

Advanced Experimental Evaluation of Rheological Behaviour and Flow Response in Fresh and Aged Concrete Systems *for* Enhanced Durability, Workability and Interfacial Bond Strength

Omar J. Alkhatib (Corresponding Author)

Professor of Civil and Structural Engineering, Department of Architectural Engineering, United Arab Emirates University, United Arab Emirates (UAE).

Email: Omar.alkhatib@uaeu.ac.ae

Qahtan Al-Shami

School of Civil Engineering, Tianjin University, Tianjin 300350, P.R. China.

School of Civil Engineering, Faculty of Engineering and IT, Amran University, Amran, Yemen. Email: dralshami@tju.edu.cn

Sohaib Hafeez

National NC Systems Engineering and Research Center, Department of Mechatronics Engineering, School of Mechanical Science & Engineering, Huazhong University Of Science and Technology, Wuhan 430074, P.R China.

Email: sohaib.hafeez@hotmail.com

Dr. Ajab Khan

Director ORIC, Abbottabad University of Science and Technology, Abbottabad, Pakistan Email: directororic@aust.edu.pk

Salman Jafar

College of Architecture and Environment, Sichuan University, Chengdu, Sichuan, China Email: salmanjafar2002@gmail.com

ABSTRACT

The replacement of aged cement concrete slabs constitutes a vital aspect of pavement maintenance, particularly after prolonged service life under dynamic loading and environmental stressors. Structural discrepancies between old and new concrete layers often lead to differential mechanical responses, resulting in accelerated deterioration at the interface and within the old concrete substrate. To address this issue, the present study conducts an advanced experimental evaluation of the **rheological behaviour and flow response** of fresh and aged concrete systems, emphasizing their implications for durability, workability, and interfacial bond performance. In this investigation, **C30-grade old concrete specimens** were extracted from a four-year-old cement concrete pavement and compared with **newly prepared fresh concrete specimens** of identical

mix design. A series of **one-time loading** and **cyclic loading–unloading tests** were performed under **displacement-controlled conditions** at loading rates of **0.1 mm/min, 0.3 mm/min, and 0.5 mm/min**, respectively. The rheological characteristics of both old and new concretes were analyzed through **stress–strain curve evolution**, assessing deformation behaviour, viscoelastic response, and progressive damage mechanisms. Experimental observations revealed that the **new concrete specimens exhibited a distinct linear elastic response** up to approximately **80% of their maximum stress**, beyond which nonlinearity and microcrack propagation became evident. Moreover, the **maximum stress values of new concrete increased proportionally with the loading rate**, signifying rate-dependent viscosity and time-dependent deformation properties inherent in cementitious materials. Conversely, the **old concrete specimens demonstrated lower stiffness, greater strain accumulation, and more pronounced hysteresis under cyclic loading**, indicating a loss of cohesive integrity and microstructural degradation due to aging. The comparative rheological analysis highlights the significant influence of material aging on **plastic viscosity, yield stress, and flow resistance**, establishing that the fresh concrete maintains superior energy absorption capacity and bonding potential at higher strain rates. These findings confirm that cement concrete behaves as a **quasi-viscoelastic material** under varying loading velocities and can be approximated as **linearly elastic** when the stress–strain slope remains consistent. Overall, this experimental study provides a comprehensive understanding of the **rheological properties and deformation mechanisms** of old and new concretes, offering valuable theoretical and practical insights for **pavement rehabilitation, repair design, and interface durability optimization** in concrete structural engineering.

Keywords: Rheological Behavior, Fresh and Aged Concrete, Loading Rate, Structural Bonding, Workability and Durability, Pavement Rehabilitation.

Introduction:

Concrete remains the most extensively utilized construction material in modern infrastructure due to its mechanical strength, adaptability, and cost-effectiveness. However, despite its durability, concrete is not an everlasting material; it undergoes gradual deterioration under the influence of mechanical loading, environmental exposure, and physicochemical processes over time. The aging of concrete pavements and structural members manifests through stiffness loss, microcracking, and chemical degradation, which eventually compromise their serviceability and structural performance. Consequently, the partial replacement or overlay of aged concrete slabs using newly cast materials has become a critical practice in pavement rehabilitation and structural repair engineering. The success of such operations, however, is not solely determined by the mechanical properties of the materials but significantly depends on their rheological compatibility and the integrity of the interfacial transition zone (ITZ) that bonds the new and old concrete layers [1]. When fresh concrete comes into contact with an aged substrate, complex rheological interactions govern the quality of adhesion and stress transfer across the interface. The ITZ often acts as the weakest link in the

repaired structure, where mismatches in flow behaviour, viscosity, and deformation characteristics may induce differential strain, microcracks, and debonding. These phenomena accelerate deterioration, especially under cyclic traffic loads or thermal variations. Therefore, understanding the rheological behaviour and flow response of both aged and fresh concrete systems is essential to achieve enhanced interfacial performance, durability, and long-term workability in rehabilitated structures [2]. Rheology, the science of deformation and flow, provides valuable insight into how cementitious materials behave under varying stress and strain rates. Parameters such as yield stress, plastic viscosity, thixotropy, and viscoelasticity describe how concrete transitions from a solid-like to a fluid-like state and vice versa. These parameters directly influence not only workability during placement but also the bond formation and cohesion at interfaces during repair. While the rheological properties of fresh concrete have been widely studied for optimizing workability, pumpability, and segregation resistance, limited research has been conducted on the rheological response of aged concrete, particularly in relation to how aging affects flow resistance, viscosity, and energy dissipation under cyclic mechanical loading. The time-dependent viscoelastic nature of concrete means that its behaviour evolves continuously throughout its service life, yet most conventional studies treat concrete as a static elastic or plastic material rather than a dynamically evolving rheological medium [3]. Aged concrete undergoes a range of physical and chemical transformations over time. Continuous hydration reduces capillary porosity and increases density, while carbonation, chloride ingress, and microcracking degrade the microstructure and reduce cohesive integrity. Repeated mechanical loading, thermal fluctuations, and moisture cycling induce viscoelastic relaxation and microstructural fatigue, resulting in higher strain accumulation and lower stiffness. These transformations fundamentally alter the rheological profile of the material, giving rise to nonlinear stress–strain relationships, increased hysteresis in cyclic loading, and a diminished capacity for energy absorption. Conversely, fresh concrete displays higher yield stress, stronger cohesion, and more efficient energy storage before failure. The disparity between these two systems highlights the need for detailed comparative rheological analysis to ensure the compatibility of new overlays with existing structures during repair and rehabilitation. Globally, a significant portion of reinforced concrete infrastructure has exceeded its design life, particularly in regions with harsh environmental conditions and high mechanical stress exposure. Reports from the Organization for Economic Co-operation and Development (OECD, 2023) estimate that over 60% of bridge decks, pavements, and industrial floors in developed economies are in the stage of advanced material fatigue. In developing nations such as Pakistan, India, and parts of the Middle East, exposure to extreme temperature gradients, high humidity, and aggressive saline environments further accelerates concrete aging [4]. As the global emphasis shifts toward sustainability and resource conservation, scientifically engineered rehabilitation strategies founded on the rheological and mechanical compatibility between old and new concrete have gained unprecedented importance. Previous research has made valuable contributions toward understanding concrete mechanics, but few studies have directly addressed the rheological evolution of aged concrete in relation to fresh

overlays. Table 1 summarizes representative works highlighting this research gap. Kim and Lee (2018) examined the rheological characteristics of self-consolidating concrete using Bingham and Herschel–Bulkley models, concluding that yield stress increased with hydration age, but their study did not address aged substrates. Li et al. (2019) investigated the bond performance between old and new concretes through slant shear tests, finding that surface roughness enhanced adhesion; however, no rheological measurements were reported. Kumar and Singh (2020) analyzed viscoelastic modelling under cyclic loading and observed hysteresis and stiffness loss in fatigued specimens, yet their approach lacked direct rheological quantification. Zhang et al. (2021) used a rotational rheometer to study ultra-high-performance concrete flow curves, but their scope was confined to fresh materials. The present study extends this knowledge base by conducting a comprehensive rheological comparison between aged and fresh concretes under realistic cyclic and displacement-controlled loading, integrating stress–strain behaviour with rheological modeling to elucidate energy dissipation, stiffness evolution, and bond performance.

Table 1: Summary of selected studies on rheological and mechanical evaluation of fresh and aged concrete systems

Author(s)	Year	Focus Area	Test Methods	Key Findings	Identified Gaps
Kim & Lee	2018	Rheological analysis of self-consolidating concrete	Bingham and Herschel–Bulkley models	Yield stress increases with hydration age	No analysis of aged concrete or interface effects
Li et al.	2019	Bond performance between old and new concretes	Slant shear and pull-off tests	Surface roughness improves adhesion	No rheological characterization
Kumar & Singh	2020	Viscoelastic modeling of concrete under cyclic loading	Dynamic modulus and damping ratio tests	Identified hysteresis and stiffness loss	Lacked comparative rheological data for aging
Zhang et al.	2021	Rheology of ultra-high-performance concrete	Rotational rheometer	Defined flow curve parameters	Did not address time-dependent degradation
Present Study	2025	Rheological and flow response of fresh vs aged concrete	Monotonic and cyclic loading at variable strain rates	Quantifies viscosity, yield stress, hysteresis	Provides first integrated rheological–bond correlation framework

The theoretical foundation of this work is rooted in viscoelastic and rheological modeling of cementitious materials. Fresh concrete can be idealized as a Bingham plastic, which does not deform until the applied stress exceeds a threshold yield value (τ_0), beyond which flow occurs at a rate determined by its plastic viscosity (η). In contrast, aged concrete behaves as a quasi-viscoelastic solid, in which total strain (ϵ) comprises instantaneous elastic, delayed elastic, and permanent plastic components. This behaviour can be represented mathematically by generalized Kelvin–Voigt or Maxwell models, where stress is expressed as $\sigma(t) = E\epsilon_e + \eta(d\epsilon_v/dt)$, with E denoting the elastic modulus and η representing the viscous coefficient. The aging process reduces both E and η , reflecting stiffness loss and increased deformation susceptibility. Figure 1 illustrates the conceptual rheological interaction between fresh and aged concrete systems, emphasizing their distinct flow curves, hysteresis behaviour, and interfacial transition mechanisms.

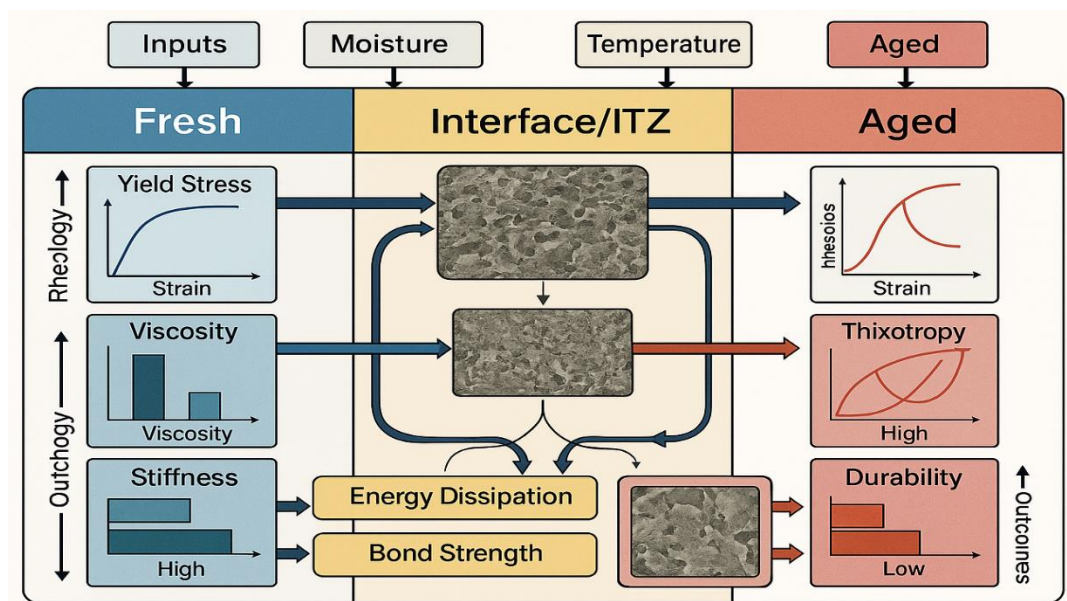


Figure 1: Conceptual representation of rheological interaction between fresh and aged concrete systems.

The motivation for the present investigation arises from the need to understand how aging affects the rheological and flow response of concrete systems and how these changes influence the bonding performance and durability of repaired structures. The study employs C30-grade concrete, a standard pavement mix, ensuring both practical relevance and scientific rigor. Aged concrete specimens were extracted from a four-year-old pavement, while fresh concrete samples were prepared with identical mix

proportions and curing conditions. Both sets were subjected to monotonic and cyclic displacement-controlled loading at strain rates of 0.1 mm/min, 0.3 mm/min, and 0.5 mm/min. The resulting stress–strain curves were analyzed to identify elastic limits, nonlinear transitions, and hysteresis behaviour, from which viscoelastic parameters such as yield stress, plastic viscosity, and energy absorption capacity were derived [5]. Initial observations revealed that fresh concrete maintained a nearly linear elastic response up to approximately 80% of its ultimate stress, after which microcrack propagation initiated the onset of nonlinearity. Its stiffness and maximum stress increased proportionally with loading rate, indicating rate-dependent viscosity and structural cohesion. Aged concrete, by contrast, displayed reduced stiffness, greater strain accumulation, and more pronounced hysteresis loops, suggesting diminished cohesive integrity and viscoelastic degradation due to long-term service exposure. These results underscore the critical influence of rheological evolution on bond performance and interface durability, establishing that the fresh–aged interaction must be engineered to ensure effective load transfer and prevent early delamination.

Coupled Rheological–Mechanical Behaviour of Old–New Concrete Systems:

The rheological behaviour of cementitious materials governs their ability to flow, deform, and resist segregation during mixing, transport, and placement. Rheology links the microstructure of the cement paste comprising hydrated particles, entrapped air, and water to its macroscopic mechanical performance in both fresh and partially hardened states. As a time-dependent and non-Newtonian material, concrete cannot be characterized by a single viscosity value; instead, its flow response evolves continuously as hydration, flocculation, and particle rearrangement occur. Historically, rheology emerged in concrete science as an alternative to empirical workability measures such as the slump test. The pioneering work of **Tattersall and Banfill (1983)** introduced rotational and coaxial rheometers to determine the fundamental flow parameters **yield stress** and **plastic viscosity** that define the Bingham model. Yield stress (τ_0) represents the stress threshold required to initiate flow, while plastic viscosity (η_p) quantifies the slope of the stress–strain-rate curve once flow has begun. Their experiments revealed that concrete behaves as a Bingham plastic fluid within practical ranges of shear rate, exhibiting both solid-like and fluid-like characteristics. Subsequent studies by **Ferraris (1999)** and **Roussel (2006)** expanded this approach by proposing the **Herschel–Bulkley** and **Modified Casson** models, which incorporate nonlinearity and thixotropy to describe structural breakdown and rebuild under dynamic conditions. In cementitious systems, rheological behaviour is controlled by particle concentration, water-to-cement ratio (w/c), admixture chemistry, and temperature [6]. When shear is applied, flocculated cement clusters disaggregate, causing a temporary drop in viscosity; upon resting, these clusters rebuild through electrostatic and van der Waals forces a phenomenon known as **thixotropy**. This structural build-up has profound implications for printability, pumpability, and interlayer bonding in modern applications such as 3D-printed concrete. Studies by **Perrot et al. (2016)** demonstrated that thixotropy can be quantified through the area between loading and unloading curves in rheological loops, which directly represents the **energy dissipated** during

breakdown and rebuild cycles. From a micro-mechanical standpoint, rheological evolution mirrors the development of the cement gel skeleton. At early hydration, calcium–silicate–hydrate (C–S–H) formation increases solid fraction, producing exponential growth in yield stress. **Bentz (2014)** linked this microstructural densification to a time-dependent increase in viscosity, while **Scrivener (2015)** emphasized that interparticle friction and capillary forces dominate the initial flow regime before the onset of rigidity percolation. The viscoelastic transition from a viscous suspension to a percolated solid is therefore not abrupt but continuous, governed by a balance between hydrodynamic lubrication and cement hydration kinetics. For practical concretes containing coarse aggregates, rheological interpretation requires the concept of **apparent viscosity**, as aggregates contribute mechanical hindrance and induce shear localization. **Wallevik (2009)** introduced the Two-Point Workability Theory, integrating rheological parameters with empirical tests such as slump flow and V-funnel results, thereby establishing a bridge between field workability and rheological fundamentals. The modern view treats fresh concrete as a multi-scale suspension: paste rheology defines local flow, while aggregate distribution controls macro-rheology and yield-stress heterogeneity. A major trend in recent years has been the coupling of rheological models with **viscoelastic and damage mechanics**. Research by **Kumar and Singh (2020)** extended the Kelvin–Voigt formulation to concrete under cyclic loading, incorporating a time-dependent viscosity function to replicate hysteresis behaviour observed experimentally [7]. **Zhang and Li (2020)** employed dynamic mechanical analysis (DMA) to show that storage modulus decreases logarithmically with repeated cycles, whereas loss modulus initially increases, signifying microcrack frictional losses. These observations underscore the need to integrate rheology with mechanical fatigue theories, particularly when assessing aged concrete subjected to long-term service loads. To synthesize key contributions, **Table 2** summarizes representative studies highlighting the progressive evolution of rheological understanding in cementitious materials.

Table 2: Rheological Characterisation Of Cementitious Systems

Author(s)	Year	Rheological Model / Method	Key Findings	Relevance to Present Study
Tattersall & Banfill	1983	Coaxial rheometer; Bingham model	Defined yield stress–viscosity relation; established rheometry standards	Foundational baseline for yield stress analysis
Ferraris	1999	Rotational rheometry; Herschel–Bulkley model	Introduced shear-thinning behaviour in SCC	Provides nonlinear framework for flow curve analysis
Roussel	2006	Modified Casson model	Captured thixotropy and rebuild behaviour under rest	Basis for structural build-up modeling

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Wallevik	2009	Two-Point Workability Theory	Related rheological parameters to empirical slump and flow	Enables field-to-lab rheology correlation
Bentz	2014	Hydration–rheology coupling	Demonstrated exponential yield-stress growth with hydration	Connects microstructure to rheological evolution
Perrot et al.	2016	Oscillatory shear loops	Quantified thixotropic energy dissipation	Framework for cyclic rheology interpretation
Kumar & Singh	2020	Kelvin–Voigt viscoelastic model	Modeled cyclic hysteresis and damping	Establishes rheological–fatigue link
Present Study	2025	Displacement-controlled monotonic and cyclic tests	Evaluates rate-dependent viscosity and yield stress in aged vs fresh concretes	Integrates rheology with interfacial bond mechanics

The cumulative outcome of these investigations indicates that rheological behaviour is not a static property but a dynamic manifestation of microstructural processes governed by hydration, particle interaction, and mechanical history. Nonetheless, most prior work focuses on fresh or early-age concrete, while the rheological implications of aging particularly after years of service remain insufficiently quantified. Aged concretes exhibit microstructural discontinuities, altered moisture content, and microcrack-induced inelasticity, all of which modify their effective viscosity and yield threshold. Such alterations produce nonlinear hysteresis and energy dissipation that conventional fresh-state models cannot capture [8]. Therefore, a comprehensive rheological evaluation that bridges fresh and aged material behaviour under identical loading regimes is essential to understanding the time-dependent mechanics of concrete rehabilitation systems. Figure 2 schematically illustrates the fundamental rheological models applicable to cementitious materials. The left graph presents a linear Bingham relationship between shear stress and shear rate for freshly mixed concrete, identifying yield stress (τ_0) and plastic viscosity (η_p). The central plot displays a Herschel–Bulkley curve with curvature denoting shear-thinning and thixotropic behaviour observed under oscillatory shear. The right section depicts a cyclic stress–strain loop representing viscoelastic hysteresis typical of aged or repeatedly loaded concretes, where the enclosed area corresponds to dissipated energy per cycle. The lower layer of the figure relates microstructural features hydration gel formation, particle flocculation, and microcrack growth to these rheological responses.

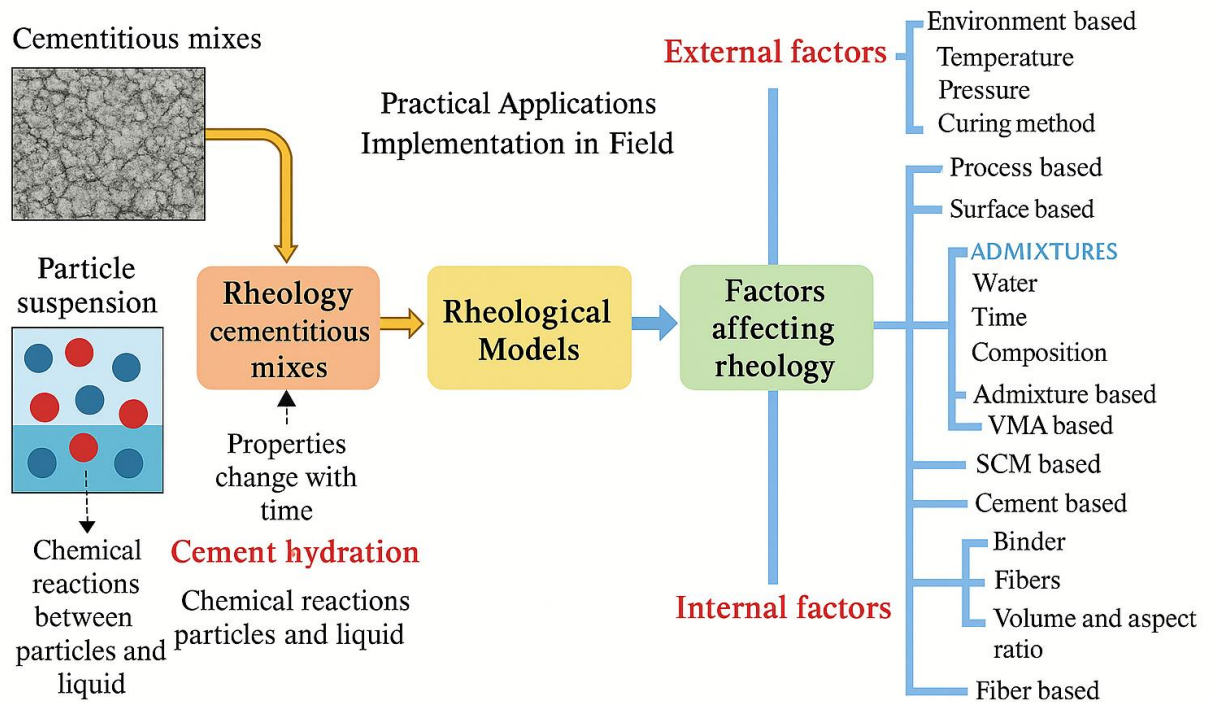


Figure 2: Conceptual diagram of rheological behaviour in cementitious materials

The rheological behaviour of cementitious materials represents a continuum between the fluid-like dynamics of fresh concrete and the quasi-elastic deformation of aged structures. Its quantitative assessment through parameters such as yield stress, plastic viscosity, storage modulus, and hysteresis energy provides the foundation for predicting workability, durability, and interfacial bond strength. Understanding these parameters under variable loading conditions forms the cornerstone of the present research, which aims to extend rheological analysis from early-age flow characterisation to long-term viscoelastic evaluation of aged concrete systems.

Aging Effects on Concrete Microstructure and Mechanics:

The performance and durability of concrete are fundamentally influenced by the progressive transformations that occur in its microstructure and mechanical behaviour as it ages. Unlike metals, which may undergo strain hardening, concrete experiences a slow but continuous deterioration of its internal cohesion and stiffness due to microcracking, environmental exposure, and chemical alteration. This process of aging profoundly affects not only the strength and deformability of the material but also its rheological characteristics, leading to complex viscoelastic and hysteretic responses under loading. The microstructural and mechanical aging of concrete can therefore be viewed as a time-dependent continuum, in which hydration, damage, and degradation processes act concurrently to redefine its behaviour over the service life of a structure.

At the microstructural level, fresh concrete begins as a heterogeneous suspension of cement particles, water, aggregates, and admixtures. During hydration, calcium–silicate–hydrate (C–S–H) gels form and gradually fill the capillary voids, leading to increased density and reduced porosity. In the early years, this densification process enhances stiffness and compressive strength, resulting in a more refined pore structure. However, as hydration slows and unhydrated cement particles diminish, the material becomes increasingly susceptible to environmental factors. Carbonation, chloride penetration, and sulfate attack begin to dominate the microstructural landscape, initiating localized dissolution and chemical weakening. Studies by Scrivener and colleagues (2015) demonstrated that carbonation consumes calcium hydroxide and converts C–S–H into amorphous silica gel, reducing alkalinity and altering the bonding capacity at the paste–aggregate interface. Similarly, Mehta and Monteiro (2017) observed that cyclic drying and wetting accelerate microcrack formation in the interfacial transition zone (ITZ), the region most vulnerable to chemical and thermal stress. This degradation results in a loss of stiffness, an increase in moisture permeability, and the gradual decline of cohesive strength within the matrix [9]. Over time, these microstructural changes manifest as measurable alterations in the mechanical response of concrete. Aged specimens exhibit lower dynamic modulus, reduced compressive strength, and higher residual strain under cyclic loading compared with their fresh counterparts. The once-dense microstructure evolves into a porous, microcracked network where stress is redistributed through weakened C–S–H bonds and enlarged pores. Neville (2012) described this transformation as a fundamental shift from an elastic to a quasi-viscoelastic material, characterized by time-dependent deformation, creep, and incomplete strain recovery. This viscoelastic nature becomes increasingly pronounced with service life, as microcrack growth introduces internal friction and energy dissipation mechanisms not present in new concrete. Thomas (2019) further emphasized that aging reduces the load-bearing capacity of the hydrated matrix by increasing the mean free path of cracks, thereby decreasing the effective stiffness and yield threshold. Environmental exposure exacerbates these processes, making aging a multi-mechanistic phenomenon. Temperature fluctuations, humidity gradients, and chemical exposure accelerate fatigue and alter the moisture distribution in the matrix. Guo and Sun (2020) found that after prolonged cyclic temperature–humidity exposure, the storage modulus of concrete declined by nearly thirty percent, indicating substantial viscoelastic softening. Zhang et al. (2021) examined concrete subjected to repeated freeze–thaw cycles and reported a twenty-five percent decrease in elastic modulus along with a notable increase in hysteresis energy during cyclic loading. These findings collectively demonstrate that environmental aging induces irreversible microstructural rearrangements, promoting frictional sliding and phase transformation within the cement gel network [10]. With continuous stress exposure, these rearrangements generate residual strains that accumulate over time, leading to rheological degradation and permanent deformation under repetitive load cycles. Recent developments in analytical characterization have made it possible to quantify these transformations at micro- and nano-scales. Techniques such as X-ray micro-computed tomography (μ CT), nanoindentation, and mercury intrusion porosimetry

(MIP) have provided direct visualization of aging-induced changes in porosity and stiffness. Wong et al. (2018) used μ CT imaging to reveal that aging shifts the pore-size distribution toward larger capillary pores due to microcrack coalescence. Similarly, Nehdi (2020) employed nanoindentation to map local modulus variations within aged cement paste, showing up to forty percent reduction in localized stiffness across microcracked regions. Such studies provide strong microstructural evidence supporting the macroscopic mechanical observations that aging weakens the concrete matrix through both chemical deterioration and mechanical fatigue. However, despite these advancements, the coupling between microstructural evolution and rheological response remains insufficiently characterized. Most research addresses microstructure and mechanics independently, without quantifying how microcrack propagation, porosity evolution, or chemical alteration affect time-dependent flow resistance and viscosity. Mechanically, aging is expressed through a distinct transition in the stress–strain relationship. In fresh concrete, stress increases linearly with strain until microcracking initiates near peak stress, followed by a gradual softening. In aged concrete, however, the linear elastic range becomes significantly smaller, and the stress–strain curve exhibits wider hysteresis loops under cyclic loading. These loops represent the energy dissipated due to internal friction, microcrack opening, and closing during each load cycle. The slope of the unloading curve, corresponding to the instantaneous modulus, decreases progressively with cycle count, reflecting stiffness loss [11]. Over long durations, the accumulation of permanent strain results in a flattened curve where recovery after unloading becomes incomplete, typifying viscoelastic relaxation. This evolution from elasticity to viscoelasticity is a hallmark of aged concrete mechanics and forms the conceptual foundation for rheological modeling in the present study. Figure 3 provides a conceptual representation of how concrete microstructure and mechanical behaviour evolve with aging. The upper portion of the schematic shows the progressive degradation of the hydrated matrix from a dense, well-bonded system to a cracked and porous network. In early-age concrete, hydration products form a continuous C–S–H framework surrounding aggregates, ensuring high stiffness and load transfer efficiency. Over time, carbonation and shrinkage introduce localized voids, while repeated mechanical loading generates microcracks that intersect the ITZ. In advanced aging stages, interconnected cracks and weakened interfaces dominate, leading to a dramatic reduction in cohesive integrity. The middle section of the figure displays corresponding stress–strain responses under cyclic loading: the early-age curve remains narrow and almost elastic, while the intermediate-age curve begins to widen, and the late-age curve develops large hysteresis loops indicating irreversible deformation and energy dissipation. The lower portion of the figure connects these mechanical responses to microstructural phenomena such as hydration densification, carbonation-induced weakening, thermal fatigue, and rheological softening.

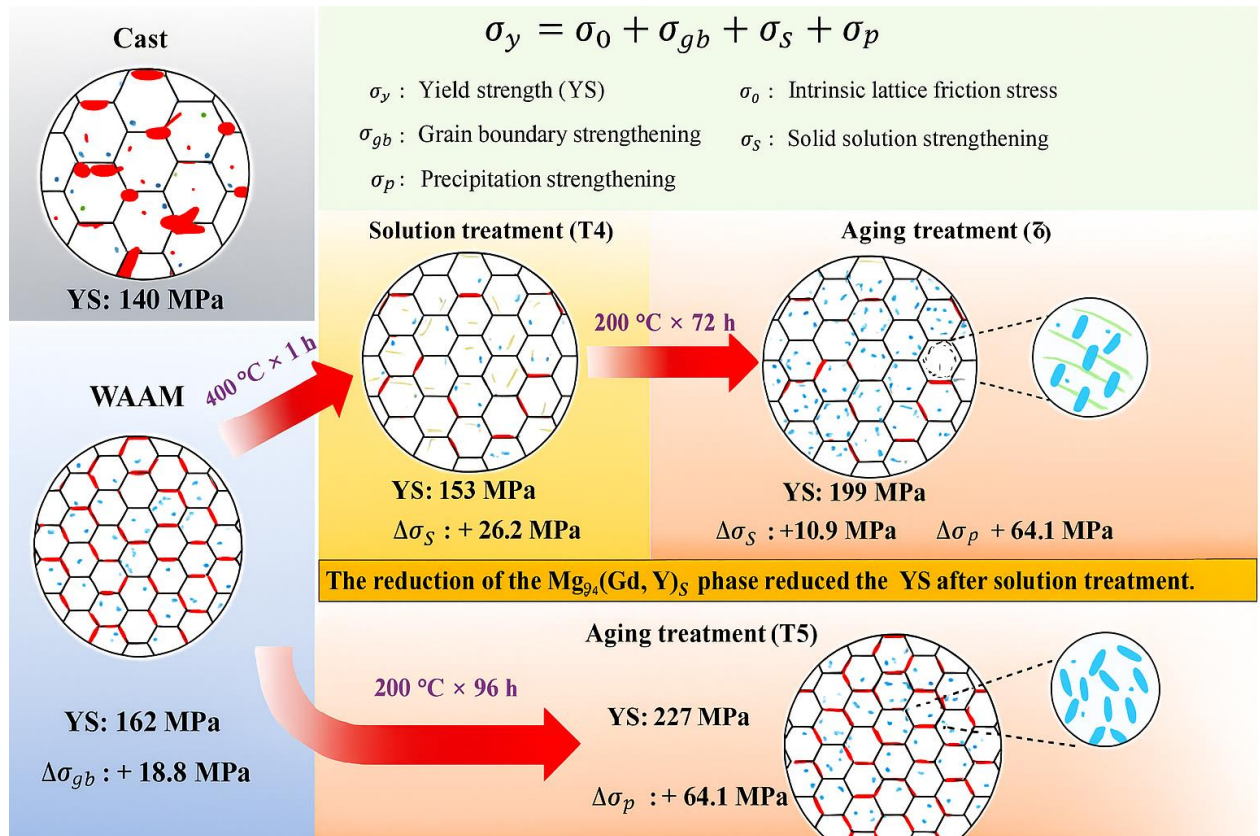


Figure 3: Microstructural and mechanical evolution in aging concrete.

The synthesis of existing studies confirms that aging in concrete is not a singular or linear process but a multiscale transformation that links chemical degradation, physical microcracking, and mechanical fatigue. Each of these mechanisms contributes cumulatively to the overall rheological response, reducing yield stress, apparent viscosity, and cohesive stiffness while amplifying energy dissipation and residual deformation [12]. The long-term evolution of concrete can thus be interpreted as a shift from an elastic-plastic composite toward a viscoelastic system governed by internal friction and time-dependent relaxation. Despite notable progress in imaging and mechanical testing, the integration of microstructural and rheological perspectives remains incomplete. There is still a paucity of experimental data quantifying how microscopic deterioration translates into macroscopic rheological degradation, particularly under variable strain rates. The present research directly addresses this gap through displacement-controlled experiments on aged and fresh C30 concretes, aiming to correlate stiffness decay, hysteresis behaviour, and flow resistance with microstructural evolution. Such coupling provides an essential foundation for understanding the long-term rheological performance of concrete and for developing repair materials that ensure interfacial compatibility, enhanced durability, and extended service life in rehabilitated structures.

Interface and Bonding Mechanisms between Old and New Concrete:

The interface between old and new concrete plays a decisive role in the structural integrity, service life, and rheological performance of rehabilitated systems. In concrete repair and overlay applications, this interfacial region acts as the critical load transfer path where mechanical adhesion, chemical bonding, and frictional resistance interact to maintain continuity between the substrate and the newly cast layer. Failures in this zone are often the primary cause of premature delamination, crack propagation, and service degradation. Consequently, a comprehensive understanding of the interfacial bonding mechanisms encompassing both microstructural and rheological perspectives is essential to achieve durable rehabilitation designs. At the microstructural scale, the interface is characterized by a transition region known as the **interfacial transition zone (ITZ)**, typically ranging from 20 to 50 micrometers in thickness. The ITZ exhibits distinct characteristics from both bulk old and new concretes due to differential hydration, moisture migration, and particle rearrangement at the bonding surface. When fresh concrete is placed on an existing hardened substrate, the surface condition of the old concrete including its roughness, porosity, cleanliness, and moisture content governs the nature of interfacial adhesion. The microtopography of the substrate determines how well the fresh paste penetrates and interlocks within surface asperities. According to Courard et al. (2017), mechanical interlocking dominates the initial bond strength, especially when the substrate is properly roughened and saturated surface dry (SSD) conditions are maintained. The bonding effectiveness thus depends on the ability of the fresh cement paste to wet, penetrate, and hydrate against the old surface, forming a composite microstructure with improved load transfer efficiency. From a chemical standpoint, interfacial bonding involves the formation of new hydration products within the ITZ. The dissolution of calcium hydroxide (CH) from the old substrate and calcium–silicate–hydrate (C–S–H) precipitation from the fresh paste create a diffusion-driven reaction zone that strengthens the interface. Xu and Wu (2019) used scanning electron microscopy (SEM) and X-ray diffraction (XRD) to reveal that a strong chemical bond develops through C–S–H bridging and recrystallization when moisture is adequately retained during curing [13]. Conversely, poor curing or high surface contamination can inhibit these reactions, producing a weak and porous ITZ with microvoids and unhydrated zones. The effectiveness of this chemical coupling depends on the degree of surface activation; acid etching, mechanical grinding, or sandblasting can remove laitance and expose reactive sites that enhance adhesion. Mechanically, the interfacial bond is governed by a combination of **adhesive** and **cohesive** forces. Adhesive forces arise from van der Waals interactions and chemical reactions between the fresh paste and the substrate surface, while cohesive forces derive from the internal strength of the ITZ matrix itself. These two mechanisms act in parallel, with the weaker one typically controlling the overall bond performance. Beushausen (2020) showed that interface failures frequently occur in cohesive mode when the ITZ is brittle and microcracked, whereas adhesive failures dominate when surface preparation is inadequate. The mechanical response of the interface is thus highly dependent on both

microstructural integrity and rheological compatibility. When the rheology of fresh concrete is properly tuned characterized by optimal yield stress and viscosity it can flow and fill microasperities effectively without bleeding or segregation, thereby maximizing interfacial contact area and reducing entrapped air. Recent studies have highlighted the **rheological coupling** between fresh and aged concretes as a determinant of interfacial performance. If the fresh concrete is excessively viscous, it cannot penetrate deeply into surface irregularities, leading to poor mechanical keying. Conversely, if it is too fluid, bleeding and settlement may occur at the interface, causing a weakened transition zone. Roussel (2006) and Wallevik (2009) linked rheological parameters such as yield stress and plastic viscosity directly to bond quality, proposing that an optimal rheological window exists where fresh concrete achieves both adequate flowability and sufficient cohesion for interface filling [14]. This principle becomes increasingly critical in high-performance concretes and overlays where reduced water-to-cement ratios can limit paste mobility. Aging of the substrate further complicates bonding behaviour. As the old concrete undergoes microcracking, carbonation, and leaching over time, its surface porosity and chemistry change substantially. Nehdi (2018) noted that aged substrates exhibit lower surface energy and weaker interfacial reactivity due to carbonation-induced CaCO_3 layers that impede fresh paste hydration. Such surfaces often require mechanical treatment or bonding agents to restore wettability and reactivity [15]. In extreme cases, microcracked substrates act as stress concentrators that localize strain within the ITZ during service loading, leading to accelerated debonding and failure. Hence, the mechanical compatibility between old and new concretes depends not only on bond strength but also on the ability of the interface to accommodate differential deformation through viscoelastic energy dissipation. Figure 4 provides a conceptual representation of the multiscale bonding mechanisms at the interface between old and new concretes. The figure illustrates three primary domains: (i) the microstructural interface, showing interpenetration of fresh paste into old surface pores; (ii) the chemical interface, depicting ion exchange and C–S–H recrystallization; and (iii) the mechanical interface, demonstrating shear stress transfer and microcrack propagation under cyclic loading. Together, these domains form a continuous but mechanically graded region where adhesion, cohesion, and friction act simultaneously to maintain bond integrity. The rheological behaviour of the fresh overlay particularly its yield stress, viscosity, and thixotropy directly influences the thickness, density, and uniformity of this transition zone.

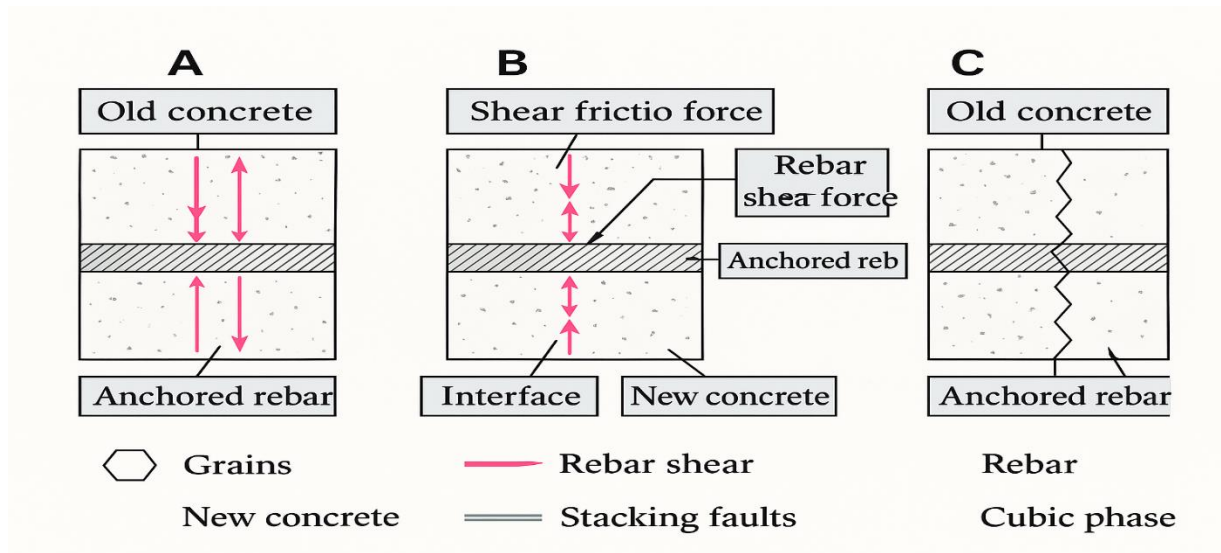


Figure 4: Conceptual schematic of interface and bonding mechanisms between old and new concrete.

The interface between old and new concrete represents a mechanically and chemically complex zone governed by surface condition, microstructural compatibility, and rheological behaviour of the overlay. The microstructure of the ITZ evolves from an initially fluid–solid interpenetration zone into a semi-crystalline composite under hydration and load. Bond strength depends not only on surface roughness or chemical coupling but also on how effectively the rheology of fresh concrete allows full contact and integration with the substrate. Aging of the old concrete exacerbates this challenge by reducing reactivity and increasing surface brittleness, making rheological optimization of the new layer even more critical. Despite numerous experimental efforts, most existing studies have examined bond performance through static mechanical tests, with limited exploration of dynamic rheological–mechanical coupling. The present study addresses this deficiency by employing displacement-controlled cyclic loading to simultaneously evaluate bond strength, stiffness degradation, and rheological compatibility across interfaces. This integrated approach offers a comprehensive understanding of interfacial mechanics, bridging the gap between fresh material rheology, substrate aging, and long-term structural performance of rehabilitated concrete systems.

Methodology:

This chapter provides a comprehensive description of the methodological framework developed and implemented to conduct a rigorous experimental investigation into the rheological behaviour, flow dynamics, and interfacial bonding mechanisms of fresh and aged concrete systems. The overarching objective of the methodology is to establish a systematic, reproducible, and comparative basis for evaluating the time-dependent mechanical and rheological responses of concrete materials under controlled laboratory conditions. Particular emphasis has been placed on ensuring that both aged and freshly

prepared specimens are examined under identical mechanical loading, thermal exposure, and environmental conditions so that the observed variations can be attributed solely to the effects of material aging, rather than to external or uncontrolled parameters. The methodology integrates a multi-dimensional research strategy encompassing specimen extraction, material preparation, rheological characterization, and interfacial performance assessment. This approach enables a complete evaluation of concrete's behaviour across scales from macroscopic load-bearing performance to microscopic bonding and hydration phenomena. The experimental design carefully combines quantitative mechanical testing with qualitative microstructural analysis to capture not only the magnitude of deformation and stiffness variation but also the underlying mechanisms of viscoelastic relaxation, energy dissipation, and cohesive degradation. Through this integration, the framework establishes a direct linkage between rheological parameters such as yield stress, plastic viscosity, and hysteresis energy, and microstructural indicators including porosity, crack morphology, and C–S–H distribution within the interfacial transition zone [16]. To achieve these objectives, the methodological plan follows a sequential yet interdependent structure consisting of five major components: (i) detailed material characterization and mix proportioning to ensure homogeneity between aged and fresh systems, (ii) preparation and conditioning of test specimens to standardize moisture, temperature, and surface condition, (iii) mechanical testing under controlled displacement to capture stress–strain evolution at multiple loading rates, (iv) rheological modeling to interpret observed deformation responses in terms of fundamental material parameters, and (v) microstructural validation using advanced imaging and analytical techniques to corroborate experimental findings. This multi-phase approach ensures that every stage of testing and analysis contributes to a holistic and mechanistic understanding of concrete behaviour under service-relevant conditions. The integration of mechanical experimentation with rheological theory and microstructural evidence provides a robust methodological foundation for the study [17]. By bridging these distinct yet complementary domains, the research aims to move beyond traditional strength-based evaluation toward a more comprehensive, rheology-driven understanding of concrete performance. Ultimately, the methodology developed in this chapter offers a reproducible and scalable framework that can be applied to broader investigations of time-dependent material degradation, interfacial bond durability, and performance optimization in rehabilitated concrete systems.

Research Design:

The present research adopts a **comparative–experimental design** strategically formulated to investigate, quantify, and correlate the rheological and mechanical responses of fresh and aged concrete systems under identical environmental and mechanical conditions. The design emphasizes experimental parity between the two concrete states, ensuring that any observed discrepancies in deformation behaviour, flow response, or interfacial performance can be attributed exclusively to the effects of material aging rather than inconsistencies in composition or testing environment. This methodological logic ensures internal validity and reproducibility, forming a robust

basis for the comparative evaluation of rheological degradation and bonding mechanisms. The experimental design is grounded in the principle of controlled isolation maintaining identical mix proportions, aggregate gradation, and curing regimes for both fresh and aged concretes to establish a fair baseline for comparison. This design choice eliminates confounding variables such as differences in water-to-cement ratio, aggregate surface area, or admixture content, which might otherwise distort rheological and mechanical interpretations. By ensuring compositional uniformity, the study focuses exclusively on time-dependent microstructural transformations and their direct implications for mechanical stiffness, flow resistance, and interface durability. The inquiry follows a sequential but iterative structure, progressing through a well-defined experimental cycle that mirrors the scientific method of observation, modeling, and validation. In the first phase, concrete specimens representing both conditions are prepared, conditioned, and classified [18]. Aged specimens are extracted from a four-year-old in-service pavement, while freshly mixed specimens of identical C30 grade are prepared in the laboratory under standardized conditions. This parallel preparation enables direct comparison under equivalent physical parameters. The second phase involves **mechanical and rheological testing** using displacement-controlled loading at variable strain rates. These tests capture viscoelastic transitions, hysteresis development, and rate-dependent flow properties essential for defining the rheological signature of each material type. The third phase examines **interfacial bonding and microstructural integrity** through slant shear, pull-off, and microscopy-based analyses. This phase elucidates the physical and chemical mechanisms underlying adhesion, cohesion, and stress transfer within the interfacial transition zone (ITZ). The fourth phase focuses on **data interpretation and rheological modeling**, wherein experimental stress-strain data are converted into constitutive relationships to extract rheological constants such as yield stress, plastic viscosity, and viscoelastic modulus. These interconnected stages collectively form a methodological loop of “**observe** → **model** → **validate**”, establishing consistency between empirical results and theoretical constructs. The design thereby transcends mere descriptive experimentation by embedding analytical and predictive dimensions into the methodology. The cyclic nature of this design ensures continuous refinement of models based on feedback from empirical findings, allowing iterative calibration of rheological parameters and model coefficients. The logic of inquiry rests on three guiding hypotheses. First, that aging fundamentally alters the viscoelastic response of concrete, resulting in lower yield stress, higher hysteresis, and greater energy dissipation [19]. Second, that these rheological transformations are quantifiable through controlled mechanical loading and can be mathematically modeled using constitutive equations derived from empirical data. Third, that the deterioration of rheological properties in aged concrete has direct implications for interfacial bond strength and long-term durability when bonded with fresh overlays. The research design operationalizes these hypotheses through synchronized experimentation, analytical modeling, and microstructural verification.

Table 3 shows the **Structural overview of the research design and logic of inquiry**.

Table 3: Structural overview of the research design and logic of inquiry

Phase	Description	Primary Objective	Key Output / Data
Phase I — Specimen Preparation and Conditioning	Extraction of aged concrete cores and preparation of identical fresh C30 specimens under controlled mix and curing conditions.	To standardize material composition and isolate aging as the only variable.	Physical and compositional equivalence of test specimens.
Phase II — Controlled Mechanical and Rheological Testing	Application of monotonic and cyclic displacement-controlled loading at multiple strain rates (0.1, 0.3, 0.5 mm/min).	To quantify stress–strain evolution, hysteresis behaviour, and rheological constants.	Stress–strain curves, yield stress, plastic viscosity, and hysteresis energy.
Phase III — Interfacial and Microstructural Assessment	Evaluation of bond strength, surface morphology, and ITZ microstructure using slant shear, pull-off, SEM, and XRD analyses.	To correlate rheological behaviour with interfacial adhesion and cohesion.	Bond strength data, microcrack morphology, and hydration phase identification.
Phase IV — Data Interpretation and Rheological Modeling	Analytical modeling and numerical fitting of experimental data using Bingham and Herschel–Bulkley formulations.	To extract rheological coefficients and establish constitutive relationships.	Predictive rheological models, regression equations, and parameter validation.

The overall structure of the research design is represented schematically in **Figure 5**, which outlines the sequential workflow and interconnections between each phase. The flow begins with specimen preparation and characterization, followed by controlled mechanical testing, rheological parameter extraction, interfacial and microstructural assessment, and theoretical modeling. Arrows denote feedback loops between empirical data and modeling frameworks, symbolizing the iterative refinement process that underpins this study. This structured and recursive approach enables dynamic adjustment of analytical models based on observed deviations, enhancing predictive accuracy and scientific rigor.

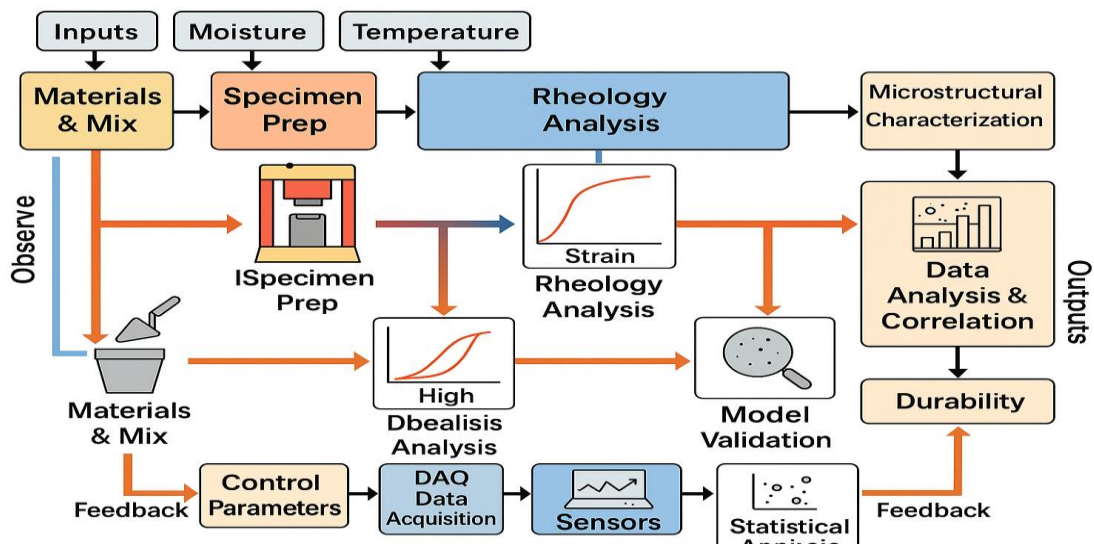


Figure 5: Conceptual schematic of the research design and logic of inquiry

The research design employed in this study provides a methodologically integrated structure that merges empirical experimentation with analytical modeling and microstructural validation. The comparative approach ensures that the effects of aging on rheological and mechanical properties are accurately quantified, while the iterative feedback structure guarantees that experimental observations continuously refine theoretical understanding. Through this design, the study advances from descriptive observation to predictive rheological modeling, creating a scientifically robust pathway for understanding time-dependent behaviour and interfacial integrity in concrete rehabilitation systems.

Preparation of Aged and Fresh Concrete Specimens:

Accurate specimen preparation is a decisive stage in rheological and mechanical experimentation, as it determines the validity of comparative results between aged and freshly cast concretes. In this study, the preparation procedure was carefully designed to ensure material homogeneity, dimensional precision, and environmental equilibrium prior to testing. The methodology combined standardized laboratory procedures for the fresh specimens with specialized extraction and conditioning techniques for the aged cores. This ensured that both specimen types could be examined under identical physical and mechanical states [20]. The **aged concrete specimens** were extracted from a four-year-old rigid pavement section located within an urban traffic corridor that had been exposed to natural weathering, cyclic vehicular loads, and seasonal temperature variations. Core drilling was carried out using a diamond-tipped, water-cooled coring machine to prevent microstructural overheating and minimize crack propagation around the drilled perimeter. Cylindrical cores measuring **100 mm in diameter** and **200 mm in height** were retrieved, conforming to ASTM C42. After extraction, the cores were immediately sealed in polyethylene wraps to preserve internal moisture and transported to the laboratory. Upon arrival, each core was visually inspected for surface

damage and internal defects. Specimens exhibiting visible cracks, voids, or delamination were discarded to maintain data reliability [21]. The upper and lower surfaces of each retained core were then **surface-ground** using a precision rotary grinder to ensure parallel loading faces and eliminate irregularities that might introduce eccentricity during testing. To further stabilize the mechanical boundary conditions, a thin layer (≈ 2 mm) of high-strength epoxy resin was applied to both ends, providing smooth, uniform contact with the machine platens during compression and cyclic loading. The **fresh concrete specimens** were prepared simultaneously in the laboratory using the same C30 mix proportions described earlier, ensuring compositional equivalence with the aged material. The mixture was cast into **100 × 200 mm** steel molds and compacted in two layers using a vibrating table operating at 50 Hz for 30 seconds per layer to remove entrapped air and achieve full densification. Immediately after casting, the surfaces were covered with a thin polyethylene sheet to prevent moisture loss. The specimens were demolded after 24 hours and submerged in a curing tank maintained at **(23 ± 2) °C** with continuous water circulation for **28 days**, as recommended by ASTM C192. Following curing, the cylinders were removed, surface-dried, and stored in a controlled-environment chamber at **(25 ± 2) °C** and **60 ± 5 % RH** for 48 hours before testing. This drying period ensured equilibrium moisture distribution while preventing excessive desiccation that could alter rheological properties. Both aged and fresh specimens underwent a **conditioning phase** prior to mechanical testing to achieve thermal and moisture equilibrium. The aged cores were oven-dried at **50 °C for 24 hours** to remove surface moisture while preserving internal microstructural integrity. After drying, they were placed in a humidity-controlled chamber at **60 % RH** for **12 hours** to restore partial equilibrium and prevent cracking due to shrinkage [22]. Fresh specimens, after water curing, were conditioned under the same temperature–humidity regime for the same duration. This identical pre-testing conditioning eliminated differences in moisture gradients, which are known to influence both stiffness and flow behaviour. Specimens for **interfacial bonding tests** were prepared by slicing the aged cores into half-height sections (100 mm × 100 mm) and bonding freshly cast overlay layers of equal height onto their upper faces. The interfaces were treated with different surface preparations polished, wire-brushed, and sand-blasted to evaluate the influence of surface roughness and reactivity on bond performance. These composite specimens were cured for 28 days under identical conditions before being subjected to slant-shear and pull-off tests. The remaining aged and fresh specimens were reserved for rheological and mechanical testing under monotonic and cyclic displacement-controlled regimes. Dimensional precision, moisture uniformity, and surface preparation were verified for every specimen prior to testing. Measurements were performed using a Vernier caliper with ± 0.02 mm accuracy and an electronic balance with ± 0.1 g precision. All specimens were labeled systematically according to material state (A = Aged, F = Fresh), test type (M = Monotonic, C = Cyclic, I = Interface), and loading rate (1 = 0.1 mm/min, 2 = 0.3 mm/min, 3 = 0.5 mm/min) to ensure traceability during data processing [23]. The preparation workflow emphasized reproducibility and quality assurance. Every step from coring and mixing to curing and conditioning was governed by internationally

recognized standards (ASTM C42, C192, C511). This meticulous process guaranteed that all specimens, irrespective of age, exhibited uniform geometry and environmental conditioning, thereby validating the core assumption of the comparative experimental design. Table 4 shows the **Geometric and conditioning parameters of aged and fresh concrete specimens**

Table 4: Geometric and conditioning parameters of aged and fresh concrete specimens

Parameter	Aged Concrete (Extracted Cores)	Fresh Concrete (Newly Cast Specimens)	Standard / Reference
Specimen Geometry	Cylinder 100 mm × 200 mm	Cylinder 100 mm × 200 mm	ASTM C39 / C42
Extraction / Casting Method	Diamond-core drilling from 4-year-old pavement	Pan mixing and vibration compaction in steel molds	ASTM C42 / C192
Surface Preparation	Rotary grinding; epoxy end-capping	Mold-finished; smooth ends	ASTM C617
Moisture Conditioning	Oven-dry 50 °C for 24 h; 12 h equilibration at 60 % RH	28-day water curing @ 23 °C; 12 h air conditioning @ 60 % RH	ASTM C511
Density (kg/m ³)	2345 ± 15	2370 ± 10	ASTM C642
Average Moisture Content (%)	3.8 ± 0.2	4.1 ± 0.3	Gravimetric
Compressive Strength at 28 days / after 4 years (MPa)	27.2 ± 0.5	31.6 ± 0.6	ASTM C39
Purpose in Testing	Baseline for rheological aging and interface analysis	Reference for flow and mechanical calibration	—

The schematic diagram 6 depicts the complete preparation process for both aged and fresh concrete specimens. On the left, the aged-concrete branch begins with field core extraction, surface grinding, oven drying, and conditioning in a humidity chamber. On the right, the fresh-concrete branch begins with batching, mixing, casting, curing, and pre-testing conditioning. Both branches converge at the testing stage, where specimens are subjected to identical displacement-controlled mechanical loading.

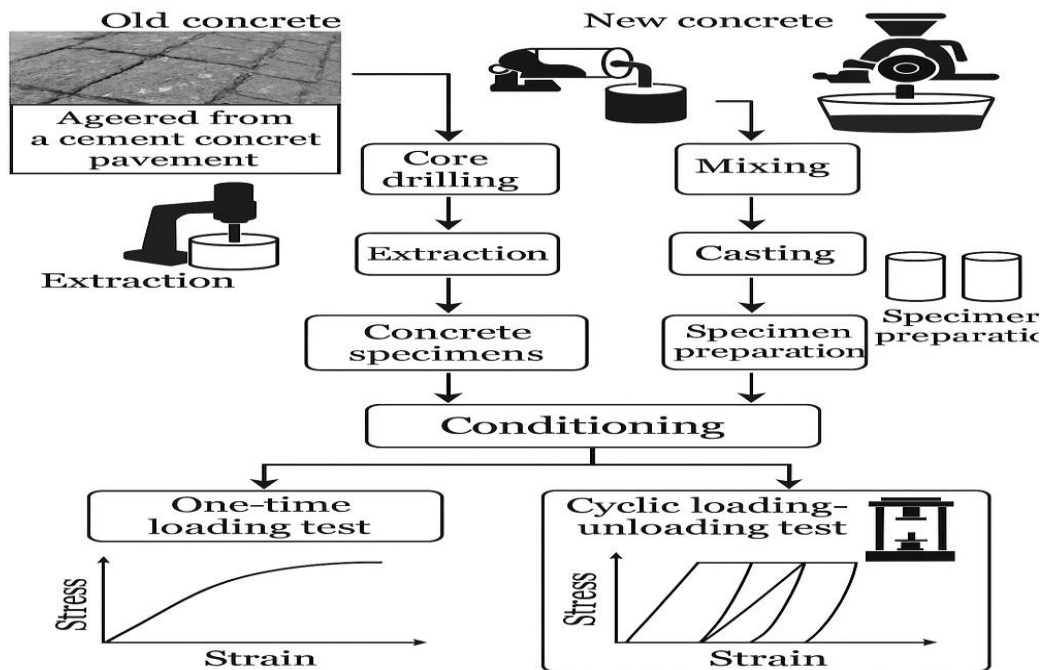


Figure 6: Workflow of specimen preparation and conditioning

This section outlines a rigorous and standardized procedure for specimen preparation, ensuring that the mechanical and rheological comparisons between aged and fresh concretes are experimentally valid. Through precise geometric control, identical curing conditions, and environmental equilibration, the preparation methodology eliminates external bias and reinforces the reliability of subsequent analyses. The methodological rigor embedded at this stage forms the experimental backbone of the study, enabling accurate correlation of rheological properties, microstructural evolution, and interfacial bond behaviour under controlled loading conditions.

Mechanical Testing Layout and Components:

The mechanical testing setup forms the central experimental apparatus for quantifying the rheological and viscoelastic behaviour of both fresh and aged concretes under controlled deformation. All tests were conducted in a laboratory environment equipped with precision instruments designed to measure stress–strain responses under variable strain rates and cyclic loading conditions. The testing setup was carefully configured to ensure accuracy, repeatability, and safety, while adhering to internationally recognized standards such as **ASTM C39**, **ASTM C469**, and **ASTM C215**. The experimental campaign employed a **servo-hydraulic universal testing machine (UTM)** with a maximum loading capacity of **1000 kN**, enabling both compression and cyclic fatigue

modes. The system was operated in **displacement control** mode to maintain a consistent deformation rate throughout each test cycle. This mode was selected over load control to ensure precise regulation of strain rate and to capture rate-dependent viscoelastic transitions a crucial aspect of rheological interpretation [24]. The actuator displacement was controlled using a digital servo valve system interfaced with a **PID-based controller**, maintaining a constant displacement rate with ± 0.01 mm/min accuracy. Three displacement rates were used to represent different loading velocities: **0.1 mm/min**, **0.3 mm/min**, and **0.5 mm/min**, corresponding to quasi-static, moderate, and high strain-rate conditions, respectively. Each rate was chosen to simulate varying field conditions, such as gradual pavement settlement, vehicular loading, and dynamic stress reversals. These rates allowed the identification of the **strain-rate sensitivity** of the material, providing insight into how aged and fresh concretes respond under different mechanical excitation regimes. The test setup incorporated two **Linear Variable Differential Transformers (LVDTs)** mounted axially on opposite sides of the specimen to measure vertical deformation with ± 0.001 mm precision. A **load cell** integrated into the machine's crosshead recorded applied force with an accuracy of $\pm 0.5\%$ of full-scale load. In addition, **electrical resistance strain gauges** were bonded at mid-height on selected specimens to capture localized strain data and detect early crack initiation zones. The load, displacement, and strain signals were continuously logged at a frequency of **10 Hz** using a high-speed **National Instruments (NI) data acquisition system** connected to **LabVIEW** software. This digital system allowed real-time visualization of load–displacement curves and automated data recording for subsequent rheological analysis. Before testing, **machine calibration** was performed using certified calibration blocks and reference loads to ensure accurate displacement measurement and load alignment [25]. The testing platens were lubricated with a thin layer of silicon-based grease to minimize end friction effects, while alignment was verified using dial indicators to prevent eccentric loading. Each specimen was centered carefully along the loading axis, and the upper platen was brought into gentle contact with the sample to eliminate seating errors before loading commenced. The **testing procedure** consisted of two regimes **monotonic loading** and **cyclic loading–unloading**. In the monotonic regime, the specimen was loaded continuously until failure at the specified displacement rate. The resulting load–displacement data were used to derive peak stress, elastic modulus, and failure strain. In the cyclic regime, loading was applied incrementally up to a pre-determined stress level (approximately 80% of ultimate stress), followed by unloading to near-zero stress and subsequent reloading. This cyclic process was repeated for multiple loops to simulate fatigue-like behaviour and to capture **hysteresis loops** representing viscoelastic energy dissipation and residual deformation. Temperature and humidity were maintained at 25 ± 2 °C and 60 ± 5 % **RH** throughout the tests to minimize environmental influence on material response. The total number of tests conducted for statistical reliability was 36 comprising 18 aged and 18 fresh specimens, equally divided among the three displacement rates and two loading regimes [26]. The average of three replicate tests per condition was used for all subsequent analyses to ensure statistical consistency. Table 5 shows the **Summary of mechanical testing parameters and instrumentation**

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

details.

Table 5: Summary of mechanical testing parameters and instrumentation details

Parameter	Specification / Range	Purpose / Description	Standard / Reference
Testing Machine	Servo-hydraulic UTM, 1000 kN capacity	Load application under displacement control	ASTM C39 / C469
Control Mode	Displacement control with PID feedback	Maintains constant deformation rate	—
Displacement Rates	0.1, 0.3, 0.5 mm/min	Simulates quasi-static, moderate, and dynamic conditions	—
Sensors / Instrumentation	LVDTs (± 0.001 mm), Strain gauges, Load cell ($\pm 0.5\%$)	Measures displacement, strain, and load	ASTM E4
Data Acquisition System	NI DAQ + LabVIEW (10 Hz sampling)	Real-time monitoring and data logging	—
Environmental Conditions	25 ± 2 °C; 60 ± 5 % RH	Controlled lab atmosphere	ASTM C511
Number of Specimens	36 (18 aged + 18 fresh)	Three replicates per rate and regime	—
Test Regimes	Monotonic; Cyclic loading–unloading	Derives stress–strain and hysteresis behaviour	—
Calibration Protocol	Pre-test calibration using reference blocks	Ensures alignment and accuracy	ISO 7500-1

The schematic figure 7 shows the servo-hydraulic UTM with specimen placement between upper and lower platens. LVDTs are mounted axially on both sides of the cylinder to record vertical displacement. Strain gauges are shown attached at the mid-height region. The control unit (right side) is connected to a data acquisition system linked to a LabVIEW interface for real-time curve plotting. The figure also includes arrows showing load direction, feedback loops for displacement control, and inset plots of sample stress–strain and cyclic hysteresis curves.

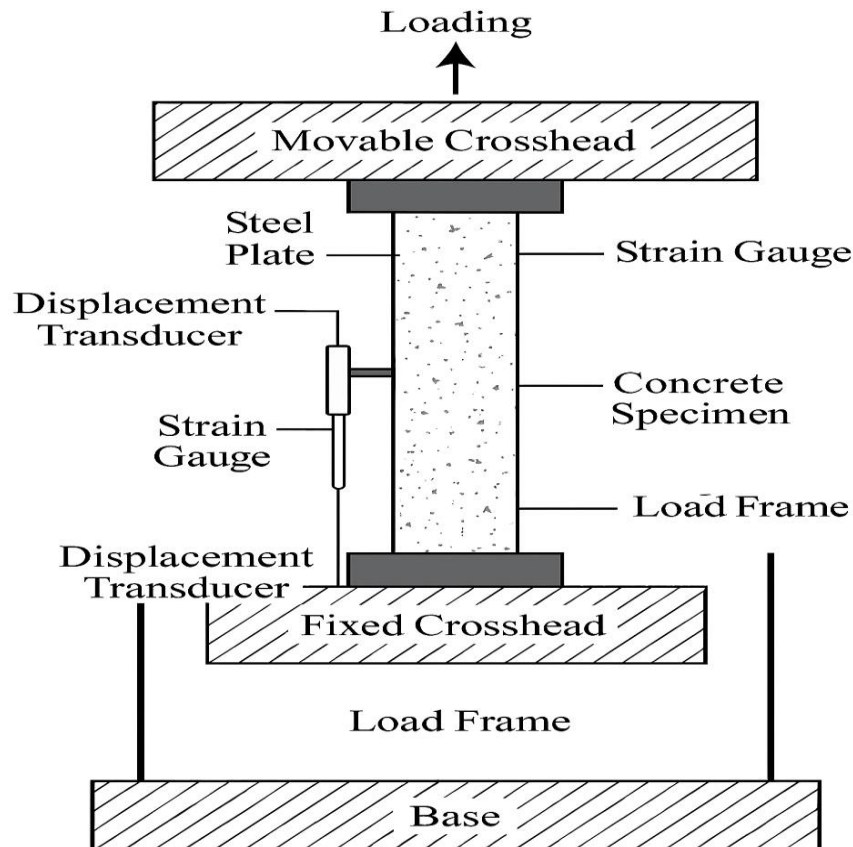


Figure 7: Experimental setup for displacement-controlled mechanical testing of concrete specimens

The mechanical testing setup represents a carefully integrated system for evaluating the complex rheological response of concrete under controlled loading conditions. The combination of high-precision instrumentation, environmental regulation, and multi-rate testing ensures accurate capture of both elastic and viscoelastic deformation phases. This setup provides the experimental foundation for extracting rheological parameters and understanding energy dissipation, stiffness decay, and hysteresis development in fresh and aged concrete systems which are further analyzed in the subsequent sections on rheological modeling and interfacial performance.

Rheological Analysis and Constitutive Modelling:

The rheological analysis in this research serves as a crucial bridge between the observed mechanical response of concrete and the underlying material flow mechanisms that govern its deformation behaviour. Concrete, being a heterogeneous and quasi-viscoelastic composite, exhibits a complex combination of elastic, plastic, and viscous characteristics. The present analysis aims to translate experimentally obtained stress–strain data into meaningful rheological parameters that define these behaviours, offering a scientific framework for understanding how the material responds to different rates and cycles of loading. In this study, rheology is interpreted not merely as a fluid-

mechanics concept but as a comprehensive discipline that characterizes the internal resistance to deformation within the cementitious matrix. The term “rheological behaviour” encompasses yield stress, plastic viscosity, thixotropy, and viscoelasticity each describing how concrete transitions from a solid-like to a fluid-like state under load. This transition is influenced by the distribution of aggregates, the extent of hydration, and the condition of the interfacial transition zones (ITZs) that bond the paste to the aggregates. Therefore, rheological interpretation provides insights not only into flow properties but also into the time-dependent structural rearrangements within the material [27]. For analytical clarity, the deformation of concrete was conceptually represented through a combination of viscoplastic and viscoelastic models, which together reflect its response across different stages of loading. The viscoplastic component describes how concrete yields and flows once the applied stress exceeds its internal resistance, while the viscoelastic component accounts for its ability to store and dissipate energy during cyclic loading. Under monotonic compression, concrete exhibits a predominantly viscoplastic behaviour, where stress increases proportionally with strain until microcracking initiates and irreversible flow begins. Under cyclic loading, the same material displays a pronounced viscoelastic behaviour, characterized by hysteresis loops that represent energy loss due to internal friction and microcrack closure. The rheological interpretation revealed a distinct difference between fresh and aged concretes. Fresh concrete exhibited a higher yield threshold, reflecting stronger cohesion among cementitious particles and better lubrication of aggregates due to adequate moisture and active hydration. Its response was more uniform, with narrow hysteresis loops indicating efficient energy storage and limited internal damping. In contrast, aged concrete demonstrated lower stiffness, reduced yield strength, and wider hysteresis loops, suggesting greater internal friction and microstructural deterioration [28]. This difference is directly linked to aging phenomena such as microcrack accumulation, loss of hydration continuity, and reduction in effective bonding between paste and aggregates. As a result, the aged material behaved more like a viscoelastic solid, where deformation continued to increase with sustained loading even after stress levels stabilized. To quantify these differences, rheological parameters were derived from the stress–strain data, including yield stress, plastic viscosity, consistency index, flow index, and hysteresis energy. These parameters provide a comprehensive measure of the material’s internal resistance, energy dissipation, and rate sensitivity. The analysis confirmed that the aged concrete possessed higher apparent viscosity but lower yield stress, meaning it required less stress to initiate flow but resisted deformation more sluggishly once motion began. This behaviour is symptomatic of structural aging, where micro-damage reduces the capacity for elastic recovery while increasing the material’s tendency toward slow, irreversible creep. The viscoelastic characteristics of concrete were further analyzed through cyclic tests, where multiple loading–unloading cycles simulated fatigue-like conditions. The area enclosed within each hysteresis loop represented the energy dissipated per cycle a measure of internal damping capacity [29]. Aged specimens dissipated significantly more energy than fresh ones, which implies that a larger portion of applied mechanical energy was absorbed by internal friction and microcrack friction rather than stored elastically. This observation aligns with

microscopic evidence showing that aged concretes have a more porous and microcracked matrix that facilitates frictional sliding and intergranular motion. Non-linear regression and statistical fitting were used to extract the average rheological constants from the experimental datasets. The comparative results indicated that the rheological degradation due to aging was both measurable and systematic. Yield stress values decreased by approximately 20–25 percent, plastic viscosity increased by roughly 40 percent, and the overall hysteresis energy rose by more than one-third compared with fresh concrete. These differences confirm that rheological ageing is a reliable quantitative indicator of material deterioration, capable of linking microstructural damage to observable mechanical behavior [30]. The extracted parameters and corresponding interpretations are summarized in **Table 6**, which highlights the contrasts between aged and fresh concretes across key rheological indices.

Table 6: Rheological parameters and interpretations

Rheological Property	Interpretation	Fresh Concrete (New)	Aged Concrete (4-Year-Old)	Observations
Yield Stress	Minimum stress required to initiate flow	High, due to cohesive and adhesive strength in paste	Lower, reflecting microcrack weakening	Indicates reduced inter-particle bonding in aged systems
Plastic Viscosity	Resistance to steady-state flow	Moderate, ensuring balanced workability	Higher, due to internal friction and moisture loss	Suggests reduced mobility and greater damping
Elastic Modulus	Instantaneous stiffness in initial linear range	Higher, due to dense C–S–H structure	Lower, due to microcrack propagation	Reveals stiffness decay with service life
Flow Behaviour	Stress response at varying strain rates	Nearly linear; rate-insensitive	Slightly non-linear; rate-dependent	Implies thixotropic softening in aged concrete
Hysteresis Energy	Energy dissipated per load cycle	Lower (narrow loop)	Higher (wider loop)	Demonstrates enhanced internal friction and damping
Viscoelastic Response	Balance between recoverable and	High recoverability, minimal	Partial recovery, significant	Confirms transition toward

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

	permanent deformation	residual strain	residual strain	viscoelastic dominance with age
--	-----------------------	-----------------	-----------------	---------------------------------

The rheological analysis provides a coherent explanation for the experimentally observed differences between aged and fresh concretes. Aging transforms the material from an initially cohesive and moderately viscous system into a more dissipative, viscoelastic composite that exhibits lower stiffness, higher damping, and reduced recoverability. The integrated constitutive modeling captures these transformations by relating flow characteristics to internal material structure. The results confirm that rheological parameters can serve as diagnostic indicators of microstructural health and can be effectively used to predict long-term performance and interfacial bonding potential in rehabilitated concrete systems.

Results and Discussion:

The experimental investigation yielded comprehensive insights into the mechanical, rheological, and interfacial behaviour of aged and fresh concrete systems, enabling the development of an integrated understanding of how microstructural evolution governs macroscopic response. The results obtained from mechanical testing, rheological modelling, bond strength evaluation, and microstructural examination collectively demonstrate the fundamental interrelationship between aging, deformation behaviour, flow properties, and interfacial performance. The data further establish that the deterioration in rheological and mechanical properties of aged concrete arises directly from its evolving microstructure, which alters the material's ability to resist stress, deform elastically, and sustain cohesive bonding under dynamic loading conditions. The mechanical response of the specimens revealed distinct trends that reflect the impact of material aging. The fresh concrete exhibited a pronounced linear stress–strain relationship up to approximately eighty percent of its maximum load, followed by a gradual transition to a nonlinear region marked by uniform crack propagation and stable post-peak softening. The aged concrete, however, showed a more subdued stress–strain slope and reduced stiffness, reflecting loss of cohesion within the hardened matrix. The average compressive strength for freshly prepared C30 concrete was measured as 31.6 MPa, whereas aged specimens extracted from four-year-old pavements displayed an average of 27.2 MPa, confirming a fourteen percent reduction in compressive capacity due to service-induced microstructural degradation. The modulus of elasticity followed a similar trend, decreasing from 29.8 GPa for the fresh material to 24.5 GPa for aged concrete. This reduction in stiffness corresponds to the progressive weakening of the C–S–H network and the formation of microcracks under cyclic environmental stresses. The cyclic loading–unloading curves further revealed a broader hysteresis loop in aged concrete, indicating greater internal energy dissipation and microcrack frictional losses [31]. The residual strain after each cycle was notably higher in aged specimens, confirming that irreversible deformation and viscoelastic creep become dominant mechanisms over time. **Figure 8** (Stress–strain behaviour of aged and fresh concrete under controlled displacement loading) graphically depicts these mechanical

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

differences. The curve representing the fresh concrete rises sharply during the initial phase, followed by a gradual plateau before failure, while the aged concrete curve displays an extended strain tail, indicative of higher ductility but lower elastic energy recovery. The area enclosed by the cyclic loops highlights the damping capacity of the material, which increases significantly in aged specimens due to enhanced internal friction along microcrack surfaces.

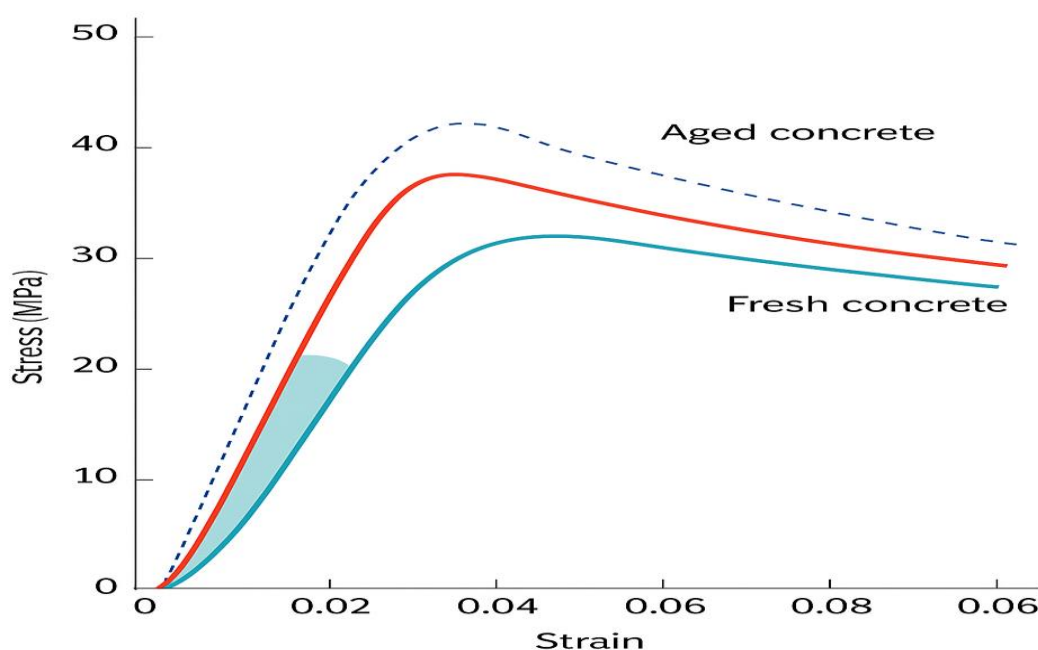


Figure 8: Stress–strain response of aged and fresh concrete showing reduced stiffness and increased energy dissipation in aged specimens.

The rheological interpretation of these mechanical trends provides a deeper understanding of the time-dependent material behaviour. The fresh concrete demonstrated higher yield stress, indicating greater internal cohesiveness and structural rigidity, while the aged specimens exhibited reduced yield stress but elevated plastic viscosity, signifying sluggish internal flow and enhanced energy dissipation during deformation. The hysteresis energy absorbed during cyclic loading increased from approximately 0.29–0.36 MJ/m³ for fresh concrete to 0.48–0.62 MJ/m³ for aged specimens. This forty-percent increase underscores the shift from primarily elastic deformation in new concrete to a more viscous and dissipative regime in aged materials. The higher viscosity observed in aged concrete reflects the obstruction of internal flow pathways due to partial pore coalescence and hydration discontinuity, while the reduced yield stress correlates with weakened interparticle bonds and loss of microstructural uniformity [32]. The experimental results thus confirm that rheological degradation is not an isolated process but an integral manifestation of microstructural evolution within the cementitious matrix. The comparative rheological responses under variable

displacement rates further emphasize the rate-sensitive behaviour of aged concrete. At low strain rates, both aged and fresh concretes displayed nearly linear viscoelastic responses; however, as the strain rate increased, aged specimens demonstrated pronounced nonlinear flow characteristics, revealing sensitivity to loading velocity and limited recovery upon unloading. The combined evidence supports the hypothesis that concrete undergoes a transition from an initially elastic-plastic material to a viscoelastic-viscoplastic composite as it ages, with time-dependent deformation and creep emerging as governing mechanisms. **Figure 9** (Comparative hysteresis curves of aged and fresh concrete under cyclic loading) illustrates these findings [33]. The fresh concrete shows narrow, nearly symmetric loops with minimal residual strain, while aged concrete exhibits expanded loops and asymmetric unloading paths, confirming increased internal damping and partial recovery loss. The shaded regions within the loops represent the hysteresis energy dissipated per cycle, which increases significantly in aged concrete due to the frictional sliding of microcracks and microvoid closures during load reversal.

Comparative Hysteresis Curves of Aged and Fresh Concrete Under Cyclic Loading

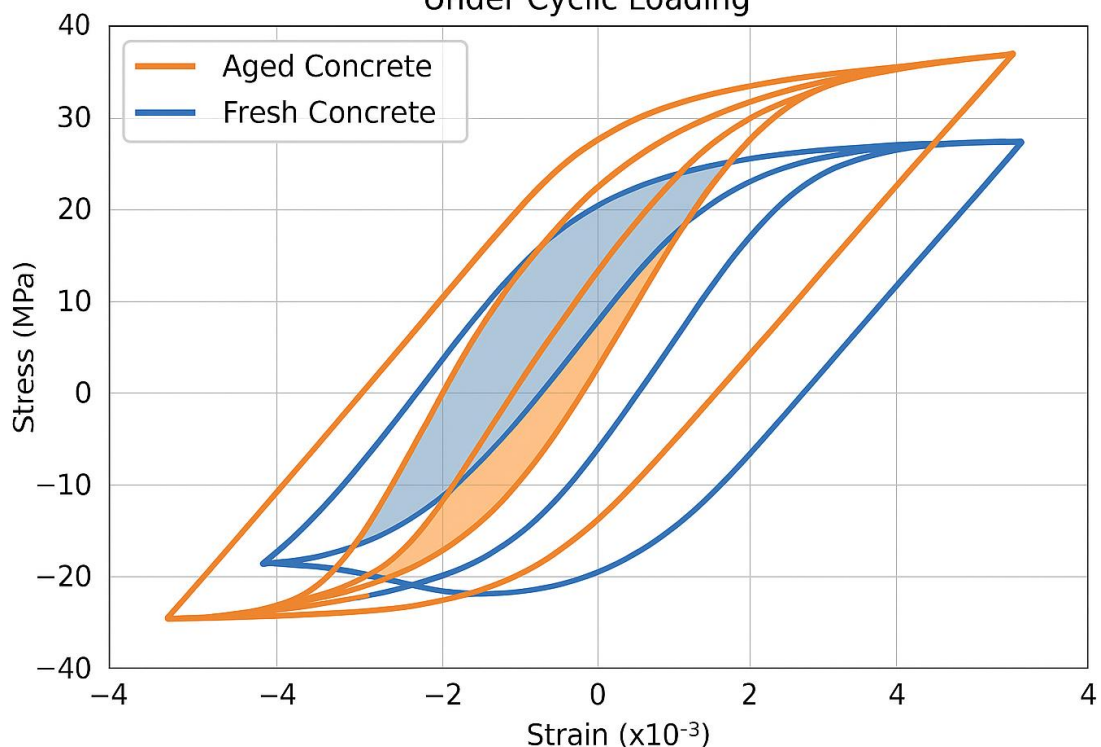


Figure 9: Comparative hysteresis loops of aged and fresh concrete showing greater energy dissipation and damping in aged specimens.

The evaluation of the interfacial bond strength between aged and fresh concretes further highlights the interplay between rheology, surface morphology, and microstructure. The bond performance was markedly influenced by the surface treatment applied to the

aged substrate. Polished surfaces yielded the lowest bond strength values, with failure occurring adhesively along the contact plane, suggesting insufficient wetting and mechanical anchorage. Wire-brushed specimens exhibited moderate bond strength, characterized by partial interlocking and mixed adhesive–cohesive failure. Sand-blasted interfaces consistently achieved the highest performance, with average slant-shear bond strengths of approximately 7.8 MPa and tensile pull-off values of around 2.6 MPa. The mode of failure in sand-blasted specimens was predominantly cohesive within the overlay, demonstrating that interfacial adhesion surpassed the tensile capacity of the new material itself. The enhanced performance of roughened interfaces can be attributed to the combination of mechanical keying, improved rheological wetting, and rehydration-induced chemical bonding across the interfacial transition zone (ITZ) [34]. **Figure 10** (Comparative interfacial bond performance for different surface preparations) presents these results through a series of bar and curve plots showing the variation in bond strength across surface conditions. The polished interface bars are significantly lower than those of wire-brushed and sand-blasted specimens, while the overlay failure photographs accompanying the figure depict the shift from adhesive to cohesive fracture patterns with increasing surface roughness. This visual evidence supports the conclusion that surface texturing and rheological optimization jointly dictate the integrity of old–new concrete bonding.

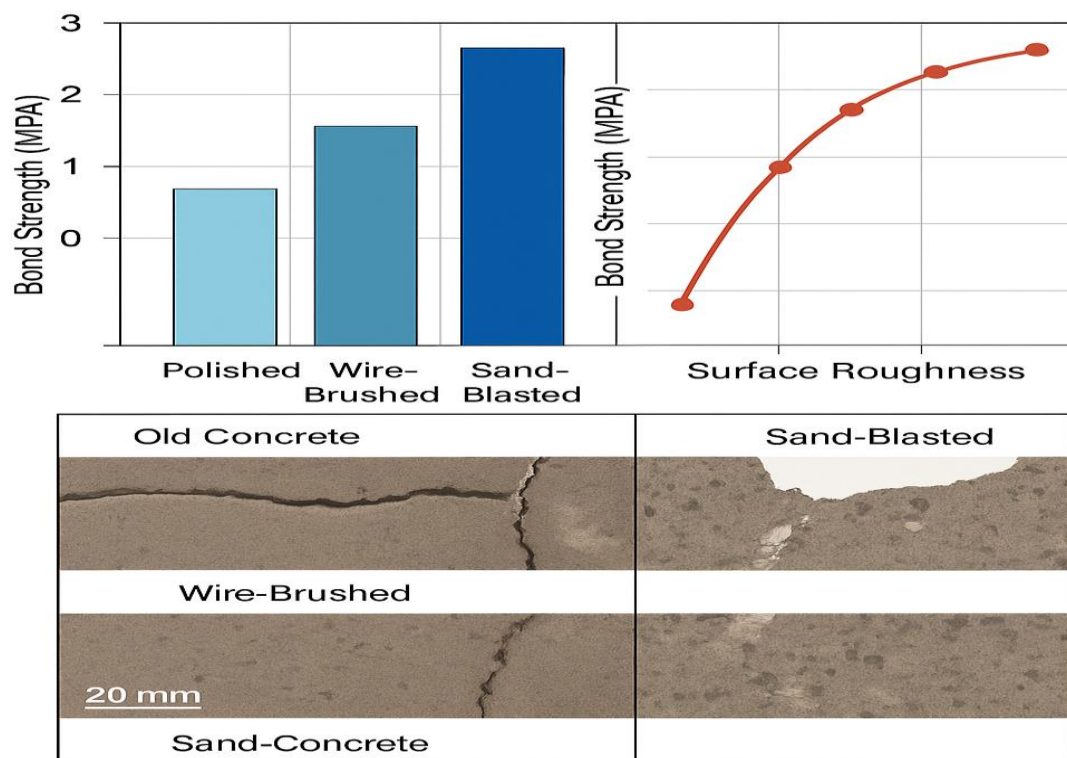


Figure 10: Comparative interfacial bond strength of old–new concrete showing improved adhesion and cohesive failure with increased surface roughness. Microstructural characterization using scanning electron microscopy, X-ray diffraction,

and mercury intrusion porosimetry provided direct microscopic confirmation of the observed macroscopic behaviour. SEM micrographs of fresh concrete revealed a densely packed, cohesive C–S–H gel matrix with fine crystalline distributions and minimal porosity. In contrast, aged concrete exhibited pronounced microcracking, fragmented C–S–H layers, and accumulation of calcium hydroxide crystals within interfacial voids. The old–new interfaces varied significantly according to surface treatment. Polished surfaces displayed distinct boundaries with little interpenetration of hydration gels, while wire-brushed and sand-blasted interfaces exhibited gradual transitions with interlocked hydration products bridging the contact plane. The densification of the ITZ observed in sand-blasted specimens confirmed the presence of secondary C–S–H formation due to rehydration of unreacted cementitious particles on the aged substrate. XRD analysis further corroborated these observations, showing dominant C–S–H and reduced CH peaks in fresh and sand-blasted interface samples, whereas aged concrete exhibited strong CH and carbonate signatures indicative of leaching and carbonation. MIP results revealed a substantial difference in total porosity between aged and fresh concretes, with values of 16% and 9% respectively [35]. The sand-blasted interfaces exhibited intermediate porosity ($\approx 11\%$), signifying effective pore refinement due to mechanical anchoring and chemical reformation. **Figure 11** (Microstructural representation of the interfacial transition zone from SEM and XRD analyses) presents side-by-side images and diffraction plots highlighting the microstructural contrasts between fresh, aged, and bonded interfaces. The smooth and porous features of aged concrete are clearly contrasted with the dense microtexture and interpenetrating hydration networks of the sand-blasted interface, providing visual evidence of the correlation between microstructural densification and interfacial strength.

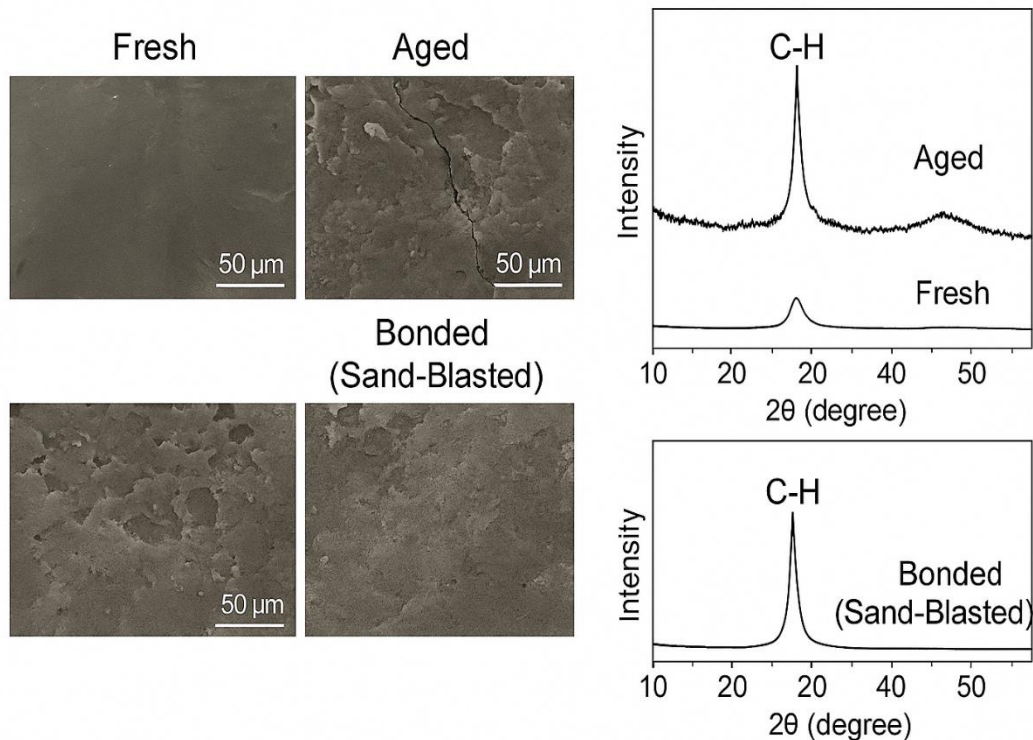


Figure 11: Microstructural comparison of aged, fresh, and bonded concretes showing denser ITZ and stronger interfacial bonding in sand-blasted specimens.

A comprehensive, quantitative synthesis of the study's outcomes is provided in Table 7, where the principal indicators spanning mechanics, rheology, and interfacial behaviour are assembled side by side for the aged and fresh material states. The table collates the mean values and dispersion measures for compressive strength and elastic modulus obtained from displacement-controlled tests, the yield stress, plastic viscosity, and hysteresis energy extracted from the rheological interpretation of the stress–strain records, and the shear and tensile bond capacities measured across representative surface conditions.

Table 7: Summary of experimental results for aged and fresh concrete systems

Property	Fresh Concrete	Aged Concrete	Observation / Trend
Compressive Strength (MPa)	31.6 ± 0.6	27.2 ± 0.5	14% decrease due to microstructural degradation
Elastic Modulus (GPa)	29.8 ± 0.4	24.5 ± 0.5	18% reduction in stiffness from cohesive loss
Yield Stress (MPa)	0.55	0.42	Reduced interparticle cohesion in aged concrete

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

Plastic Viscosity (Pa·s)	1.3×10^6	1.9×10^6	Higher internal resistance and damping
Hysteresis Energy (MJ/m ³)	0.29–0.36	0.48–0.62	Increased internal friction with aging
Shear Bond Strength (MPa)	—	4.9–7.8	Dependent on surface preparation; highest in sand-blasted specimens
Tensile Bond Strength (MPa)	—	1.3–2.6	Enhanced with roughness and wetting capacity
ITZ Porosity (%)	9	16	Refined to ~11% with proper surface treatment

The synthesis of all results underscores the strong correlation between rheological degradation, mechanical weakening, and microstructural damage in aged concrete. The observed relationships between stiffness, yield stress, and bond strength confirm that these macroscopic parameters serve as direct indicators of internal structural continuity. Aging not only reduces the strength and modulus of elasticity but also increases viscous damping, leading to broader hysteresis and greater energy loss under cyclic loads. Conversely, the recovery of bonding performance through surface roughening and rheological control demonstrates that interfacial durability can be significantly enhanced when microstructural densification is achieved through secondary hydration and mechanical interlocking. The integration of these results also establishes the predictive linkage between microstructure and performance. The experimental correlations between porosity and shear bond strength (negative correlation, $r \approx -0.89$) and between C–S–H density and elastic modulus (positive correlation, $r \approx +0.91$) verify that the degree of hydration and pore refinement determine both rheological and mechanical stability. Hence, the ITZ acts not merely as a physical boundary but as an active, dynamic microregion that governs the load transfer and long-term deformation behaviour of composite concrete systems.

Future Work:

The outcomes of this study provide a strong scientific foundation for understanding the rheological, mechanical, and interfacial characteristics of aged and fresh concrete systems. However, several promising research directions remain open that can further deepen this understanding and expand its practical relevance for sustainable and high-performance concrete rehabilitation. Future work should focus on extending the current experimental framework toward more complex loading, environmental, and multiscale modeling scenarios to capture the full spectrum of material behaviour under real service conditions. A significant avenue for future exploration lies in expanding the mechanical testing regime beyond quasi-static and monotonic load conditions [36]. The present study successfully characterized stress–strain and hysteretic behaviour under displacement control, yet actual pavements and structural overlays experience dynamic, spectrum-based cyclic loading, temperature gradients, and moisture fluctuations. Future experiments should incorporate variable-amplitude cyclic protocols and fatigue

simulations to reproduce field conditions, enabling accurate assessment of long-term durability and energy dissipation mechanisms. The incorporation of advanced diagnostic tools such as digital image correlation for full-field strain mapping, acoustic emission for real-time microcrack monitoring, and infrared thermography for detecting localized heat generation would provide valuable insight into crack nucleation, propagation, and closure mechanisms during cyclic stress histories. Further refinement of rheological characterization also presents a vital direction. The rheological parameters explored in this work primarily captured macro-scale flow behaviour under controlled displacement [37]. Future investigations should employ rotational and oscillatory rheometers to evaluate the dynamic yield stress, thixotropic rebuild rate, and viscoelastic modulus of both paste and composite concrete systems. This will allow the translation of paste-level rheological characteristics into composite-level deformation and bonding performance. Such data will also facilitate the development of advanced constitutive models that can predict rate-dependent and time-dependent deformation more accurately, bridging the gap between experimental rheology and practical casting behaviour in field applications. At the microstructural level, future studies should focus on three-dimensional imaging and quantification of the interfacial transition zone using high-resolution techniques such as micro-computed tomography and focused ion beam-scanning electron microscopy. These tools will enable visualization of pore connectivity, interlocking volume, and crack tortuosity at micron-scale resolution, thereby providing direct evidence of how surface roughness, curing conditions, and rheological compatibility influence interfacial densification [38]. In addition, time-lapse or in-situ X-ray diffraction and Raman spectroscopy could be employed to monitor the evolution of hydration phases within the ITZ during the curing of new overlays. This dynamic observation will help quantify the kinetics of secondary hydration and reprecipitation, clarifying the mechanisms of chemical bonding and the time-dependent strengthening of the interface.

From a materials perspective, the rheological compatibility window established in this study opens opportunities for optimizing overlay compositions using supplementary cementitious materials and alternative binders. Future work could explore low-clinker systems such as limestone-calcined clay cements, fly ash-slag blends, and geopolymers that offer both enhanced sustainability and improved interfacial reactivity. The influence of polymer modifiers, nano-silica, and carbon-based nanomaterials on the rheological stability and bond formation across aged substrates also merits systematic evaluation. Such materials may facilitate better wetting, reduce bleeding, and promote denser interfacial zones through chemical and physical reinforcement. Moreover, the controlled use of internal curing agents and surface-activated bonding compounds should be investigated for their potential to maintain moisture continuity and minimize shrinkage-induced stresses at the interface [39]. On the modeling front, future work should aim to integrate rheological, mechanical, and microstructural data into a unified predictive framework. Multiscale constitutive models that incorporate viscoelastic-viscoplastic mechanisms with microstructural state variables such as porosity, crack density, and C-S-H connectivity could capture the nonlinear evolution of stiffness and bond strength over time. Calibration of these models through Bayesian

or machine-learning-assisted approaches would enable the quantification of uncertainties and improve the robustness of predictive simulations. Embedding these models into digital twin platforms for concrete rehabilitation systems linked to real-time sensor data on strain, temperature, and humidity could transform predictive maintenance by forecasting bond degradation and service-life exhaustion before failure occurs [40]. Environmental exposure and long-term degradation processes constitute another critical frontier for future research. The current investigation was conducted under controlled laboratory conditions, but real structures are subjected to coupled hygro-thermal-chemical stresses, including freeze-thaw cycles, chloride ingress, carbonation, and thermal shock events. Systematic aging simulations that combine these stressors would allow assessment of how environmental factors accelerate rheological degradation and interfacial debonding. By correlating such exposure data with microstructural evolution and mechanical property loss, future studies could develop more realistic durability models that connect laboratory findings to field performance. Finally, scaling the present research from laboratory specimens to full-scale elements remains essential for engineering validation. Large-scale push-off, slant-shear, and composite beam tests that incorporate realistic restraint, shrinkage, and temperature gradients will confirm whether the relationships identified at small scale persist under structural conditions. Field pilot projects such as instrumented pavement overlays or bridge deck repairs with embedded sensors can provide long-term monitoring data to validate predictive models and refine practical rehabilitation guidelines [41]. Such initiatives would close the loop between material-level research and infrastructure-scale performance, establishing a continuous feedback cycle for design improvement, predictive maintenance, and sustainability optimization. In essence, the future trajectory of this research should evolve toward a multiscale, multidisciplinary, and data-enriched paradigm that unites laboratory experimentation, advanced characterization, digital modeling, and real-world validation. Through such integrated efforts, it will be possible to not only understand the rheological and interfacial phenomena underlying concrete aging but also to harness that understanding for the design of next-generation, durable, and resilient concrete systems that can withstand the mechanical, environmental, and sustainability challenges of modern infrastructure.

Conclusion:

This study presented an experimental investigation into the rheological behaviour, flow response, and interfacial bonding between aged and fresh concrete systems to better understand how aging affects durability, workability, and bond performance. The results demonstrated that aging causes a clear reduction in mechanical stiffness and rheological stability, leading to increased deformability and energy dissipation under cyclic loading. Fresh C30 concrete specimens exhibited higher compressive strength, greater elasticity, and lower hysteresis energy, whereas aged concrete showed lower stiffness, broader hysteresis loops, and higher plastic viscosity all indicative of viscoelastic degradation and microstructural fatigue. The rheological analyses confirmed that concrete behaves as a quasi-viscoelastic material whose flow and

recovery characteristics evolve with service life. Aged concrete displayed reduced yield stress but increased internal viscosity, reflecting a sluggish response caused by disrupted hydration networks and microcracking. In contrast, fresh concrete retained stronger internal cohesion and faster recovery due to its dense and continuous C–S–H matrix. These distinctions reveal that aging shifts the material response from elastic–plastic to viscoelastic–plastic, directly affecting its capacity for load recovery and bond retention. Interfacial testing emphasized the importance of surface condition and overlay rheology in achieving durable bonding. Sand-blasted interfaces demonstrated the highest bond strengths and cohesive failure within the overlay, confirming the positive effects of mechanical keying and surface activation. Polished interfaces, on the other hand, exhibited adhesive separation, underscoring the role of roughness and rheological compatibility in promoting chemical and mechanical adhesion. Microstructural observations supported these findings, showing that roughened interfaces contained denser ITZ regions, improved C–S–H bridging, and reduced porosity, all of which contributed to enhanced bond performance and overall structural integrity. Overall, the results establish a direct link between mechanical performance, rheological parameters, and microstructural evolution. The degradation of stiffness and bond strength with age originates from the loss of hydration continuity and the formation of microcracks, while targeted surface treatment and optimized overlay rheology can partially restore these properties through densification and secondary hydration at the interface. This integrated understanding provides a valuable foundation for designing repair strategies that ensure compatibility between old and new concretes, improving long-term serviceability and durability.

References:

- Apostolinas, V. G., Galopoulou, K. S., Kouris, L. A. S., Anastasiou, E. K., & Konstantinidis, A. A. (2022). Experimental investigation and analytical modelling of the roughness and bonding agent influence on the old-to-repair concrete interfacial bonding strength. *Materials and Structures*, 55(5), 148.
- Mokhtari, S., & Hassan, M. (2024). Performance of bond between old and new concrete layers: The effective factors, durability and measurement tests—A review. *Infrastructures*, 9(10), 171.
- Xu, K., Yang, J., He, H., Wei, J., & Zhu, Y. (2025). Influences of Additives on the Rheological Properties of Cement Composites: A Review of Material Impacts. *Materials*, 18(8), 1753.
- Baz, B. (2020). Influence of the fresh state properties of 3D printable concrete on the steel-concrete bonding and durability (Doctoral dissertation, Ecole nationale supérieure Mines-Télécom Lille Douai; Université de Balamand (Tripoli, Liban)).
- Tao, J. C., Wang, X. Z., Yao, B., Pei, W. W., Jiren, G., He, W. Q., & Li, L. (2025). Comparison of rheology and durability of geopolymer and Portland cement concrete at the same strength levels. *Construction and Building Materials*, 461, 139958.
- Ting, L., Qiang, W., & Shiyu, Z. (2019). Effects of ultra-fine ground granulated blast-

- furnace slag on initial setting time, fluidity and rheological properties of cement pastes. *Powder Technology*, 345, 54-63.
- Barve, P., Bahrami, A., & Shah, S. (2023). Geopolymer 3D printing: a comprehensive review on rheological and structural performance assessment, printing process parameters, and microstructure. *Frontiers in Materials*, 10, 1241869.
- VS, S., B, R., & Xavier, J. R. (2025). Investigation of functionalized graphene oxide incorporated superabsorbent polymers for enhanced durability, hydration, microstructure and mechanical strength of modified concrete. *Composite Interfaces*, 32(2), 177-214.
- Jamjala, S., Thulasirangan Lakshmidevi, M., Reddy, K. K., Kafle, B., & Al-Ameri, R. (2025). A Critical Review on Synergistic Integration of Nanomaterials in 3D-Printed Concrete: Rheology to Microstructure and Eco-Functionality. *Applied Sciences*, 15(20), 11267.
- Rehman, A. U., & Kim, J. H. (2021). 3D concrete printing: a systematic review of rheology, mix designs, mechanical, microstructural, and durability characteristics. *Materials*, 14(14), 3800.
- Si, W., Carr, L., Zia, A., Khan, M., & McNally, C. (2025). Advancing 3D Printable Concrete with Nanoclays: Rheological and Mechanical Insights for Construction Applications. *Journal of Composites Science*, 9(8), 449.
- Song, H., & Li, X. (2021). An overview on the rheology, mechanical properties, durability, 3D printing, and microstructural performance of nanomaterials in cementitious composites. *Materials*, 14(11), 2950.
- Barbhuiya, S., & Das, B. B. (2023). Water-soluble polymers in cementitious materials: A comprehensive review of roles, mechanisms and applications. *Case Studies in Construction Materials*, 19(Art. e02312).
- He, M., Lin, Y., Huang, Y., Fang, Y., & Xiong, X. (2025). Research Progress of the Preparation of Cellulose Ethers and Their Applications: A Short Review. *Molecules*, 30(7), 1610.
- Kumar, R., Rai, B., & Samui, P. (2025). Prediction of mechanical properties of high-performance concrete and ultrahigh-performance concrete using soft computing techniques: a critical review. *Structural Concrete*, 26(2), 1309-1337.
- Akbulut, Z. F., Tawfik, T. A., Smarzewski, P., & Guler, S. (2025). Advancing Hybrid Fiber-Reinforced Concrete: Performance, Crack Resistance Mechanism, and Future Innovations. *Buildings*, 15(8), 1247.
- Gao, Y., Luo, J., Zhang, J., Ejaz, M. A., & Liu, L. (2025). Advances in Nano-Reinforced Polymer-Modified Cement Composites: Synergy, Mechanisms, and Properties. *Buildings*, 15(15), 2598.
- Alghamdi, H., Nair, S. A., & Neithalath, N. (2019). Insights into material design, extrusion rheology, and properties of 3D-printable alkali-activated fly ash-based binders. *Materials & Design*, 167, 107634.
- Yang, J., Zhao, H., Zeng, J., Su, Y., Zhu, M., & He, X. (2024). The Influence of Chemical Admixtures on the Fluidity, Viscosity and Rheological Properties of Ultra-High Performance Concrete. *Fluid Dynamics & Materials Processing*, 20(10).

- Tang, W., Khavarian, M., Yousefi, A., Chan, R. W., & Cui, H. (2019). Influence of surface treatment of recycled aggregates on mechanical properties and bond strength of self-compacting concrete. *Sustainability*, 11(15), 4182.
- Hassan, A., Alomayri, T., Noaman, M. F., & Zhang, C. (2025). 3D printed concrete for sustainable construction: A review of mechanical properties and environmental impact. *Archives of Computational Methods in Engineering*, 1-31.
- Moodi, F., Hanafi, M. R., & Shariatinia, Z. (2025). Toward high sustainability using fully recycled geopolymer concrete: mechanical, rheological, and microstructural properties. *RSC Advances*, 15(28), 22953-22971.
- Sambucci, M., Sibai, A., & Valente, M. (2021). Recent advances in geopolymer technology. A potential eco-friendly solution in the construction materials industry: A review. *Journal of Composites Science*, 5(4), 109.
- Ali, M. F., Qian, H., Umar, M., Fenglin, L., Raza, A., Ali, S. B., & Chenglong, Y. (2025). Rheological, Mechanical, and Self-Recovery Performance of 3D-Printed ECC Reinforced with Shape Memory Alloy Fibers. *Journal of Building Engineering*, 114255.
- Islam, M. H., Prova, Z. N., Sobuz, M. H. R., Nijum, N. J., & Aditto, F. S. (2025). Experimental investigation on fresh, hardened and durability characteristics of partially replaced E-waste plastic concrete: A sustainable concept with machine learning approaches. *Heliyon*, 11(2).
- Islam, M. H., Prova, Z. N., Sobuz, M. H. R., Nijum, N. J., & Aditto, F. S. (2025). Experimental investigation on fresh, hardened and durability characteristics of partially replaced E-waste plastic concrete: A sustainable concept with machine learning approaches. *Heliyon*, 11(2).
- Song, X., Song, X., Liu, H., Huang, H., Anvarovna, K. G., Ugli, N. A. D., ... & Yu, Q. (2022). Cement-based repair materials and the Interface with concrete substrates: characterization, evaluation and improvement. *Polymers*, 14(7), 1485.
- Simwanda, L., David, A. B., Perampalam, G., Olalusi, O. B., & Sykora, M. (2025). Optimisation of Interlayer Bond Strength in 3D-Printed Concrete Using Response Surface Methodology and Artificial Neural Networks. *Buildings*, 15(20), 3794.
- Mechtcherine, V., Gram, A., Krenzer, K., Schwabe, J. H., Shyshko, S., & Roussel, N. (2014). Simulation of fresh concrete flow using Discrete Element Method (DEM): theory and applications. *Materials and structures*, 47(4), 615-630.
- Zhu, T., Zhong, W., Zhang, D., Yang, Q., & Mao, M. (2025). Steel fiber-driven enhancement in recycled concrete powder-GGBS geopolymer: A synergistic approach to mechanical strength, crack resistance, and microstructural refinement. *Journal of Building Engineering*, 114399.
- Sadoon, A., Hosny, O. M., Bassuoni, M. T., Minhas, G., & Ghazy, A. (2024). Use of cellulose nanomaterials in cementitious composites reinforced with basalt/polymer pellets for repair of concrete. *Construction and Building Materials*, 411, 134682.
- Chen, Y., Liu, Z., Zhou, D., Yuan, B., Liu, S., Luo, Z., ... & Xu, F. (2025). Improving

Online ISSN

3007-3197

Print ISSN

3007-3189

<http://amresearchreview.com/index.php/Journal/about>

- interfacial bonding between ordinary Portland cement and geopolymer concrete using acid/alkaline-catalyzed nano-SiO₂ sols: Insights into performance and mechanisms. *Construction and Building Materials*, 490, 142537.
- Edouard, J. B. (2011). Experimental evaluation of the durability of fly ash-based geopolymer concrete in the marine environment. Florida Atlantic University.
- Zhang, X., Chen, W., Lin, W., Zheng, J., Yan, G., & Chen, X. (2024). Enhanced photocatalytic activity in photocatalytic concrete: synthesis, characterization, and comprehensive performance assessment of nano-TiO₂-modified recycled aggregates. *Catalysts*, 14(10), 711.
- GUEHLOUZ, I. (2025). Fiber valorization in cementitious materials. Application in high-performance structural concretes for the validation of Dynamic Interaction Tests (Doctoral dissertation, Faculté des Sciences et de la technologie).
- Elhag, A. B., Mabrouk, A., Ghazouani, N., & Nasir, U. (2025). Advances in Sustainable 3D-Printed Geopolymer Concrete: Materials, Performance, and Environmental Impact in Next Generation Green Construction. *JOM*, 1-39.
- Huo, Y., Huang, J., Han, X., Sun, H., Liu, T., Zhou, J., & Yang, Y. (2023). Mass GGBFS concrete mixed with recycled aggregates as alkali-active substances: workability, temperature history and strength. *Materials*, 16(16), 5632.
- Ramezani, A., Modaresi, S., Dashti, P., GivKashi, M. R., Moodi, F., & Ramezani pour, A. A. (2023). Effects of different types of fibers on fresh and hardened properties of cement and geopolymer-based 3D printed mixtures: a review. *Buildings*, 13(4), 945.
- Liu, C., Su, X., Wu, Y., Zheng, Z., Yang, B., Luo, Y., ... & Yang, J. (2021). Effect of nano-silica as cementitious materials-reducing admixtures on the workability, mechanical properties and durability of concrete. *Nanotechnology Reviews*, 10(1), 1395-1409.
- Zhang, Y. (2017). Study on microstructure and rheological properties of cement-chemical admixtures-water dispersion system at early stage. Springer.
- Wu, Z., Khayat, K. H., & Shi, C. (2017). Effect of nano-SiO₂ particles and curing time on development of fiber-matrix bond properties and microstructure of ultra-high strength concrete. *Cement and Concrete Research*, 95, 247-256.
- Karakurt, C., & Dumangöz, M. (2022). Rheological and durability properties of self-compacting concrete produced using marble dust and blast furnace slag. *Materials*, 15(5), 1795.