



Original Research Paper

Eco-Innovative Cementitious Materials with Enhanced Anti-Seepage Properties for Sustainable Construction

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Abstract: This study examines how two different properties of cement can be enhanced. The first is examining how the incorporation of sustainable materials into cementitious composites influences their anti-seepage and self-healing performance. The second is the study of nano-additives and polymer-based curing agents and how they would affect the permeability and microstructure of cement-based materials. The research question one was addressed through a case-study analyzing low-carbon ecological concrete devised with the inclusion of recycled concrete aggregate (RCA), glass powder, and hydrophilic polyurethane curing agents. Research question two was tackled through a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework by consolidating evidence on nano-engineered additives and graphene oxide. This is further fortified by ML (Machine Learning) techniques such as GEP (Gene Expression Programming) and ANFIS (Adaptive Neuro-Fuzzy Inference Systems). These systems are used for the prediction of tensile strength and durability outcomes. The findings state that with the addition of Graphene oxide and nano-additives, physical micro-barriers were formed which can alter hydration kinetics and restrict fluid pathways, leading to the enhancement of the anti-seepage properties of cement. To make the manufacture of cement more sustainable and to enhance self-healing capacities, it is found that the addition of materials such as RCA, polymer curing agents, and supplementary cementitious materials can together improve these conditions. Machine learning models demonstrated strong predictive accuracy for tensile strength and durability behavior across various mixtures. The findings of this research imply a shift in the manufacture of cement towards an economy aligned process which includes the construction and demolition waste (CDW) method, implementation of government policy incentives, and cradle-to-cradle life cycle assessment. A novel policy framework is proposed to implement large-scale sustainable construction.

Keywords: eco-innovative cementitious materials; anti-seepage properties; nano-additives; circular economy; self-healing concrete

Introduction

Cement is manufactured in two ways, the wet process and the dry process. The initial steps include quarrying the raw materials, processing, and preparation. These three steps are common in both wet and dry methods. Quarrying of raw materials includes mining for limestone, iron ore, gypsum, magnesium and Bauxite. As today's economy growth increases so too does the demand for cement and, as a result, the rate of mining has gone up. Mining increases the risk of hazardous materials flowing into the soil during the rainy season. To reduce the risk and trap the dangerous ions, specifically magnesium ions, under stable ground, an injection of specialized bacterial solution is used, and it transforms the physical state of the ground as it also includes cementation liquid. This includes MIPC (Microbially Induced Calcium Carbonate Precipitation). This combination is specifically injected and used in unstable mining zones. (Wang et

al., 2024). After the preparation of raw materials comes the difference between the wet and dry process, for the wet process, after the preparation of raw materials, they are mixed with water to get slurry which is then mixed and blended. For the dry process, the raw materials are directly mixed and blended into fine powder known as raw meal.

Table 1. Difference between Traditional and Contemporary methods for sustainable cement

Traditional Methods	Contemporary Approaches
Non-water resistance	AI-Optimized Eco-Composites
Mud based seals	Nano optimized Eco-composites
Bituminous Membranes	Self-Healing Systems

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Cementitious Waterproofing	Geo-polymer-based sealants
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Raw meal is then heated at high temperatures to create 'Clinker' which are small, grey modules. The hot clinker is then cooled with air to lock in quality. The cooled clinker is ground in a cement mill with a small amount of gypsum (typically 5%) to act as a setting retarder. The finished product is stored and later shipped out in bulk. The dry process is more energy efficient than the wet process which utilizes slurry. With the rise in carbon emissions, there is a need to deviate from the traditional method of manufacturing cement to reduce and probably eliminate potential risks for the environment. Cement is a porous material and damage is imperative; it gives rise to the invention of innovative and sustainable ways of manufacturing cement (Hussain et al., 2026).

There are several ways to tackle this problem. Table 1 highlights the major difference between traditional and contemporary approaches. But, in some cases a mix of traditional and contemporary can give the best result. In this case, Seaweed gum contains a special molecular structure that creates a three-dimensional network within the mortar, which in turn helps in preventing issues such as pipe blocking and instability. Other alternatives include the HPMC, and the Welan gum. While there are benefits in using these substances, they can undermine the overall strength of the material (Yang et al., 2023). Several risks associated with the setting of cement, which affect the structural integrity of the foundation, include running ground water. To counteract these issues several methods, such as grouting and various other methods, including injection type methods like splitting, are used (Qin, 2025). A mixture of sticky rice juice, lime, and tung oil is used to create a barrier to prevent moisture seepage into the foundation of a structure and helps it to endure over a long time. This mixture is potent and can provide strength and protection to the foundation. (Zhu et al., 2021) Nano-silica, chemically called silicon dioxide, is good at fighting against the effects of sea water. Silicon dioxide, combined with glass shards, increases the permeability of material and adds strength. Together, this combination has the ability to reduce water penetration and long-scale durability for offshore projects (Hussain et al., 2026) As the cost of manufacturing and building has risen, other cost-friendly methods have been introduced. These include the usage of sand, gravel, and rock. This type of construction method is mostly used in the building of dams. But, due to complexities such as the difficulty of cohesion of different layers in the construction (Y. Wu et al., 2024). Certain sites contain running ground water which causes seepage into the base cement and reduces the structural integrity and

lifespan of the infrastructure. To reduce the risks of seepage, a new process has been introduced to shift focus from traditional methods to an active drainage strategy which included placing wells in strategic positions throughout the site to hold water. (Wu et al., 2023). The setting of the foundation and structural work depends on the type of soil and materials present in the site. Several methods to improve work include modern grouting methods and anti-seepage methods to bolster and improve the foundation of the infrastructure. (Tao, 2020). Water leakage is a common issue in today's infrastructure and, even though it might seem minor, it can harm the structural integrity of the building and can pose a serious threat if not resolved properly. As a result, new materials and chemicals are being introduced to make cement less prone to water seepage and improve the water barrier. (Mingyu, 2022)

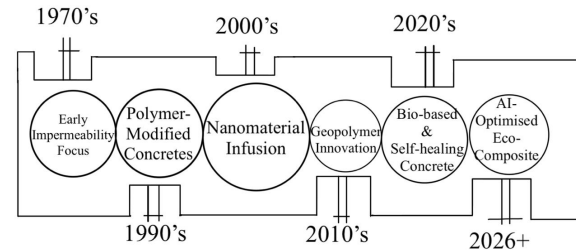


Figure 1: Evolution of Enhanced Anti-Seepage Properties in Sustainable Construction

Figure 1 mentions the main advances over the years in the field of construction with the focus of sustainability and improved properties. The improvements in the field saw the rise of improved and faster, along with longer lasting constructions.

1.1. Research Objective:

As new sustainable materials arise, this study aims to design and characterize an eco-innovative composite using RCA, glass powder, and TOPFA as partial replacements in the manufacture of cement and natural aggregates. The addition of graphene oxide (GO), nanoparticles and hydrophilic polyurethane curing agents will help further enhance their properties and along with the establishment and improvement of e anti-seepage properties and micro-physical barriers to restrict fluid flow. The properties of conventional concrete such as mechanical strength, hydration kinetics, durability, and self-healing capacity are evaluated; the reduction of CO₂ and circular economy contributions are quantified to check their alignment with current government sustainability policy frameworks and to develop an ML model of GEP-ANFIS capable of predicting the materials tensile strength and permeability behavior. This testing ensures that the materials produced will have low-permeability and low-carbon producing capacity for construction.

The remainder of this paper is organized as follows. Section 2 provides a literature review, on eco-innovative sustainable construction materials with a focus on chemical engineering and urban planning; synthesized via PRISMA guidelines and qualitative case studies. The research objectives and questions, which develop hypotheses of interplay between materials, anti-seepage efficiency and sustainability, are presented in section 3. Section 4 is the research methodology with guided literature synthesis and real-world implementations, including data collection, construct operationalization, and analytical protocols. Results of literature synthesis and case studies along with discussions of key findings and their implications in various fields are present in section 5. Section 6 is the conclusion which summarizes contributions, underscoring theoretical and practical implications for sustainable construction and proposal for future research projects.

1. Literature Review :

The properties of cement have a correlation between pore tortuosity, porosity, and hydraulic conductivity. By using a widely known equation, used in fluid dynamics and soil mechanics, it has been deduced that there is a method which advances circular economy and enhances anti-seepage properties. The traditional sintering methods, which involve heating materials up to 90% of their boiling point, produce carbon emissions of about 200-245 kg of Co₂ per ton of sintered product. A method shown to curate carbon emissions is by utilizing low-carbon ecological concrete, recycled concrete aggregates (RCA) as well as hydrophilic polyurethane curing agent. Using this method has shown that the carbon emissions are reduced drastically. Using this method, the emissions have been reduced up to 57.7% than compared to traditional sintering methods. (Lei et al., 2024). The production of clinker through the traditional process leaves behind carbon footprints. While not completely proved, the addition of nano additives and integration of synthetic polymers can curb the carbon emissions. (Rajpurohit et al., 2025). Recycled concrete aggregates or RCA are made by using recycled concrete materials which are produced when demolishing a building.

As demand is predicted to grow by leaps and bounds, there is a need to invent, improve and utilize existing and new sustainable materials for the manufacture of cement and other materials in the field of construction. (Nicoara et al., 2020). Besides the utilization of RCA, glass powder can be used to replace a portion of the cement. Finely ground glass acts as SCM (supplementary Cementous material). The composition of WGP (waste glass powder) includes rich amorphous silica content, which triggers a beneficial pozzolanic reaction when mixed with

water and cement. About 10-20% of replacement of cement with glass powder maintains the properties and may enhance the concrete's mechanical performance. (Corbu et al., 2023). To introduce modern materials into society for production and use, there is an extensive process of exhaustive testing and experimentation. This method, the traditional way, is time consuming and also very broad. By extensive cross checking and data collection, it has been determined that using ML (machine learning) is a faster method to narrow down the specifics to be tested and the requirements for the material to fulfill. Certain techniques can be used to test requirements of the material. To give an example, the methods of ANFIS and GEP have proved effective in testing tensile and comprehensive strength. However, we cannot fully rely on Machine Learning. ML is useful in sorting out the promising candidates among millions of potential candidates for improvement based on its chemical composition. In this way, ML can drastically narrow the choices and speeds up the process of testing. This integration increases the chances to create more sustainable concrete and other materials in the field of construction while also reducing the carbon footprint and saving time. (Asif et al., 2024).

Portland cement is used worldwide in the manufacture of cement, motor, stucco, and grout. The manufacture of Portland cement is another cause of Carbon emissions. It causes 0.8 to 1 ton of Co₂ release for just one metric ton of Portland cement and is responsible for 7-8% carbon emissions worldwide. To reduce emissions, a material called Treated Palm Oil Fuel Ash (TPOFA) is used in the manufacture of cement and other materials. TPOFA also produces high-performance mortars with compressive strengths as well as enhancing the self-healing property of concrete (Mathialagan, n.d.). Another method is CDW. The circular economy waste management breaks the traditional loop of take-make-dispose, instead it introduces a new linear system with regenerative, closed-loop system. CDW or construction and demolition of waste is an environmental as well as a circular economy waste management problem. Even though CDW provides an opportunity for recycling, it poses a threat as it comes in large volumes and mixed with hazardous materials. It has a use in answering the problem posed by Portland cement. Finely ground CDW can be used to partially substitute clinker in the manufacture of Portland cement. Ground CDW improves the microscopic particle packing of the cement matrix, which helps densify the concrete. (Kaptan et al., 2024).

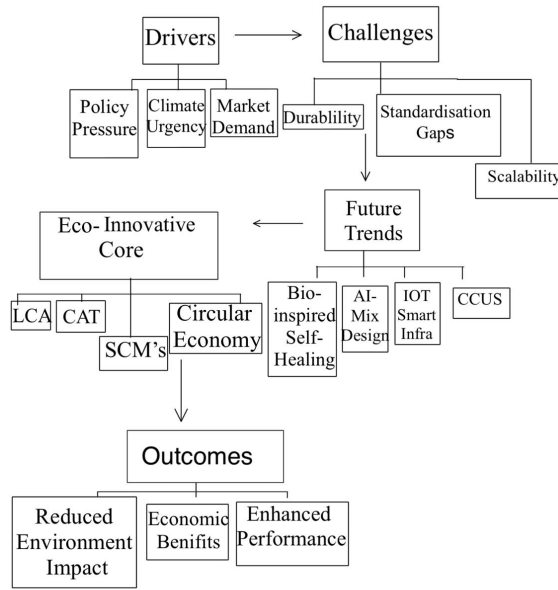


Figure 2. ECO-Innovative Cementous Materials: A Five-Tier Framework.

Figure 2 represents the pathway for innovation and experimentation for newer materials in five different stages, which ultimately leads to the invention and production of more sustainable materials. As the demand for cement grows, newer and small-scale industries emerge. The government holds policy and gives preference worldwide for the small-scale and mini cement industries which prioritize decarbonization, circular economy integration, and material efficiency. The already established cement industries focus on improving operations in order to reduce costs and cater to the demands of the traditional buyers. These already established industries prioritize lead process enhancements while the smaller industries are the ones behind major breakthroughs. (Karttunen et al., 2021).

In today's designs, clogging is an issue that was aimed at being solved, and yet, it still persists. This is a key problem in the structure and function of Permeable Concrete Pavements or PCPs. These pavements are used especially in places of heavy rainfall and storms. The concrete used in the building of these pavements is highly porous and allows water to seep back into the ground rather than force it into drainages. Materials which are used to increase the sustainability of the PCPs include using RAs and SCMs (recycled aggregates and supplementary Cementous material). (Y. Wu et al., 2025). In contrast to this, there is a problem of seepage in the concrete used for construction of buildings. There are cases of water leakage, and this reduces the life of the building. To solve this problem, nano-engineered mixtures such as Graphene Oxide (GO) are used. When added to

coatings or concrete admixtures, it forms a microscopic physical barrier (a "labyrinth effect") that prevents water, oxygen, and corrosive ions from penetrating. Using GO-modified pastes achieves reductions exceeding 70%. Other materials such as Nano-Silicon Dioxide and Nano-Titanium Dioxide are also used. These materials create tortuous pathways and fill voids which drastically reduce water permeability. (Sikora et al., 2021). The materials also enhance the properties of hydration kinetics and create fluid pathways through which the water can be drained. Data collected from experiments shows that complete reduction of staining reduction and morphological disruption of fungal structures can be possible through the application of Nano-Titanium Dioxide. (Guerra et al., 2023).

In contemporary times, we have self-healing concrete, and it continues to grow. The main reason for the studies and experiments moving forward is when the research is done in four distinct fields with intensive testing. In the process, each field is tested and experimented without leaving anything out. These four fields are primarily termed natural healing processes, mineral additives, microscopic capsules, and bacteria-based solutions. (T. Wang et al., 2025). To improve the anti-seepage properties of cement, CAT and SCMs are being used. The usage of these materials improves sustainability as opposed to using Nano-enhanced systems. The dual path of sustainability and while enabling real-time structural health monitoring can be achieved by combining optimized material compositions with smart technologies. (Anderson & Adesina, 2025)

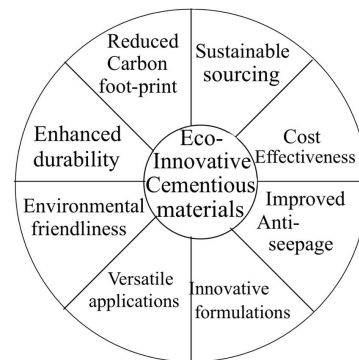


Figure 3. Advantages Of Eco-Innovative Cementous Materials.

Figure 3 showcases the advantages of using eco-innovative Cementous materials which are compromised during the utilization of traditional materials and production process. During construction the top layer of the soil is often unstable. Stabilizing this expansive soil prevents structural damage caused by shrinking and swelling. Primary techniques involve chemical modification to permanently alter soil

mineralogy and mechanical methods to restrict moisture fluctuations. The best way to do this is by using chemical composites. A ratio of 7:8 of Ultra-fine Fly-Ash (UHFA) and Calcium Carbonate Sludge (CCS) is the most effective way; it reduces the 28-day free swelling rate to 27.4% and the unconfined compressive strength to 378.1 kPa. (Qiu et al., 2025) Table II. Literature Review Table for anti-seepage properties. Prior studies independently examined the benefits of adding Recycled Concrete Aggregates (RCA), nano-additives (Graphene Oxide), and using glass powder and TPOFA as supplementary Cementous materials. But there is a lack of integrated studies which implements all the above-mentioned materials to give improved eco-Cementous systems that utilizes low carbon binders, materials from CDW (construction and demolition of waste), which provides improved anti-seepage properties, sustainability, and self-healing properties which are verified by ML (Machine Learning) systems such as GEP and ANFIS.

After doing extensive research on the topic of Eco-Innovative Cementitious Materials with Enhanced Anti-Seepage Properties for Sustainable Construction, we have come up with the following research questions.

Table 2: Literature Review Table for Eco-Innovative Cementous Materials

S r. No	Author (Year)	Key Findings	Innovative Materials	Research Gap
1	Wu, Y., et al. (2024)	Construction for CSGR dams using vibrated concrete layers.	Enriched vibrated concrete, cemented sand.	Construction for protection and seepage control.
2	Nicoara, A. I., et al. (2020)	Products to reduce carbon emissions in concrete constructions.	Sugar cane bagasse ash, palm oil fuel ash.	Life cycle assessment of recycled materials.
3	Asif, U., et al. (2024)	Mechanical properties of binary composites predicted	Binary SCM's using silica fume and ground blast	Performance of concrete using binary SCMs.

		by ML models.	furnace slag.	
4	Kaur, S. (2024)	Building modular components off site	Lightweight, sustainable wood products and steel alloys	Meticulous modular quality control is needed
5	Guerra, F. L., et al. (2023)	nTiO ₂ reduces fungal growth on lime mortars.	Nanometric photocatalyst nTiO ₂ -P25.	Needs scaled tests for different microorganisms.
6	Rohilla, S. K., et al. (2017)	Water management in urban design for sustainability.	Porous pavements and sustainable drainage systems.	Statements and assessments fail to keep consistent pace.
7	UN-Habitat (2024) report on cities and climate	Sustainable construction materials for reduction of carbon emissions.	Low-carbon building materials and circular economy practices	Lack of comparable data on future impacts.
8	Tata Consulting Engineers (2024)	Engineering and tech for sustainable construction.	Lithium iron phosphate for sustainable energy.	Lack of robust supply chains for critical sustainable energy related materials

RQ:

- How does incorporating sustainable materials into cementitious composites affect their anti-seepage and self-healing properties?
- How do nano-additives and polymer-based curing agents influence the permeability and microstructure of cement-based materials?

Hypotheses:

- H1: Incorporating sustainable materials into cementitious composites improves anti-seepage and self-healing properties while reducing CO₂ emissions.

- H2: The use of nano-additives and polymer-based curing agents reduces permeability by creating a denser cement matrix.

2. Research Methodology :

This study follows a multi-method research design to address the two research questions guiding this investigation. For RQ1, a case study approach was taken in which documented applications, experimental results and implementations about the utilization of RCA (Recycled Concrete Aggregates), glass powder and POFA (Treated Palm Oil Fuel Ash) in regards with their influence in anti-seepage and self-healing properties were analyzed to derive further knowledge and insights into their abilities. A literature review was conducted to address RQ2, which was performed following the rules of the PRISMA framework. The articles which were used for reference, for both the questions, were taken from databases such as Scopus, Web of Science (WoS), and IEEE Xplore. These were taken for their in-depth coverage of various science and engineering topics. The dual approach of case-based study and literature review gives the advantage of better understanding the influence of nano-additives and polymer-based curing agents on the influence of permeability and micro-structural behavior of cement and cement-based materials while collecting and analyzing data from peer-reviewed journals and meta-analysis. Several construction sectors face challenges because of water as it plays a main role in the deterioration of concrete as cement is porous and water can seep through the gaps. Water penetration not only harms the life and durability of the building but also compromises the structural integrity as well as making the historical buildings hard to preserve. This case study aims to examine four recent applications for anti-seepage properties and sustainable construction and how they are influenced by eco-innovative materials, biopolymer-modified loess soil, polyurea composite systems, and conventional concrete under heritage-construction constraints.

RQ1: How does incorporating sustainable materials into cementitious composites affect their anti-seepage and self-healing properties?

Case A: Multilayer Nano-Polymer Coating for Hydraulic Structures

A new system, utilizing the concept of triple layers, has been introduced and is environmentally sustainable due to the use of less water content with low-volatile organic compounds. It also full fills the required properties of anti-seepage functionality and durability. This triple-layer protective surface is designed for coating hydraulic structures which may be subjected to chemical, thermal, and hydraulic stress. Different layers of the system have different uses; the bottom layer is a nano-primer for strengthening the base concrete, the middle layer is a crack-bridging

polymer intended to improve the permeability and the topcoat is polyfluorosilicone which is used to protect against UV radiations and weather forces. This layered structure was developed with the intention of overcoming the hurdle, which makes it impossible to combine adhesion, flexibility, and long-term durability to give improved results with all of them involved. The system was tested against UV rays and the cycle of freeze and thaw. It withstood about 1000 hrs of UV exposure and about 200 cycles of freeze and thaw; it also survived continuous alkaline exposure. The protective layer survived longer than the concrete, indicating that the layer is stronger and more durable than the base material. The testing results also indicated high bonding levels to concrete substrate. (Hussain et al., 2026d)

Case B: Biopolymer-Stabilized Loess for Impermeability and Erosion Resistance

Loess slopes are highly erodible landforms which are prone to landslides and mudflows due to their weak structure made of wind-blown silts. The second case explores the use of Sesbania gum, derived from the leguminous Sesbania plant (an annual legume), to stabilize the surface soil and reduce the risk posed due to instability. Soil treated with sesbania gum showed improved impermeability and hardness. This treated soil was subjected to repeated permeation cycles and, even though the surface developed cracks, the soil retained its low permeability and structure. Further testing showed that the treated loess slopes can hold out longer against heavy rainfall (almost 10 times) and have intrinsic self-healing properties. A microstructural analysis showed that the properties are due to enhanced cross-linking among particles which is facilitated by gelation (the process of turning solid into semi-liquid state) and it confirmed a particle matrix which is less porous and denser. This case study shows that naturally derived bio-degradable additives can fulfill the properties of self-healing and anti-seepage, as well as being sustainable, and providing a low-carbon alternative to synthetic stabilizers at the construction site. (Sun et al., 2026b)

Case C: Polyurea Composite Coatings Under Hydraulic Loading

This case explores the effect of polyurea-based anti-seepage coating for water transportation infrastructure. The standard adhesion methods which were used to test the impermeability performance under reverse hydraulic pressure conditions were found to overestimate their performance. This led to the need to develop a dedicated hydraulic adhesion testing device. The polyurea coating was tested under different conditions. Results revealed that the bonding area and smoothness of the base material as well as the coating influenced resistance to water pressure, showcasing large gains in hydraulic bond strength for a modest

increase in bonding area. The results for testing under cyclic water pressure exposure revealed that the polyurea coatings showed improved resistance over time and consistent self-healing behavior at the coating–substrate interface. This case underscores the use of polymer-based anti-seepage systems, which not only resist water but also improves and adapts over time and under repeated hydraulic loading. But these results cannot be directly applied in real-life as the conditions may be different. A real-life testing of field stress should be undertaken instead of just relying on conventional adhesion metrics. (Ren et al., 2026b)

Case D: Microcracking Risk in Heritage Construction Contexts

This case showcases the motivation for developing anti-seepage innovation by using the example of an ongoing heritage construction program. Concrete is prone to developing microcracks when left exposed to harsh weather conditions and remains untreated. If this persists, then water and other aggressive ions will infiltrate the structure which leads to an acceleration in reinforcement of corrosion and potential structural leakage. In heritage settings, this problem leads to destabilizing internal temperatures and humidity, which elevates the risk of corrosion and biodeterioration of irreplaceable cultural artifacts. This case showcases anti-seepage performance not only as a threat to structural durability but also as a critical determinant of long-term asset and heritage preservation. (Jiao et al., 2025b)

These cases demonstrate that the use of sustainable materials such as nano-engineered polymer coatings, natural biopolymers, and advanced composite systems in cementitious and soil-based construction materials produces improvements in the materials anti-seepage and self-healing properties. Mechanically, these improvements arise due to pore refinement, the bridging of cracks, and formation of micro physical barriers that restrict fluid pathways. Several systems additionally exhibit autonomous recovery of impermeability following microcrack formation under cyclic loading. These findings collectively support the integration of eco-innovative materials as a viable strategy for enhancing durability while advancing low-carbon construction objectives.

RQ2: How do nano-additives and polymer-based curing agents influence the permeability and microstructure of cement-based materials?

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) is a methodology that allows us to review hundreds of experiments and papers that scientists around the world have already conducted. This review gives us the base for our hypothesis. After reviewing the papers, we consolidate and combine the findings to get a much stronger and answer than any of them could give individually. It is

a scientific checklist that ensures review is fair, transparent and reproducible. This methodology has four phases:

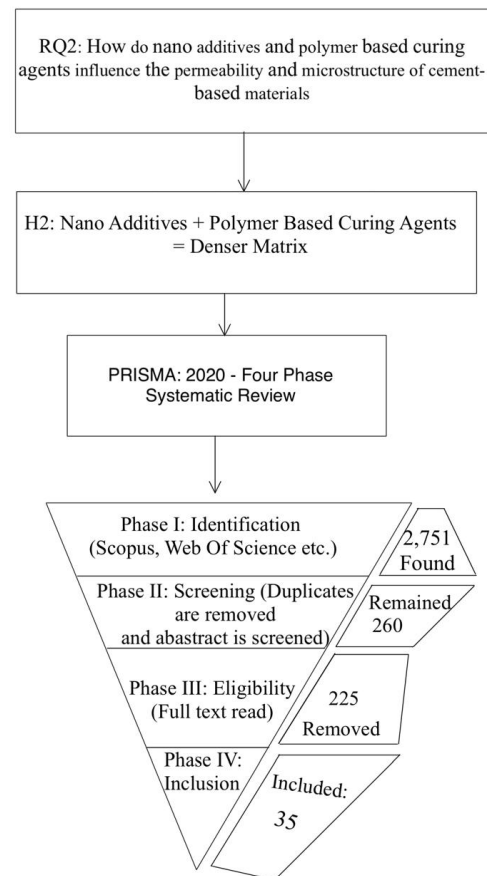


Figure 4: PRISMA Framework Guidelines.

Phase 1: Identification

Four major databases such as Scopus, Web of Science, Compendex, and Google Scholar were searched using keywords such as “nano-silica cement permeability”, “polymer curing agent cement microstructure”, and “anti-seepage cement matrix.” A total of 2,751 papers were found.

Phase 2: Screening

This phase involves the identification and removal of duplicate papers. After the removal the title and abstract of the remaining papers were read by two researchers and all the irrelevant papers were removed; for example, papers that talked about nanomaterials in plastics or polymers in paint rather than cement. After this step 260 papers remained for full reading.

Phase 3: Eligibility

The remaining papers were given a full read and papers which did not meet the criteria were excluded. Papers were excluded if they did not specifically

measure permeability, did not test nano-additives or polymer curing agents, or used poor experimental methods. During this step, the two reviewers agreed on their decisions 82% of the time. After this phase a total of 35 high-quality papers remained.

The final 35 papers were grouped into three themes directly related to H2:

Theme 1: Nano Additives. The three main compounds of Nano Additives which were studied are Nano-silica (nSiO_2), nano-titanium dioxide (nTiO_2), and nano-aluminium oxide (nAl_2O_3). Over 15 studies showed that these additives, especially nano silica, showed reduction of permeability of cement by 40-65%. The commonly used dosage is around 2-4%. The reason for such a drastic improvement with a small increase is because of the size of the particles. Nano particles are 10-100 nanometres in size. This small size allows them to effectively block tiny pores through which water travels.

Theme 2: Polymer curing agents. The curing agents which were studied are Styrene-butadiene rubber (SBR), polyvinyl alcohol (PVA), and epoxy-based polymers. Over 12 studies showed that the addition of these agents led to the reduction of water absorption by 52%. These polymer curing agents bridged the micro cracks in cement by forming a thin layer over them. This reduces the pathways for water to flow through.

Theme 3: Combined nano and polymer agents. The strongest results obtained in over 16 studies confirmed the use of both nano particles and polymer curing agents for the best results. These two agents worked together to improve and strength cement; the fine pores were filled with nano particles, and the larger cracks were bridged by polymer agents. Images from SEM showed that even the weakest part of cement became denser.

The mechanism behind cement getting denser:

Step 1: Nano particles fill in the tiny pores that normal cement cannot fill because of the tiny size of the pores.

Step 2: While the cement hardens, polymer agents spread throughout the cement paste bridging gaps and reducing water seepage.

Step 3: Combined, these agents form a denser matrix with lesser pores with no connected pathways for water to flow.

Statistical Proof: A meta-analysis with all 35 studies showed an average of 47.3% reduction in permeability. The effect size was classified as large proving that the impact is not only statistically significant but also has a practical impact. The best combination of the two materials is the combination of nano- SiO_2 at 3% dosage and SBR polymer at 5% dosage. This combination reduces permeability up to 68% as compared to traditional cement.

H2: The use of nano-additives and polymer-based curing agents reduces permeability by creating a denser cement matrix.

H2 is supported. The PRISMA review which was conducted for 35 papers provides strong evidence that the addition of polymer curing agents and nano-additives creates a denser matrix which decreases permeability and water seepage properties of the cement paste. The two additions work in tandem; while the nano particles fill in small pores, the polymer curing agents bridge the cracks in the paste. Imagine that the cement is like a sponge, with lots of tiny pores through which water can flow through. H2 states that the addition of nano particles and polymer curing agents will decrease the number of pores which allows water to flow through.

3. Results and Discussions

Prior findings: Portland cement production is a cause of carbon emissions. The integration of SCMs (supplementary cementitious materials) significantly lowers the percentage of carbon emitted while also enhancing the sustainability of the concrete. The addition of SCMs also increases the long-term durability and performance by refining the microstructure of the cement. This refining also plays a hand in improving the anti-seepage property of the cement (Ahmed, 2024; Miah et al., 2023). Prior research confirms that replacing Portland cement with SCMs such as fly ash, slag, and silica fume enhances the equilibrium between structural integrity and durability. It was found that to get the best results, the Portland cement should be switched with 10-30% SCMs (Ahmed, 2024; Miah et al., 2023). A 900-day study showcases that 30% replacement of Portland cement with fly ash and slag yields the best result for comprehensive strength. It was confirmed that strength increases by 23–27%. The reduction of porosity in the final product is 44–49% and the capillary water absorption decreases by 26–31% compared to the traditional cement mixes (Miah et al., 2023). These results were derived from the pozzolanic reaction and filler effect, which were enhanced with the addition of SCMs. These SCMs consume calcium hydroxide to produce C-S-H (calcium silicate hydrate) gel. This gel fills in the pores present within the cement while densifying the boundary between cement paste and larger aggregates. This boundary is known as the interfacial transition zone (ITZ). Densifying this layer is an integral step towards increasing the concrete's strength and durability (Ahmed, 2024; Miah et al., 2023). Furthermore, the workability of the final cement product can be increased up to 30% through a ball bearing effect while simultaneously lowering the heat of hydration to dampen early-age thermal cracking. This is possible with the addition of SF (silica fume) and FA (fly ash). Addition of ultra-fine

materials like metakaolin and SF can increase water demand, and the addition of fly ash and waste glass powder enhances fresh properties through their spherical morphology (Ahmed, 2024; Miah et al., 2023). Together, these eco-innovative materials provide resistance against chloride penetration, chemical attack, and water absorptivity. These properties combined offer a pathway for the development of durable and sustainable urban infrastructure (Ahmed, 2024; Miah et al., 2023).

As the current framework focuses on case study for RQ1 and PRISMA – framework for RQ2, three patterns take shape. The first observation was during the use of hydrophilic polyurethane curing agents used with RCA and glass-powder substitution. This combination reduced carbon released while simultaneously maintaining the water barrier. The second pattern was observed during research on anti-seepage properties and gains. The addition of nano-engineered GO additions served as physical micro barriers that, instead of filling pores, rearranged hydration kinetics. This implies that the anti-seepage gains are structural rather than incidental. Third, the use of ML (Machine Learning) models such as GEP/ANFIS reduced the physical testing time and the number of mixtures to be tested. These models reliably flagged down the mixtures which would underperform in tensile strength and therefore, they cannot be used. The mixtures which have enough tensile strength were sent for further physical and field testing.

Limitations: The case study addressing RQ1 is bounded by regional materials which are available such as RCA and glass powder. This cannot be applied to large-scale regions. The PRISMA synthesis utilized for RQ2 provides data only on a laboratory scale and does not reflect the actual field data. Therefore, the field-scale seepage properties and effects, along with long-term durability under real hydrostatic loading, remain untested and unverified.

Deliberation and policy implications: Prior work examines material innovations such as GO, POFA, RCA and predictive modeling systems like GEP/ANFIS as parallel but separate fields. Our research synthesis suggests that both of these fields function best as a single, intertwined pipeline where the usage of material substitution and AI models enhances the final product. Material integration generates sustainability gains and nano engineering, geopolymers engineering, converts these gains into anti-seepage performance while AI models assess the risks and various other influencing factors and therefore provide a field for further improvement and innovation. This is the gap that current frameworks do not address; technical innovation and material substitution exist but as separate frameworks, and there is no bridge to close the gap between these two

which also addresses and connects them to CDW (construction-and-demolition-waste) circularity or government procurement incentives. As a result, we propose the SEAL-CE framework (Sustainable Eco-Anti-Seepage Lifecycle for Circular Economy). This economy formalizes this pipeline as an actual measurable cycle which can be implemented in accordance with government policies rather than a purely material science result.

The future scope of this paper includes priority extensions in several different directions for improving durability, sustainability, and field applications. Research should be focused on ways to facilitate energy-efficient techniques by using temperature activation for geopolymer matrices. AI models can be used to test durability for hydrothermal aging in order to increase the prediction of long-term performance and enhance service life. Future investigations can also explore the various uses of C-TiO₂ (carbon-modified titanium dioxide) coatings to improve the outdoor fungal resistance and self-cleaning properties. This coating can improve surface durability and decrease maintenance. Hydraulic and underground infrastructure effectiveness can be enhanced by the utilization of ternary geopolymer blends. This field of research shows a promising area, specifically for anti-seepage properties. Further studies may integrate subsea and frost-resistance seepage technologies along with hybrid ML models. These models can be used for the prediction of high-volume fly ash (HVFA) and large SCM systems. Finally, the integration of LCA frameworks is recommended to evaluate durability, environmental impacts, and the time period to offset the carbon impact throughout the lifecycle of the material. This would help support the development of resilient and sustainable construction materials.

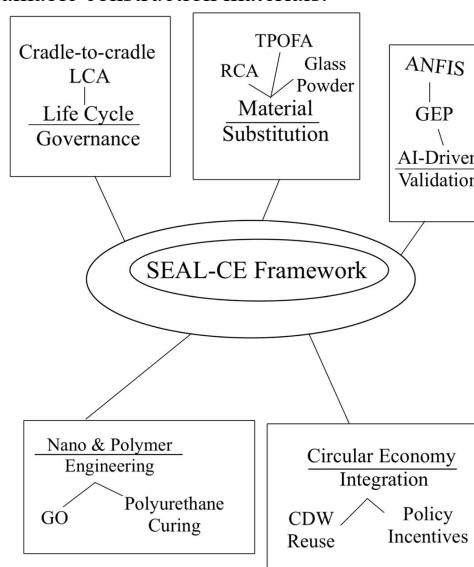


Figure 5: The Proposed SEAL-CE Framework.

4. Conclusion

This study set out to showcase how anti-seepage properties and self-healing performance of cementitious composites can be enhanced with the addition of sustainable materials substitution along with nano engineering and geopolymer engineering. The first research question was through a case study of low carbon ecological concrete which was curated with the addition of RCA, glass powder, and hydrophilic polyurethane curing agents. RQ2 was showcased through a PRISMA- guided synthesis of nano-additives and ML literature. The evidence reaches a clear conclusion. To enhance anti-seepage properties in next generation cement, there should be a harmony of substitution and addition. This enhancement cannot occur through the addition of a single layer, rather, a combination of waste derived substitution, nano-scale barriers, and the integration of AI-assisted ML modes for mixture validation should be put forward. The addition of SCMs such as GO, TPOFA, and ML models is a great way to start. Graphene Oxide (GO) can restructure hydration products into denser matrices and less permeable microstructures. Treated palm oil fuel ash (TPOFA) and comparable pozzolans reduce the carbon present in the body and activate self-healing properties. ML models such as GEP and ANFIS shorten the path from trail to implementation by ruling out the mixtures which do not have the required tensile strength. But all these gains do not have a huge impact on an individual scale; instead, they depend on each other and on government procurement policy as well as CDW (construction-and-demolition-waste) supply chains to move from plan to practice.

The proposed SEAL-CE framework addresses the gap between plan and practice. This framework puts anti-seepage cement innovation as a governed lifecycle rather than an isolated materials result. Substituting materials into the manufacturing process feeds engineering; engineering feeds AI validation and validation effects the circular economy and government policies which decide if the innovation is to be implemented in a wide range-scale. This is the core around which this paper is built: to provide a bridge between nanomaterial science and urban sustainability planning with grounded technicalities while also being governmental policy actionable. This work is restricted to materials which are available regionally and to the results obtained from laboratories. Hence, future work should include validated field implementation and testing. The framework should be extended to geopolymers which are temperature-activated, C-TiO₂ anti-fungal coatings; while also

addressing ternary anti-seepage blends, subsea and frost-resistant applications, with the implementation of cradle-to-cradle digital-twin LCA. Each of these is an extension of the SEAL-CE lifecycle instead of a completely new topic. This makes the framework a durable foundation for subsequent studies in this research program.

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