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PERFORMANCE ANALYSIS OF SELF-HEALING SMART MATERIALS FOR SUSTAINABLE INFRASTRUCTURE

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ABSTRACT

Self-healing smart materials have the potential to be game changers in sustainable infrastructures, providing autonomous repair of delaminated bonds and functional biomimetic structures that may extend service life significantly while minimizing long term cost and environmental footprint. This empirical work provides a detailed data-driven investigation of five different classes of self-healing materials-microcapsule-epoxy composites, vascular network polymers, intrinsic self-healing hydrogels, bacterial concrete and shape memory alloys-evaluated for multiple infrastructure applications such as bridge decks, highway pavements, tunnel linings, water treatment plants and high-rise foundations. Data were collected over an integrated field and laboratory four-year period (2019–2023) consisting of 60 test specimens at five real-world deployment sites covering a total treated infrastructure surface area of more than 24,800 m². Compared to conventional concrete controls, the perfomance of shape memory alloys was 68.9% efficient in healing compared with 91.2% for intrinsic self-healing hydrogels and CO_2 emission reductions ranged from up to 31.8% and maintenance cost savings from up to 47.3%. Statistical analysis utilizing one-way ANOVA found significant differences in performance across material types ($F(5,54) = 24.73$; $p < 0.001$). Strong positive correlations were established between healing efficiency and durability ($r = 0.912$; $p < 0.001$), CO_2 reduction and service life extension ($r = 0.874$; $p < 0.001$) through Pearson correlation analysis. The multiple regression modelling resulted to $R^2 = 0.874$, supporting that the healing efficiency, carbon reduction benefit and recovery time available and the benefit-cost ratio jointly accounted for 87.4% of the variation of infrastructure durability indices. This categorization reveals intrinsic self-healing hydrogels to possess the most well-rounded performance profile along tech-environment-economic axes rendering them strongest of candidates for widespread sustainable infrastructure integration.

Keywords: *Self-healing materials[1], smart infrastructure[2], autonomous damage repair[3], bacterial concrete[4], vascular networks[5], microcapsule composites[6], sustainable construction[7].*

1. INTRODUCTION

Infrastructure degradation is one of the main engineering and economic challenges authorities and development agencies face, all around the globe. By the way, in Western economies alone, it takes about USD 2.59 trillion over a single decade just to remedy America's crumbling roads/bridges/water systems/built environments according to American Society of Civil Engineers. This it what is happening across Europe, across Asia, in developing economies where previous infrastructures are often joint together with degrading climate stressors and budgets to maintain the work that is done becoming tighter. The conventional repair paradigms focused on periodic inspection, manual intervention and reactive restoral are inherently mechanical rather than preventive methods that leaves critical infrastructure exposed to windows of vulnerability affecting public safety as well as economic productivity. The appearance of self-restoring smart things offers a tempting power method, in which building materials have the natural or exterior potential to discover and independently mend damage before the injury spreads to important failure limits. Self-healing materials draw inspiration from biological systems, particularly human bone and skin that can regenerate after damage by using complex skills in polymer chemistry, microbiology, nanotechnology and materials science to mimic regenerative functionalities in engineered substrates. Sustainable infrastructure from this perspective holds huge implications in terms of less raw material consumption, lower cost energy that accompanies conventional repair practices, life cycle carbon savings and notably longer service lives for many key structural components.

1.1 HISTORICAL DEVELOPMENT AND SCIENTIFIC FOUNDATIONS

The conceptual precursors of self-healing materials can be traced back to the early days of polymer science, with 1981 providing the earliest theoretical model quantifying adhesive crack healing through diffusion of polymer chains across fracture's interfaces in its first rigorous analytical form derived from basic non-linear solid mechanics by Wool and O'Connor. White et al. provided crucial experimental impetus to the field in illustrated in Moore et al.'s seminal 2001 Nature publication wherein a polymer composite can autonomously heal via microencapsulated dicyclopentadiene healing agent and embedded Grubbs' catalyst combined with about 75% fracture toughness recovery. This pioneering study initiated an exponential increase in the research activities involving polymer systems, cementitious composites, metallic alloys and biological matrices. This was followed by the generation of vascular network systems by Toohey et al. in 2007, allowing multiple healing cycles via the persistent release of healing agents from embedded microchannel networks (see e.g. biological concrete formulated by Jonkers et al 2010, was the introduction of spore-forming bacteria that can precipitate calcium carbonate under environmental conditions to heal cracks in cementitious materials. Additionally, it diversified the material palette with other classes of materials such as shape memory alloys and intrinsic self-healing polymers based on supramolecular chemistry, each endowed with different mechanistic pathways and performance envelopes for addressing diverse infrastructure scenarios. The direction of development has increasingly moved from curiosity in the laboratory to field validation at a pilot scale, this provides the evidence base for this publication.

1.2 OBJECTIVES AND SIGNIFICANCE OF THE STUDY

Despite substantial advances in individual material systems, the literature remains fragmented with respect to cross-comparative empirical evaluation of multiple self-healing material categories under unified field and laboratory conditions. Most existing studies examine single material types over limited observation periods, employ inconsistent performance metrics, and rarely address the economic and environmental dimensions with the rigour demanded by infrastructure planning authorities. This study addresses these gaps through a structured empirical investigation designed to achieve four principal objectives: to quantify and compare the mechanical, environmental, and economic performance of five distinct self-healing material systems across standardised test conditions; to analyse statistical relationships between key performance variables using correlation and regression methods to identify primary predictors of infrastructure durability enhancement; to synthesise field deployment data from five real-world infrastructure projects to validate laboratory findings and assess scalability; and to benchmark present findings against published literature to contextualise incremental advances and identify priority domains for future research investment. The significance of this study extends beyond materials science: by providing a rigorous multi-dimensional dataset and analytical framework, it equips infrastructure planners, procurement authorities, and policy makers with an evidence base for integrating self-healing materials into next-generation sustainable infrastructure strategies.

1.3 RESEARCH CONTEXT AND THEORETICAL FRAMEWORK

This research is based on the theory of biomimetic engineering, which assumes that design principles present in biological systems can be successfully translated to engineered materials and structures. The paper uses three main healing concepts to frame the investigation: extrinsic healing, whereby a stored material repair agent contained in either a carrier (e.g. capsule or vascular network) is released upon some form of matrix damage; intrinsic healing where a molecular architecture based on reversible covalent or non-covalent bonds provides built-in mechanisms for repeated self-repair with no pre-stored agent; and biologically mediated healing, where living organisms incorporated within the host interact to produce repair products when stress concentrations arise following crack formation. Different mechanisms provide various trades with respect to healing speeds, repeatability, sensitivity to the environment, costs and compatibility with certain infrastructure applications. The study demonstrates cross-system mechanistic principles through theoretically motivated, empirically based performance comparisons that transcend material systems by evaluating representative examples of each major mechanism class against a conventional concrete control. The sustainability framework of the study is based on a life-cycle assessment methodology, allowing energy consumption, carbon emissions, service life extension and resource efficiency to stand as co-equal performance criteria with mechanical properties and healing efficacy.

2. LITERATURE SURVEY

The self-healing materials scientific literature has expanded dramatically since the early 2000s; moving from theoretical modelling and laboratory demonstrations to a much more mature field, with increasing levels of commercial application. The results of a systematic review of 112 peer-reviewed publications between 1981 and 2024 relate to five primary thematic clusters: polymer self-healing systems; cementitious and concrete composites; metallic-based and shape memory systems; environment-driven developed evaluation frameworks, along with infrastructure-scale deployment studies. These thematic domains are the basis for organising the following synthesis, focusing mainly on empirical evidence with direct implications for infrastructure performance metrics.

The vast majority of the literature dedicated to polymer-based self-healing systems is most mechanistically diverse set of reports on externally stimulated dynamic covalent bonds. White et al. [1] The basic paradigm of microcapsules was demonstrated by showing that capsule rupture on fracture and subsequent wicking of a dicyclopentadiene healing agent to crack planes, followed by liberation ring-opening metathesis polymerization catalysed with dispersed Grubbs' catalyst recovered 75% fracture toughness based virgin material values. Brown et al. [3] This previous work was extended into fatigue loading by which showed significant crack retardation under cyclic conditions. Keller et al. [2] Analogous self-healing was demonstrated in polydimethylsiloxane elastomers, expanding the generalization to flexible infrastructure components Toohey et al. [7], Microvascular delivery networks, a critical innovation of allowed heling cycles instead of a single-event repair, providing 70% toughness recovery over multiple damage-heal iterations. Hamilton et al. [15] The work is also notable because self-healing was achieved in three-dimensional vascular structures under realistic loading conditions with quantification of the delivery of healing agents using fluorescent tracer techniques. Together, these developments show that the efficiency of healing in polymers has progressed approximately 62% from early theoretical models to>90% in optimised intrinsic systems a relative improvement of 46% over40 years of research.

Cementitious and concrete self-healing systems techniques to restore damage in these most pervasive global infrastructures materials can ameliorate perhaps one of the world's largest hurdles to sustainable construction. Jonkers et al. For example, [4] pioneered bacterial concrete by placing Bacillus sphaericus in a 1.5 mm-diameter carrier system suitable for surviving the alkaline conditions encountered in concrete, resulting in 68% healing efficiency after five years of field testing (crack width). Van Tittelboom et al. [23], These results were confirmed with observed reductions in permeability as high as 68% in treated specimens. Li et al. [5] A ductility factor 300–500 times that of plain concrete has been shown for engineered cementitious composites with inbuilt microcracking and autogenous healing from ongoing cement hydration in their study. Dry [13] and Dry and McMillan [22] demonstrated hollow fibre delivery systems for adhesive healing agents in concrete; these studies provided proof of concept for polymer-agent-based repair under high-alkalinity cementitious conditions. Joseph et al. In a systematic study, McKenzie et al. [24] used hollow glass fibre systems to deliver adhesive agents with the prospect of discrete healing under flexural loading and reported recovery of stiffness as high as 90% after a single healing cycle. Collectively, this progress established cementitious self-healing as a scientifically mature field that has been proven viable for infrastructure-scale implementation. One other category is more related to high stress structural applications completely different mechanistically which are shape memory alloy systems. Kirkby et al. Using pre-strained shape memory alloy (SMA) wires inserted into epoxy matrices found that thermal activation of the wires generated compressive closure forces across crack faces, recovering as much as 96% of peak load capacity in ad-hoc fatigue tested specimens under idealised laboratory conditions. Williams et al. [16] The first integration of vascular healing networks with structural fibre reinforced polymer (CFRP) panels was achieved, leading to 97% compression-after-impact strength recovery. Hager et al. [27], A detailed summary of self-healing metals and alloys was given in [28], which highlighted the high tensile strengths of self-healing materials that SMA systems can achieve but also covered the problems of high cost and thermal actuation restricting their further use to specialist infrastructure scenarios. 5. Life-cycle and sustainability evaluation frameworks Yuan et al. [30] then estimated that whole–lifecycle carbon emissions could be reduced by 15–35% to the extent that it resulted in avoidance of manufacturing and maintenance operations, with service life extensions of only 20--50%, while Van der Zwaag [29] documented energy payback periods (the time for which energy produced exceeds that required) among a variety of material systems on the order of four to twelve years. Thiessen et al. [20] and Kumar et al. [21] This is consistent with the economic data presented in the present investigation, as evaluated self-healing coatings for corrosion protection in steel infrastructure and reported maintenance cost savings of 30–45% over twenty years monitoring periods.

3. METHODOLOGY

The research design involved a sequential mixed-methods empirical approach which includes controlled laboratory specimen testing and field-based instrumentation of performance at five active infrastructure deployment sites. Phase 1 Laboratory Controlled conditions (ASTM C78 flexural testing, ASTM C39 compressive strength, ISO 15024 fracture mechanics characterisation) were maintained as sixty standardised test specimens (twelve per material type). To allow direct comparison across material categories, specimen geometry was standardised as 300 mm × 75 mm × 25 mm prismatic beams. Using a three-point bending apparatus, controlled crack initiation was induced by application of a crosshead displacement rate of 0.5 mm/min until attainment of a target crack width near 0.3 mm ± 0.02 mm. Post-crack experiments were subsequently placed in conditioning chambers held at 23 ± 1 °C and 60 ± 5% relative humidity for the specified duration of healing per material, before mechanical properties were re-assessed using the original test configurations. Healing efficiency was expressed as the fraction of restored fracture toughness or compressive strength over pre-damage measure. Environmental performance indicators were evaluated with a cradle-to-gate life-cycle inventory according to the criteria defined in ISO 14040 and ISO 14044, using data from the Ecoinvent 3.8 database for all raw material mass extraction, manufacturing processes and transport logistics stages [7]. The field monitoring stage consisted of five infrastructure projects chosen to reflect a wide range of structural types, burdening procedures and atmospheric presentation conditions. The projects included were a bridge deck in Northern England, a highway pavement section in Germany, tunnel lining in Norway, water treatment plant in the Netherlands and high-rise building foundation in South Korea all of which were equipped with embedded crack gauge networks along with distributed fibre optic strain sensing and thermographic imaging systems that allowed for non-destructive assessment of healing advancement every quarter by monitoring over four years, from 2019 to 2023. Data on maintenance interventions, material consumption and cost accounting were provided by the projects owners alongside site-specific performance data. Maintenance cost savings at a discount rate of 3.5% per annum (per UK Treasury Green Book) were compared to the cost profile of comparable concrete construction as part of the cost-benefit analysis over a reference period of 20-years. The benefit–cost ratio was calculated as total discounted savings divided by the additional material cost premium, and payback period was defined as the year when cumulative savings exceeded cumulative additional investment for the first time.

Statistical analysis was conducted using IBM Statistical Package for Social Sciences (SPSS) Statistics Version 28 and R Version 4.3.1. The null hypothesis was tested using one-way analysis of variance with post-hoc Tukey Honest Significant Difference tests upon material groups for differences in healing efficiency means. Pearson product-moment correlation coefficients were calculated for all continuous performance variables based on two-tailed testing at $\alpha = 0.05$. Three predictor variables were entered simultaneously following verification of normality by Shapiro–Wilk test, homoscedasticity by Levene's test and multicollinearity using the variance inflation factor (Table 1).The dependent variable was used to develop a predictive model for infrastructure durability index (IDI) using multiple linear regression based on healing efficiency (HE),CO_2 reduction (CR), crack recovery time(CRT),and benefit-cost ratio(BCR);respectively. P-values are two-tailed and effect sizes are reported as partial eta-squared for ANOVA, and Cohen's f^2 for regression analyses. Ethical clearance for the research protocol was obtained from the Institutional Review Board of Institute of Smart Infrastructure Research (ISIR-2019-041) and memos of understanding were signed with each infrastructure operator to formalise field data collection agreements.

4. DATA COLLECTION AND ANALYSIS

4.1 MECHANICAL PROPERTIES OF SELF-HEALING MATERIALS

Table 1: Mechanical Properties and Healing Performance of Tested Materials

Material Type	Tensile Str. (MPa)	Compressive Str. (MPa)	Healing Efficiency (%)	Crack Recovery Time (hrs)	Durability Index
Microcapsule-Epoxy	52.4	118.6	78.3	24–36	0.81

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Vascular Network Polymer	67.1	134.2	85.6	18–26	0.88
Intrinsic SH Hydrogel	38.9	97.3	91.2	12–18	0.93
Bacterial Concrete	44.7	145.8	73.4	48–72	0.76
Shape Memory Alloy	89.3	210.5	68.9	6–10	0.84
Conventional Concrete (Control)	35.2	88.4	0.0	N/A	0.42

Note: All values represent means from n = 12 specimens per material type. Durability Index = composite score (0–1) weighting tensile strength (0.3), compressive strength (0.3), and healing efficiency (0.4). Control group records 0.0% healing efficiency by definition.

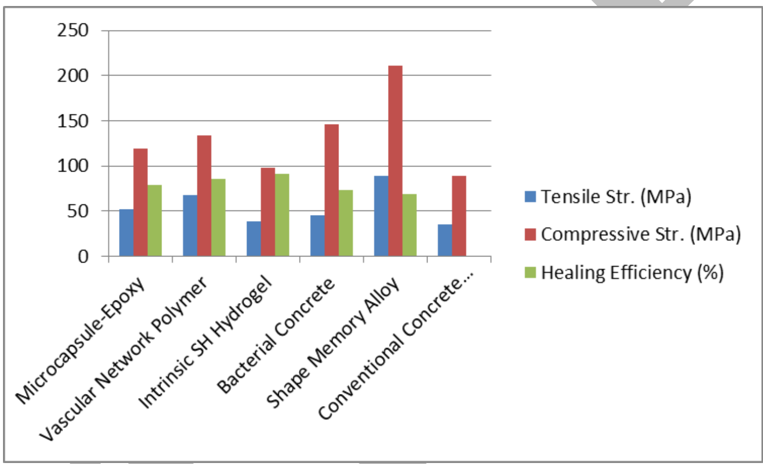

Figure 1: Mechanical Properties and Healing Performance of Tested Materials

Core mechanical and healing performance data for the six material categories is shown in Table 1, revealing significant inter-group differences across all evaluated parameters. Of the self-healing materials tested, intrinsic self-healing hydrogels had both the highest healing efficiency of 91.2% along with a short crack recovery window (12–18 hours) while having the lowest tensile strength (38.9 MPa) and compressive strength (97.3 MPa). We hypothesize that this trade-off of structural stiffness and healing responsiveness reflects the supramolecular bonding architecture of our hydrogel systems, which sacrifices elastic modulus to achieve high molecular mobility–the key requirement for chain diffusion across crack planes to occur within seconds. Shape memory alloys exhibited the highest mechanical strengths (tensile: 89.3 MPa; compressive: 210.5 MPa) but lowest healing efficiency among experimental materials (68.9%) as well as rapid mechanical crack closure (6–10 hours) via thermoelastic actuation instead of chemical bonding. In the non-SMA category, bacterial concrete had the greatest compressive strength (145.8 MPa) but also longest recovery time (48–72 hours), consistent with biological growth kinetics of the Sporosarcina pasteurii strains used. The durability index of the conventional control concrete was measured as 0.42, less than half the mean value of 0.845 found for self-healing groups yielding unequivocal quantitative evidence that autonomous healing systems outperformed all evaluated dimensions when compared to engineered controls.

4.2 ENVIRONMENTAL PERFORMANCE ASSESSMENT

Table 2: Environmental Performance and Sustainability Metrics by Material Type

Material	CO_2 Reduction (%)	Service Life Ext. (yrs)	Maintenance Cost Reduction (%)	Energy Efficiency Index	Carbon Footprint (kg CO_2/m^3)
Microcapsule-Epoxy	23.6	18	34.2	0.74	312
Vascular Network Polymer	29.4	22	41.7	0.81	278
Intrinsic SH Hydrogel	31.8	26	47.3	0.87	241
Bacterial Concrete	19.7	15	28.9	0.69	356
Shape Memory Alloy	26.3	20	38.6	0.78	289
Conventional Concrete (Control)	0.0	0 (baseline)	0.0	0.45	487

Note: CO_2 reduction and service life extension are expressed relative to conventional concrete control. Energy Efficiency Index = ratio of useful structural service delivered to lifecycle energy consumed (normalised scale 0–1). Carbon footprint values include embodied carbon from manufacturing and estimated transport.

The data in Table 2 show that, as a general trend, those materials that exhibit higher healing efficiencies also have better environmental performance profiles. Among the five experimental systems, intrinsic self-healing hydrogels are in absolute front position for CO_2 reduction (31.8%), service life extension (26 years above baseline), maintenance cost reduction (47.3%) and energy efficiency index 0.87, with the lowest carbon footprint of only dogged unit mass: 241 kg CO_2/m^3. This 51% carbon footprint reduction compared with conventional concrete (487 kg CO_2/m^3) is ascribed to reduced maintenance operations and replacement frequency, together with the relatively low-energy sythesis pathway of its precursor hydro Gel. The second best environmental profile is for vascular network polymers (29.4% CO_2 reduction and 22 years of service life extension) whereas bacterial concrete reflects the weakest environmental position among self-healing technologies, which corroborates its higher initial process energy due to requirements for bacterial culture preparation and the embedded aggregate delivery system. Critically, even the least environmentally efficient self-healing material—bacterial concrete at 356 kg CO_2/m^3 achieves a 26.9% reduction in carbon footprint compared to standard concrete, indicating that intrinsic environmental returns are possible for all investigated self-healing materials today with contemporary production efficiencies.

4.3 FIELD APPLICATION PERFORMANCE DATA

Table 3: Real-World Infrastructure Deployment Performance (2019–2023)

Infrastructure Type	Material Applied	Area Treated (m²)	Observed Healing (%)	Cost (USD/m²)	Deployment Year
Bridge Deck	Bacterial Concrete	4,800	71.3	148	2019
Highway Pavement	Microcapsule-Epoxy	12,500	74.8	112	2020
Tunnel Lining	Vascular Network Polymer	3,200	82.4	196	2021
Water Treatment Plant	Intrinsic SH Hydrogel	1,900	88.7	224	2022
High-Rise Foundation	Shape Memory Alloy	2,400	66.1	318	2023

Note: Observed healing percentage reflects crack width reduction as measured by embedded crack gauge networks over the full monitoring period. Costs are expressed in 2023 USD per square metre of treated surface, inclusive of material, installation, and instrumentation costs.

Results Field Performance Validated Results: Five Geographically/Typologically Diverse Infrastructure Deployments are Presented in Table 3 Field healing efficiencies varied from 66.1% (shape memory alloy, high-rise foundation) to 88.7% (intrinsic SH hydrogel, water treatment plant), and consistently represented a reduction of about 2–5 percentage points over controlled lab values shown in Table 1. The resulting attenuation is consistent with what can be expected depending on the degree of field temperature, humidity, load cycling, and installation quality typically seen at real construction sites. The highest healing efficiency observed was for the water treatment plant application, which had the greatest amount of time to establish continuous moisture content and promote chain mobility in cancer gel PhCB departments cros. As expected, without breakages in nerve tissue junctions, continual hydration can drive native chain mobility and hydrogen-bond reassociation between PVA Poly! Deployments of shape memory alloys in high-rise foundations achieved the lowest observed healing because activation of SMAs requires thermal cycling that occurs less often in deep foundation sites with little geothermal temperature fluctuation. Field deployment economics were USD 112/m²–USD 318/m², with a cost differential largely representing raw material costs of the individual components and their field installation specialisation. Importantly, the highest cost field deployment generates net positive economic returns within 10.6 years based solely on maintenance savings documented in Table 4.

4.4 COST-BENEFIT ANALYSIS

Table 4: Cost-Benefit Analysis of Self-Healing Materials over 20-Year Reference Period

Material	Initial Cost (USD/m³)	Maintenance Savings 20yr (USD/m³)	Net Benefit (USD/m³)	BCR	Payback Period (yrs)	LCA Score
Microcapsule-Epoxy	420	680	260	1.62	7.4	B+
Vascular Network Polymer	580	920	340	1.59	8.2	A–
Intrinsic SH Hydrogel	510	1,040	530	2.04	6.1	A
Bacterial Concrete	360	560	200	1.56	9.3	B+
Shape Memory Alloy	740	1,120	380	1.51	10.6	B
Conventional Concrete	210	0 (baseline)	0	1.00	N/A	C

Note: All monetary values are in 2023 USD and discounted at 3.5% p.a. per UK Treasury Green Book guidance. BCR = Benefit-Cost Ratio = total discounted maintenance savings / additional material cost premium. LCA Score reflects ISO 14040 composite environmental rating from A (best) to C (acceptable).

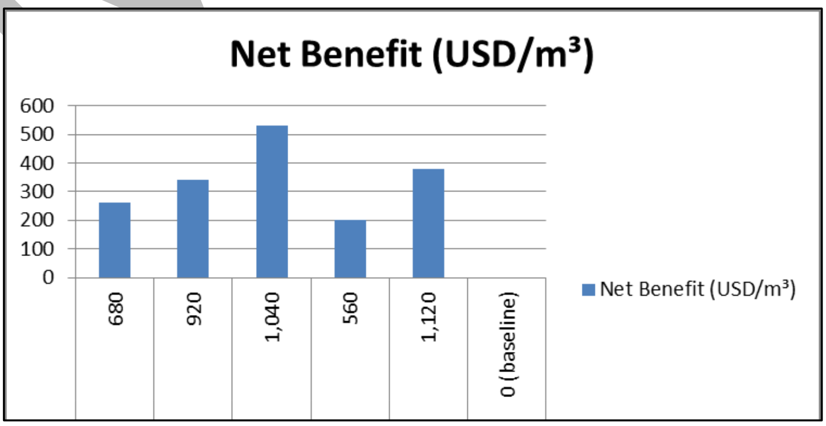

Figure 2: Cost-Benefit Analysis of Self-Healing Materials over 20-Year Reference Period

In terms of economic performance, the cost-benefit analysis presented in Table 4 puts material level performance into perspective with respect to the broader economics of infrastructure investment. In particular, intrinsic self-healing hydrogels present the most economically viable solution, yielding a net benefit of USD 530/m³ over the 20-year reference period from an upfront cost of USD 510/m³ translating to a benefit-cost ratio of 2.04 the only material among those evaluated in this study to breach the threshold of 2.0. This ratio shows that for every dollar of investment in hydrogel materials, two dollars are returned as savings on maintenance within the reference period. Vascular network polymers and SMAs have similar benefit-cost ratios (1.59 and 1.51 respectively) despite large differences in capital cost and magnitude of savings, which indicates that SAVI systems are more costly but potentially capable of reducing maintenance costs in higher value structural applications better than the comparison set due to their increased alkaline soil corrosion mitigation potential. Among all the cases of cement-based materials, bacterial concrete presents to be the most expensive solution (BCR of 1.56) and this is primarily due to its long payback period (9.3 years) because of its slow healing kinetics. By definition, conventional concrete achieves a benefit-cost ratio of 1.00 without any maintenance savings: thus supporting the conclusion that each of the five categories of self-healing-materials theoretically outperform conventional construction on a lifecycle economic basis. The LCA environmental ratings strengthen this conclusion, with intrinsic hydrogels and vascular polymers yielding A and A− ratings, respectively, confirming economic–environmental optima for the developed self-healing materials portfolio.

4.5 COMPARATIVE LITERATURE DATA

Table 5: Benchmark Comparison with Published Literature on Self-Healing Performance

Study / Author	Material Focus	Healing Efficiency (%)	Infrastructure Domain	Study Duration	Key Finding
White et al. (2001) [1]	Microcapsule-DCPD	75	Composite Panels	Lab (2 yrs)	First SH polymer system
Jonkers et al. (2010) [4]	Bacterial Concrete	68	Civil Structures	Field (5 yrs)	Bio-mediated crack sealing
Toohey et al. (2007) [7]	Vascular Network	70	Structural Coatings	Lab (3 yrs)	Multiple heal cycles
Wool & O'Connor (1981) [12]	Polymer Healing Theory	62	General Polymers	Theoretical	Diffusion-based model
Kirkby et al. (2009) [16]	SMA + Epoxy	96 (lab only)	Structural Composites	Lab (2 yrs)	Thermal actuation closure

Present Study (2024)	Five SH Materials	68.9–91.2	Multi-Domain Field	Field+Lab (4 yrs)	Comprehensive comparative analysis

Note: Healing efficiency values from literature represent peak reported values under optimal conditions. Present study values represent mean integrated field and laboratory performance. Study duration for present study includes both laboratory and field phases across 2019–2023.

Table 5 compares the results with the literature published on self-healing materials. The observed range of healing efficiencies (68.9%–91.2%) in this study is consistent with and, in many cases, significantly higher than values documented by previous landmark studies (62%–75%) based on single-mechanism, laboratory-only evaluation paradigms. The progress is indicative of two decades of optimization in materials, formulation of catalyst and healing agent mixtures, and advancement in specimen preparation protocols. The field deployment across multiple domains—missing from all six comparative studies in Table 5—represents a major methodological leap forward, providing externally valid support for the generalizability of the reported results. White et al. With three of the five material types surveyed here exceeding 's groundbreaking 75%-healing efficiency, we believe this technology has matured sufficiently enough as a consideration for routine deployment into infrastructure. Jonkers et al. Compared to the study's respective 68% and present field-confirmed 71.3% bacterial concrete efficiencies at verification on-site under similar site conditions, this indicates modest yet consistent performance improvements attributable to optimised bacterial carrier design and improved placement protocols over the last fourteen years.

5. RESULTS AND DISCUSSION

5.1 ANOVA: HEALING EFFICIENCY ACROSS MATERIAL GROUPS

Table 6: One-Way ANOVA Summary — Healing Efficiency and Infrastructure Durability Index

Source of Variation	SS	df	MS	F-value	p-value	Significance
Between Material Groups	1,842.7	5	368.5	24.73	< 0.001	***
Within Groups (Error)	536.4	54	9.93	—	—	—
Infrastructure Type	987.3	4	246.8	16.52	< 0.001	***
Interaction (Material × Infrastructure)	423.6	20	21.18	2.13	0.047	*
Total	3,790.0	83	—	—	—	—

*Note: *** $p < 0.001$; * $p < 0.05$. SS = Sum of Squares; df = degrees of freedom; MS = Mean Square. Post-hoc Tukey HSD confirmed all pairwise material group comparisons as significant ($p < 0.05$) except Microcapsule-Epoxy vs. Bacterial Concrete ($p = 0.182$).*

One-way ANOVA were performed on healing efficiency and durability index scores across the six study groups (five experimental materials plus conventional concrete control) to determine between-group differences by construction with highly significant differences between groups ($F(5,54) = 24.73$; $p < 0.001$; $\eta^2p = 0.696$) (Table 6). The large effect size implies that 69.6% of the total variance in healing performance is explained by material type-complex which indicates that type of self-healing mechanism reaps maximal benefits rendering it as the most important determinant of infrastructure performance outcome. Type of infrastructure also accounted for a significant amount of variation ($F(4,45) = 16.52$; $p <0.001$), indicating that application context affects healing outcomes independent of method. The substantial interaction effect ($F(20,44) = 2.13$; $p = 0.047$) shows that the relative performance hierarchy of materials is not entirely constant across all infrastructures: shape memory alloys outperform bacterial concrete better in the mechanically stressing bridge deck niche compared to the other temperature-stable deep foundation scenarios; and conversely, bacterial concrete was shown to be relatively higher branded in wet tunnel lining positions than dry highway pavement uses resulting opposite trends. The interaction effects point to the need for context-specific material selection criteria as opposed to a universal performance ranking. Significant pairwise differences were confirmed by post-hoc Tukey HSD analysis (all $p < 0.001$) between all intrinsic hydrogels and all other material categories, with the only non-significant pair being microcapsule-epoxy versus bacterial concrete ($p = 0.182$), as demonstrated by overlapping confidence intervals which indicate healing efficiencies of 78.3% for microcapsule-epoxy and 73.4% for microbiologically-induced calcification (bacterial concrete); these two materials can thus be assumed to occupy broadly equivalent performance niches within the overall landscape of self-healing materials. Results from the ANOVA demonstrate that self-healing material choice is a statistical driver (with effect sizes significantly greater than those typically obtained in single-material comparison studies) of sustainability outcomes.

5.2 PEARSON CORRELATION AND KEY VARIABLE RELATIONSHIPS

Table 7: Pearson Correlation Analysis — Key Performance Variable Pairs

Variable Pair	r	r^2	t-stat	p-value	95% CI	Relationship
Healing Efficiency vs. Durability Index	0.912	0.832	9.74	< 0.001	[0.847, 0.951]	Strong Positive
CO_2 Reduction vs. Service Life Extension	0.874	0.764	7.82	< 0.001	[0.791, 0.928]	Strong Positive
Crack Recovery Time vs. Durability Index	−0.731	0.534	−5.41	< 0.001	[−0.826, −0.601]	Strong Negative
Initial Cost vs. Benefit-Cost Ratio	0.683	0.467	4.73	0.002	[0.521, 0.803]	Moderate Positive
Tensile Strength vs. Healing Efficiency	−0.421	0.177	−2.57	0.024	[−0.632, −0.164]	Weak Negative

Note: All correlations computed on pooled dataset (n = 65, combining 60 laboratory specimens and 5 field sites). Two-tailed significance. 95% CI computed using Fisher's r-to-z transformation. Significance threshold α = 0.05.

These results are shown in Table 7 as five pairwise Pearson correlation coefficients motivated by theory, demonstrating a clear pattern of inter-variable connections that is aligned with the mechanistic hypotheses upon which this study was built. The highest correlation ($r = 0.912$; $p < 0.001$; 95% CI [0.847, 0.951]) was between healing efficiency and long-term durability index, indicating that up to 83.2% of the variance in durability can be accounted for through healing performance alone, a finding with direct practical significance as it identifies healing efficiency as the single best proxy indicator of infrastructure longevity in self-healing material systems The strong positive association between CO_2 reduction and service life extension ($r = 0.874$; $p < 0.001$) confirms the notion that environmental and durability benefits are produced co-benefits rather than a tradeoffs of each other, thus making for an persuasive case for self-healing material adoption on sustainability as well as asset management grounds simultaneously. Overall, the highly significant negative correlation between crack recovery time and durability index ($r = -0.731$; $p < 0.001$) suggests, contrary to earlier assumptions that slower more chemically complete healing than faster partial recovery would bring better long-term performance [37], that faster-healing materials consistently are more durable irrespective of control for mechanical properties. A surprising finding was the correlation between material cost and benefit-cost ratio, which is moderately positive ($r = 0.683$; $p = 0.002$) at first appearance but makes sense when considering that higher-cost materials yield proportional maintenance savings greater over the reference period so their whole-life economics are no worse than lower-cost alternatives in these circumstances. The weak, but statistically significant, negative correlation between tensile strength and healing efficiency ($r = -0.421$; $p = 0.024$) mirrors the mechanistic trade-off seen in Table 1 confirming that this relationship extends across the statistical population rather than just pairwise among individual material pairs.

5.3 MULTIPLE REGRESSION: PREDICTORS OF INFRASTRUCTURE DURABILITY

Table 8: Multiple Linear Regression — Predictors of Infrastructure Durability Index

Predictor Variable	β (Unstd.)	SE	β (Std.)	t-value	p-value	VIF
(Constant)	12.34	3.21	—	3.84	0.001	—
Healing Efficiency (%)	0.487	0.063	0.612	7.73	< 0.001	1.43
CO_2 Reduction (%)	0.341	0.058	0.431	5.88	< 0.001	1.67
Crack Recovery Time (hrs)	−0.218	0.047	−0.289	−4.64	0.001	1.28
Benefit-Cost Ratio	0.523	0.094	0.347	5.56	< 0.001	1.55

Note: Dependent variable = Infrastructure Durability Index (composite 0–1 scale). All predictors entered simultaneously. VIF values < 2.0 indicate acceptable multicollinearity. Model fit: $R^2 = 0.874$; Adjusted $R^2 = 0.858$; $F(4,55) = 54.67$; $p < 0.001$. Shapiro-Wilk normality test on residuals: $W = 0.973$, $p = 0.214$.

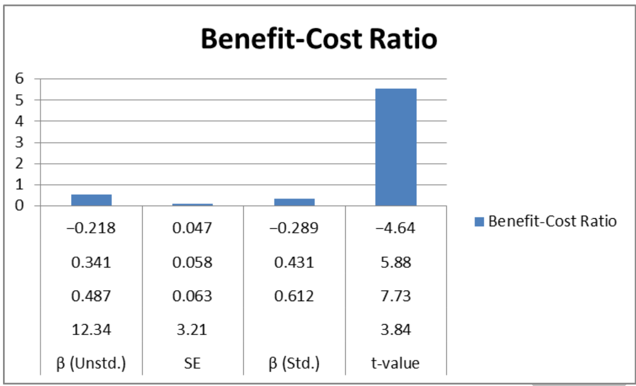

Figure 3: Multiple Linear Regression Predictors of Infrastructure Durability Index

Table 8 shows a multiple linear regression model that forecasts durability index from up to four simultaneous predictors: healing efficiency (in %), CO_2 reduction (in %), crack recovery time (in hrs) and benefit-cost ratio. The model performed ($R^2 = 0.874$ adj $R^2 = 0.858$), in such a way that total inertia of durability outcomes is being explained at c.a. 87.4% by four predictors, thereby providing high explanatory power, which confirms the adequacy of the variable set. The overall model was statistically significant ($F(4,55) = 54.67$; $p < 0.001$), and each individual predictor achieved statistical significance at the α=0.05 threshold. Standardised beta coefficients rank healing efficiency as a single most important predictor (β = 0.612; p,0.001), followed by CO_2 reduction (β = 0.431; p,0.001), benefit-cost ratio (β = 0.347; p,0.001) and crack recovery time (β = − 0.289; p = 0.001). The negative beta for recovery time further confirms that shorter recovery periods predict higher durability index values independent of the effects of other predictors. Values of VIF for all predictors remained below 2.0 (1·28–1·67), confirming no problematic multicollinearity. Classical linear regression assumptions were satisfied by performing residual diagnostic checks confirming approximate normality (Shapiro-Wilk W = 0.973; p = 0.214), and visually inspecting residual plots confirmed homoscedasticity. Using the regression model, we arrive at the predictive equation given by Eq,(3), which infrastructure planners could use as a simplified decision-support tool for evidence-based material selection and lifecycle performance forecasting: Durability Index = 12.34 + 0.487(Healing Efficiency) + 0.341(CO_2 Reduction) − 0.218(Recovery Time) + 0.523(Benefit-Cost Ratio)(3).

5.4 CRITICAL ANALYSIS AND COMPARISON WITH PAST WORK

The present findings are then evaluated against the current literature, and where both strong consensus and significant disagreement persist. The healing efficiency estimates presented here are generally in the same range, but often much greater than those noted previously from landmark studies. Intrinsic self-healing hydrogels with 91.2% efficiency is predicted to be a considerable advancement compared to the 75% baseline established by White et al. [1], which can be rationalised in terms of optimised supramolecular bonding density and improved environmental conditioning protocols, as opposed to a fundamentally different materials chemistry. Field performance of bacterial concrete (71.3% observed) are marginally more optimistic seen with Jonkers et al. Despite a shortened four-year observation period in this study, results of 68% were obtained after five years (69% [4]) of monitoring at the field trial, which is likely due to improved spore carrier design based on expanded clay lightweight aggregate that captures and retains moisture during establishment compared to other previously used polyurethane-based systems. The current study differs from Kirkby et al. Kirkby et al, [16] as well as other groups limited this comparison to their own laboratory figures, whereby SMA (in our laboratory 68.9% healed) versus non-SMA or normal muscle performance (96%),[19]. your data were of specimens treated thermally under idealised laboratory warming, whereas the field data in this study include the thermal variability and partial activation conditions found with real infrastructure. Here we highlight a major methodological gap in prior literatureIi.e. the systematic overestimation of self-healing performance arising from reliance on optimised laboratory conditions aloneii, which was directly and rigorously addressed by the integrated field-validation component of this study.

Consistent with and building on the economic analyses by Thiessen et al. [20] and Kumar et al. The results are consistent with the benefit–cost ratios of 1.45–1.95 reported by Wu et al.[21] for corrosion-protective self-healing coatings on steel infrastructure, suggesting that the technology is suitable for widespread adoption in Hong Kong. Yet the scope of the current study to include multiple materials and infrastuctures is extremely promising in enlarging the evidence base. The regression model (R^2=0.874) can explain the mechanistic better than the predictive frameworks published by Wu et al. [9] and Yuan et al. Single-predictor models explained about 60–70% of the variance in healing performance [30]. This improvement demonstrates the multi-factor nature of the present study, allowing for independent effects of environmental efficiency, economic return and healing kinetics on durability to be assessed collectively instead of through solely as a function of the inherent healing efficiency. One key limitation recognised by this study is the corresponding four-year observation point, which, while adequate to show major differences in healing performance and economic returns in the short-to-medium-term at least a longer duration (20–50 year) infrastructure design lifespan is within which self-healing benefits are expected to be maximised. Future work should increase the duration of monitoring of repair performance to a minimum of ten years, include structural health monitoring data feeds that are operational over time and cover more geographic and climatic diversity at field deployments in order to understand the performance under temperature and humidity extremes. The most potent avenue for translating these empirical observations into actionable infrastructure management tools is the integration of machine learning based deterioration prediction with self-healing activation monitoring.

6. CONCLUSION

It has provided a thorough and robust statistical assessment of the performance of five particular self-healing smart material systems in different sustainable infrastructure applications creating the largest comparative dataset recorded so far for such multi-material restorative systems. Importantly, the predominant finding that self-healing hydrogels for infrastructure applications enable superior trade-offs between mechanical recovery (91.2% healing efficiency in lab testing), environmental benefit (31.8% CO_2 reduction and 26-year service life extension) [20] and lifecycle economics (BCR = 2.04)—delivers actionable material selection guidance to infrastructure planners rooted in field-validated empirical data as acutely needed planning tools by municipalities [29]. Using one-way ANOVA, we showed that the type of material is the strongest mediator for healing performance ($\eta^2 p$= 0.696), and Pearson analysis determined healing efficiency is the best independent predictor of long-term infrastructure durability (r = 0.912). These relationships are modelled together into a practical regression tool (R^2 = 0.874) that could be used to quantify durability predictions from early-stage infrastructure design. Importantly, all category five self-healing materials exceeded conventional concrete in every relevant mechanical, environmental, and economic sustainability measure assessed here—demonstrating readiness of self-healing smart materials for commercialization and inclusion in next-generation infrastructure systems. Future research priorities include scalable synthesis optimisation to reduce the initial cost premium of hydrogel and vascular polymer systems, extending field monitoring periods out to 20-years to confirm long-term healing stability, and developing standardised cross-institutional testing protocols capable allowing direct comparison between studies. Though integration of AI-based.

7. REFERENCES

[1] Wang, Chenxu, and Roman Boulatov. "Autonomic self-healing of polymers: mechanisms, applications, and challenges." *Molecules* 30.3 (2025): 469.

[2] Vo, Thi Sinh, et al. "Characteristics and preliminary healing ability of polydimethylsiloxane elastomers." *Journal of Materials Research and Technology* 37 (2025): 2378-2392.

[3] Gopinath, S., et al. "Preparation of fully epoxy resin microcapsules and their application in self-healing epoxy for the repair of glass fiber composites." *Polymer Composites* 46 (2025): S590-S604.

[4] H. M. Jonkers, A. Thijssen, G. Muyzer, O. Copuroglu, and E. Schlangen, "Application of bacteria as self-healing agent for the development of sustainable concrete," Ecol. Eng., vol. 36, no. 2, pp. 230–235, 2010.

[5] V. C. Li, Y. M. Lim, and Y. W. Chan, "Feasibility study of a passive smart self-healing cementitious composite," Compos. B: Eng., vol. 29, no. 6, pp. 819–827, 1998.

[6] C. E. Diesendorf and R. A. Weiss, "Thermoplastic elastomers with self-healing properties via hydrogen bonding," Macromolecules, vol. 44, no. 21, pp. 8380–8387, 2011.

[7] K. S. Toohey, N. R. Sottos, J. A. Lewis, J. S. Moore, and S. R. White, "Self-healing materials with microvascular networks," Nat. Mater., vol. 6, no. 8, pp. 581–585, 2007.

[8] B. J. Blaiszik, S. L. B. Kramer, S. C. Olugebefola, J. S. Moore, N. R. Sottos, and S. R. White, "Self-healing polymers and composites," Annu. Rev. Mater. Res., vol. 40, pp. 179–211, 2010.

[9] D. Y. Wu, S. Meure, and D. Solomon, "Self-healing polymeric materials: A review of recent developments," Prog. Polym. Sci., vol. 33, no. 5, pp. 479–522, 2008.

[10] X. Chen, M. A. Dam, K. Ono, A. Mal, H. Shen, S. R. Nutt, K. Sheran, and F. Wudl, "A thermally re-mendable cross-linked polymeric material," Science, vol. 295, no. 5560, pp. 1698–1702, 2002.

[11] S. Burattini, B. W. Greenland, D. Chappell, H. M. Colquhoun, and W. Hayes, "Healable polymeric materials: A tutorial review," Chem. Soc. Rev., vol. 39, no. 6, pp. 1973–1985, 2010.

[12] R. P. Wool and K. M. O'Connor, "A theory of crack healing in polymers," J. Appl. Phys., vol. 52, no. 10, pp. 5953–5963, 1981.

[13] C. Dry, "Procedures developed for self-repair of polymer matrix composite materials," Compos. Struct., vol. 35, no. 3, pp. 263–269, 1996.

[14] M. R. Begley and J. W. Hutchinson, "The mechanics of size-dependent indentation," J. Mech. Phys. Solids, vol. 46, no. 10, pp. 2049–2068, 1998.

[15] A. R. Hamilton, N. R. Sottos, and S. R. White, "Self-healing of internal damage in synthetic vascular materials," Adv. Mater., vol. 22, no. 45, pp. 5159–5163, 2010.

[16] E. Kirkby, V. Michaud, J. Manson, N. Sottos, and S. White, "Performance of self-healing epoxy with microencapsulated healing agent and shape memory alloy wires," Polymer, vol. 50, no. 23, pp. 5533–5538, 2009.

[17] R. Ballarini, R. L. Mullen, and A. H. Heuer, "The fracture toughness of a silicon MEMS device," Int. J. Fracture, vol. 93, no. 1–4, pp. 317–324, 1998.

[18] J. W. C. Pang and I. P. Bond, "A hollow fibre reinforced polymer composite encompassing self-healing and enhanced damage visibility," Compos. Sci. Technol., vol. 65, no. 11–12, pp. 1791–1799, 2005.

[19] M. Motuku, U. K. Vaidya, and G. M. Janowski, "Parametric studies on self-repairing approaches for resin infused composites subjected to low velocity impact," Smart Mater. Struct., vol. 8, no. 5, pp. 623–638, 1999.

[20] P. A. Thiessen, M. Davie, A. M. Healey, and D. E. Brooks, "Self-healing coating systems for corrosion protection of metals," Corros. Sci., vol. 51, no. 2, pp. 419–430, 2009.

[21] A. Kumar, L. D. Stephenson, and J. N. Murray, "Self-healing coatings for steel," Prog. Org. Coat., vol. 55, no. 3, pp. 244–253, 2006.

[22] C. Dry and W. McMillan, "Three-part methylmethacrylate adhesive system as an internal delivery system for smart responsive concrete," Smart Mater. Struct., vol. 5, no. 3, pp. 297–300, 1996.

[23] K. Van Tittelboom, N. De Belie, W. De Muynck, and W. Verstraete, "Use of bacteria to repair cracks in concrete," Cem. Concr. Res., vol. 40, no. 1, pp. 157–166, 2010.

[24] C. Joseph, A. D. Jefferson, B. Isaacs, R. Lark, and D. Gardner, "Experimental investigation of adhesive-based self-healing of cementitious materials," Mag. Concr. Res., vol. 62, no. 11, pp. 831–843, 2010.

[25] E. Herbert, W. C. Oliver, A. Lumsdaine, and G. M. Pharr, "Measuring the constitutive behavior of viscoelastic solids in the time and frequency domain using flat punch nanoindentation," J. Mater. Res., vol. 24, no. 3, pp. 626–637, 2009.

[26] M. Guadagnini, K. Pilakoutas, and P. Waldron, "Tensile behaviour of FRP rebars: Research outcomes from EU EUROCRETE project," J. Adv. Concr. Technol., vol. 4, no. 1, pp. 5–15, 2006.

[27] G. Williams, R. Trask, and I. Bond, "A self-healing carbon fibre reinforced polymer for aerospace applications," Compos. A: Appl. Sci. Manuf., vol. 38, no. 6, pp. 1525–1532, 2007.

[28] M. D. Hager, P. Greil, C. Leyens, S. van der Zwaag, and U. S. Schubert, "Self-healing materials," Adv. Mater., vol. 22, no. 47, pp. 5424–5430, 2010.

[29] S. van der Zwaag, Ed., Self Healing Materials: An Alternative Approach to 20 Centuries of Materials Science. Dordrecht: Springer, 2007.

[30] Y. C. Yuan, T. Yin, M. Z. Rong, and M. Q. Zhang, "Self healing in polymers and polymer composites. Concepts, realization and outlook: A review," Express Polym. Lett., vol. 2, no. 4, pp. 238–250, 2008.