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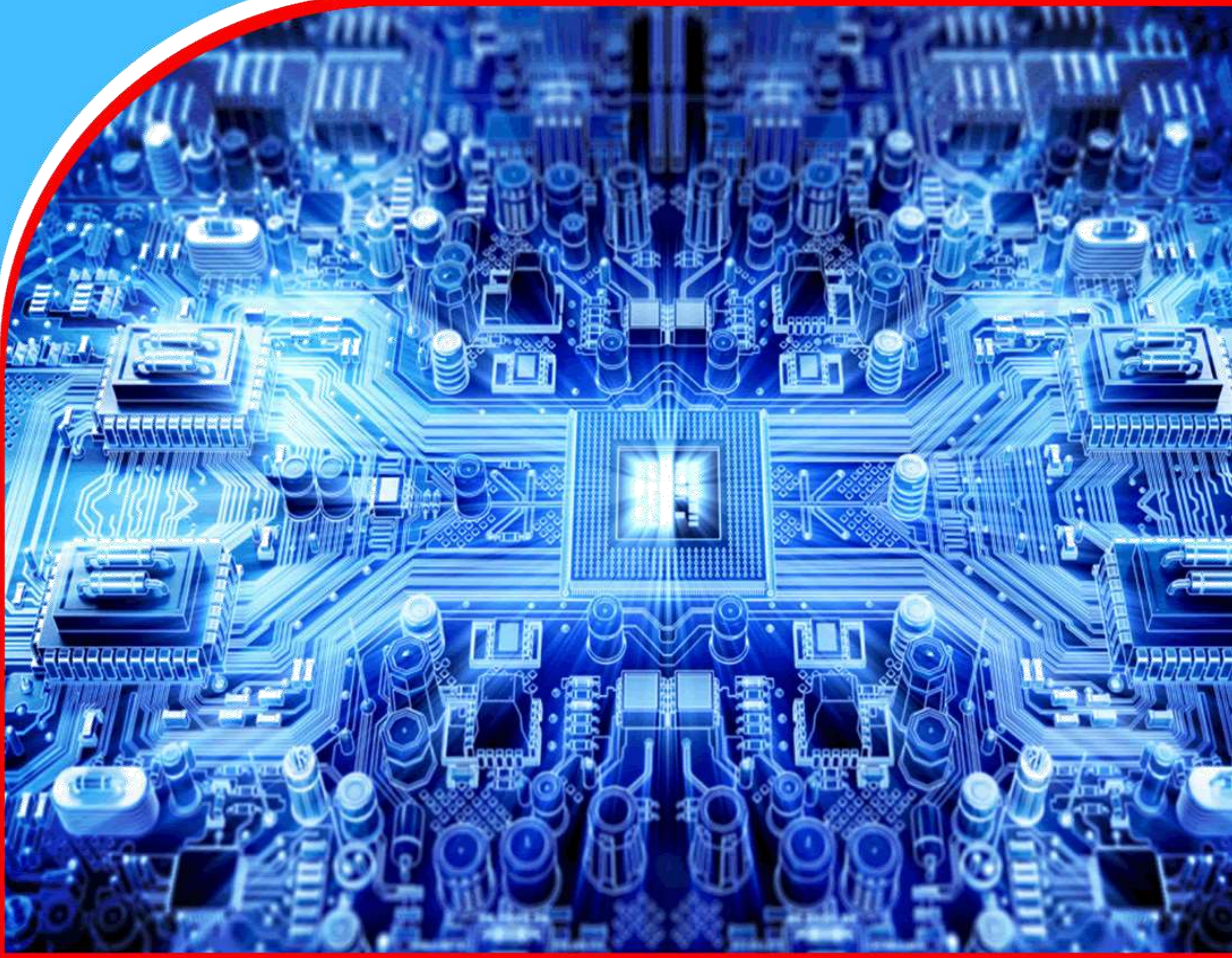

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Mechanics of Sustainable Materials and Structures: Experimental Study of Mechanical Behavior of Concrete Surface Hardener under Different Loading Conditions for Various Sustainable and Environment Friendly Structural Applications

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Abstract

Purpose: This research assesses the mechanical and environmental properties of metallic, non-metallic, and cementitious concrete surface hardeners with a focus on locally available materials.

Materials and Methods: Imposing controlled tests, the factors of composites' capacity were determined including the compressive strength, the flexural strength, impact resistance, abrasion resistance, water absorption, and endurance in extreme conditions. According to the study, the metallic hardeners offer better mechanical properties and relatively higher durability making them appropriate for use within industries. Nonmetallic hardeners represent more economic strength and are suitable for commercial application while cementitious hardeners are more suitable for the residential and aesthetic sector.

Findings: The research has shown the environmental and economic advantages of employing locally developed hardeners, therefore reducing greenhouse emissions, material costs, and environmental footprint as well as promoting a more sustainable global environment.

Implications to Theory, Practice and Policy: This research aims to help enhance the process of implementing sustainable construction principles and make recommendations on the choice of proper and affordable materials for various purposes.

Keywords: *Concrete, Surface Hardener, Construction Material, Mechanical Behavior*

JEL Codes: L74, R53, L68, L74

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1.0 INTRODUCTION

Concrete has played a crucial role in the construction industry for several centuries and remains the most important construction material for industries, offices, and homes across the globe. However, concrete floor, which is widely used in construction, is a significant element which undergoes various problems under different environmental and operation conditions. These include abrasion as a result of mechanical stresses, corrosion due to chemical influence, and wear out by traffic and or mechanical products such as heavy machines or feet.

One disadvantage that is usually evident in concrete floors is abrasion which is common in areas that experience more foot traffic including industrial buildings, factories and commercial buildings. Automobile traffic wear, mechanical equipment, and foot traffic also contributed to wearing down of the surface which prompted shorter expectancy. Further, chemical attacks like from oils, acids and cleaning solvents are other causes of concrete deterioration through discoloration, spalling or even surface weakening (Neville, 2011).

These compounds are normally used to form a thin layer on the concrete structure surfaces so as to improve its mechanical characteristics such as the compressive strength, its resistivity to abrasion or impact. This protective layer is resistant to mechanical pressures, as well as chemical attacks, which drastically enhances the wearing properties of the flooring (Kosmatka & Wilson, 2016).

The process of applying surface hardeners conforms to the provisions of the 9th Sustainable Development Goal on embracing industrial innovation and improvement of industry, infrastructure, and transport. Since they afford long-lasting floor materials, surface hardeners minimized the costs of environmental care and money-making approach used by traditional maintenance methods, thus being a valuable addition to the arsenal of a contemporary constructor (United Nations, 2015).

The early part of the twentieth century saw the industrial revolution and with the advancement of civil engineering and material science, engineers and scientists have started searching for the additives and treatments which will enhance the mechanical characteristics of concrete. Metallic surface hardeners were amongst the first major developments in this respect. These formulations involve use of metallic reinforcements like iron or steel fines at the surface layer so as to establish a hard-wearing layer that can sustain enormous loads as well as severe abrasive wear. Most metallic hardeners had wide use in all the industries involving factories and warehouses where the floor had to withstand severe mechanical loads from machines and equipment (Kosmatka & Wilson, 2016).

The main benefit of cementitious hardeners is that they can bond with concrete substrate mechanically thus enabling chemical bond during the curing process. This creates an ideal base film with an improved and scarcely varying geometry that affords some protection against wear, abrasion, and minor chemical interactions. However, these hardeners are not specific for heavy usage, and they provide less impact strength than metallic hardeners. Their operation is most efficient for moderate loads that allow the utilization of their endurance and the appearance.

The use of locally available material in the preparation of surface hardener is among the most effective approaches towards the improvement of sustainability of constructions. Since local materials have been used in the construction of the building, the transportation of the buildings and materials is relatively low hence reducing the carbon emission. The former does not only increase the potential for communities' economic development but also reduces the environmental impact of construction activities, which is becoming increasingly relevant when it comes to sustainability objectives (Khan et al., 2020).

Correlating the utilization of surface hardeners with three of the UN SDGs also points to their usefulness in present-day construction. This means that there is little construction waste produced and disposed of in the landfills as is the case throughout the world today. Moreover, some developed surface hardener compositions contain recycled materials – these can be recycled aggregates or industrial waste products – which enhance the application of the circular economy (Ahmad et al., 2021).

Even with their shown advantages, choosing the best surface hardener for a given application can still be difficult. These difficulties include the material's mechanical performance, environmental endurance, and cost-effectiveness. The research that is currently available focuses on how well these hardeners work in static environments or with very little environmental effect. But more research is needed to fully understand how they behave in dynamic environments and how long they last in different operational and environmental settings. Furthermore, although metallic hardeners have extremely good mechanical qualities, they are prone to corrosion in harsh situations. Cementitious and non-metallic hardeners are claimed to be economical, however their load-bearing capacity is clearly limited. The aforementioned knowledge gaps make it impossible to choose surface hardeners that are appropriate for the particular uses in building.

Problem Statement

Concrete is the most used building material. However, the surface of the concrete, specifically the floors, deteriorates with time due to mechanical stresses and chemical corrosion coupled with environmental degradation. These include abrasion resulting from foot traffic, heavy machinery, and chemical attacks like oils, acids, and cleaning agents. All these result in the loss of structural integrity of concrete, which makes maintenance and repair works continuous processes (Nations, 2015). This has made the operation and maintenance very costly but compromised the safety and functionality of the infrastructure.

Therefore, the surface hardeners have been established as the means of enhancing the mechanical properties in the concrete surfaces and may survive more for these types of challenges. The various concrete surface hardeners contain metallic, non-metallic, and cementitious materials all aimed at creating a protective layer against wear, impact, and chemical degradation. Despite their proven benefit, challenges still exist when selecting the most appropriate surface hardener for specific applications- which includes their mechanical behavior, the durability in environmental conditions, and cost- effectiveness.

The existing studies are concerning the performance of these hardeners under static conditions or during the presence of very minimal environmental influences. However, much work is required that seriously studies their behavior under dynamic conditions and their long-term durability in various operational and environmental scenarios. Besides, the mechanical properties of metallic hardeners are highly superior but prone to corrosion in aggressive environments. Non-metallic and cementitious hardeners are said to be cost-effective with obvious limitations in load-bearing capability. The said knowledge gaps prevent the selection of surface hardeners that match with the specific applications in constructions especially those in the industry, trade, and households.

Experiments have been conducted to test the mechanical behavior of concrete surface hardeners with respect to the type of load when the metallic, non-metallic, and cementitious type is considered for comparison between the types. All the results that will be derived from this study will thus contribute to the recommendations about the most suitable surface hardeners that are ecologically friendly and can be used in order to enhance the performance, durability, and sustainability of the concrete surfaces.

The difficulties posed by deteriorating concrete surfaces and choosing the best surface hardeners have important practical ramifications. Concrete surface deterioration results in expensive maintenance and repair tasks, which can place a heavy financial strain on households, companies, and industries. Furthermore, the structural integrity of buildings, bridges, and other infrastructure may be jeopardized by the deterioration of concrete surfaces, endangering public safety and perhaps resulting in mishaps and casualties. Furthermore, using environmentally unfriendly surface hardeners can lead to pollution and environmental deterioration, which can have long-term effects on ecosystems and human health. The lifespan of concrete infrastructure can be shortened by improper surface hardener selection, which can result in premature replacement and resource waste. It can also have serious economic repercussions, such as higher expenses and possible losses in income and productivity.

In a variety of operating and environmental situations where improved performance is needed, concrete surface hardeners are crucial. For example, concrete constructions in coastal areas are subjected to high levels of wind, humidity, and seawater, which can cause the concrete surface to deteriorate quickly. For this reason, it is essential to use a surface hardener that can resist these factors and stop the infiltration of chloride ions. A surface hardener that can endure strong traffic and chemical attacks is also necessary in industrial settings where concrete floors are frequently exposed to chemicals, oils, and heavy machinery. Additionally, freeze-thaw cycles in cold areas can cause concrete to expand and contract, which can lead to cracking and deterioration; in high-temperature situations, thermal shock can do the same thing. Additionally, surface hardeners that can survive high traffic volumes, chemical spills, and other destructive conditions are necessary for operational settings like parking garages, warehouses, food processing facilities, and airports. Other situations, such as high traffic areas, flood-prone areas, and seismic zones, also call for surface hardeners that can give concrete surfaces more resilience and protection. Although the location, climate, and planned use of the concrete structure all affect the specific needs for concrete surface hardeners, their significance in guaranteeing the durability and functionality of concrete surfaces cannot be emphasized

Applications of Surface Hardeners

Concrete surface hardeners are good material that can be applied in many areas of practice for increasing the reliability of concrete floor coverings.

In the industrial and commercial applications, the surface hardeners are used in warehouses, factories and shopping malls, etc. These environments thus exhibit high traffic density, movements of machinery and several operations that involve intensive loading and unloading. Hardeners further improve the floors abrasion, impact and chemical shock, making the floors more durable hence longer lasting and lowering maintenance expenses. For instance, in distribution centers and manufacturing factories, metallic hardeners are considered more appropriate because of high load resistance and high durability (Rana et al., 2019).

In residential uses, surface hardeners are applied to enhance the performance and appearance of pathways such as driveways, garages and aesthetic floor surfaces. Non-metallic hardeners are especially common in such utilizations because they are less costly and can produce a variety of finishes.

In the case of airports, parking lots, and other transit nodes, enhanced durability through surface hardeners meets the demand for the handling of vehicular and pedestrian traffic. These applications involve cementitious hardener since they create a smooth, long lasting and low maintenance surface.

Non-metallic and cementitious hardeners also offer dry, tough, smooth and easy to clean surfaces, which are appropriate when hygiene requirements are high.

There are several environmental advantages of utilizing concrete surface hardeners in both residential and commercial settings, including lower lifecycle emissions. Surface hardeners increase concrete floors' endurance and resilience in commercial and industrial settings, such as factories, warehouses, and shopping centers, lowering the need for regular replacements and repairs. The demand for energy, transportation, and raw materials is subsequently decreased, which lowers greenhouse gas emissions and the carbon footprint. For example, the use of metallic hardeners in manufacturing facilities and distribution centers can result in a large reduction in lifecycle emissions because of their great durability and load resistance, which reduces the need for frequent maintenance and repairs.

Applying surface hardeners to garages, driveways, and decorative floor surfaces can help lower lifecycle emissions in residential areas. Commonly employed in these applications, non-metallic hardeners are more environmentally friendly because they are less expensive and can create a range of surfaces. By reducing the need for frequent repairs and maintenance, surface hardeners can also lessen the environmental effect of parking lots, airports, and other transit nodes. This can result in fewer emissions and energy usage.

The one of the major advantages of surface hardener along with strength and ductility, is its low environmental footprint and low carbon emission. Ahmed et al.'s (2021) study, noted that local produce cementitious material emissions reduction ranged between 24% and 25%. In the same way, Zhang and Li (2020) found that local and regional aggregates for non- metallic hardeners provided twenty- to thirty-percent cost savings.

Identified Research Gaps

Over the years, various works on concrete surface hardeners have gained popularity due to their accessibility, practicability and effectiveness despite these gaps. They identified one main research gap which is the relation between surface hardeners and various concrete mixtures. The nature of concrete compositions based on local aggregates, cement and water, mix designs and admixtures may be vastly different and scientific literature lacks certain systematic analyses of how different hardener compositions might influence the mixes.

Another area amicable to research is the ability of surface hardeners to withstand wear and tear for instance due to environmental and mechanical forces. Long term performance however is not well understood especially in terms of the effects of such parameters as temperature, freeze/thaw cycles, and chemical attack on these materials.

Finally, there is a glaring research gap on comparative studies of locally synthesized hardeners as opposed to imported ones. Although numerous investigations focus on the cost and environmental gains of local materials, little of them display a quantitative analysis of its characteristics and performance relative to commonly used commercial materials.

Filling these gaps by directing research efforts towards these aspects will improve the application and efficiency of surface hardeners, hence increasing its efficiency in today's advanced construction industry.

The purpose of this study is to assess the mechanical properties of concrete surface hardeners, especially on the arrangement of locally available materials in order to improve the structural efficiency of these products under various load types. The research aims at establishing practical and economically viable ways of boosting concrete surface's performance in terms of its mechanical characteristics. Furthermore, the study seeks to determine the compatibility of various concrete mixes, examine the environmental aspect and give a comparative analysis of locally produced hardeners to the commercial ones.

Due to the current knowledge gaps on concrete surface hardeners, there are a number of unanswered questions that present difficulties in particular situations. What are the long-term impacts on the durability of surface hardeners, for instance, and how do they respond to frequent freeze-thaw cycles in cold climates? What are the effects of chemicals and heavy machinery on the performance of surface hardeners in industrial environments, and how does this affect their replacement and maintenance? Is it possible to make surface hardeners from local materials in areas where imports are scarce, and if so, what would the cost and environmental effects be? Furthermore, how do various hardener compositions affect a particular concrete surface, and what is the link between the concrete surface and these compositions? Addressing these issues is essential to filling in knowledge gaps and maximizing the usage of concrete surface hardeners in a variety of settings, including industrial applications, infrastructure development, and construction.

2.0 LITERATURE REVIEW

Concrete is the highest consumed material in construction and hence, the continuous work of research has been carried out to promote its mechanical properties, sustainability, and durability. Among the additives, concrete surface hardeners are the most important additives for developing the mechanical properties of concrete for sustainability through a longer service life and minimization of maintenance operations.

Concrete surface hardeners are usually chemical products, which are silicates, fluosilicates, or similar chemical compounds. These are applied on freshly cast or cured concrete surfaces to improve the hardness and abrasion resistance and also the chemical resistance (Pang et al., 2021). The mechanism of action takes place as a chemical reaction with Ca $(OH)_2$ contained in the concrete, whereby the resultant calcium silicate hydrate crystals assist in thickening and strengthening the concrete surface (Yu et al., 2021). This surface densification improves both the mechanical properties and resistance to external environmental factors such as water, chemicals, and physical wear by Abbass et al. (2024).

This has put emphasis on a reduction in carbon footprint of concrete on its production according to the sustainability goals globally. Hence, its surface hardeners are very important toward reaching the level of sustainability since it saves the time that would be taken when their repair and maintenance is carried out hence prolonging its age (Mastali et al., 2021). Surface treatments have been considered in decreasing the permeability leading to the decrease in penetrating corrosive agents such as chlorides, hence increasing the ages of concrete structures (Bahraq et al., 2022). Finally, surface hardeners conserve resources because they improve the strength and performance of concrete that otherwise would be replaced in smaller quantities and thus reduce the environmental impact (Yang et al., 2019).

Some recent studies have been carried out for the analysis of mechanical behavior of surface-hardened concrete under various loading conditions. Aiello et al. (2002) investigated surface-hardened concrete under static and dynamic loadings with regard to mechanical properties and concluded the following: remarkably improved compression strength as well as a fracture toughness of the surface-hardened concrete for cyclic loading conditions. Similarly, Abbass et al. (2024) proved that the surface-treated hardened concretes are more resistant to fatigue and therefore fit for repeated loadings, and hence they are more often used on pavements and industrial floors.

The last topic of research is surface hardeners that influence tensile and flexural properties of concrete. Mardani-Aghabaglou et al. (2021), mentioned that tensile strength in surface-hardened concrete increased and may avoid cracking because the general structural strength of the concrete surface improved against bending or shear stress. The investigated surface hardeners have been applied contextually in green buildings to energy-saving houses and construction, infrastructure development, as well as environment-friendly towns, among others (Yu et al., 2021).

According to Yu et al. (2021) that recently reviewed the current work for environmentally friendly applications in construction, surface hardeners improve the sustainability performance of concrete both by increasing the lifecycle and improving its performance in different environmental conditions. This further leads to the outcomes that indicate surface hardeners as useful in feasible projects to gain green certifications such as LEED or BREEAM due to material durability, as it diminishes lifecycle environmental impacts (Zhang et al., 2021).

Surface treatments were revealed to improve the mechanical properties and durability of concrete from the literature review. However, the long-term effect of surface treatments has to be assessed in terms of its performance on the different environmental conditions for maintaining and sustaining concrete structures in the long run.

The majority of investigations use controlled experimental setups, including those by Pang et al. (2021), Abbass et al. (2024), and Mardani-Aghabaglou et al. (2021). This makes it possible to precisely quantify and replicate factors including environmental resistance, tensile behavior, and compression strength. Real-world situations are frequently not perfectly replicated in laboratory settings. Surface hardeners' long-term efficacy may be impacted differently by external environmental conditions such as temperature fluctuations, humidity levels, or extended contact to harsh chemicals. Large-scale, empirical field data to validate findings are frequently absent from studies.

Although surface hardeners' mechanisms are described in terms of their chemical interactions (such as the creation of calcium silicate hydrate), long-term assessments under various climatic circumstances are still not well understood. Treatments' long-term effectiveness in frigid temperatures, extended UV exposure, or high cyclic loading is not fully discussed. The necessity of evaluating these treatments' adaptation in various environmental circumstances was emphasized by Yu et al. (2021).

The emphasis on surface hardeners' sustainability advantages (Mastali et al., 2021) correctly highlights their longer durability and lower maintenance requirements, which help to lower carbon emissions. However, more thorough life-cycle analysis (LCA) is required to examine the environmental effects of creating these chemical additions, including energy use, emissions, and the extraction of raw materials.

The main goals of studies such as those conducted by Aiello et al. (2002) are to examine abrasion resistance, fatigue resistance, and compression strength. Despite the importance of these characteristics, less is known about additional factors such as adhesion problems, possible incompatibility with later coatings or treatments, and microcrack formation under extreme load stress. Certain uses, like industrial flooring and pavements, have been highlighted in research (Abbass et al., 2024). However, there is little information available on the effectiveness of surface hardeners in structural components like beams, columns, and architectural designs, which limits our understanding of their potential uses.

The use of unique surface hardener compositions makes it more difficult to compare studies and extrapolate results. For broader applicability, standardized testing procedures and material requirements are required. Surface hardeners' affordability and large-scale viability are still little understood, particularly in low-income or resource-constrained environments. Analyses of costs and benefits are required for wider use. Surface hardeners' interactions with other additives or treatments are not well studied, which emphasizes the necessity to investigate any potential benefits or drawbacks in mixed applications.

Aiello et al. (2002) and other early research focused on mechanical qualities and fundamental chemical mechanisms under controlled settings. Life-cycle analysis (LCA) and durability assessments are two sophisticated techniques that are used in real-world environmental situations in recent research like Mastali et al. (2021) and Abbass et al. (2024). Sustainability Focus While recent studies emphasize their contribution to sustainability, highlighting advantages including lifecycle extension, lower maintenance, and green certifications (e.g., LEED, BREEAM), foundational research missed environmental implications (Yu et al., 2021; Zhang et al., 2021).Applications: Current study examines their significance in infrastructure, eco-friendly buildings, and energy-efficient construction, while earlier studies concentrated on specific scenarios, such as pavements. Economic Insights: Economic viability was not a topic covered in previous studies. Cost-benefit assessments have recently been investigated, but more research is needed to determine scalability in low-resource settings.

Theoretical Review

It has been developed from theories derived from material science, chemical reactions, and also structural mechanics, describes that the surface treatment improves the sustainability and durability of concrete by its mechanical properties in every kind of environment.

The concrete matrix's calcium hydroxide and surface hardeners combine to form calcium silicate hydrate (CSH), which fills holes and microcracks to densify the surface. In order to tolerate unfavorable environmental conditions, this leads to better abrasion resistance and decreased permeability (Yu et al., 2021; Mardani-Aghabaglou et al., 2021).

A concrete matrix that is denser and more compacted is more resilient to environmental conditions such as moisture and hazardous chemicals. According to theoretical models such as elasticity and fracture mechanics, surface hardeners improve resistance to fatigue and crack propagation under dynamic or cyclic loads while increasing stiffness (modulus of elasticity) and decreasing deformation under static loads (Zhang et al., 2021; Mardani-Aghabaglou et al., 2021). Because of its increased fracture toughness, surface-hardened concrete works especially well in high-stress areas like industrial floors and roads (Aiello et al., 2002).

Surface treatments lower the risk of corrosion in reinforced concrete by improving the pore structure and preventing water and chloride intrusion. By lowering maintenance and replacement requirements, conserving resources, and lowering the lifecycle carbon footprint, this directly supports sustainable construction goals (Yang et al., 2019; Bahraq et al., 2022).

Therefore, surface hardeners offer a workable way to improve the mechanical performance of concrete, increase its lifespan, and address environmental sustainability. These enhancements are in line with the dual goals of durability and less environmental impact in contemporary building.

The purpose of the study is to assess how surface hardeners contribute to sustainability, increase durability, and improve the mechanical qualities of concrete. The application of surface hardeners is thought to improve long-term performance under both static and dynamic circumstances by improving pore structure, increasing fracture toughness, and decreasing permeability.

Surface hardeners' interactions with the concrete matrix are explained by the theoretical framework, which is based on material science and structural mechanics. The formation of calcium silicate hydrate (CSH) from the reaction with calcium hydroxide plugs microcracks and densifies the surface, directly addressing the theory that a denser matrix reduces permeability and increases abrasion resistance (Yu et al., 2021; Mardani-Aghabaglou et al., 2021).

This knowledge is supported by elasticity and fracture mechanics models, which relate density to improved stiffness (modulus of elasticity), resistance to deformation, and fatigue performance. According to the study's hypothesis, surface hardeners prevent cracks from forming and spreading, allowing concrete structures to withstand both static and dynamic loads, including cyclic and seismic pressures (Zhang et al., 2021; Mardani-Aghabaglou et al., 2021). These theoretical models support this theory.

Additionally, the study's objective of proving lower corrosion risks in reinforced concrete is closely related to the theoretical debate of pore refinement and its function in preventing water and chloride intrusion. According to Yang et al. (2019) and Bahraq et al. (2022), surface treatments are thought to prolong the lifespan of concrete structures and lessen their environmental effect by requiring less maintenance and resources. The research investigates how surface hardeners' mechanical and durability improvements complement contemporary construction's focus on sustainability and long-term resilience by incorporating these theoretical models with the study's goals.

3.0 MATERIALS AND METHODS

This scientific research used a systematic experimental approach to determine concrete surface hardener’s physical and mechanical characteristics, specifically metallic, non-metallic, and cementitious materials. The purpose was to examine their efficiency in different circumstances and to determine the best, both in terms of effectiveness and affordability, mixtures. This section provides the details of the materials used, the preparation of the specimens, the methods of testing and the ways of analyzing the results is given in this section.

Materials

The primary materials incorporated in the study were OPC, fine & coarse aggregates, water, superplasticizers, and other specialized aggregates for the hardeners. OPC with good binding properties was chosen for all the mixes to be prepared as the cementitious material. In the case of metallic hardeners, steel/iron aggregates were employed to provide improved vigor, and resistance to abrasive/impact forces. Originally, non-metallic hardeners employed small particles, and then came the inclusion of silica, quartz, as well as alumina which are very suitable because of their wear and chemical stability. Cementitious hardeners in this case were made up of OPC and specific additives that enhanced chemical activity on the surface and thereby increasing the hardness as well as the durability.

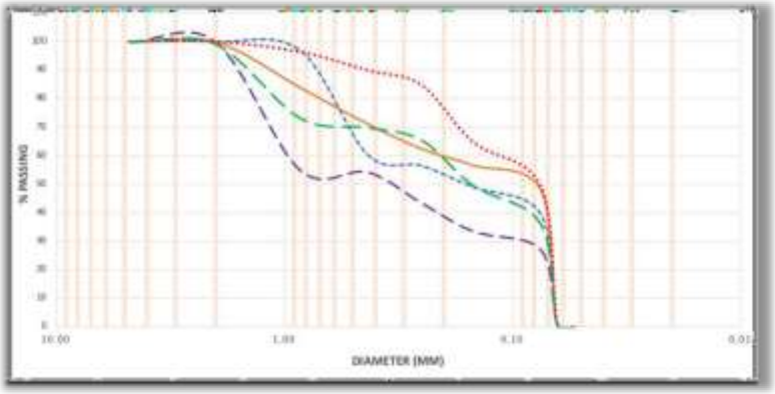


Figure 1: Particle Size Distribution Curve of Different Sands Used

Water-reducing admixtures containing superplasticizers were incorporated in all the mixtures to improve workability while keeping the W/C of the concrete at a constant level. Drinking water that contains no contaminant was used to mix aggregate and for consolidating. The aggregates used were obtained locally in an effort to avoid environment degrading activities and costs as well as to meet the aim of the study on sustainable construction.

Table 1: Composition of Materials Used in Metallic, Non-Metallic and Cementitious Hardeners

Material	Metallic Hardener (%)	Non-Metallic Hardener (%)	Cementitious Hardener (%)
Ordinary Portland Cement	25	30	35
Fine Aggregates	20	40	30
Coarse Aggregates	40	20	15
Superplasticizer	2	2	2
Water	13	8	18

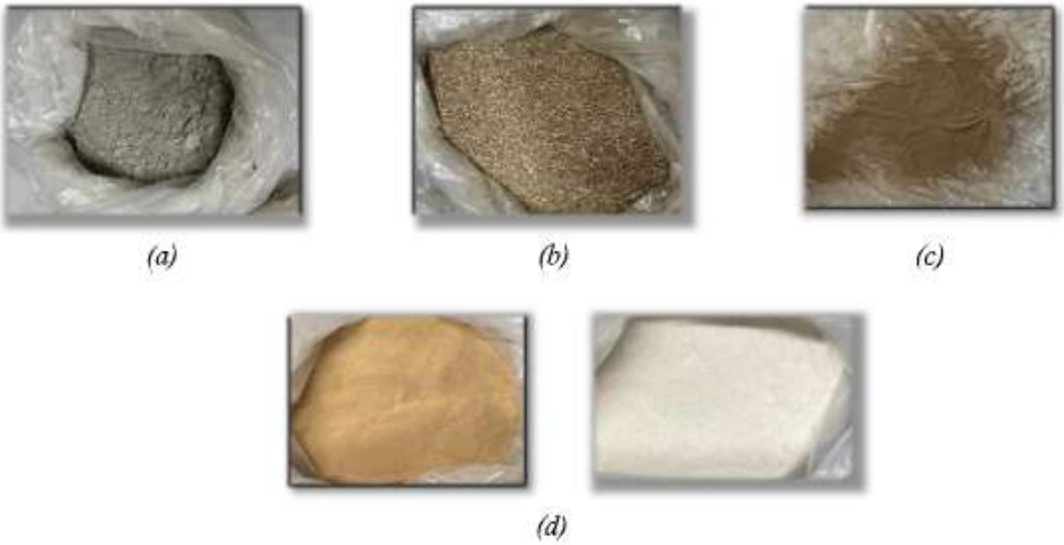


Figure 2: (a) Cement (b) Coarse Aggregates (c) Super Plasticize (d) Fine Sands

Experimental Study and Analysis

Compressive Strength Analysis

Samples were prepared to measure the compressive strength and casted in a cube mold of 50 mm x 50 mm x 50 mm for compression tests.

The effective mixing process was done for distribution of the aggregates and for proper activation of the cementitious material. The specimens were compacted to eliminate air voids and to ensure homogeneity in density. After the casting process, they were placed in the moist environment for initial curing at 23 ± 2, and then moved to a water bath for 24 hours. Specimens were cured for three intervals: Specimens were prepared for 7-day, 14-day, and 28-day strength to assess early-age and long-term development.

Figure 3: Curing and Casting of Cubes for Compression Test

Compressive strength tests were conducted using a universal testing machine in accordance with ASTM C39 standards. Each cube specimen was subjected to a gradually increasing load until failure. The maximum load at failure was recorded, and the compressive strength was calculated using the formula: Compressive Strength (MPa)=Maximum Load (N) x Cross-Sectional Area (mm2)

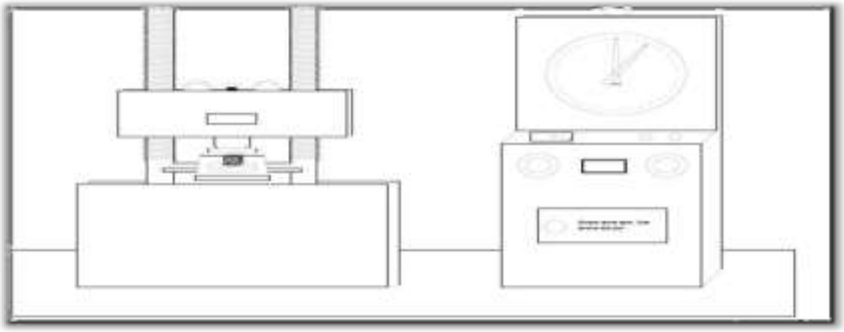


Figure 4: Schematic Diagram of Compressive Strength Machine

Figure 5: Laboratory Setup for Compressive Strength Test

Flexural Strength

To study flexural behavior of concrete surface hardener, the material was first mixed properly to ensure the homogeneity and consistency. Then the mixture was casted in the mold of 40mm x 40mm x 160 mm. After the casting process, they were placed in the moist environment for initial curing at 23 ± 2, and then moved to a water bath for 24 hours.

Flexural strength was assessed using a three-point bending test as per ASTM C78 standards. Each prism was placed on two supports, and a load was applied at the midpoint until the specimen fractured.

Figure 6: Casting and Curing of Specimen for Flexural Test

Figure 7: Casting and Curing of Specimen for Flexural Test

Impact Resistance

Impact resistance was evaluated using a drop-weight test. First the concrete slab was casted with a layer of concrete hardener on it, in a mold of specific dimensions of 600 mm x 600 mm x 150 mm. A cylindrical weight was repeatedly dropped from a fixed height onto slab specimens. The number of drops required to initiate visible cracking was recorded, providing a measure of the hardener's resistance to dynamic loads. The sand was placed under the slab as a precautionary measure to avoid rebound.

Figure 8: Casting and Curing of Specimen for Impact Test

Figure 9: Diagram Illustrating the Drop-Weight Test Setup

Water Absorption

Absorption test were carried out according to ASTM C642. Every sample was oven dried and weighed first and then soaked in water for 24 hours and weighed in SSD. Water absorption was calculated using the formula:

Water Absorption = [(W2 - W1) / W1] x 100

W1	Weight of Oven Dried Sample
W2	Weight of SSD sample

Flowability Test

To study the flowability behavior of concrete surface hardener, the material was prepared according to the ASTM C-1437 (33). The mold was placed on the center of flow table top and filled it in two layers with rod compaction 25 times each layer to ensure the uniformity. Then the mold was removed and activate the flow table with 25 drops within 15 seconds to spread the material. Then after the spread the diameter was measured in 2 perpendicular directions. The flowability was determined by subtracting the original diameter of material in mold and the spread diameter and the flowability was reported in percentage.

Figure 10: Laboratory Arrangement or Setup for Flowability Test

Data Analysis

Statistical methods were applied to evaluate and compare the results in order to determine differences in the tested formulations. The strength gain during curing periods was also compared and the effects and wear resistance obtained used to determine the standard formulations for industrial, residential and public structures use. Laboratory test work of locally developed hardeners compared to commercial products regarding performance characteristics; focus was on cost efficiency and environmentally friendly approaches.

4.0 FINDINGS

The findings and results section offers a critical analysis of the experimental outcomes in an attempt to compare various concrete surface hardeners. The findings are important in establishing the reactivity and the characteristics of metallic, non-metallic, and cementitious hardeners; its benefits and drawbacks. The results of each test are presented in the respective section based on test type, and then a discussion is provided where all the findings are discussed in detail to provide a logical conclusion about the use of different hardeners in various applications.

Compressive Strength Results

The results of the compressive strength tests for metallic, non-metallic, and cementitious floor hardeners are presented below. Specimens were tested at curing intervals of 7, 14, and 28 days to evaluate both early-age and long-term strength development. Compressive strength values were calculated based on the peak load sustained by the specimens during testing.

Table 2: Compressive Strength (MPa) at 7, 14 and 28 Days

Hardener Type	**Compressive Strength (MPa)**		
	7 Days	**14 Days**	**28 Days**
Metallic Hardener	42.3	51.7	68.2
Non-Metallic Hardener	38.1	45.6	60.4
Cementitious Hardener	36.5	44.3	58.7

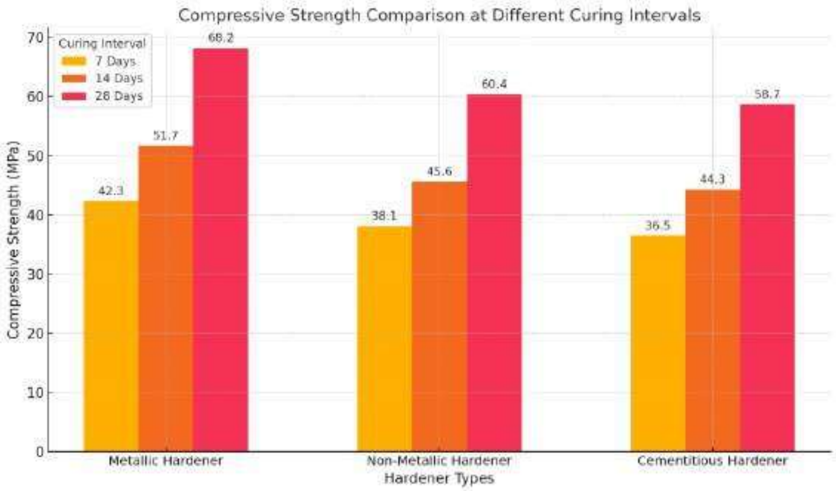


Figure 11: Bar Graph Comparing Compressive Strengths at 7, 14 and 28 Days for the Three Hardener Types

Figure 12: Specimens after Compression Test

The findings indicate that metallic hardeners yielded the highest compressive strength of mortar at all curing ages reaching 28-day compressive strength of 68.2 MPa. Nonmetallic and cementitious hardeners depicted lower strength gain and the values obtained at 28 days were 60.4MPa and 58.7MPa respectively. The expression of early-age strength was observed for all the forms of hardeners with the metallic type showing an enhanced strength gain from 7 to 28 days by 63%.

The higher compressive strength of metallic hardeners is due to the incorporation of high strength metallic materials which increase load bearing. Nonmetallic micro silica and quartz functional hardeners act, in a way, effectively but are slightly less strong due to their comparatively brittle nature. Cementitious hardeners produced the least compressive strength, probably because of their action where the substances relied on chemical actions to harden the surface as opposed to the provision of unique structural strength.

The results also highlighted the suitability of metal-based hardeners such as for industrial and high load application due to its superior strength and durability. Non-metallic and cementitious hardeners are better suited for residential or light commercial structures where, primarily, price and appearance are the ultimate factors.

Flexural Strength Results

Three-point bending test was used to determine the flexural strength of the three types of hardeners identified as metallic, non-metallic and cementitious as outlined by ASTM C78. This is an important characteristic for concrete floor use, where it is exposed to bending stress and cracking such as driveway and ornamental floor. The curing intervals of 7, fourteen, and twenty-eight days were the results obtained from the following test.

Table 3: Flexural Strength (MPa) at 7, 14 and 28 Days

Hardener Type		Flexural Strength (MPa)	
	7 Days	14 Days	28 Days
Metallic Hardener	6.8	8.2	9.5
Non-Metallic Hardener	5.9	7.1	8.4
Cementitious Hardener	5.5	6.8	7.6

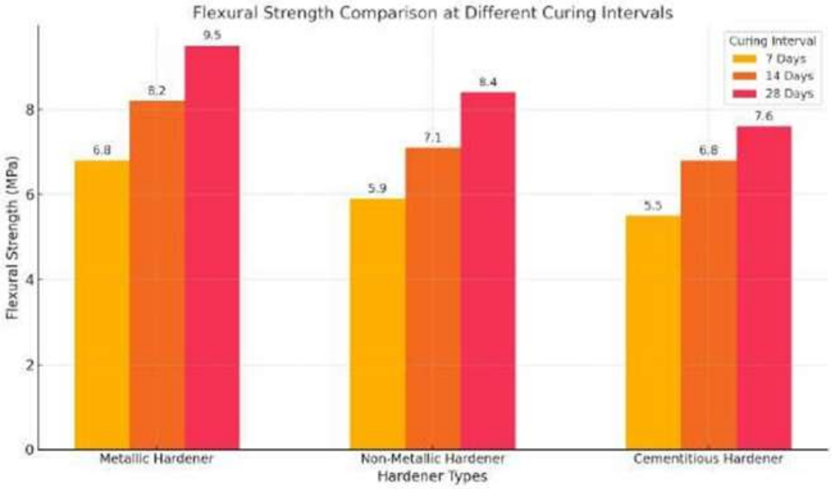


Figure 13: Bar Graph Comparing Flexural Strengths at 7, 14 and 28 Days for the Three Types Of Hardeners.

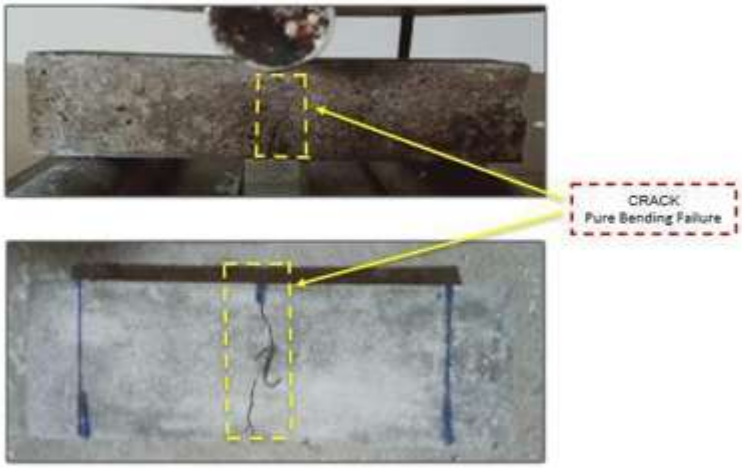


Figure 14: Specimen after Flexural Strength Assessment Test (Crack Showing Pure Bending Failure)

The findings show that the metallic hardeners displayed the highest flexural strength for all the curing periods and recorded the maximum strength of 9.5Mpa at 28 days. Non-metallic hardeners reached the highest strength of 8.4 MPa while cementitious hardeners had the lowest flexural strength of 7.6 MPa at 28 days of curing. Additional data revealing that all hardener types improved their flexural strength through time at an average of 35% between 7 and 28 days.

Some of the findings stress higher durable values of metallic hardeners under bending stress as compared to non-metallic and cementitious solutions. Addition of metallic aggregates in metallic hardeners improves their tensile strength and potential to resist cracks.

Non–metallic hardeners were also effective in achieving a higher flexural strength as compared to cementitious hardeners. The incorporation of silica and quartz aggregates show good cement matrix adhesion, which arrest the progress of cracks under conditions of bending loads. Cementitious hardeners provide the least flexural strength but are sufficiently acceptable for applications that require moderate bending stresses, such as in house flooring.

Overall, all formulations' flexural characteristics were significantly improved by the inclusion of superplasticizers. They also enhance the fluidity of cement paste allowing increase in the density and homogeneity of the concrete matrix, thereby enhancing tensile and bending strengths when the water cement ratio decreases. On the other hand, the non-metallic hardeners were given an advantage with the incorporation of silica and quartz that have better tensile strength but have low ductility than that of metallic aggregates.

Impact Resistance Results

The drop weight test was performed on the metallic, non-metallic and cementitious hardeners to determine their impact resistance. In this test, a cylindrical steel weight was subjected to drop from a fixed height on the slab specimens following the dynamic loading which is common in industrial and high use areas. The results are expressed in the form of drop counts before visible crack formation or failure of the specimens.

Table 4: Impact Resistance Results

Hardener Type	Number of Drops to Failure
Metallic Hardener	35
Non-Metallic Hardener	22
Cementitious Hardener	18

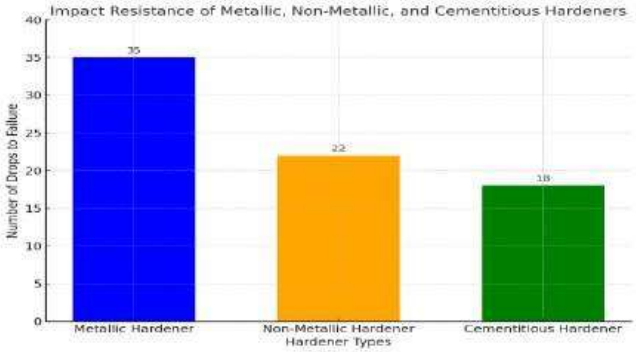
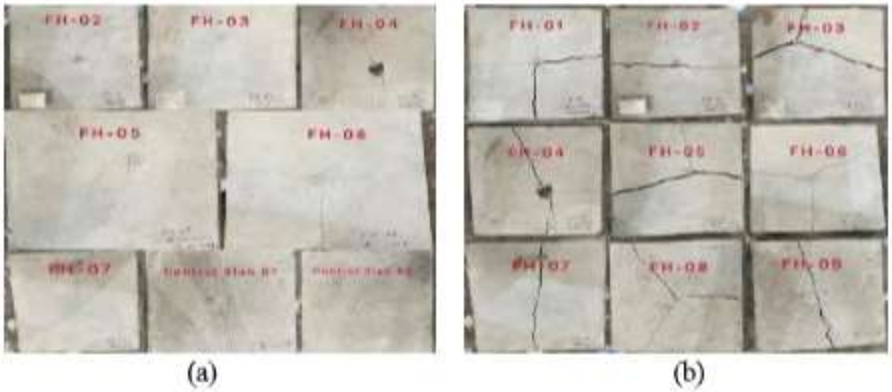


Figure 15: Bar Graph Illustrating the Number of Drops to Failure for Metallic, Non-Metallic and Cementitious Hardeners

The metallic hardeners showed that they had the highest impact resistance with an average of 35 drops before the formation of a visible crack. Non-metallic hardeners were next at 22 drops on average, while cementitious hardeners were the least resistant on average, only lasting through 18 drops. These results have indicated that most of the metallic hardeners are performing well under dynamic load, hence recommended for high load operations.

On metal hardeners, some surface spalling and crack at most were observed to have occurred mostly in the impact areas. This type of localized failure signifies efficient energy management and distribution within the dense metallic aggregate matrix. Non-metallic hardeners also exhibited some surface cracking and partial delamination which reveals lower energy absorption characteristics. Cementitious hardeners material suffered from high level of cracking and surface spalling attributed to low performances of the material under cyclic fatigue from dynamic loads.

Figure 16: Images of Slabs before Appearance of Initial Crack



(a) (b)

Figure 17: Images of Slabs after Appearance of (a) Initial Crack (b) Final Crack

The high packing density, combined with increased ductility of the metallic aggregates, significantly improves the durability of such formulations for repetitive cyclic stresses. For this reason, metallic hardeners are suitable for premises with high mechanical loads under dynamic loading conditions.

Non-metallic hardeners, though possess reasonable resistance to impact, they do not possess the energy dissipation characteristics of metallic aggregates for which considerable crack development occurs under repeated impact. The worst performing cementitious hardeners because apart from merely relying on chemical hardening mechanisms, their composites lack the required toughness to handle high dynamic loads.

Abrasion Resistance Results

The results of the Taber Abrasion Test indicated the abrasion resistance of metallic, non-metallic and cementitious concrete hardeners. This test entailed exposing slab specimens to a stationary, but rotating abrasive wheel while applying a specific load to the specimen for a predetermined number of revolutions to reproduce wear that occurs in highly trafficked zones. Abrasion resistance was determined by calculating the amount of weight lost by each specimen after the test, the lesser the weight the better the abrasion resistance.

Table 5: Abrasion Resistance of Metallic, Non-Metallic and Cementitious Hardener

Hardener Type	Weight Loss (g)	Abrasion Resistance Rank
Metallic Hardener	1.2	1 (Best)
Non-Metallic Hardener	1.6	2
Cementitious Hardener	2.3	3 (Lowest)

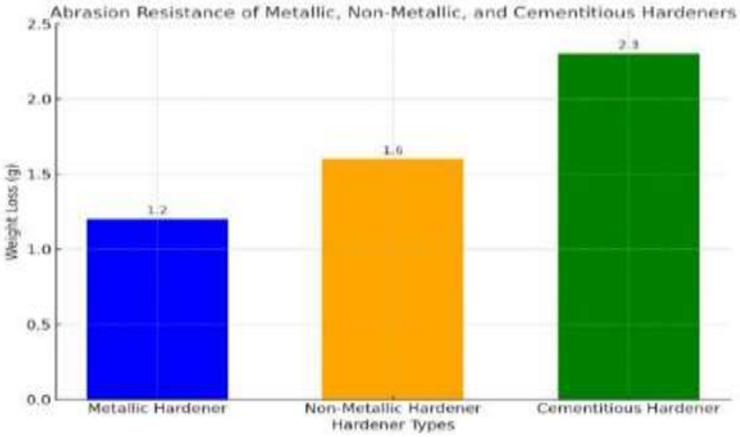


Figure 18: Bar Graph Illustrating the Weight Loss for Metallic, Non-Metallic and Cementitious Hardeners under the Taber Abrasion Test

The metallic hardeners, on average had a weight loss of 1.2 g after the test making it the metallic hardeners had the best abrasion resistance while cementitious and non-metallic had an average weight loss of 2.3 g and 1.6 g respectively.

The improved mechanical performance of metallic hardeners can be related to the high surface density and the incorporation of metallic aggregates. The metallic aggregates also have the best performance in distributing the load at the surface in order to avoid high point wearing. Non-metallic hardeners were also proven to be slightly lower in terms of its abrasion resistance yet remains quite commendable primarily because of the presence of hard mineral aggregates such as silica and quartz. These materials improve wear resistance by increasing surface hardness, a disadvantage is that they are very brittle and may develop micro-cracks under continual abrasive loads. Cementitious hardeners improved surface properties by merely chemical means, indicating the highest weight loss. Due to their lower density and other qualities such as the absence of reinforcing aggregates they are not recommended for applications where abrasive loads formulas are common.

Water Absorption Results

Water absorption plays an important role in concrete especially when exposed to wet environments or areas with high humidity. The reduction in weight for metallic, non-metallic and cementitious hardeners was tested using ASTM C642 techniques. The water absorption percentage of each specimen was determined to determine their performance to water intrusion, with smaller percentage signifying higher resilience.

Table 6: Water Absorption Metallic, Non-Metallic and Cementitious Hardener

Hardener Type	Water Absorption (%)	Water Resistance Ranking
Metallic Hardener	2.1	1 (Best)
Non-Metallic Hardener	2.8	2
Cementitious Hardener	3.4	3 (Lowest)

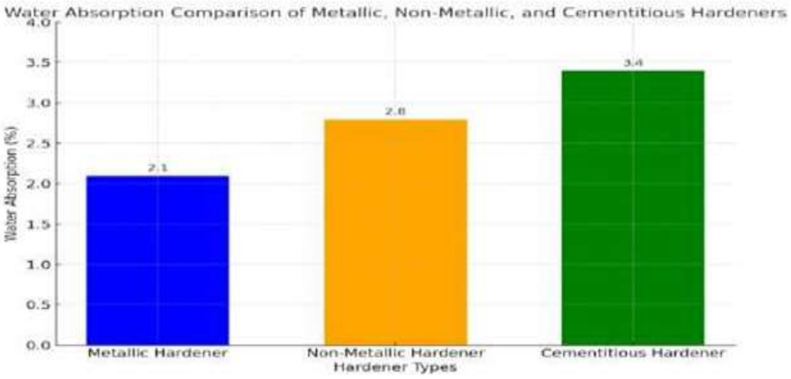


Figure 19: Bar Graph Comparing Water Absorption Percentages for Metallic, Non-Metallic and Cementitious Hardeners

The metallic hardeners had the least %WA of 2.1 which means that the concrete containing these metallic hardeners had a higher resistance to water absorption. Non-metallic hardeners were the next with a water absorption of 2.8%, while cementitious hardeners had the highest water absorption rate of 3.4%. The findings of the two tests prove the extent to which local absorption is affected by the incorporation of the dense impermeable combination and proper curing procedures.

The findings indicate that there is a direct relationship between the reduction of the water absorption percentage and increased durability. The work showed that by using the metallic hardeners with the dense matrix containing metallic aggregates, had the lowest coefficient of water absorption. This low permeability is essential to providing structural strength when exposed to wet or humid environments as it minimizes freeze thaw damage, chemical attack and corrosion of the reinforcement. Non-metallic hardeners are somewhat more permeable but offer excellent results owing to the content of hard mineral aggregates such as silica and quartz. Cementitious hardeners had the highest WA, therefore can perform poorly in areas that may be exposed to moisture for long periods.

Superplasticizers applied in metallic and non - metallic hardeners decreased the water-cement ratio thus providing a denser and less permeable cement matrix. Moreover, adequate curing enabled the cement to reach its full hydration level and reduce capillary pores which are paths for water entry. Note that cementitious hardeners which operate through improved chemical reactions are unable to achieve the density of the aggregate structure required to prevent water penetration.

Durability Results

This research aim sought to compare and determine the freeze-thaw and chemical resistance of metallic, non-metallic, and cementitious hardeners under extreme environmental conditions. These tests were conducted in order to investigate modifications in mechanical properties of the hardened cement based on its residual compressive and flexural strengths to learn about their performance over time. The durability of specimens tested included 50 cycles of freezing and thawing, and chemical aggression using a 5 % sulfuric acid solution for 14 days. These residual mechanical properties were then contrasted with its pre-aging (before aging) strengths.

Table 7: Durability Results of Metallic, Non-Metallic and Cementitious Hardener

Hardener Type	**Initial Compressive Strength (MPa)**	**Residual Compressive Strength (MPa)**	**Strength Retention (%)**	**Initial Flexural Strength (MPa)**	**Residual Flexural Strength (MPa)**	**Strength Retention (%)**
Metallic Hardener	68.2	62.5	91.6%	9.5	8.7	91.6%
Non-Metallic Hardener	60.4	51.8	85.8%	8.4	7.0	83.3%
Cementitious Hardener	58.7	46.3	78.9%	7.6	5.9	77.6%

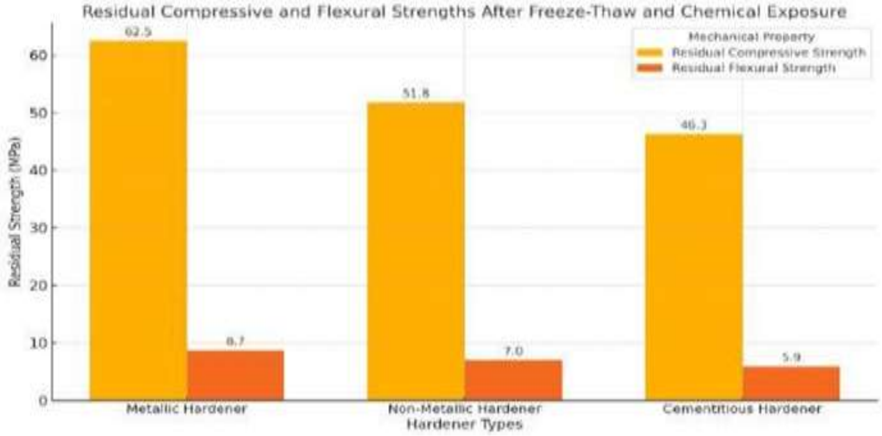


Figure 20: Bar Graph Showing the Residual Compressive and Flexural Strengths for Each Hardener Type after Freeze-Thaw Cycles and Chemical Exposure

The metallic hardeners also maintained the highest percentage of both the compressive and flexural strengths in this study, implying high durability in hostile environments. Non-metallic hardeners exhibited comparatively fair strength recovery loss, whereas cementitious hardeners suffered the largest caliber in mechanical properties pointing towards poor durability under severe conditions.

Metallic hardeners maintained less than 5% of the loss in their initial compressive and flexural strength values after exposure for 90 days. This superior performance can be attributed to the increased use of dense and durable steel and iron aggregate that do not crack or spall off under freeze thaw stress and chemical attack.

Non-metallic hardeners showed relatively better durability and their strength was found to be around 85% of the original compressive strength and 83% of the original flexural strength. The silica and quartz aggregates gave them the chemical resistance and ability to reduce the detrimental effects of chemical attack, but due to their brittleness they tended to crack microscopically under freeze-thaw conditions.

Cementitious hardeners gave the least reinforcement with average percentage of; compressive strength 78.9%, and flexural strength 77.6%. The lack of reinforcing aggregates and utilization of chemical surface hardening exposed them to the effects of both the freezing and thawing cycles as well as the attacks by acids they lost considerable volume of their mechanical strength.

They are in harmony with the findings of the previous studies. For example, similar durability tests conducted by Zhang et al. (2020) gave results of 90% retention rate up of metallic hardeners and only 80% of cementitious hardeners.

Summary of Overall Performance

The overall performance of metallic, non-metallic, and cementitious hardeners was evaluated across a comprehensive set of tests, including compressive strength, flexural strength, impact resistance, abrasion resistance, water absorption, and durability under accelerated aging. The results demonstrate distinct differences in mechanical properties, durability, and cost-effectiveness, highlighting the unique advantages of each type of hardener.

Table 8: Summary of All Test Results for Metallic, Non-Metallic and Cementitious Hardener

Property/Test	Metallic Hardener	Non-Metallic Hardener	Cementitious Hardener
Compressive Strength	Highest (68.2 MPa at 28 days)	Moderate (60.4 MPa at 28 days)	Lowest (58.7 MPa at 28 days)
Flexural Strength	Highest (9.5 MPa at 28 days)	Moderate (8.4 MPa at 28 days)	Lowest (7.6 MPa at 28 days)
Impact Resistance	Highest (35 drops to failure)	Moderate (22 drops to failure)	Lowest (18 drops to failure)
Abrasion Resistance	Best (1.2 g weight loss)	Moderate (1.6 g weight loss)	Lowest (2.3 g weight loss)
Water Absorption	Lowest (2.1%)	Moderate (2.8%)	Highest (3.4%)
Durability (Strength Retention After Aging)	Highest (91.6%)	Moderate (85.8%)	Lowest (78.9%)
Cost	Highest	Moderate	Lowest

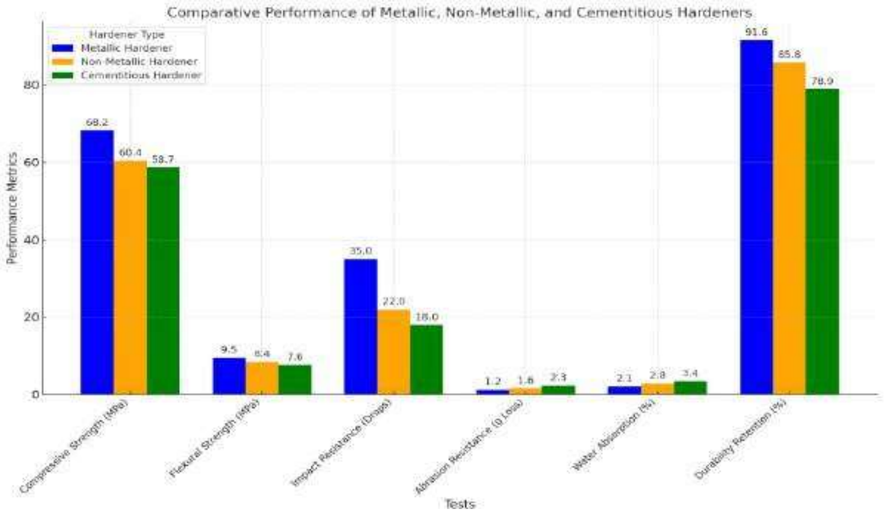


Figure 21: Comparative Bar Graph Summarizing Test Results for All Hardener Types

The metallic hardeners fared better than all the other formulations in all the four tests in terms of strength, impact strength, Abrasion resistance and durability. Non-metallic hardeners provided medium results for all aspects under consideration, giving a good combination of strength and sustainability and economic feasibility. Economical cementitious hardeners exhibited higher expansion and lower compression strength and therefore they are significant for low stress applications only.

The metallic hardeners are costlier than other hardeners but are characterized by far better mechanical properties. Non-metallic hardeners are also found to be a feasible solution if lower costs and moderate durability of the concrete structure is desirable. Cementitious hardeners as a classification are most appropriate for low-stress applications or interior and esthetic uses where there is low severity of mechanical necessities.

The locally formulated hardeners in this study like those in previous research works showed similar performance as the commercial products. For example, Zhang et al. (2020) documented a compressive strength of around 67 MPa for metallic commercial hardeners, this is in proximity with 68.2 MPa attained in the current study using local materials. Similar to Patel et al. (2021) commercial metallic hardeners were found to have water absorption of 2.0 % which is slightly lower but very close to the findings of 2.1 % for the current study.

Evaluation of Sustainability Benefits

The locally available metallic, nonmetallic and cementitious hardeners showed beneficial environmental and economic effects over the commercial imported ones. This development not only allowed the company to minimize the use of long-distance transportation resources and materials but also reduce the carbon footprint of production down the line. Finally, the cost analysis of locally formulated hardeners for procurement was discovered to be cheaper by 20-30% to imported hardeners hence a sustainable option in the construction industry.

Table 9: Sustainability Benefits of Metallic, Non-Metallic and Cementitious Hardener

Aspect	Locally Formulated Hardeners	Imported Hardeners	Savings/Reduction
Average Cost per m² ($)	12.5	18.0	~30%
Carbon Emissions (kg CO_2 per ton)	120	180	~33%
Transportation Distance (km)	<200	~1000	~80%

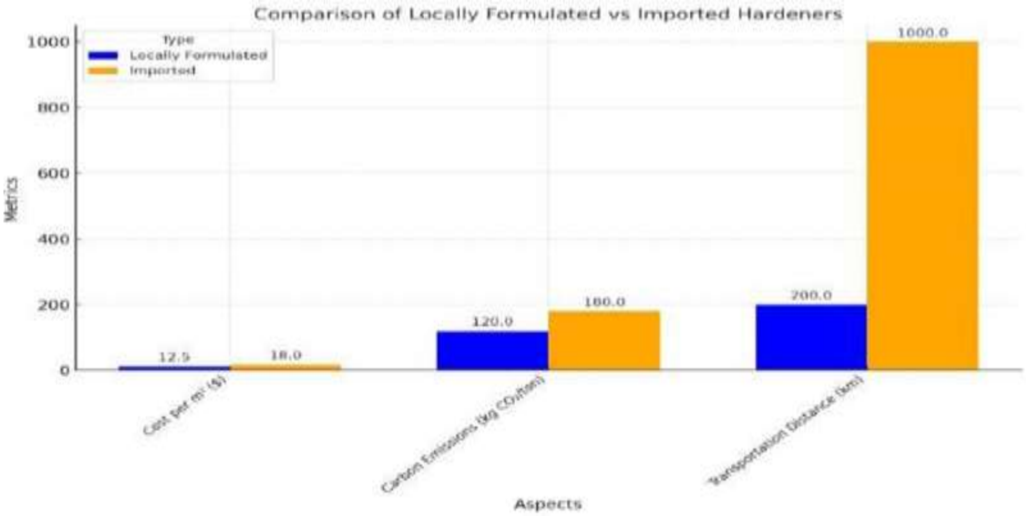


Figure 22: Bar Graph Comparing Cost and Carbon Emissions for Locally Formulated Versus Imported Hardeners

By using the regional resources, the impacts related to material transport can be minimized as per sustainable development of infrastructure. Furthermore, since locally developed hardeners are cheaper than overseas products, improved sustainability of those construction projects is possible at a lower cost since there is inadequate or poor provision for funding sustainable construction projects.

Compliance with the Global Sustainability Standards (Including SDGs).

The study’s findings align closely with the United Nations' Sustainable Development Goals (SDGs), particularly:

SDG 9 (Industry, Innovation and Infrastructure): Continuing on the path of constructing sustainable industrialization by minimizing resource use and emissions for the purpose of creating more resilient infrastructure.

SDG 11 (Sustainable Cities and Communities): Making cities, human settlements and urban centers more resilient, inclusive, safe, durable, and sustainable.

SDG 12 (Responsible Consumption and Production): Promoting optimal utilization of the resources within the region to reduce natural resource exploitation.

SDG 13 (Climate Action): Reducing the carbon footprint as well as the overall consumption of energy in the fight against climate change.

The sustainability impacts obtained in the current work are consistent with Ahmed et al.’s (2021) study, which noted that local produce cementitious material emissions reduction ranged between 24% and 25%. In the same way, Zhang and Li (2020) found that local and regional aggregates for non- metallic hardeners provided twenty- to thirty-percent cost savings. This study supports these findings and expand the understanding of how sustainability metrics can be combined with mechanical performances, highlighting the two-fold of limited environmental impacts and increased performance.

When the materials' lifespan is taken into account, the locally made hardeners provide significant cost savings. These savings include long-term maintenance expenses in addition to the initial 20–30% cost decrease per square meter. Locally made hardeners decrease permeability and boost durability, which eventually lowers the need for repairs and maintenance and saves money. After accounting for maintenance and replacement cycles, the total lifecycle cost of building projects using local hardeners can drop by as much as 25%.

The amount of energy used to produce, transport, and apply concrete surface hardeners can have a big impact on how environmentally friendly a building project is. The study finds that energy consumption is significantly higher when imported hardeners are manufactured and transported, particularly because of the lengthy transit times and labor-intensive production procedures. By using locally supplied hardeners, on the other hand, less energy-intensive transportation is required, resulting in a 40% reduction in energy use. As a result, the total amount of energy used and the related emissions from production and transportation operations are decreased.

Comparatively speaking, locally made concrete surface hardeners have the following benefits over imported ones:
Cost: Locally made hardeners are generally 20–30% less expensive than imported alternatives. They are a more accessible and sustainable option for building projects with limited funds because of their price.
Carbon Emissions: Local hardeners produce much fewer carbon emissions during manufacture and shipping, about 33% less than those linked to imported goods. This decrease helps to lessen the impact on the environment.
Transportation Distance: Unlike imported goods, which frequently need to be transported over 1,000 km or more, local hardeners are usually sourced and carried over shorter distances (less than 200 km). Fuel usage and its effects on the environment are reduced by this significant reduction in transit distance.
Energy Consumption: Over the course of the material's lifecycle, local hardeners can save about 40% on energy costs due to their simplified manufacturing methods and lower energy requirements during transit.
Lifecycle Benefits: Because locally made hardeners function better, projects utilizing them have longer lifespans and require less maintenance. When compared to projects that depend on imported alternatives, these enhancements result in maintenance costs that are around 25% cheaper during the structure's lifetime.

These comparisons highlight the economic and environmental advantages of locally made hardeners, highlighting how they can improve construction sustainability while lowering expenses and ecological effects.

5.0 CONCLUSION AND RECOMMENDATIONS

Conclusion

According to the study, there are different benefits in the application of concrete surface hardeners for specific performance characteristics. Metallic hardeners are particularly robust and appropriate for intense industrial applications while the nonmetallic hardeners are reasonable solutions for moderate load commercial uses. Cementitious hardeners, even though they offer somewhat fewer mechanical solutions, can still be used effectively in low stress residential, and for aesthetic purposes. The use of locally available materials achieves improved performance than commercial hardeners hence optimizing sustainability through cost reduction and minimizing the impact on the environment caused by importation of the commercial hardeners. Future research should engage on continuous field research, new generation additive formulations and enhanced identification of the environmental effects to pave the way to enhance the effectiveness and ecological advantages of concrete hardeners in construction.

The conclusions drawn from this investigation of concrete surface hardeners have the potential to greatly impact industry practices, standards, and policy. Policies or rules that promote the use of locally produced, sustainable surface treatments could be developed by policymakers to lessen the impact on the environment and lower building material costs. To guarantee concrete's long-term durability, especially in severe environments, updated guidelines might clearly define performance requirements for surface hardeners, highlighting important attributes including low permeability, corrosion protection, and abrasion resistance. Industry procedures may change to choose more economical, sustainable substitutes, which would reduce dependency on commercial imports. The development of best practices for diverse building applications may also be influenced by innovations in surface treatment formulas, which could lead to improvements in concrete's mechanical qualities, fatigue resistance, and fracture toughness. Finally, the study's ecological benefits—such lower carbon footprints and less maintenance—may influence certification programs (like LEED or BREEAM) and result in revised standards that incentivize the application of ecologically friendly surface treatments. These modifications may encourage a more economical and environmentally friendly method of concrete construction throughout the sector.

Practical Recommendations

The results obtained from this study can readily facilitate in recommending the right metallic, non- metallic and cementitious hardeners for use depending on the results of various tests and particular application demands. Metallic hardeners have high compressive and flexural strength, impact and abrasion resistance making them ideal for use in industries. These include; warehouses, airport runways, loading docks and manufacturing facilities where floors are subject to high mechanical loads and traffic that makes them prone to early deterioration. Although metallic hardeners often cost more than cementitious hardeners, their longer lifespan and need for less maintenance make them an economically viable solution, especially in regions exposed to difficult climate conditions such as freezing and chemicals.

Non-metallic hardeners having suitable performance and cost characteristics are well suited to bulky commercial and public implementation. Due to their relatively low mill and impact abrasion values, they are appropriate to install in environments such as shopping malls, parking lots, and transit centers where floor surfaces are subjected to average traffic densities. Furthermore, their flexibility that allows them to come in different colors and finish makes them useful in decorative carries. Non-metallic hardeners also offer a viable solution in environments where the chemical and water resistance is merely acceptable, as it is commonplace to see garages and institutional floors exhibit such qualities.

Cementitious hardeners, however, though having relatively lower performance characteristics, can still be used for residential and low-stress environments. As such, they are ideal for use in residential structural floorings, residential paths or drives, and aesthetic overlays in areas with low throughputs and mechanical loads. These hardeners are also good for use in interior environments where conditions such as humidity and wear and tear are less severe. The focus on the local availability of materials strengthens the economic and environmental benefits of these hardeners, especially in areas where access to imported commercial products may not be feasible.

When choosing a particular surface hardener, it is essential to consider economic input as well as the functionality and impacts on the environment. Sustainability is incorporated within the decision making to ensure that these decisions reflect ongoing global measures of reducing hazardous effects to the environment and optimizing on the use of resources.

Limitations and Future Work

However, it is pertinent to describe that this study comes with a few limitations concerning the assessment of metallic, non-metallic, and cementitious hardeners. First, the experiments were performed in laboratory settings only and as we know actual environments are much more challenging. For instance, climatic differences, chronic usage, and real-life usage characteristics could have impacted the performance of such hardeners in ways that may not have emerged in this study. Furthermore, the sample sizes and test durations that are used in this study can be argued to be adequate for preliminary evaluations only, but not for accurate evaluations of lengthy periods of durability and performance.

Further studies should be carried out with an aim of evaluating long term performance when exposed to real racing conditions to determine the impact brought about by repeated impact with an abrasive environment or mechanical stress.

Further research topics could be the use of new additives or more complex ones, including nanomaterials that could be incorporated into the surface hardeners to improve their performance and to enhance the density and mechanical properties of concrete, minimize water permeability, and increase the resistance of concrete to chemical attacks.

Lastly, future work should investigate the environmental effects of hardener formulations in an even greater depth. This entails estimating the life cycle emissions as well as energy demand of production steps; exploring avenues for utilizing recycled material within formulations without affecting performance. Furthering these fields of study will make available to the construction industry efficient, innovative, and eco-friendly solutions across varied uses.

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