Two-lift paving is based on functional material allocation. The lower lift normally occupies the larger fraction of slab thickness and carries most of the structural demand, while the thinner upper lift provides a durable wearing surface. The source literature indicates that placement interval is important: studies summarized in the report show that excessive delays between lifts can reduce shear bond strength and fatigue life, while shorter intervals can promote mechanical interlocking and chemical continuity.

2.2 Roller Compacted Concrete

RCC differs from conventional PQC through its lower water content, higher aggregate proportion and dependence on compaction to obtain high density. The report emphasizes that density is a key performance variable: small reductions in field density can produce disproportionately large strength losses. Maximum-density mix design and appropriate compaction are therefore critical. Supplementary cementitious materials such as fly ash, silica fume and GGBS can further influence strength, durability and microstructure.

2.3 Geopolymer Concrete

GPC is produced by activating silica- and alumina-rich materials such as fly ash and GGBS with alkaline solutions. The literature summarized in the source report describes dissolution of aluminosilicate species followed by formation of a three-dimensional geopolymeric network. The relative amounts of fly ash, slag, sodium hydroxide and sodium silicate, together with curing conditions, strongly influence strength development. The source study uses an 8 M NaOH solution and sodium silicate in the GPC system.

2.4 UHPFRC

UHPFRC is characterized by a dense cementitious matrix, low water-to-binder ratio, fine particle packing and fibre reinforcement. Silica fume refines the pore structure and contributes to strength, while steel fibres bridge cracks and provide post-cracking resistance. The source literature identifies approximately 2–3% steel fibre by volume as a frequently effective range, although the optimum value is mixture-dependent. These properties make UHPFRC

particularly attractive for thin wearing layers subjected to heavy traffic.

2.5 Engineered Cementitious Composite

ECC is designed to develop tensile strain hardening through micromechanical control of matrix fracture and fibre bridging. Unlike conventional fibre-reinforced concrete, ECC is intended to form many fine cracks rather than a single dominant crack. The literature summarized in the source report indicates tensile strain capacities of several percent and crack widths that can remain very small under large deformation. ECC is therefore attractive as a pavement surface material where ductility, crack control and durability are important.

2.6 Research Gap

- Limited integrated research on sustainable two-lift pavement systems in the Indian context.
- Need for systematic evaluation of different bottom-lift materials because the bottom lift controls structural support.
- Need for improved high-performance wearing layers with varied material systems.
- Limited fatigue-life information for two-lift concrete under repeated traffic loading.
- Absence of a widely standardized RCC mix-design approach despite extensive use.
- Limited research on GPC as a bottom-lift material in two-lift pavements.
- Limited investigation of UHPFRC as a top lift in two-lift pavement systems.
- Need to combine mechanical, bond, microstructural, fatigue and structural evidence rather than optimizing a material using a single response.

3. MATERIALS AND METHODOLOGY

3.1 Experimental Programme

The experimental programme was divided into five linked stages. Stage 1 characterized the raw materials. Stage 2 established an M40 PQC reference mix and developed RCC, GPC, UHPFRC and ECC variants. Stage 3 evaluated optimized single-layer mixes under mechanical and fatigue loading and prepared composite two-lift specimens. Stage 4 scaled the selected configurations to full-size slabs for plate-load testing. Stage 5 used finite-element modelling to reproduce the structural response and support interpretation of the experimental observations.

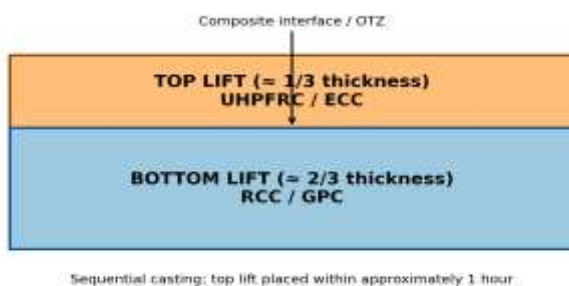


Figure 2. Simplified experimental framework used in the source investigation.

3.2 Materials Characterization

OPC 43-grade cement, Class F fly ash, silica fume and GGBS formed the cementitious system. The aggregates were locally sourced from Jalandhar, Punjab. Geopolymer concrete used sodium hydroxide and sodium silicate activators. Steel fibres were used in UHPFRC and polypropylene fibres in ECC. A polycarboxylate-based superplasticizer was used in the high-performance mixes. Potable municipal water with a measured pH of 7.3 was used for mixing and curing.

Table 1. Physical properties of OPC 43-grade cement.

Material/Test	Obtained value	Reported requirement/reference
OPC surface area	2348 cm ² /g	2250 cm ² /g minimum
OPC specific gravity	3.15	3.00–3.15
OPC consistency	31%	30–35%
Initial setting time	42 min	30 min minimum
Final setting time	480 min	600 min maximum
Soundness	3 mm	10 mm maximum
3-day compressive strength	24.3 MPa	23 MPa
7-day compressive strength	34.6 MPa	33 MPa
28-day compressive strength	45.1 MPa	43 MPa

Table 2. Physical properties of fine and coarse aggregates.

Property	Fine aggregate	Coarse aggregate
Specific gravity	2.48	2.54
Fineness modulus	2.81	6.46
Water absorption	1.65%	0.95%
Los Angeles abrasion	—	9.06%
Crushing value	—	12.08%
Impact value	—	10.40%

Table 3. Chemical composition of cementitious materials.

Oxide (%)	Cement	Fly ash	GGBS	Silica fume
SiO ₂	20.78	60.51	31.49	94.30
Al ₂ O ₃	5.91	26.98	12.28	0.16
Fe ₂ O ₃	3.99	5.01	1.15	0.55
MgO	0.94	0.81	4.58	0.81
CaO	60.78	1.45	44.58	0.73
SO ₃	2.81	0.29	3.29	0.29
K ₂ O	1.08	1.12	0.36	—

Na ₂ O	0.91	0.17	0.21	—
TiO ₂	0.22	1.72	1.02	—
Loss on ignition	2.10	1.81	0.81	—

Table 4. Physical properties of fibres.

Fibre	Diameter (μm)	Length (mm)	Elastic modulus (GPa)	Tensile strength (MPa)	Density (kg/m ³)
Steel	200	12	200	2580	7850
Polypropylene	30	12	9	480	910

3.3 Mix Proportions and Development

The baseline mixture was an M40 PQC designed according to IRC:44-2017 with a target 28-day flexural strength of 4.5 MPa. The specialized concretes were developed by modifying this baseline according to the intended pavement function. RCC was optimized using a density-based approach; GPC replaced the Portland-cement paste with fly ash/GGBS and alkaline activators; UHPFRC reduced aggregate size, increased binder content, introduced silica fume and then steel fibres; and ECC removed coarse aggregate, introduced fly ash and progressively increased polypropylene fibre content.

Table 5. PQC and RCC trial mix proportions per 1 m³.

Mix	Cement (m ³)	Fine aggregate (m ³)	Coarse aggregate (m ³)	OMC (%)	MD (kg/m ³)	Water (m ³)
PQC	0.14	0.30	0.40	—	—	0.155
RC C1	0.07	0.40	0.30	4.19	2302	0.089
RC C2	0.08	0.40	0.30	4.49	2323	0.097
RC C3	0.09	0.38	0.32	4.78	2346	0.103
RC C4	0.10	0.38	0.32	5.06	2374	0.109
RC C5	0.11	0.36	0.34	5.33	2397	0.116
RC C6	0.12	0.36	0.34	5.59	2418	0.122
RC C7	0.13	0.36	0.34	5.84	2433	0.127
RC C8	0.14	0.34	0.36	5.88	2445	0.131

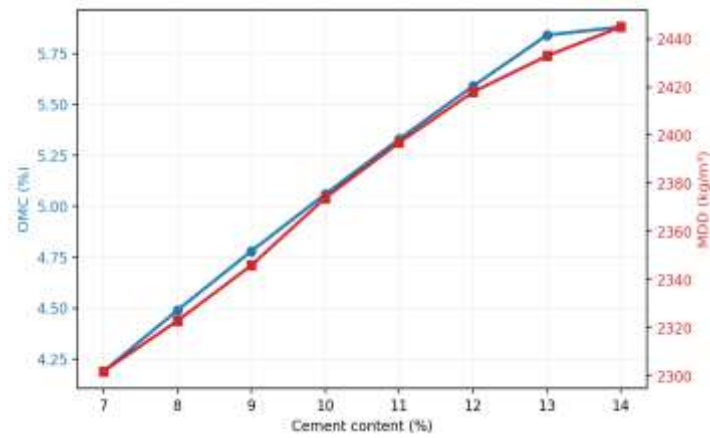


Figure 3. OMC and MDD variation with RCC cement content (redrawn from the reported trial data).

Table 6. Geopolymer concrete mix proportions per 1 m³.

Mix	Fly ash (kg)	GGBS (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	NaOH (kg)	Water (kg)	Na ₂ SiO ₃ (kg)	SS/SH
GPC 1	334.30	0.00	744	1016	21.96	62.56	146.88	1.5
GPC 2	300.87	33.43	744	1016	21.96	62.56	146.88	1.5
GPC 3	267.44	66.86	744	1016	21.96	62.56	146.88	1.5
GPC 4	234.01	100.29	744	1016	21.96	62.56	146.88	1.5
GPC 5	200.58	133.72	744	1016	21.96	62.56	146.88	1.5

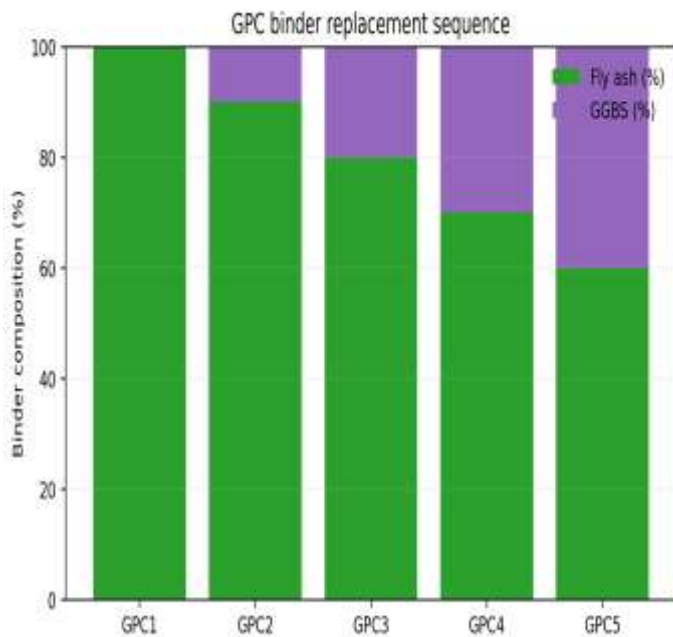


Figure 4. GPC fly ash–GGBS replacement sequence used in the investigation.

3.3.1 UHPFRC Development

UHPFRC development proceeded in stages. U1 reduced the nominal maximum aggregate size from 20 mm to 10 mm. U2 and U3 progressively replaced coarse-aggregate volume with cement. U4–U7 introduced silica fume at 5%, 10%, 15% and 20% cement replacement. U8–U13 then introduced steel fibres from 0.5% to 3.0% by volume. The final optimized fibre-reinforced mix was obtained after considering strength, workability and durability response.

Table 7. UHPFRC development mix proportions per 1 m³.

Mix	Cement (kg)	Silica fume (kg)	Fine agg. (kg)	Coarse agg. (kg)	Water (kg)	SP (kg)	Steel fibre (%)
PQC	433	—	744	1016 (20 mm)	156	—	—
U1	433	—	744	1016 (10 mm)	86.6	4.50	—
U2	756	—	744	762 (10 mm)	151.2	7.86	—
U3	1071	—	744	508 (10 mm)	214.2	10.81	—
U4	1017	54	744	508 (10 mm)	214.2	10.81	—
U5	964	107	744	508 (10 mm)	214.2	10.81	—

U6	910	161	744	508 (10 mm)	214.2	10.81	—
U7	857	214	744	508 (10 mm)	214.2	10.81	—
U8	910	161	744	508 (10 mm)	214.2	10.81	0.5
U9	910	161	744	508 (10 mm)	214.2	10.81	1.0
U10	910	161	744	508 (10 mm)	214.2	16.22	1.5
U11	910	161	744	508 (10 mm)	214.2	16.22	2.0
U12	910	161	744	508 (10 mm)	214.2	16.22	2.5
U13	910	161	744	508 (10 mm)	214.2	10.22	3.0

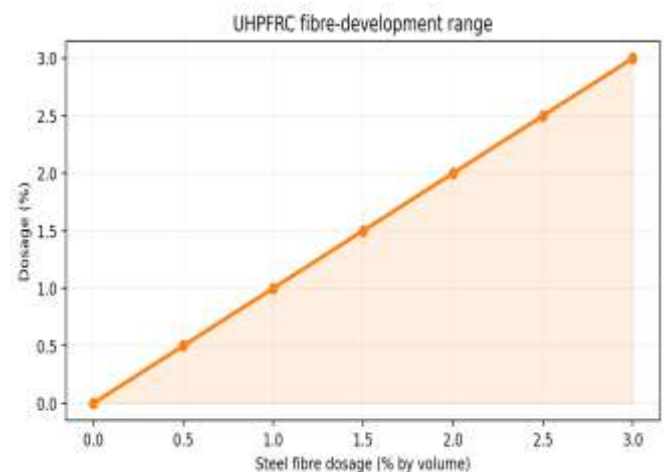


Figure 5. Steel-fibre dosage range investigated during UHPFRC development.

3.3.2 ECC Development

ECC was developed from a cement-mortar base in which the coarse aggregate was removed and fly ash was introduced. The fine aggregate was reduced to below approximately 300 µm to improve homogeneity. Polypropylene fibre was then increased from 9.10 to 27.30 kg/m³ while the water-to-binder ratio was maintained at 0.24 and superplasticizer was used to preserve workability.

Table 8. ECC development mix proportions per 1 m³.

Mix	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Fly ash (kg)	PP fibre (kg)	W/B	SP (kg)
PQC	433	744	1016	—	—	0.36	—
CM	433	744	—	840	—	0.24	8.96
E1	433	744	—	840	9.10	0.24	8.96

E2	433	744	—	840	13.6 5	0.24	8.9 6
E3	433	744	—	840	18.2 0	0.24	8.9 6
E4	433	744	—	840	22.7 5	0.24	8.9 6
E5	433	744	—	840	27.3 0	0.24	8.9 6

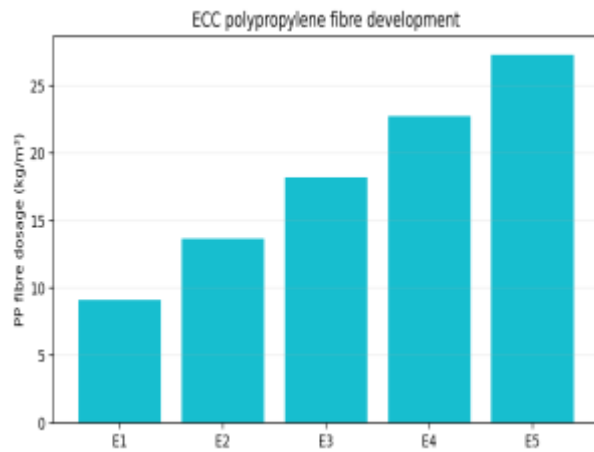


Figure 6. Polypropylene-fibre dosage used for ECC development.

3.4 Mixing, Specimen Preparation and Testing

PQC was mixed in accordance with IRC:44 by dry mixing aggregates, adding cement and part of the water, and then introducing the remaining water. RCC was produced in full-size slabs rather than relying only on conventional mould compaction. Slabs measuring 500 × 300 × 100 mm were cast in three layers, each compacted with 25 blows using a 150 mm diameter, 15 kg rammer, followed by vibration for 2–3 minutes at 60 Hz in accordance with ASTM C1176. After 24 hours, specimens were de-moulded; cubes, saw-cut beams and cores were extracted after burlap curing.

Fresh workability was assessed using the slump test. Compressive strength was measured on 100 × 100 × 100 mm cubes at 7 and 28 days using a 2000 kN compression testing machine. Split tensile strength was evaluated on 100 mm diameter × 200 mm high cylinders. Static modulus of elasticity was measured on 150 × 300 mm cylinders at 28 days. Flexural strength was determined using four-point loading on beam specimens. The wider programme also included tensile, pull-out, pull-off, bi-surface shear, abrasion, shrinkage, fatigue, SEM, XRD, plate-load testing and finite-element analysis using the Concrete Damage Plasticity model in ABAQUS.

3.5 Two-Lift Specimen Configuration

Optimized RCC or GPC was used as the bottom lift and optimized UHPFRC or ECC as the top lift. The bottom layer occupied approximately two-thirds of the total thickness and the top layer approximately one-third. The top lift was placed within one hour after casting the bottom lift. This short interval was selected to promote mechanical interlocking, chemical continuity and strong composite action. The

principal combinations were designated R+U, R+E, G+U and G+E.

3.6 Multi-Criteria Decision Analysis: AHP–TOPSIS

Material selection is inherently multi-dimensional because strength, durability, cost, sustainability and fatigue performance do not necessarily favour the same alternative. The source study therefore adopted a hybrid AHP–TOPSIS framework. AHP provides structured criterion weighting through pairwise comparison using Saaty’s 1–9 scale, while TOPSIS ranks alternatives by their distance from an ideal and a negative-ideal solution.

- Construct the decision matrix with alternatives as rows and criteria as columns.
- Normalize each criterion using the vector normalization relation $r_{ij} = D_{ij} / \sqrt{\sum D_{ij}^2}$.
- Form the weighted normalized matrix $V_{ij} = r_{ij}w_j$.
- Identify ideal and negative-ideal values, reversing the direction for cost-type criteria.
- Calculate the distances d^+ and d^- from the ideal and negative-ideal solutions.
- Calculate relative closeness $C_i = d^- / (d^+ + d^-)$.
- Rank alternatives in descending order of C_i ; the highest value represents the preferred configuration.

The principal benefit of the hybrid procedure is that it avoids selecting a pavement material from a single strength parameter. Instead, the preferred configuration is identified by considering the competing technical and sustainability objectives within one decision framework.

Table 9. Principal tests and analytical methods.

Test / analysis	Main purpose	Principal standard approach /
Slump	Fresh consistency and workability	IS 1199
Compressive strength	Load-carrying capacity	IS 516
Split tensile strength	Indirect tensile/cracking response	IS 516
Flexural strength	Pavement bending capacity	Relevant IS/IRC procedure
Modulus of elasticity	Elastic stiffness	Standard cylinder method
Abrasion / Cantabro	Surface wear resistance	Cantabro-based evaluation
Drying shrinkage	Dimensional stability	Relevant shrinkage procedure
SEM	Microstructure and OTZ	Scanning Electron Microscopy
XRD	Phase identification	X-ray diffraction
Fatigue	Repeated-load resistance	S–N + Weibull methods
Plate load	Full-scale structural response	Laboratory plate loading
FEA	Stress/deformation validation	ABAQUS CDP model

4. RESULTS AND DISCUSSION

4.1 Roller Compacted Concrete

The RCC results show a clear relationship between cement content, density and engineering performance. RCC mixtures with lower cement contents were comparatively lean and developed lower strength because the available paste was insufficient to create a dense continuous matrix. As cement content increased from RCC4 through RCC7, additional hydration products improved aggregate–paste bonding and reduced internal voids. RCC6 and RCC7 therefore showed the most favourable combination of strength, abrasion resistance and shrinkage behaviour, and RCC7 was selected for subsequent investigations.

Table 10. Reported RCC workability results.

Mix	Cement volume (m ³)	Cement mass (kg)	Fine aggregate (m ³)	Coarse aggregate (m ³)	Water (kg)	Slump (mm)
RCC 1	0.07	219.1	0.40	0.30	89.88	0
RCC 2	0.08	250.4	0.40	0.30	96.60	0
RCC 3	0.09	281.7	0.38	0.32	103.15	0
RCC 4	0.10	313.0	0.38	0.32	109.52	0
RCC 5	0.11	344.3	0.36	0.34	115.71	0
RCC 6	0.12	375.6	0.36	0.34	121.72	0
RCC 7	0.13	406.9	0.36	0.34	127.55	0
RCC 8	0.14	433.0	0.34	0.36	131.87	35

RCC strength increased with curing age, consistent with continued cement hydration. The split tensile and flexural responses followed the same overall trend. The source report also records lower Cantabro loss and lower shrinkage for RCC6 and RCC7, indicating that higher-density RCC mixes were simultaneously stronger and more resistant to surface deterioration and dimensional instability. These observations support RCC7 as the preferred structural bottom-lift material.

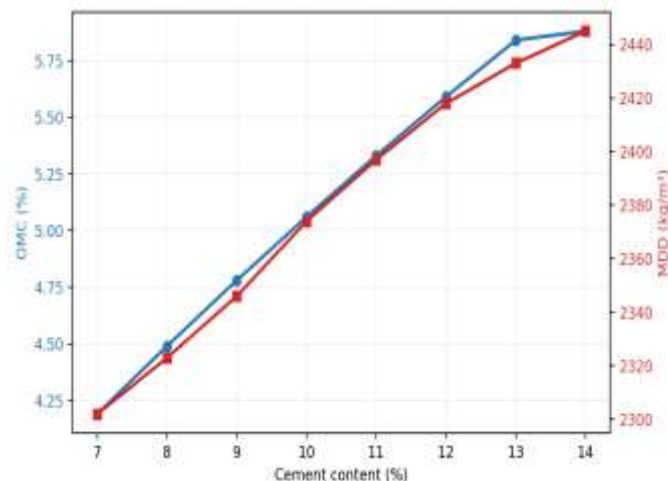


Figure 7. Redrawn OMC–MDD relationship for RCC trials.

4.2 Geopolymer Concrete

The GPC programme used five binder combinations ranging from 100% fly ash to 60% fly ash + 40% GGBS, with the same aggregate quantities and alkaline activator quantities. The source report indicates that all five mixtures exhibited workable slumps, ranging from approximately 163 mm for GPC1 to 98 mm for GPC5. Increasing GGBS content altered the rheology while also contributing calcium-rich reaction products that support strength development.

Strength development was progressive with curing age, reflecting continued geopolymerization and formation of a dense aluminosilicate binder matrix. The source report also describes satisfactory abrasion resistance and shrinkage behaviour, together with favourable fatigue and bond characteristics reported in the broader investigation. The GPC results support the use of geopolymer concrete as a sustainable bottom lift where structural capacity is required while reducing dependence on conventional Portland cement.

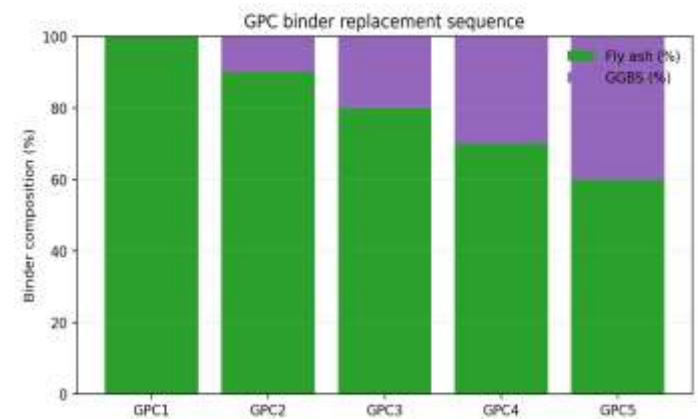


Figure 8. Binder replacement sequence used for the GPC mixtures.

4.3 UHPFRC and ECC Performance

UHPFRC showed the strongest overall mechanical response among the investigated single-layer high-performance concretes. Its performance is associated with low water-to-binder ratio, refined particle packing, silica-fume reaction and steel-fibre bridging. The fibres delayed crack propagation and increased energy absorption after matrix cracking. These characteristics are particularly beneficial for a thin surface layer that must resist repeated wheel loading, abrasion and environmental deterioration.

ECC provided a different performance advantage. Rather than maximizing strength alone, its micromechanically controlled matrix and polypropylene fibres were intended to promote multiple fine cracks and greater deformation capacity. The source report notes that ECC-based composites therefore displayed greater deflection before failure than UHPFRC-based composites. This makes ECC attractive where ductility and crack-width control are prioritized.

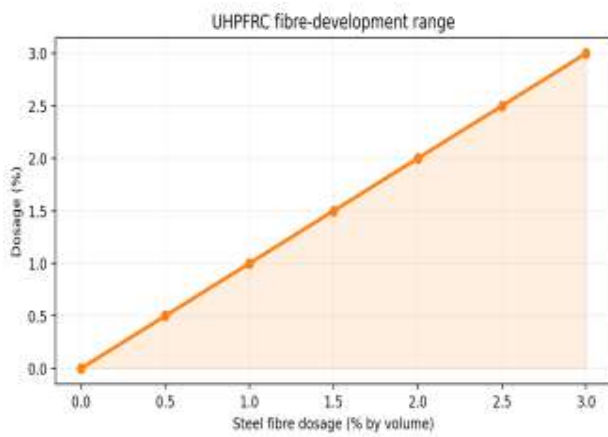


Figure 9. Steel-fibre dosage range investigated in UHPFRC development.

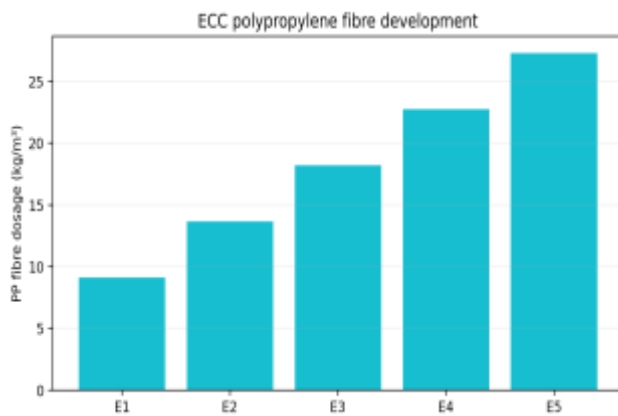


Figure 10. Polypropylene-fibre dosage used in ECC development.

4.4 Selection of Optimized Materials

On the basis of the combined experimental evidence and multi-criteria selection philosophy, optimized RCC, GPC, UHPFRC and ECC mixtures were carried forward to the two-lift stage. RCC and GPC were assigned to the bottom lift because of their structural and economic/sustainability advantages, whereas UHPFRC and ECC were assigned to the top lift because of their high-performance surface characteristics.

Table 11. Two-Lift Concrete configurations evaluated in the source study.

Configuration	Bottom lift	Top lift	Functional role
R+U	Optimized RCC	Optimized UHPFRC	Economical structural support + high-strength surface
R+E	Optimized RCC	Optimized ECC	Economical structural support + ductile crack-resistant surface
G+U	Optimized GPC	Optimized UHPFRC	Sustainable structural support + high-

			strength surface
G+E	Optimized GPC	Optimized ECC	Sustainable structural support + ductile crack-resistant surface

5. PERFORMANCE OF TWO-LIFT CONCRETE PAVEMENT

5.1 Composite Action and Compressive Strength

The two-lift specimens were produced with a 1:2 top-to-bottom thickness ratio. The top lift was placed within approximately one hour of the bottom lift, so the interface could develop strong mechanical and chemical continuity. Compressive strength was evaluated at 7 and 28 days and compared with the corresponding single-layer materials. The source report states that the TLC specimens generally achieved strengths between those of the bottom and top layers, while the UHPFRC-top systems produced the strongest composite response.

Table 12. Explicitly reported 28-day TLC compressive-strength results.

TLC configuration	28-day compressive strength (MPa)	Source interpretation
R+U	69.67	Highest-strength RCC-bottom composite reported for TLC
G+U	78.12	Highest-strength GPC-bottom composite reported for TLC
R+E	Not numerically stated in source result text	Strength close to corresponding RCC bottom layer
G+E	Not numerically stated in source result text	Strength close to corresponding GPC bottom layer

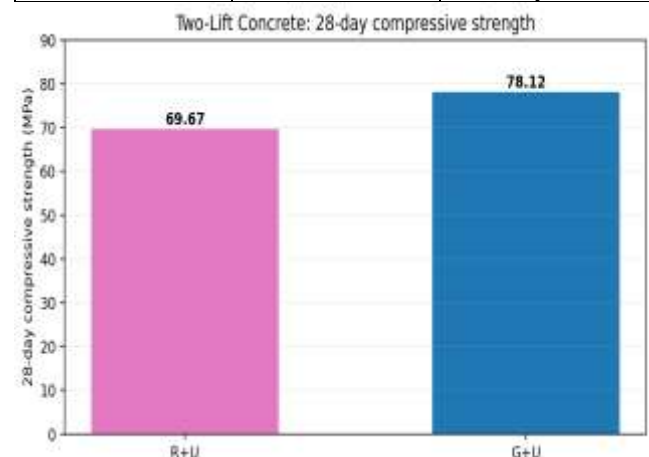


Figure 11. Explicitly reported 28-day compressive strength of UHPFRC-top TLC configurations.

The higher strength of R+U and G+U is attributed to the dense UHPFRC matrix, fibre reinforcement and strong interfacial continuity. The ECC systems did not maximize compressive strength to the same extent, but their ductile

response contributed to improved deformation capacity. Thus, the two-lift concept provides a deliberate balance between structural strength and surface toughness rather than forcing one concrete to provide every required property.

5.2 Flexural Strength and Load–Deflection Behaviour

Flexural performance is critical because pavement slabs primarily resist wheel loads through bending. The source investigation reports that all TLC configurations improved with curing age and that UHPFRC-top configurations R+U and G+U developed the highest flexural strengths. ECC-top configurations R+E and G+E also improved the response relative to their bottom-lift concretes, but at somewhat lower peak strength. The load–deflection curves provide a complementary interpretation: RCC and GPC showed relatively linear pre-peak response followed by brittle failure, while UHPFRC and ECC showed more gradual post-cracking behaviour because fibres continued to transfer tensile stress across cracks.

UHPFRC-top beams combined higher peak load with comparatively lower deflection, reflecting higher stiffness. ECC-top beams exhibited larger deflections and therefore greater deformation capacity. This difference is important for pavement design because maximum strength and controlled deformation are not identical objectives. The two-lift configuration permits the engineer to choose the surface material according to the dominant performance requirement.

5.3 Pull-Off Bond Strength

Pull-off testing was used to assess tensile bond between the two lifts. Bond strength increased with curing age for all composite specimens. R+U and G+U exhibited higher pull-off strengths than the ECC-top combinations, which is consistent with the dense UHPFRC matrix and strong fibre–matrix interaction. The observed failure modes included epoxy failure, interfacial failure and top-lift failure. A few early specimens were re-tested after re-bonding the loading disc where the epoxy bond was inadequate.

Importantly, the majority of reliable failures occurred either within the bottom lift or at the interface rather than through the top lift. This indicates that the interface developed sufficient tensile resistance to transfer stresses without premature delamination. The short placement interval between the two layers is therefore a key construction variable in achieving the observed composite action.

5.4 Bi-Surface Shear Bond

Bi-surface shear testing demonstrated continued increase in interlayer shear strength with curing age. UHPFRC-top systems generally showed higher shear resistance than ECC-top systems. All tested TLC configurations exhibited failure within the bottom lift rather than along the interface, corresponding to the reported failure mode (c). The result indicates that the interface was stronger than the adjacent bottom-layer concrete and that the TLC section behaved as a monolithic structural unit under shear.

The shear results reinforce the pull-off findings: timely placement of the top lift before complete setting of the bottom lift can create effective mechanical interlocking and chemical bonding. For field implementation, maintaining a controlled casting interval is therefore essential.

5.5 Microstructural Analysis

SEM was used to examine the Overlay Transition Zone (OTZ) between the bottom and top lifts after 7 and 28 days. At 7 days, the microstructure contained comparatively more calcium hydroxide (CH) and fewer developed C–S–H products. The interface was already bonded, but the hydration process was still progressing. At 28 days, continued hydration produced a denser cementitious matrix, increased C–S–H formation and reduced the relative presence of CH. The OTZ also became more continuous and uniform.

These observations provide a microstructural explanation for the measured age-related improvements in compressive strength, flexural strength and interlayer bond. A dense OTZ allows more efficient stress transfer across the interface and reduces the likelihood of premature debonding. The source report therefore links the macro-scale performance of the TLC system to the progressive development of the interfacial microstructure.

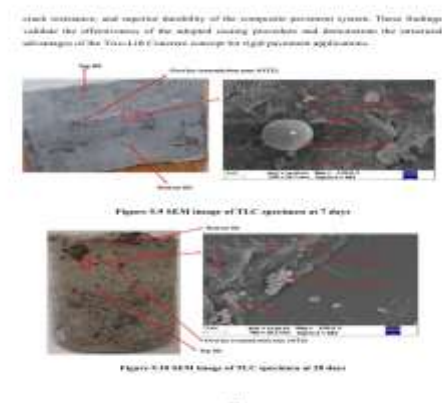


Figure 12. Source-report SEM figure illustrating the microstructural investigation of the TLC system (28-day page image reproduced from the supplied report).

5.6 Fatigue Life and Weibull Analysis

Fatigue behaviour was evaluated using stress–number of cycles (S–N) relationships. Because fatigue life is inherently scattered, the source study used Weibull statistical analysis and compared several parameter-estimation approaches: Graphical Method (GM), Method of Moments (MOM), Least Squares Regression in both directions, Empirical Method of Lyson (EML), Mean Standard Deviation Method (MSDM), and Energy Pattern Factor Method (EPFM). The average Weibull shape parameter α and scale parameter u were used for subsequent interpretation.

The source results show that fatigue life decreases as stress level increases for every configuration. Nevertheless, the rate of reduction is less severe for fibre-reinforced top-layer composites. R+U and G+U exhibited the most favourable fatigue response among the two-lift combinations, while R+E and G+E also outperformed the conventional RCC and GPC single-layer systems. The mechanism is attributed to fibre bridging, delayed crack propagation and greater energy absorption.

Table 13. Average Weibull parameters for TLC configurations.

Configu- ration	S=0 .55 α	S=0. 55 u	S=0 .65 α	S=0. 65 u	S=0 .75 α	S=0 .75 u	S=0 .85 α	S=0 .85 u
R+U	3.1 6	1,643 ,218	2.9 9	242, 926	3.0 0	34, 721	3.1 7	4,9 14
R+E	2.8 9	1,552 ,198	2.8 0	154, 603	2.8 5	32, 010	2.9 7	4,7 07
G+U	2.2 1	899,2 90	2.2 4	118, 462	2.3 6	18, 356	2.7 9	2,2 24
G+E	2.2 0	1,130 ,645	2.3 4	126, 213	2.4 4	21, 664	2.5 8	2,4 46

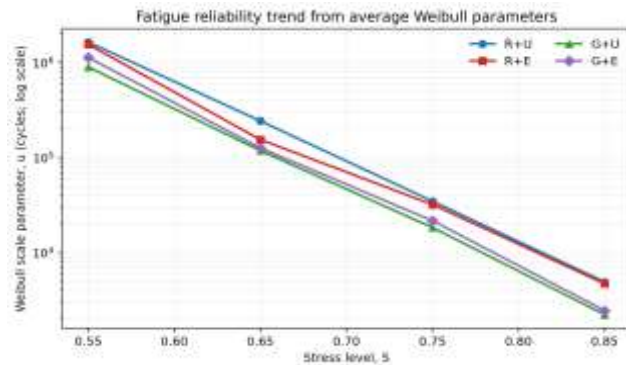


Figure 13. Weibull scale parameter u versus stress level for the four TLC configurations.

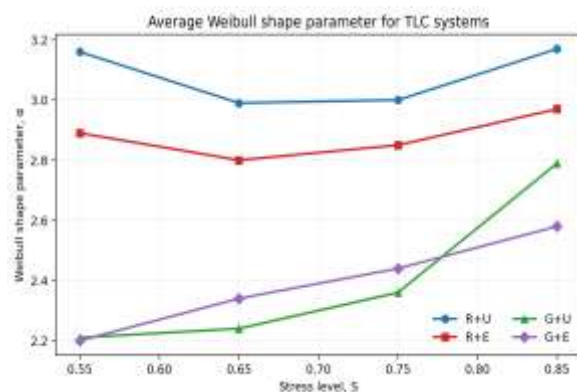


Figure 14. Weibull shape parameter α versus stress level for the four TLC configurations.

6. INTEGRATED DISCUSSION

6.1 Mechanical Performance

The experimental evidence shows that the proposed layered strategy is effective because it assigns different performance functions to different materials. RCC and GPC provide the bulk of the structural thickness, while UHPFRC and ECC improve the surface response. The highest explicitly reported composite compressive strength was 78.12 MPa for G+U at 28 days, followed by 69.67 MPa for R+U. The source report also identifies UHPFRC-top configurations as the strongest in flexure and fatigue, while ECC-top configurations provide greater deformation capacity.

6.2 Interfacial Performance

Interlayer bond is the critical requirement of any two-lift pavement. A high-strength top lift cannot contribute effectively if the interface debonds. In the present investigation, pull-off and bi-surface shear results, together with the observed failure modes, indicate that the interface was not the weak link. Most failures occurred in the bottom lift. The SEM observations further support this conclusion by showing a dense OTZ with increasing C-S-H formation at 28 days.

6.3 Fatigue Performance

Fatigue results show a clear advantage for fibre-reinforced surface layers. The crack-bridging action of steel fibres in UHPFRC provides high stiffness and crack arrest, while ECC provides multiple fine cracks and greater deformation before failure. Consequently, the fibre-reinforced TLC systems maintained superior cyclic-load resistance compared with the conventional single-layer bottom materials. The Weibull framework is useful because it converts the scatter inherent in fatigue testing into a reliability-oriented description of pavement performance.

6.4 Sustainability and Material Efficiency

The sustainability advantage of the proposed system comes primarily from functional material allocation. The lower layer can use RCC, which reduces reliance on highly processed high-performance materials and can be produced efficiently through compaction, or GPC, which incorporates industrial by-products and reduces the Portland-cement requirement. Only the thinner surface lift requires the more resource-intensive UHPFRC or the specialized ECC matrix. The strategy therefore aims to reduce the volume of premium material while retaining high surface performance.

6.5 Construction Implications

The study highlights that material selection alone is insufficient; the construction sequence is equally important. The top layer should be placed before complete setting of the bottom layer, with the source investigation using an interval of approximately one hour. For field adoption, this implies coordinated batching, transport, placing and finishing operations so that the interface remains in a condition capable of developing strong mechanical and chemical continuity.

6.6 Structural Scale-Up and Numerical Validation

The source research also extends the programme to full-scale two-lift slabs and finite-element modelling using the Concrete Damage Plasticity model in ABAQUS. The plate-load test is intended to reproduce pavement-type loading at laboratory scale, while FEA provides an independent means of examining stress distribution and deformation. The supplied results chapter establishes that these activities form part of the validation programme; however, numerical plate-load and FEA result values are not explicitly reported in the extracted result text used for this paper, so no additional values are introduced here.

7. CONCLUSIONS AND FUTURE SCOPE

7.1 Conclusions

- The investigation successfully developed and optimized RCC, GPC, UHPFRC and ECC mixtures for use in a sustainable two-lift rigid pavement system.
- RCC and GPC provided suitable bottom-lift materials for structural support, while UHPFRC and ECC enhanced the surface layer through high strength, crack resistance and/or ductility.
- The Two-Lift Concrete configurations achieved strong composite action without increasing the overall pavement thickness.
- At 28 days, the explicitly reported R+U and G+U compressive strengths were 69.67 MPa and 78.12 MPa, respectively.
- UHPFRC-top systems produced the highest reported mechanical and fatigue performance among the composite configurations.
- ECC-top systems provided greater deformation capacity and ductile post-cracking behaviour, complementing the high-strength behaviour of UHPFRC.
- Pull-off and bi-surface shear tests indicated strong interlayer bonding; most specimens failed within the bottom lift rather than along the interface.
- SEM observations showed development of a dense Overlay Transition Zone and increased C–S–H formation at 28 days, explaining the improved composite performance with curing.
- Weibull analysis confirmed the strong influence of stress level on fatigue life and demonstrated the benefit of fibre-reinforced top layers under cyclic loading.
- The combined mechanical, interfacial, microstructural and fatigue evidence supports TLCP as a technically feasible and potentially sustainable alternative for modern rigid pavement construction.

7.2 Future Scope

- Conduct long-term field investigations under actual traffic and environmental conditions.
- Investigate different fibre types, fibre contents and hybrid fibre systems in the top lift.

- Evaluate alternative sustainable binders and supplementary cementitious materials to further reduce environmental impacts.
- Study freeze–thaw, sulphate, chloride and high-temperature durability under aggressive exposure.
- Investigate interface preparation methods and different casting intervals for long-term bond performance.
- Perform detailed life-cycle cost assessment (LCCA) and life-cycle assessment (LCA).
- Validate laboratory findings using full-scale pavement test sections and numerical modelling under different loading conditions.
- Develop national design guidelines and construction specifications for practical implementation of two-lift pavement technology.

7.3 Overall Engineering Significance

The principal contribution of the study is the demonstration of a hybrid pavement philosophy in which the material is selected according to its position and function. Instead of requiring a single concrete to provide maximum structural strength, surface durability, crack resistance, ductility, fatigue resistance and sustainability simultaneously, the two-lift concept allocates these demands to specialized layers. This provides a rational pathway toward more resource-efficient high-performance rigid pavements.

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