

The eco-concrete revolution: Manufacturing a sustainable high-performance rigid pavement with innovative materials

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Article Info	Abstract
Article History: Received: 11 Oct 2025 Accepted: 20 Nov 2025 Keywords: CRCP; Durability; Environmental impact Assessment; OpenLCA; Supplementary cementitious materials; Sustainability	Real-life strategies are applied to assess pavement functionality, high-quality performance, and durability throughout its service life. This study evaluates the sustainable rigid pavement construction using Jordanian natural zeolite (JNZ), silica fume (SF), porcelain tile waste (PTW), and spent coffee grounds (SCG) as supplementary materials. This novel technique is an original contribution to the emerging research on the long-term, durable, sustainable, and performance-based characteristics of pavements under the constraints of structural soundness. The research focused on the incorporation of sustainable building materials, specifically Jordanian Natural Zeolite in concrete structures. Further, the study described both the properties of concrete and cement savings from replacing JNZ in OPC and SRC clinkers. Furthermore, the research also compared the normal concrete with JNZ-enhanced concrete as an SCM with different proportions of cement replacement. Replacing 10% of the cement in the concrete mix increases permeability and durability. Moreover, the eco-friendly concrete is produced by using 25% of the PTW as a coarse aggregate replacement. It enhanced the workability, permeability, and mechanical characteristics of the sustainable concrete mixture. Research study also utilized spent coffee grounds (SCG) to produce sustainable CRCP structural concrete, burned at 350°C and 800°C to pyrolyze their organic compounds. It was also concluded that the 15 % SCG at 350°C concrete mix offered the best workability, permeability, sulfate resistance, mechanical properties, and impact on the natural environment. The EIA and chemical assessments also highlighted how constructing sustainable CRCP structures improved performance, saved material resources, and reduced the carbon footprint compared to earlier mixes.

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1. Introduction

Environmental impacts from the construction industry are facing numerous challenges while the call for infrastructure continues to grow as a world population, thus durable, resilient, and robust infrastructure systems are increasingly desirable. Continuous reinforced concrete pavement (CRCP) is a kind of rigid pavement that contains continuous steel reinforcement to perform a single-structure that can evenly distribute loads over it. Durable rigid pavement assessment and the decision-making for their maintenance are critical issues in civil engineering, mainly when traffic volumes increase with loss of behavior and maintenance costs. Carbon emissions resulting from the manufacture of Ordinary Portland Cement (OPC) in the conventional concrete mix get certainly through the heating of limestone, and the CO₂ emitted as part of the chemical process of making lime [1]. These points are determined from the performance assessment methods and rehabilitation techniques disciplines, leading to insufficient use of resources and unsustainable applications of pavement performance.

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There is a scientific focus on sustainable structure and the use of alternative materials in the production of supplemental cementitious materials (SCMs). This study tends to avoid this issue by determining the performance of continuously reinforced concrete pavement (CRCP) using supplemental materials and balancing the sustainability goal and structural performance application. Jordanian natural zeolite (JNZ) as a volcanic mineral pozzolanic properties material has an attracted importance for its effort to improve the characteristics, durability, and concrete strengths through its hydration reaction with water and calcium hydroxide. It applies as a suitable replacement material for cement due to its nature with sustainable construction aims [2,3]. Performing JNZ in CRCP implements new eco-friendly pavement construction by reducing carbon emissions and preserving resources in a sustainable infrastructure development. This effect of JNZ on CRCP performance haven't researched extensively yet.

A by-product silica fume (SF) with small particle size and high reactivity from silicon and ferrosilicon, is another supplementary cementitious material studied for its potential to improve concrete performance and sustainability, thereby enhancing concrete's mechanical properties including strength and durability. The individual use of natural zeolite and SF proof the potential to increase concrete mechanical properties and sustainability performance [4]. Various studies and applications are being implemented to construct sustainable concrete with reliable durable behavior by several materials' replacement technique. However, there is a leak in comprehensive effects of porcelain waste on mechanical characteristics and sustainability of concrete.

There is also no comprehensive study on integrated sustainability evaluation that considers environmental effects and resource conservation throughout the concrete's lifecycle. Spent coffee grounds (SCG), a byproduct of the coffee brewing process, represent a substantial source of organic waste that has significantly contributed to landfill accumulation due to global consumption for many years, the resultant production of methane gas, and increasing climate change. So, transforming SCG into valuable resources can produce innovations in the concrete world, mitigate landfill accumulation, reduce methane emissions, and contribute to a more sustainable future.

Several experiments were performed to identify a durable and sustainable rigid pavement structure that can be utilized as infrastructure. Plati studied different sustainable pavements, including design, materials, and preservation practices, and several viable alternatives displayed mechanical properties and the sustainability of paving materials. This study also showed, whatever method improvement on sustainable pavement performance would work [5]. Tran et al (2019) studied the effects of natural zeolite in a concrete pavement mix, and the basic structural properties of manufactured natural zeolite in concrete must be used as a pozzolan and natural zeolite structural properties. Finally, they were able to comprehend the impacts of zeolite on concrete permeability, durability, and workability. The outcome indicated that mechanical characteristics and structure durability improved with optimal mixing performance [2]. Moreover, Waghmare and Ghadvir researched the features of zeolite material and its role in rigid pavement on improving concrete's resistance to CO₂ during production. They demonstrated that the addition of zeolite into concrete-tested rigid pavement reduced the impacts of carbon dioxide and decreased environmental variability, under mainly heavy traffic load conditions [3].

Yudi et al. researched the physical, chemical, and mechanical properties of SF, in addition to its microstructure impacts on concrete, which were all dependent on flexural, tensile, and compressive strength tests and the amount of concentrate in the mixture. It was noticed that high-performance, high-strength concrete was developed using silica fume, a by-product of silicon alloy production [6,7]. Ata and Ibraheem examined the combined impact of JNZ and SF as supplementary cementitious materials (SCMs) on concrete mixtures. Several concrete mixes were developed, including a standard mix, one with natural zeolite, and another with both zeolite and silica fume, each with different amounts of cement replaced. They found that replacing 10% of the cement with zeolite increased durability compared to standard mixture. However, using both SF and zeolite together reduced the concrete's strength [8].

Research investigates the impacts of porcelain waste on compressive strength component of concrete and found that the partial substitution of cement with porcelain increased compressive strength resulting in more activity dependent on longer-term and reliable performance [9, 10]. Ata

and Ibraheem studied the effects of replacing waste, from porcelain tiles with CA on mechanical characteristics mainly compressive, tensile splitting, and flexural strengths, and permeability (water absorption). The findings showed that 25% porcelain replacement results in high permeability, workability and mechanical properties, and an environmental impact assessment that is highly positive [11]. Roychand et al.) studied the appropriateness of burning spent coffee grounds waste at different temperatures to enhance concrete mechanical properties. The results showed that concrete compressive strength raised by 29.3% with coffee biochar at 350°C [12]. The study tends to evaluate sustainable developed concrete behavior by combining multiple supplementary materials and evaluating them through both mechanical and environmental impact (EIA/LCA) perspectives.

2. Materials and Methodology

This part shows the methodology and materials applied in this study to assess sustainability aspects of rigid pavement systems and to develop suitable decision-making strategies for their rehabilitation.

- Cement: Portland cement CEM I, which has certain compositional restrictions and high durability, is applied with both physical and chemical properties based on the ASTM C150 and Jordanian standards No. 30–2024 for concrete works.
- Coarse Aggregate: The study used coarse aggregates based on standards of Jordan and ASTM. A typical amount of CA was used, and the results of experimental testing are provided in Table 1.

Table 1. Coarse aggregate tests in study

Test	Result	Specifications
Absorption %	2.4	ASTM C127
Abrasion %	27	ASTM C131
B.S.G (Dry)	2.552	ASTM C127
B.S.G (SSD)	2.631	ASTM C127
Sulfate Content %	0.042	ASTM C33
Bulk Density kg/m ³	1578	ASTM C29
Chloride Content %	0.019	ASTM C33
Soundness Loss (NaSO ₄) %	5.0	ASTM C88

- Fine Aggregate: A particle sizes less than 5 mm as a fine-grained is known as sand. It was used in concrete mixes according to ASTM C128 standards and specifications for aggregate grading. This study involved multiple tests resulting in 2.40 as a fineness modulus, 2.60 specific gravity, 1% an absorption rate, and a sand equivalent percentage of 76%.
- Jordanian Natural Zeolite (JNZ): Zeolite is a volcanic inorganic microporous mineral with a highly porous structure. There is a significant lack of JNZ use in cement and concrete manufacturing for infrastructure applications such as pavement. This study examines the characteristics of JNZ for the production of a sustainable, high-performance CRCP structure, including varying percentages of zeolite. Figure 1 shows the collection of JNZ compositions from a real site in northeastern Jordan. The Quality Directorate laboratory of the Ministry of Energy and Mineral Resources in Jordan verified JNZ characteristics via XRF analysis. Table 2 describes JNZ elements that influence the concrete mixing process, workability, and overall performance.

Table 2. XRF analysis of JNZ used in the study

SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	CL	LOI
39.7%	10.8%	12.89%	10.97%	9.23%	1.63%	1.39%	0.16%	0.035%	9%



Fig. 1. Field site source of JNZ used in the study

- Silica Fume (SF): Silica fume is high reactive pozzolan utilized in this study as a supplemental material, including a percentage of the cement weight in concrete, based on ASTM C1240 standards. Table 3 illustrates the physical and chemical specifications.

Table 3. Chemical and physical requirements of SF

Chemical Specifications	
SiO ₂ , min. %	85
Moisture content, max. %	3
Loss on ignition (LOI), max. %	6
Physical Specifications	
Percent retained on 45μm, max. %	10
Percent retained on 45μm, max. % variation from average, % points.	5
Accelerated pozzolanic activity index, With OPC at 7 days, min. % of control.	105
Specific surface, min. (m ² /g)	15

- Porcelain Tile (PT): Porcelain waste material is found particularly in Middle Eastern countries. Several Arab nations such as Jordan imports significant percentages of porcelain. This research used high-quality waste from Indian glazed porcelain tiles, which have a water absorption rate of no more than 0.05% and 2.1 g/cm³ density. Maximum size of PT was 19 mm illustrated in Figure 2, whereas chemical ingredients were analyzed using XRF presented in Table 4.



Fig. 2. Porcelain applied in concrete mixture

- Spent Coffee Grounds (SCG): Spent coffee grounds (SCG), a byproduct of coffee brewing represents a substantial source of organic waste. In this study, XRF analysis was done in Nano-Lab at the Institute of Nanotechnology (JUST-Jordan) to get information on the SCG's mineral composition and chemical characteristics.

Table 4. Chemical elements of porcelain tile using XRF

Element	Abbreviations	Mass %
Alumina	(Al ₂ O ₃)	8.65
Silica	(SiO ₂)	38.91
Magnesia	(MgO)	0.530
Lime	(CaO)	6.711
Sodium Oxide	(Na ₂ O)	0.60
Potassium Oxide	(K ₂ O)	0.850
Calcium Carbonate	(CaCO ₃)	11.98

3. Production of Concrete Mixtures for CRCP Design

This section of work describes concrete mixtures and sample preparation procedures. Four different mixtures were designed: a conventional mixture with 100% Portland cement. The other new concrete mixes with SCMs as replacement components and were created using a 400 kg/m³ concrete mix, which contained a specific proportion of weighted CA, FA and cement, combined in a dry condition with a designated water percentage, as shown in Figure 3. Table 5 shows concrete mix design for this study. Sustainably developed concrete mixes were formed in the preparation of 150 CRCP slab specimens with a uniform concrete design including SCMs. A systematic design of slab thickness, dimensions, and steel reinforcement was performed to evaluate structural integrity and resistance to failure of CRCP.

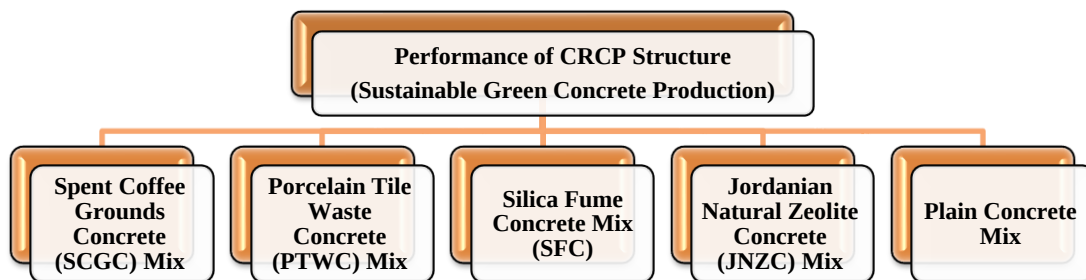


Fig. 3. Schematic flowchart of concrete production for CRCP in the study

Table 5. Conventional concrete mix design

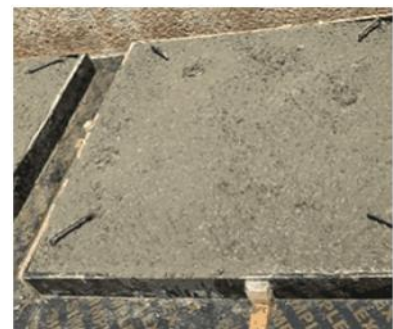
Conventional Mixture	Content of Cement (kg/m ³)	CA (kg/m ³)	FA (kg/m ³)	w/c
	400	946	946	0.45



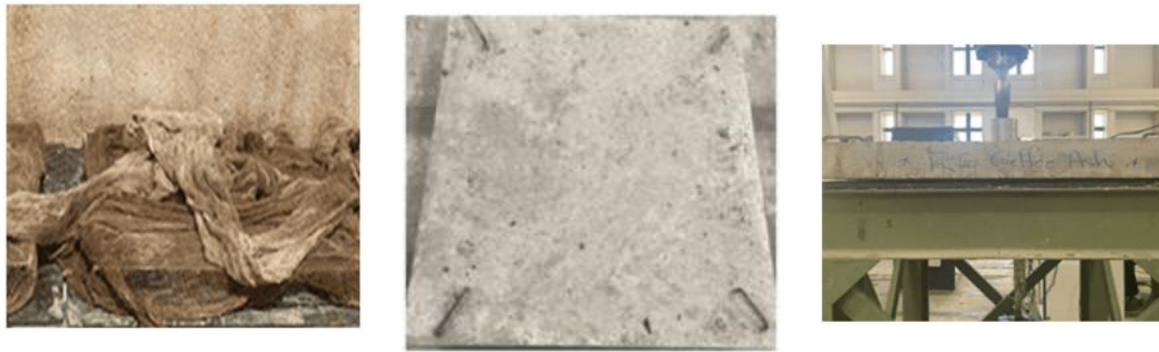
Casting Preparation



Normal RC Slabs



SCG - RC Slabs



Curing

Specimen after Curing and Setup

Fig. 4. Sustainable continuously reinforced concrete pavement slabs

A portable plywood structure of 1×1×0.1 m was constructed based on a laboratory testing configuration featuring continuous longitudinal bars with a diameter of 10 mm and transverse bars positioned every 10 cm across the width. Then, standard and specially designed reinforced concrete slabs were cast with appropriate vibration and cured using water spraying and wet burlap to enhance hydration and strength development, as illustrated in Figure 4.

4. Concrete Testing Techniques of Sustainable CRCP

The key components of any specimens have been examined for concrete mixtures evaluation focusing mainly on the assessment of strengths after cast and curing processes at 7 and 28 days. This study conducted modified concrete tests for 50 samples for each test to evaluate the sustainable CRCP performance, as depicted in a schematic flowchart in Figure 5.

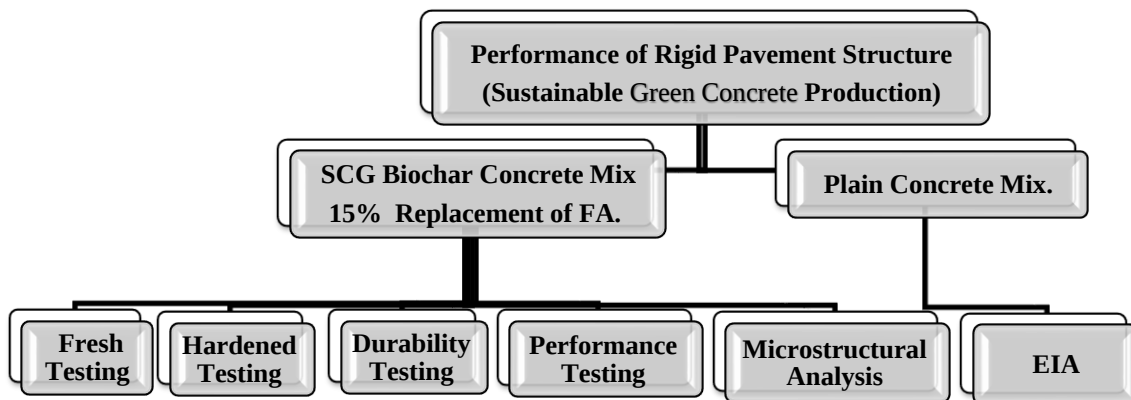


Fig. 5. Schematic flowchart of sustainable concrete key tests

4.1 Permeability Performance and Density

Compacted concrete weight used to determine concrete density by dividing the container's volume by the measured mass. Mixes permeability was measured using water absorption to measure durability factors [13]. The determination of mass increase from the initial mass forms an element of the absorption. It was measured over a 28-day of samples curing by averaging the absorption of specimens depend on ASTM C642. Specimens were dried at 100°C, weighed, immersed in water bath for 24 hours, then reweighed to determine the water absorption ratio.

4.2 Mechanical Concrete Strength Tests

Concrete specimens of standard and modified mixtures were cast into cube molds measuring 150×150×150 mm for usage in compressive strength tests [14]. A universal testing machine performed the test, applying a compression force 0.6 MPa/s. On the other hand, concrete specimens casting in standard cylindrical molds in 150 mm diameter and a length of 300 mm and

subsequently assessed for tensile strength based on ASTM C496. The third-point loading test evaluates the flexural strength of concrete by bending prisms of 100×100×500 mm until failure with ASTM C78 standards, as illustrated in Figure 6.



Fig. 6. Mechanical strengths tests of normal and modified-concrete mixes

4.3 JNZ, PTW, and SCG Development for Sustainable CRCP Future

JNZ, PTW, and SCG integration in Continuously Reinforced Concrete Pavements design and construction enhances a sustainable way to enhance the produced concrete mix strength and durability. A 450-kN cell load with a 10-m diameter was applied directly over pavement developed slab to distribute a uniform load across it. 2 mm/min displacement rate was applied to reduce the dynamic impacts due to unpredicted loadings with concrete modulus improvement. The strain was monitored until the slabs fractured, then the maximum failure load (P , kN) with the slab's cross-sectional area (A , mm²) were used to calculate CRCP concrete slab compressive strength (f_c) as shown in Figure 7.



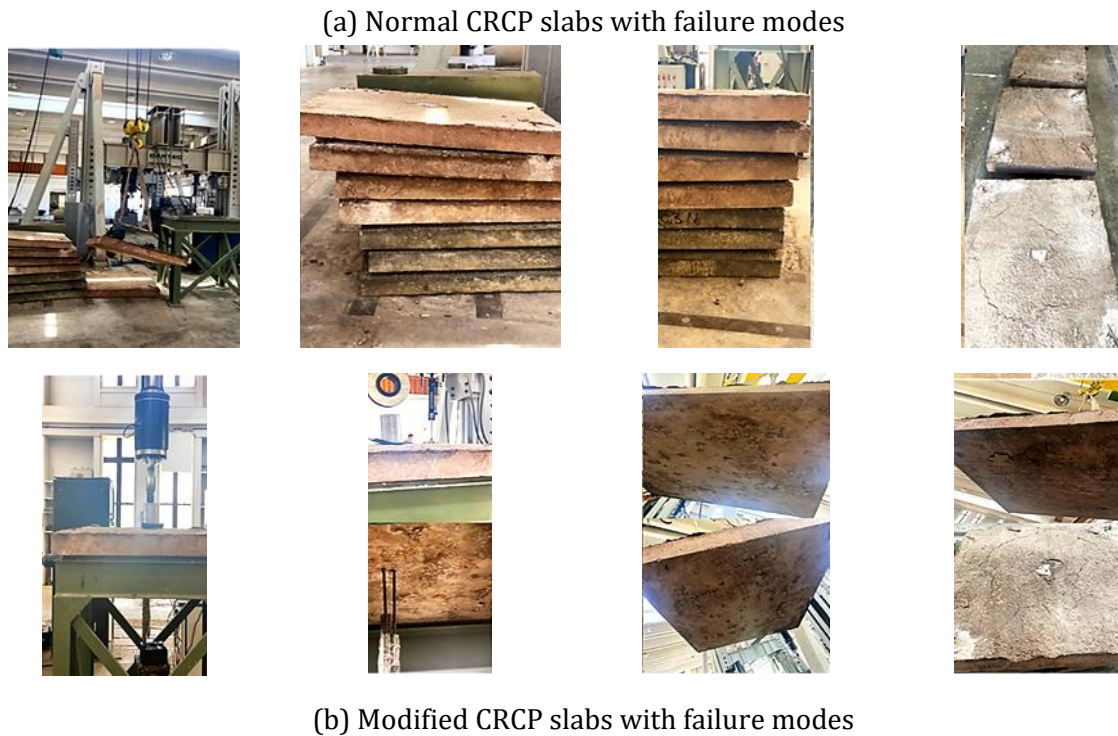


Fig. 7. Integrating SCMs into developed sustainable CRCP structure

4.4 Environmental Impact Assessment Study for the Sustainable developed CRCP

This innovative technique is a significant milestone in this research never implemented before. It determines the implications of producing a long-lasting CRCP structure, focusing on the integration between the developed sustainable CRCP and their environmental relevance based to ecological methods as environment impact assessment (EIA). The integration of Life Cycle Assessment (LCA) and Artificial Intelligence (AI) generates a comprehensive framework for evaluating the environmental impacts of a sustainable CRCP with effective modeling and predictive monitor of the pavement's service life. The EIA assess the environmental effects of this new structure system by applying RECIPE 2016, Environmental Design of Industrial Products (EDIP 2003), and Cumulative Energy Demand (CED) ways for life-cycle assessment and evaluation using OpenLCA software.

- LCA Functional Unit (FU) Phase: This step validates the reference flow to evaluate the product's elements. It must be employed to determine or adjust any data used in the LCA. The FU provides a benchmark for standardizing process inputs and outputs.
- LCA System Boundaries Phase: The system boundary is an important in identifying which processes will be included or excluded. Therefore, it should be compatible with the aims of this study. The selection of the system border affects the transfer of information, energy, or materials between systems, resulting in varied outcomes based on the boundaries established as shown in Figure 8.

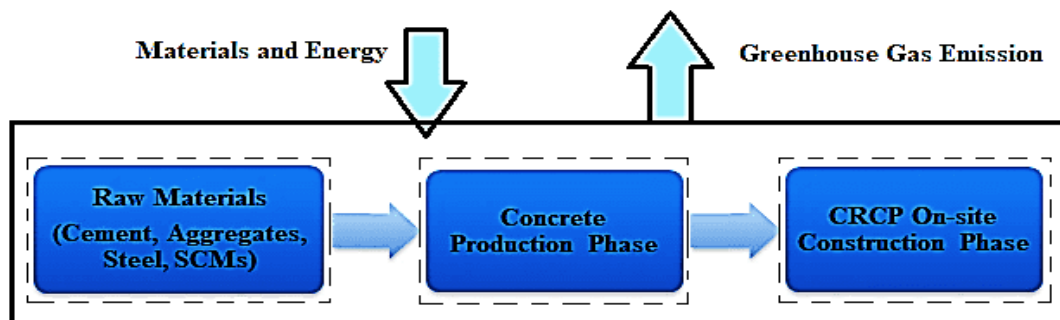


Fig. 8. System boundary of CRCP assessment

5. Results and Discussions

5.1 Workability, Wet Density and Concrete Permeability

The impacts of SCMs on concrete performance and characteristics was discussed by varying the percentages of ingredients amount in the developed concrete mixtures and compared into the standard mix. The partial replacement impacted modified concrete mixes fresh properties after 28 days, as seen in Table 6.

Table 6. Sustainable concrete wet density and permeability properties

Mixture Type	Slump (mm)	Water Absorption (%)	Wet density (kg/m ³)
Normal	25	4	2390
Zeo-Concrete	35	3.3	2350
PTW-Concrete	27	3	2316
SCG-Concrete	40	2.8	2250
SF-Zeo-Concrete	22	1.12	2300

The results shown that the zeo-concrete mixture has the highest slump with 35 mm, improving the workability of the concrete, while the SF-Zeo-concrete mix has the lowest value with 22 mm, indicating less workability with a low water absorption rate of 1.12% that preventing moisture over the normal concrete mix with absorption rate of 4%. Moreover, the study reveals that SCG-concrete has the lowest wet density at 2250 kg/m³ with enhanced strength property. The addition of 15% SCG increases workability, durability, and decreases permeability of the new developed mix. PTW-concrete mix with 2316 kg/m³ wet density optimizing recycled materials and improving the structural performance. So, mixes with JNZ and silica fume improve concrete workability and durability, while PTW mix gets an efficient recycling without significant impact on the performance.

5.2 Compressive Strengths of the Sustainable Developed Mixes

The improvement of concrete mechanical properties raised when supplementary materials were used and their ability to impact on concrete behavior. This part discovers the combination effect of this materials into concrete, focusing on durability and concrete compressive strengths. Newly developed concrete can enhance various mechanical properties, resulting in better durability for high-performance CRCP applications. Figure 9 illustrates the impact of integrating supplementary materials on the compressive strength, resulting in a developed blend after curing for 7 and 28 days and Table 7 shows a long-term durability of the new concrete mixes compressive strengths.

Table 7. Strength development of sustainable concrete mixtures with curing (MPa).

Period (Days) Mix							
	3	7	14	28	36	56	90
Normal	25.1	29.01	31.3	40.3	48.1	54.6	55.3
JNZ	29.5	32.2	36.6	52.1	64.4	69.2	72.7
JNZ+SF	25.4	27.7	31.8	35	43.8	47.4	52.1
PTW	30.2	34.43	45	49.4	55.6	64.7	70.2
SCG	26.4	27.53	34.7	47.6	50.1	56.3	65.8

The combined addition of JNZ and SF to the concrete mixture shown in a significant reduction in strength compared to the natural zeolite mix. The produced new JNZ-SF-enhanced concrete mix with the increased silica fume amount harmed concrete behavior when used at 5% and 10% JNZ, especially when sulfate-resistant cement was used. Figure 10 shows the microstructural analysis using SEM of JNZ-SF strength reduction.

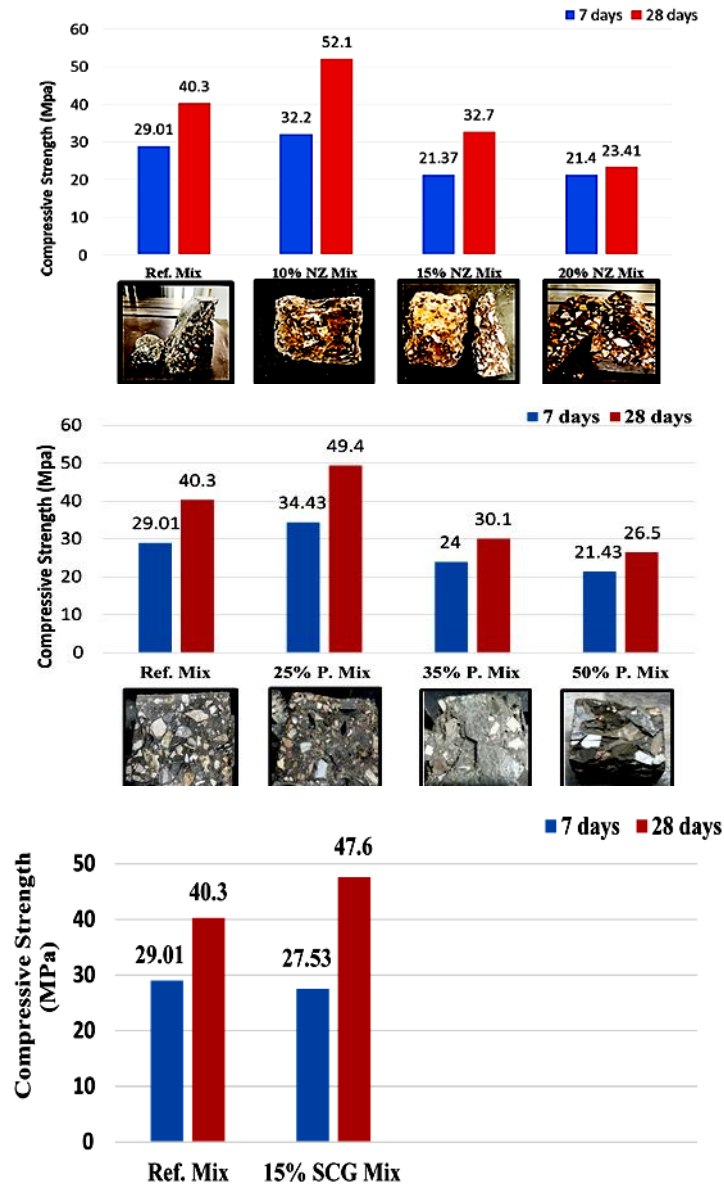
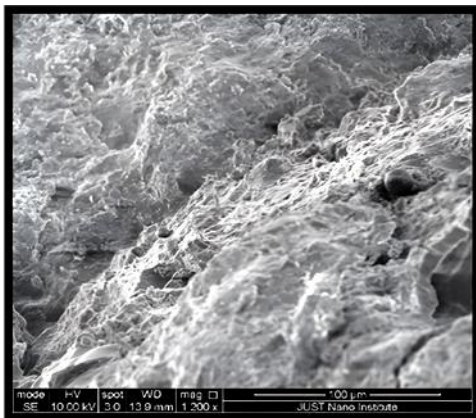
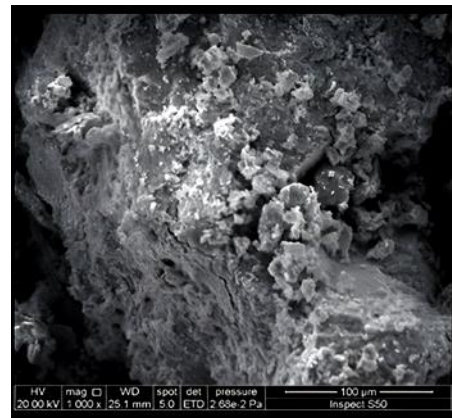


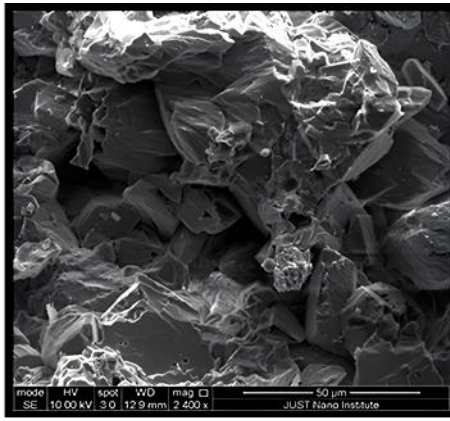
Fig. 9. Integrating compressive strength of reference and modified concrete mixes



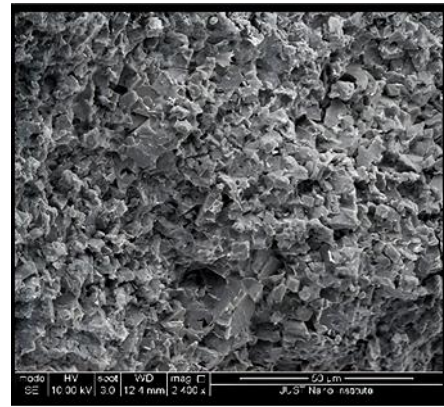
(a)



(b)



(c)



(d)

Fig. 10. Concrete Nano-SEM images for (a-c) normal mix (b-d) modified mix

5.3 Evaluating Sustainable CRCP Performance Results

Continuously reinforced concrete pavement is implemented to enhance durability and behavior over its life. The structural evaluation of CRCP, specifically determining the effect of integrating SCG, PTW, JNZ and SF into concrete mix yielded the following results. The outcomes of CRCP structure samples using normal and new modified-enhanced concrete are shown in Tables 8 and Table 9.

Table 8. Normal CRCP analysis

Load Resistance (kN)	Avg. Displacement (mm)	Avg. Compressive Stress (MPa)	Avg. Strain (mm/mm)	Avg. E (MPa)	Crack Width (mm)
Avg. Point Load, 150	3	150	0.003	32000	0.2
Avg. Dynamic Load, 225	4	225	0.001	32000	0.3

Table 9. Modified-enhanced concrete CRCP analysis.

Load Resistance (kN)	Avg. Displacement (mm)	Avg. Compressive Stress (MPa)	Avg. Strain (mm/mm)	Avg. E (MPa)	Crack Width (mm)
SCG					
Avg. point Load, 500	0.5	500	0.001	30000	0.15
Avg. Dynamic Load, 750	0.1	750	0.0015	30000	0.2
PTW					
Avg. Point Load, 700	1.5	700	0.00002	33000	0.05
Avg. Dynamic Load, 1050	2	1050	0.000035	33000	0.1
JNZ					
Avg. Point Load (kN), 1000	0.02	1000	0.0001	35000	0.2
Avg. Dynamic Load (kN), 1500	0.03	1500	0.00021	35000	0.3

5.4 EIA Results: SCMs in Concrete

AI-enhanced LCA techniques automate data acquisition from CRCP mix design sources, ensuring accurate input. Machine learning models use the random forest method to assess environmental impacts, improving predictive accuracy and data management. Furthermore, linear regression is applied to decrease ecological effects and forecast continuous results by modifying resource consumption and energy efficiency throughout life-cycle methods. The outputs of the LCA impact analysis summarize sustainable CRCP structures that integrate the SCMs used in the research across many significant environmental effect categories, as presented in Table 10. It presents an effective eco-design strategy by thoroughly evaluating the environmental performance of the new sustainable CRCP structures from cradle-to-grave.

Table 10. Comparative life-cycle study of environmental effects of the sustainable concrete mixes

Impact Categories	Normal Mix	25% PTW Concrete Mix	SCG Concrete Mix	Blended concrete- JNZ Mix
RECIPE				
1. Fossil resource scarcity (kg oil eq/m ³)	1462	1323	1300	1326
2. Global warming (kg CO ₂ eq/m ³)	750	500	610	520
3. Human carcinogenic toxicity (kg 1.4-DCB/m ³)	1.03	0.7	0.003	0.05
4. Mineral resource scarcity (kg Cu eq/m ³)	15	10	0.06	0.08
5. Ozone formation, Human health (kg NO _x eq/m ³)	1.05	0.75	0.4	0.05
6. Ozone formation, terrestrial ecosystems (kg Nox eq/m ³)	1.35	0.95	0.4	0.5
7. Stratospheric ozone depletion (kg CFC-11 eq/m ³)	1.67	0.02	0.00004	0.001
8. Terrestrial acidification (kg SO ₂ eq/m ³)	2.5	2.1	0.1	0.05
9. Terrestrial ecotoxicity (kg 1.4-DCB)	0.739	0.591	0.01	0.03
CED				
1. Non-renewable, fossil (MJ/m ³)	1560	1268	300	400
2. Non-renewable, minerals (MJ/m ³)	329	119	50	100
3. Renewable, potential (MJ/m ³)	12	6	6	5
4. Renewable, solar (MJ/m ³)	20	0.864	0.865	30
EDIP				
1. Ecotoxicity soil chronic (m ³)	0.413	0.176	0.01	0.04

Adding SCMs to concrete mixtures is expected to greatly benefit the environment, particularly by reducing CO₂ emissions and saving resources, as demonstrated by comparing three selected assessment methods. This assessment aimed to identify, forecast, and mitigate adverse environmental impacts while advancing sustainable paving practices. Figure 11 shows RECIPE impact category results for the conventional and the designed sustainable concrete mixtures for CRCP design and construction, while the CED impact analysis results are displayed in Figure 12.

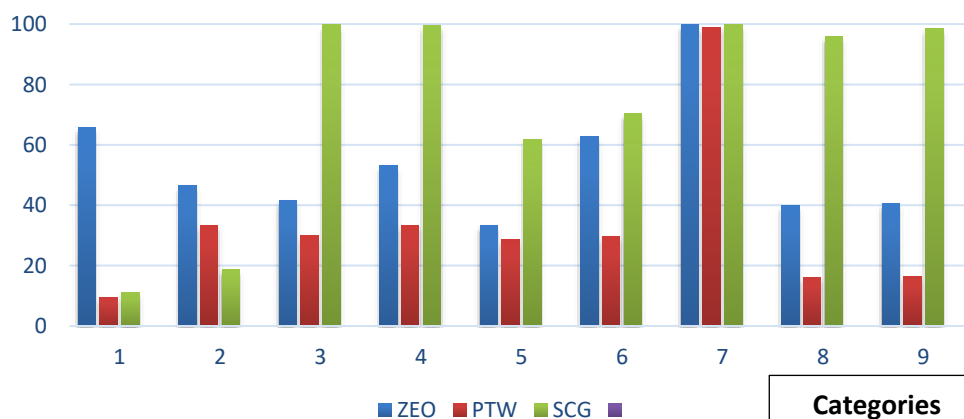


Fig. 11. RECIPE impact categories results of normal and design concrete mixes



Fig. 12. CED results for concrete mixtures in the study

6. Conclusions

Based on the studying of different supplementary materials effects on concrete behavior and characteristics, the following results are summarized:

- The integration of materials in concrete mixtures improves strength properties and durability behavior and promoting sustainability goals throughout their service life and minimizing environmental concerns to net-zero carbon footprint and each of them has a unique advantage based on the application.
- 10% JNZ-concrete mixture enhances concrete properties after 28 days, mainly its workability and setting time. It has a compressive strength of 52.1 MPa compared to the normal mix and 46.7% improvement in CO₂ reduction.
- A concrete mix containing 25% porcelain tile waste of CA enhances concrete strength by 49.4 MPa particularly its workability, water absorption capacity for high-performance uses with 33.3% improvement in carbon footprint impacts.
- The sustainable SCG biochar was resulted at 350°C and blended into mix design as a replaced percentage of 15% FA as a newly designed concrete mix, demonstrating that concrete with 15% SCG had great workability with 47.6 MPa compressive strength and 20% reduction in CO₂ effects on the environment.
- The combined mixture of JNZ and SF exhibits less strength compared to previous modified mixes containing only JNZ and others. The increase in silica fume amount harms concrete behavior and properties.

This research forms new infrastructure, enhances global sustainability concerns, and informs stakeholders and governments about developing a sustainable-durable pavement structures by identifying it as a premier framework for an innovative pavement applications and practices.

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