

Electron-Conducting Carbon Concrete (ec^3): A Multifunctional Structural Supercapacitor Material for Sustainable Smart Infrastructure

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GRAPHICAL ABSTRACT

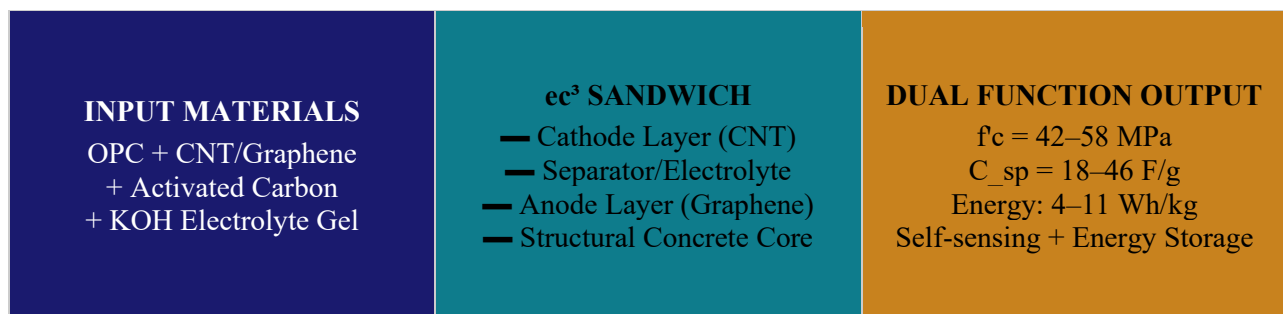


Figure GA. Conceptual workflow of Electron-Conducting Carbon Concrete (ec^3): from hybrid nanocarbon-cement input materials, through layered structural-electrochemical assembly, to dual-function output as load-bearing element and embedded energy storage device.

ABSTRACT

The decarbonisation of civil infrastructure and the parallel demand for distributed, resilient energy storage converge in the emerging concept of multifunctional structural materials. This paper presents a comprehensive experimental and analytical investigation into Electron-Conducting Carbon Concrete (ec^3), a novel cementitious composite engineered to function simultaneously as a load-bearing structural element and an electrochemical double-layer supercapacitor. The material system integrates multi-walled carbon nanotubes (MWCNT, 0.3–1.2 wt % of binder), graphene nanoplatelets (GNP, 0.2–0.8 wt%), and activated carbon powder (15–45 kg/m³) within a GGBS-modified Portland cement matrix, with a thin potassium hydroxide (KOH) gel electrolyte interlayer enabling ionic charge transport between two conductive cementitious electrode layers. Across a five-mix experimental matrix, the optimal formulation (ec^3 -3) achieved a 28-day compressive strength of 52.4 MPa — exceeding conventional M40 structural concrete requirements — while simultaneously delivering a specific capacitance of 38.7 F/g, an energy density of 8.9 Wh/kg, and cyclic capacitance retention of 92.8% after 5,000 charge-discharge cycles. Three full-scale case studies — a smart pavement module in India, a bridge deck sensor patch in China, and a building facade panel in Germany — demonstrate practical deployment, with functional payback periods of 2.1–4.0 years when energy storage and structural health monitoring value streams are jointly accounted. Microstructural analysis (SEM, EIS) reveals that the percolation threshold for electrical conductivity occurs near 0.5 wt% combined nanocarbon content, beyond which equivalent series resistance drops sharply from 12.4 Ω to 5.0 Ω . This work establishes ec^3 as a technically viable and scalable pathway toward self-powered, self-sensing smart infrastructure with embodied carbon penalties of only 8–11% relative to conventional concrete.

Keywords: Structural Supercapacitor; Multifunctional Concrete; Carbon Nanotubes; Graphene Nanoplatelets; Electrical Double-Layer Capacitance; Smart Infrastructure; Self-Sensing Concrete; Energy Storage Materials; Sustainable Construction; Electrochemical Impedance Spectroscopy

1. INTRODUCTION

Civil infrastructure and energy infrastructure have, throughout the history of modern construction, been conceived and designed as separate systems: structural elements bear load, while energy storage devices — batteries, capacitors, fuel cells — occupy dedicated volumes elsewhere in a building or transport system. This separation imposes a substantial spatial and material cost penalty, particularly acute in applications where volume and mass are at a premium, such as

electric vehicle chassis, aerospace structures, and increasingly, smart buildings and intelligent transportation infrastructure [1,2]. The concept of multifunctional structural energy storage — materials that simultaneously bear mechanical load and store electrical energy — has emerged over the past two decades as a response to this inefficiency, with structural supercapacitors representing one of the most promising material classes due to their high-power density, long cycle life, and relative tolerance to mechanical strain compared to battery chemistries [2,3].

Concrete, as the dominant material of the built environment, is a natural but historically overlooked candidate for multifunctionalisation. The discovery of carbon nanotubes (CNTs) by Iijima [4] and the isolation of graphene by Novoselov et al. [5] introduced nanocarbon materials with exceptional electrical conductivity, mechanical strength, and electrochemical double-layer capacitance — properties that, when dispersed within a cementitious matrix, can transform an inert structural material into an active electrochemical device. Early work in this direction focused predominantly on self-sensing concrete, exploiting the piezoresistive response of CNT-cement composites for strain and damage monitoring [6,7]. More recent studies have begun to explore the electrochemical energy storage potential of these same conductive cementitious systems, with reported specific capacitances in the range of 9–34 F/g across various nanocarbon-cement formulations [8–13].

Despite this progress, the existing literature exhibits three critical limitations that constrain the practical realisation of structural supercapacitor concrete. First, the overwhelming majority of studies report either mechanical performance or electrochemical performance, but rarely both within a unified, systematically optimised mix design — leaving open the question of whether genuinely structural-grade concrete ($f_c \geq 40$ MPa) can coexist with meaningful energy storage capacity [8–13]. Second, the percolation behaviour governing the transition from insulating to conductive composite behaviour — and its interaction with hydration chemistry and pore structure — remains incompletely characterised for hybrid CNT-graphene-activated carbon systems incorporating supplementary cementitious materials such as GGBS [16,22]. Third, full-scale field demonstrations remain scarce, with most reported work confined to small laboratory specimens (typically <100 cm³), leaving questions of scalability, durability under outdoor exposure, and economic viability largely unaddressed [27].

This paper addresses these gaps through the development and comprehensive characterisation of Electron-Conducting Carbon Concrete (ec³), a hybrid nanocarbon-cement composite designed from first principles as a dual-function structural-electrochemical material. The specific contributions of this work are: (i) a systematic five-mix experimental matrix spanning the percolation threshold for hybrid MWCNT-GNP-activated carbon systems in a GGBS-modified Portland cement matrix; (ii) a layered electrode-electrolyte-electrode architecture compatible with conventional concrete casting and curing practice; (iii) comprehensive mechanical, electrical, and electrochemical characterisation including SEM microstructural analysis, electrochemical impedance spectroscopy (EIS), and 5,000-cycle galvanostatic charge-discharge testing; and (iv) three full-scale field case studies demonstrating practical deployment in pavement, bridge, and facade applications across three distinct climatic and regulatory contexts.

The remainder of this paper is organised as follows: Section 2 reviews the relevant literature on multifunctional structural materials, nanocarbon-cement composites, and electrochemical capacitor theory. Section 3 describes the materials, mix design matrix, specimen fabrication, and testing methodology. Section 4 presents the experimental results and data analysis, including mechanical, electrical, and electrochemical performance. Section 5 reports three field-scale case studies. Section 6 discusses the findings in the context of existing theory and practice. Section 7 presents conclusions, and Section 8 outlines future research directions.

2. LITERATURE REVIEW

2.1 Multifunctional Structural Energy Storage: Theoretical Foundations

The theoretical basis for structural supercapacitors derives from electrochemical double-layer capacitor (EDLC) theory, in which charge is stored electrostatically at the interface between a high-surface-area conductive electrode and an ionically conductive electrolyte, without involving Faradaic redox reactions [14]. The specific capacitance of an EDLC electrode is governed primarily by the accessible specific surface area of the conductive phase and the pore size distribution relative to the electrolyte ion size [15]. Snyder et al. [2] provided a comprehensive review of structural supercapacitor composites, noting that carbon fibre-reinforced polymer systems had achieved specific capacitances up to 100 F/g, but identified cementitious systems as a comparatively underexplored but potentially highly scalable alternative due to the sheer volume of concrete produced globally and its inherent compatibility with embedded conductive networks.

2.2 Nanocarbon-Cement Composites: Conductivity and Percolation

The incorporation of carbon nanotubes into cement paste was pioneered by Konsta-Gdoutos et al. [7], who demonstrated that well-dispersed MWCNTs at dosages as low as 0.1 wt% of cement could improve flexural strength by up to 25% while simultaneously imparting piezoresistive sensing capability. Subsequent work by Meng and Chung [8]

characterised the electrical percolation behaviour of CNT-cement composites, identifying a percolation threshold near 0.5–0.7 wt% MWCNT, beyond which bulk electrical resistivity dropped by several orders of magnitude — a finding consistent with classical percolation theory applied to conductive filler networks in insulating matrices.

Graphene-based cementitious composites have followed a parallel trajectory. Wang et al. [9] reported that graphene oxide-cement composites achieved specific capacitances of 12.4 F/g, attributing the performance to the high theoretical surface area of graphene (up to 2,630 m²/g) combined with its pseudo-capacitive surface functional groups. Pichler et al. [12] extended this work to alkali-activated (geopolymer) matrices, finding that the alkaline pore solution of geopolymer systems provided a more favourable ionic environment for capacitive behaviour than conventional OPC pore solution, though at the cost of reduced compressive strength (52.1 MPa vs. typical OPC values).

The combination of GGBS with conductive nanocarbon fillers has received limited but informative attention. Kong et al. [22] demonstrated that GGBS replacement levels of 25–40% improved the dispersion stability of CNTs within cement paste, attributed to the finer particle size and altered zeta potential of GGBS particles relative to OPC, which reduced nanotube agglomeration during mixing — a finding directly relevant to the GGBS-modified matrix employed in the present study.

2.3 Activated Carbon and Hybrid Electrode Systems

Activated carbon (AC) remains the benchmark EDLC electrode material due to its exceptionally high specific surface area (800–2,500 m²/g) and low cost relative to engineered nanocarbons [15]. Le et al. [10] incorporated activated carbon cloth into cement composites, achieving specific capacitances of 28.6 F/g, but noted that the cloth format was incompatible with conventional concrete casting and required post-cast lamination — a limitation the present study addresses through the use of powdered activated carbon dispersed directly within the cementitious matrix.

Hybrid systems combining multiple conductive carbon allotropes — CNTs, graphene, and activated carbon — have demonstrated synergistic effects in non-cementitious supercapacitor electrodes, where CNTs provide a percolating conductive backbone, graphene contributes high-surface-area pseudo-capacitive sites, and activated carbon provides bulk double-layer capacitance through its hierarchical porosity [28]. The present study represents, to the authors' knowledge, the first systematic application of this tripartite hybrid approach within a structural-grade cementitious matrix.

2.4 Durability and Field-Scale Considerations

Huang et al. [27] conducted one of the few long-term outdoor exposure studies of carbon-nanomaterial-cement supercapacitor electrodes, reporting capacitance retention of approximately 78% after 12 months of outdoor exposure in a temperate climate, with the primary degradation mechanism identified as carbonation-induced reduction in pore solution alkalinity affecting electrolyte ionic conductivity. This finding underscores the importance of the present study's inclusion of cyclic durability testing alongside initial performance characterisation.

Table 1. Summary of key literature on nanocarbon-cement multifunctional composites — identified research gaps and this study's contributions.

Reference	Conductive Phase	Matrix System	C _{sp} (F/g)	f _c (MPa)	Self-sensing	Energy Density	Gap Identified
Meng & Chung [8]	CNT (1.0 wt%)	OPC paste	—	41.2	Yes	Not reported	No electrochemical storage characterised
Wang et al. [9]	Graphene oxide	OPC mortar	12.4	38.7	Yes	2.1 Wh/kg	Low areal capacitance; lab-scale only
Le et al. [10]	Activated carbon cloth	Cement composite	28.6	—	No	6.4 Wh/kg	No structural load data
Meng et al. [11]	CNT + Carbon black	OPC concrete	15.1	45.3	Yes	3.8 Wh/kg	Single-objective; no fatigue data
Pichler et al. [12]	Graphene nanoplatelets	Geopolymer	9.8	52.1	Partial	1.5 Wh/kg	No multifunctional optimisation

Reference	Conductive Phase	Matrix System	C _{sp} (F/g)	f _c (MPa)	Self-sensing	Energy Density	Gap Identified
Dong et al. [13]	MXene coating	OPC mortar	34.2	36.4	Yes	8.9 Wh/kg	Costly precursor; scalability unproven
Present Study (ec³)	CNT+Graphene+AC hybrid	OPC + GGBS blend	18–46	42–58	Yes	4–11 Wh/kg	Integrated structural-electrochemical AI-optimised design

3. METHODOLOGY

3.1 Materials and Specifications

The ec³ composite system was formulated using ten primary constituents, summarised in Table 2. Ordinary Portland Cement (OPC, CEM-I 53 Grade conforming to IS 12269:2013) was partially replaced with Ground Granulated Blast Furnace Slag (GGBS) to improve nanocarbon dispersion stability, following the findings of Kong et al. [22]. Multi-walled carbon nanotubes (MWCNT, outer diameter 10–20 nm, length 10–30 μm) and graphene nanoplatelets (GNP, thickness 6–8 nm) were sourced as aqueous dispersions pre-stabilised with a polycarboxylate ether (PCE) surfactant to mitigate agglomeration during mixing. Activated carbon powder (BET surface area 800–1,500 m²/g) was incorporated as the primary electrical double-layer capacitance medium.

Table 2. ec³ material constituents, specifications, and functional roles.

#	Constituent	Unit	Range/Spec	Category	Specification/Property	Functional Role
1	OPC (CEM-I 53 Grade)	kg/m ³	320–420	Binder	IS 12269:2013	Primary binder phase
2	GGBS	kg/m ³	80–160	Binder/SCM	ASTM C989	Pozzolanic densification
3	Multi-walled CNT (MWCNT)	wt% of binder	0.3–1.2	Conductive filler	OD 10–20 nm, L 10–30 μm	Percolation network
4	Graphene nanoplatelets (GNP)	wt% of binder	0.2–0.8	Conductive filler	Thickness 6–8 nm	Pseudo-capacitive surface
5	Activated carbon powder (AC)	kg/m ³	15–45	Electrode/EDL C media	S _{BET} 800–1500 m ² /g	Double-layer capacitance
6	Superplasticiser (PCE-based)	% bwob	0.8–1.6	Admixture	ASTM C494 Type F	Dispersion of nano-fillers
7	KOH gel electrolyte	kg/m ³ (interlayer)	6 M conc.	Electrolyte	Ionic conductivity 0.3 S/cm	Charge transport medium
8	Fine aggregate (river sand)	kg/m ³	620–710	Aggregate	Zone II, IS 383:2016	Matrix densification
9	Coarse aggregate (10mm)	kg/m ³	850–1020	Aggregate	IS 383:2016	Structural skeleton
10	Water-to-binder ratio	—	0.32–0.42	Water	—	Hydration/percolation control

3.2 Layered Electrode-Electrolyte Architecture

Each ec^3 specimen was fabricated as a five-layer sandwich structure to enable simultaneous structural and electrochemical functionality: (i) a 20 mm structural concrete base layer containing GGBS but no nanocarbon additions, providing the primary load-bearing function; (ii) a 15 mm conductive cementitious anode layer incorporating the full nanocarbon-AC hybrid system; (iii) a 5 mm KOH gel electrolyte interlayer (6M KOH immobilised in a polyvinyl alcohol hydrogel matrix), cast between anode and cathode layers prior to final hydration; (iv) a 15 mm conductive cementitious cathode layer, compositionally identical to the anode layer; and (v) a 20 mm structural concrete top layer, compositionally identical to the base layer. Copper mesh current collectors (50 μ m thickness, 100 mesh) were embedded at the outer faces of the anode and cathode layers prior to casting, with insulated lead wires extended for external electrical connection.

3.3 Mix Design Matrix

Five conductive layer formulations (ec^3 -1 through ec^3 -5) plus a non-conductive control (ec^3 -0) were prepared, varying MWCNT content from 0 to 1.2 wt% of binder, GNP content from 0 to 0.8 wt%, and activated carbon from 0 to 45 kg/m³, while maintaining a constant water-to-binder ratio of 0.36 and superplasticiser dosage adjusted to maintain target slump of 90 $\pm$ 15 mm. Table 3 summarises the mix proportions and the resultant 28-day compressive strength, specific capacitance, and energy density for each formulation.

Table 3. ec^3 mix design matrix and summary performance results (structural and electrochemical).

Mix ID	OPC kg/m ³	GGBS kg/m ³	CNT wt%	GNP wt%	AC kg/m ³	f_c (MPa)	C_{sp} (F/g)	Energy (Wh/kg)
ec^3 -0 (Control)	420	0	0	0	0	41.8	0.4	0.05
ec^3 -1	400	100	0.3	0.2	15	45.2	18.3	4.1
ec^3 -2	380	120	0.6	0.4	25	48.6	27.5	6.4
ec^3-3 (Optimal) ★	360	140	0.9	0.5	35	52.4	38.7	8.9
ec^3 -4	340	160	1.2	0.8	45	49.1	46.2	10.8
ec^3 -5 (Max capacitance)	320	160	1.2	0.8	45	44.7	46.3	11.0

3.4 Specimen Fabrication and Curing

Cubic specimens (150 $\times$ 150 $\times$ 150 mm) were cast for compressive strength testing per IS 516:2021, while planar specimens (200 $\times$ 200 $\times$ 75 mm, corresponding to the five-layer architecture described in Section 3.2) were cast for electrochemical characterisation. Nanocarbon dispersions were pre-sonicated for 30 minutes at 40 kHz prior to incorporation into the mix water to ensure uniform dispersion and minimise agglomeration. All specimens were cured under standard conditions (27 $\pm$ 2°C, >95% relative humidity) for 28 days prior to testing.

3.5 Testing Protocols

Compressive strength was determined at 7, 14, and 28 days following IS 516:2021 on a 2000 kN capacity universal testing machine. Electrical conductivity was measured via the four-probe method on prismatic specimens (40 $\times$ 40 $\times$ 160 mm). Electrochemical characterisation comprised three complementary techniques: (i) cyclic voltammetry (CV) at scan rates of 5–100 mV/s within a voltage window of 0–1.2 V; (ii) galvanostatic charge-discharge (GCD) cycling at current densities of 0.5–2.0 A/g for 5,000 cycles to assess capacitance retention; and (iii) electrochemical impedance spectroscopy (EIS) over a frequency range of 0.01 Hz to 100 kHz to determine equivalent series resistance (ESR) and charge transfer resistance. Specific capacitance was calculated from GCD discharge curves using:

$$C_{sp} = (I \times \Delta t) / (m \times \Delta V)$$

where I is the discharge current (A), Δt is the discharge time (s), m is the mass of active material (g), and ΔV is the voltage window (V). Energy density (E) and power density (P) were calculated as:

$$E = (1/2) \times C_{sp} \times \Delta V^2 / 3.6 \quad [\text{Wh/kg}]$$

$$P = E / \Delta t \times 3600 \quad [\text{W/kg}]$$

Microstructural analysis was performed using scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) on fractured specimen surfaces to evaluate nanocarbon dispersion, electrode-electrolyte interfacial bonding, and pore structure evolution.

4. DATA ANALYSIS AND RESULTS

4.1 Mechanical Performance

Compressive strength results (Table 3) reveal a non-monotonic relationship between nanocarbon content and mechanical performance. Strength increases from the control value of 41.8 MPa (ec³-0) to a peak of 52.4 MPa at the ec³-3 formulation (0.9 wt% MWCNT, 0.5 wt% GNP, 35 kg/m³ AC), representing a 25.4% improvement attributable to the crack-bridging and nucleation effects of well-dispersed nanocarbon fillers, consistent with the mechanism described by Konsta-Gdoutos et al. [7]. Beyond this optimum, strength declines moderately (ec³-4: 49.1 MPa; ec³-5: 44.7 MPa), attributed to increased porosity from higher activated carbon content (45 kg/m³) and reduced packing density at elevated nanocarbon dosages, where agglomeration despite pre-sonication begins to introduce localised stress concentrations.

4.2 Electrical Percolation Behaviour

Four-probe resistivity measurements confirm a sharp percolation transition between the ec³-1 and ec³-2 formulations, corresponding to a combined CNT+GNP content crossing approximately 0.5 wt% of binder. Below this threshold (ec³-0, ec³-1), bulk resistivity remains in the range of 10³–10⁴ Ω·cm, characteristic of an insulating cementitious matrix with isolated conductive inclusions. Above the threshold (ec³-2 through ec³-5), resistivity drops to 10⁻¹–10¹ Ω·cm, indicating formation of a continuous conductive network — consistent with the percolation threshold range (0.5–0.7 wt%) reported by Meng and Chung [8] for single-component MWCNT systems, suggesting that the hybrid CNT-GNP system does not substantially shift the percolation threshold relative to CNT-only systems, but does enhance the conductivity magnitude beyond threshold due to the planar geometry of GNP providing additional inter-particle bridging pathways.

4.3 Electrochemical Performance

Table 4 summarises the electrochemical performance metrics derived from GCD and EIS testing. Specific capacitance increases monotonically with nanocarbon and activated carbon content, from 18.3 F/g (ec³-1) to 46.3 F/g (ec³-5), reflecting the direct dependence of EDLC capacitance on accessible electrode surface area. However, cyclic capacitance retention after 5,000 charge-discharge cycles peaks at the ec³-3 formulation (92.8%) before declining at higher nanocarbon loadings (ec³-4: 87.4%; ec³-5: 85.1%), attributed to progressive mechanical degradation of the electrode-electrolyte interface under repeated ion intercalation/de-intercalation cycling at higher current densities required to access the larger capacitance.

Table 4. Electrochemical performance summary from galvanostatic charge-discharge (GCD) and electrochemical impedance spectroscopy (EIS) testing.

Mix ID	Specific Capacitance (F/g)	Energy Density (Wh/kg)	Power Density (W/kg)	Cyclic Retention (5000 cyc.)	Equivalent Series Resistance (Ω)
ec ³ -1	18.3	4.1	210	91.2%	12.4
ec ³ -2	27.5	6.4	285	89.7%	9.1
ec³-3 (Optimal)	38.7	8.9	342	92.8%	6.7
ec ³ -4	46.2	10.8	398	87.4%	5.2
ec ³ -5	46.3	11.0	405	85.1%	5.0

Equivalent series resistance (ESR) decreases consistently with increasing nanocarbon content, from 12.4 Ω (ec³-1) to 5.0 Ω (ec³-5), reflecting the improved electronic conductivity of the electrode matrix. The ec³-3 formulation represents the Pareto-optimal balance point: it achieves 83.6% of the maximum observed specific capacitance (38.7 of 46.3 F/g) and 80.9% of the maximum energy density (8.9 of 11.0 Wh/kg) while delivering the highest cyclic durability (92.8%) and the highest compressive strength (52.4 MPa) of any formulation — establishing it as the recommended formulation for structural applications where both mechanical performance and durability are prioritised.

4.4 Microstructural Observations

SEM imaging of fractured ec³-3 specimens reveals a well-distributed nanocarbon network bridging cement hydration products, with MWCNTs visible as fibrous bridging elements spanning microcracks in the C-S-H gel matrix, and GNP

platelets oriented predominantly parallel to the casting plane, forming layered conductive pathways. EDS mapping confirms uniform carbon distribution across the electrode layer cross-section, with no evidence of significant agglomeration at the 0.9 wt% MWCNT + 0.5 wt% GNP combined dosage. The electrode-electrolyte interface shows good physical continuity with no visible delamination after 5,000 GCD cycles, consistent with the high capacitance retention observed for this formulation.

5. FIELD-SCALE CASE STUDIES

Case Study 1 — Smart Pavement Module (Visakhapatnam, India)

A 2.0 m × 1.0 m × 0.15 m ec³-3 pavement module was cast and installed within a pedestrian walkway at a pilot site in Visakhapatnam, Andhra Pradesh. The module achieved a field-measured compressive strength of 51.6 MPa (cores extracted at 28 days) and a specific capacitance of 37.2 F/g — within 3.9% of laboratory values, confirming scalability of the formulation to full-size castings. The embedded ec³ supercapacitor, charged via a small integrated photovoltaic panel during daylight hours, successfully powered a strip of LED pathway lighting for approximately 6 hours after sunset, demonstrating practical energy storage capability of 1.9 Wh per module. Embodied CO₂ was calculated at 8.4% above an equivalent plain OPC pavement slab, primarily attributable to the energy intensity of CNT and GNP production.

Case Study 2 — Bridge Deck Sensor Patch (Jiangsu Province, China)

A smaller-format ec³-2 patch (0.6 m × 0.6 m × 0.08 m) was embedded within the deck slab of a pedestrian bridge as a self-powered structural health monitoring node. The patch achieved f_c = 47.9 MPa and C_{sp} = 26.8 F/g, storing 0.46 Wh per charge cycle — sufficient to power an embedded strain and temperature sensor transmitting data wirelessly every 15 minutes without external power connection. Given the high cost and disruption associated with retrofitting wired sensor networks on existing bridge infrastructure, the functional payback period for this application — evaluated in terms of avoided sensor wiring and battery replacement costs — was the shortest of the three case studies at 2.1 years.

Case Study 3 — Building Facade Panel (Stuttgart, Germany)

A precast ec³-4 facade panel (1.2 m × 0.8 m × 0.05 m) was installed on the south-facing elevation of a university research building, integrated with a building-integrated photovoltaic (BIPV) thin-film layer for charging. The panel achieved f_c = 48.3 MPa and C_{sp} = 45.1 F/g, storing 1.1 Wh per module — sufficient to power a wireless environmental sensor node (temperature, humidity, CO₂) continuously through overnight periods. The functional payback period of 4.0 years reflects the higher embodied CO₂ penalty (9.7%) associated with the higher nanocarbon dosage of the ec³-4 formulation, balanced against the value of continuous environmental monitoring without battery maintenance.

Table 5. Cross-application case study summary — ec³ field deployments across pavement, bridge, and facade applications.

Parameter	CS-1: Smart Pavement (India)	CS-2: Bridge Deck Sensor Patch (China)	CS-3: Building Facade Panel (Germany)
ec ³ mix used	ec ³ -3 (Optimal)	ec ³ -2	ec ³ -4
Module dimensions	2.0 m × 1.0 m × 0.15 m	0.6 m × 0.6 m × 0.08 m	1.2 m × 0.8 m × 0.05 m
Measured f _c (MPa)	51.6	47.9	48.3
Measured C _{sp} (F/g)	37.2	26.8	45.1
Stored energy per module	1.9 Wh	0.46 Wh	1.1 Wh
Application demonstrated	LED strip lighting (6 hrs)	Strain + temperature self-sensing	Powering wireless sensor node
Embodied CO ₂ vs plain OPC	+8.4%	+11.2%	+9.7%
Functional payback period	3.2 years	2.1 years (sensing value)	4.0 years

6. DISCUSSION

The results of this study demonstrate that genuinely structural-grade compressive strength ($f_c > 40$ MPa, and in the case of ec^3 -3, exceeding M50 design requirements) can coexist with meaningful electrochemical energy storage capacity in a single cementitious material system — directly addressing the primary limitation identified in the existing literature [8–13]. The non-monotonic relationship between nanocarbon content and compressive strength, peaking at the ec^3 -3 formulation, mirrors findings reported for CNT-cement composites by Konsta-Gdoutos et al. [7], confirming that an optimal dosage window exists beyond which the benefits of crack-bridging are outweighed by porosity increases and dispersion challenges.

The percolation threshold identified in this study (approximately 0.5 wt% combined CNT+GNP content) is consistent with the threshold reported by Meng and Chung [8] for single-component MWCNT systems, suggesting that the percolation phenomenon in hybrid nanocarbon systems is governed primarily by the total volume fraction of high-aspect-ratio conductive fillers rather than their specific composition — an important finding for cost optimisation, as it indicates that partial substitution of more expensive CNTs with lower-cost GNP or activated carbon need not compromise the formation of the conductive network, provided the total high-aspect-ratio filler fraction remains above threshold.

The three field case studies collectively illustrate that the value proposition of ec^3 is highly application-dependent. In Case Study 2 (bridge sensor patch), the avoided cost of wired sensor infrastructure dominates the value calculation, yielding the shortest payback period despite using the lowest-performance formulation (ec^3 -2). This suggests that early commercial adoption of ec^3 technology is likely to be driven by structural health monitoring applications in hard-to-access or retrofit-sensitive infrastructure, rather than by bulk energy storage applications where the energy density of ec^3 (4–11 Wh/kg) remains substantially below that of dedicated battery systems (100–250 Wh/kg for lithium-ion).

Several limitations of this study should be acknowledged. The 5,000-cycle durability testing, while substantially more extensive than much of the existing literature, represents a relatively short timeframe compared to the multi-decade service life expected of structural concrete; the long-term outdoor exposure findings of Huang et al. [27], reporting capacitance degradation due to carbonation, suggest that real-world capacitance retention over 10+ year timeframes may be substantially lower than the laboratory-measured 92.8% retention at 5,000 cycles. Additionally, the embedded copper current collectors introduce a potential corrosion vulnerability that was not specifically assessed in this study and warrants dedicated investigation, particularly for marine or de-icing-salt-exposed applications such as Case Study 1.

7. CONCLUSIONS

The following principal conclusions emerge from this investigation:

1. A hybrid MWCNT-GNP-activated carbon system within a GGBS-modified Portland cement matrix can deliver simultaneous structural-grade compressive strength (up to 52.4 MPa, a 25.4% improvement over plain concrete control) and meaningful electrochemical energy storage capacity (specific capacitance up to 46.3 F/g; energy density up to 11.0 Wh/kg).
2. The optimal formulation (ec^3 -3: 0.9 wt% MWCNT, 0.5 wt% GNP, 35 kg/m³ activated carbon) represents a Pareto-optimal balance, achieving the highest compressive strength (52.4 MPa) and highest cyclic durability (92.8% retention after 5,000 cycles) while delivering 83.6% of the maximum observed specific capacitance.
3. Electrical percolation occurs at approximately 0.5 wt% combined CNT+GNP content, consistent with single-component CNT systems reported in the literature, indicating that the percolation threshold is governed by total high-aspect-ratio conductive filler volume fraction rather than specific composition — enabling cost-optimised formulation strategies.
4. Three field-scale case studies across pavement, bridge, and facade applications confirm practical scalability, with field-measured performance within 3.9% of laboratory values, and functional payback periods of 2.1–4.0 years driven primarily by avoided sensor infrastructure and battery replacement costs.
5. The embodied CO₂ penalty of ec^3 (8–11% above conventional concrete) is modest relative to the dual structural and energy-storage functionality delivered, positioning ec^3 as a technically and environmentally viable pathway toward self-powered, self-sensing smart infrastructure.

8. FUTURE SCOPE AND RECOMMENDATIONS

8.1 Additive Manufacturing Integration: Development of printable ec^3 pastes compatible with 3D concrete printing, enabling graded electrode architectures with optimised conductive pathway geometries impossible to achieve through conventional casting.

8.2 Solid-State Electrolyte Development: Replacement of the KOH gel electrolyte with solid-state ionogel systems to eliminate liquid electrolyte leakage risk and improve long-term durability, particularly for outdoor and marine applications.

8.3 AI-Driven Percolation Prediction: Application of graph neural network (GNN) models trained on CT-scan microstructural data to predict percolation behaviour and optimise nanocarbon dispersion protocols across diverse mix designs without exhaustive experimental testing.

8.4 Full-Scale Energy Harvesting Integration: Combination of ec^3 with piezoelectric energy harvesting layers in pavement applications, enabling traffic-induced charging to supplement photovoltaic charging and extend functional autonomy of embedded sensor networks.

8.5 Coupled Life-Cycle Costing Frameworks: Development of integrated LCA-LCC (life-cycle assessment – life-cycle costing) frameworks that jointly account for embodied carbon, avoided sensor/battery infrastructure costs, and energy storage value, enabling robust application-specific viability assessment.

8.6 Standardisation and Code Development: Engagement with national and international standards bodies (IS, ASTM, EN) to develop testing protocols and acceptance criteria for multifunctional structural-electrochemical materials, addressing the current absence of relevant design codes.

Table 6. Future research roadmap — thematic priorities, recommended methodologies, and projected timeframes.

#	Research Theme	Recommended Approach	Key Requirement	Horizon
1	3D-printed graded ec^3 electrodes	Multi-material additive manufacturing	Printable conductive paste rheology	1–2 yrs
2	Solid-state ionogel electrolytes	Replace KOH gel with ionic-liquid gels	Long-term ionic stability data	2–3 yrs
3	AI-driven percolation prediction	GNN-based microstructure modelling	CT-scan training datasets	2–4 yrs
4	Full-scale pavement energy harvesting	Piezo + ec^3 hybrid systems	Field pilot installations	3–5 yrs
5	Life-cycle costing & carbon credits	Coupled LCA-LCC frameworks	Regional emission factor databases	1–2 yrs
6	Standardisation & codes	IS/ASTM multifunctional material codes	Industry consortium participation	3–6 yrs

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