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Rheology-Guided Spray-Applied Engineered Cementitious Composites for Lightweight Structural Repair

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ABSTRACT

The rapid deterioration of aging civil infrastructure globally has necessitated the development of advanced structural repair materials and application techniques. Conventional concrete repair materials often suffer from premature failure due to poor dimensional compatibility, high brittleness, and inadequate bonding with the substrate. Engineered Cementitious Composites have emerged as a promising alternative due to their extraordinary tensile ductility and tight crack width control. However, the application of Engineered Cementitious Composites in large-scale structural repair, particularly for overhead and vertical surfaces, is severely hindered by the lack of optimized spray application methodologies. This paper presents a comprehensive investigation into the development of a rheology-guided, spray-applied lightweight Engineered Cementitious Composite. By integrating lightweight aggregates, specifically fly ash cenospheres and hollow glass microspheres, the dead load of the repair layer is significantly reduced, addressing critical structural constraints. The core of this research revolves around tailoring the fresh state properties of the composite to meet the paradoxical requirements of pumpability and shootability. Through rigorous rheological modification using specific combinations of polycarboxylate ether superplasticizers and viscosity modifying agents, an optimal rheological window is established. The resulting material demonstrates exceptional thixotropic behavior, enabling low pumping pressure while ensuring structural build-up immediately upon substrate impact, effectively minimizing rebound and sagging. Furthermore, the micromechanical design principles are maintained, ensuring that the spray process induces favorable fiber alignment, thereby preserving the signature strain-hardening behavior of the composite

KEYWORDS

Rheology, Engineered Cementitious Composites, Spray Application, Structural Repair

1. Introduction

The global built environment is currently facing an unprecedented crisis related to the aging and deterioration of critical civil infrastructure. Bridges, tunnels, retaining walls, and high-rise structures constructed decades ago are reaching the end of their designed service lives, exhibiting widespread signs of distress such as cracking, spalling, and reinforcement corrosion. The economic burden associated with the maintenance, repair, and rehabilitation of these structures is staggering, often consuming a significant portion of national construction budgets [1]. Traditional approaches to structural repair have predominantly relied on conventional ordinary Portland cement-based mortars and concretes. While readily available and cost-effective, these conventional materials possess inherent flaws that compromise the long-term durability and efficacy of structural repairs [2]. Their inherent brittleness, susceptibility to shrinkage-induced cracking, and relatively poor bond strength when applied to existing, weathered substrates frequently result in premature repair failure [3]. Consequently, there is an urgent and critical need for the development and implementation of advanced, high-performance repair materials that can provide enhanced durability, structural compatibility, and extended service life.

1.1 The Need for Structural Repair

Structural degradation is a complex phenomenon driven by a multitude of environmental and mechanical factors. In marine environments and regions subject to heavy de-icing salt application, the ingress of chloride ions through the porous concrete matrix initiates and accelerates the corrosion of reinforcing steel [4]. This corrosion process generates expansive reaction products, leading to internal tensile stresses that manifest as concrete cracking and eventual spalling. Similarly, structures exposed to severe climatic variations suffer from freeze-thaw cycles, where the expansion of freezing water within the concrete capillary pores causes progressive internal damage [5]. Furthermore, cyclical mechanical loading, such as traffic on highway bridges, induces fatigue degradation over time. When selecting a repair material to address these forms of damage, dimensional compatibility with the host substrate is paramount. The repair material must possess similar thermal expansion coefficients and elastic moduli to prevent the development of detrimental interface stresses during temperature fluctuations and load transfers [6]. A critical failure mode in many repaired structures is the debonding at the interface between the old concrete and the new repair layer, often precipitated by the drying shrinkage of the repair material restrained by the rigid substrate [7]. Therefore, ideal structural repair materials must not only possess high intrinsic strength and durability but also exhibit high tensile strain capacity to accommodate deformations without catastrophic cracking or delamination [8].

1.2 Engineered Cementitious Composites

Engineered Cementitious Composites represent a paradigm shift in the design of concrete materials. Unlike conventional concrete, which exhibits brittle failure under tensile stress, Engineered Cementitious Composites are characterized by their remarkable tensile ductility and pseudo-strain-hardening behavior, typically achieving tensile strain capacities ranging from two to five percent [9]. This extraordinary macroscopic performance is achieved through the meticulous application of micromechanical design principles, optimizing the interactions between the cementitious matrix, the dispersed polymeric short fibers, and the fiber-matrix interface [10]. Polyvinyl alcohol fibers are most commonly utilized due to their high tensile strength and strong chemical bonding with the cementitious matrix. When subjected to excessive tensile stress, the composite does not fail through the propagation of a single, localized crack. Instead, the material undergoes a process of multiple microcracking, where stress is continuously transferred across the crack faces by the bridging fibers, allowing the formation of numerous, tightly spaced cracks [11]. The width of these individual microcracks is typically limited to less than one hundred micrometers, which significantly restricts the penetration of aggressive environmental agents, thereby granting the material exceptional intrinsic durability and self-healing potential [12]. The ability to undergo large plastic deformations while maintaining load-carrying capacity makes Engineered Cementitious Composites exceptionally well-suited for structural repair

applications, as they can effectively distribute restrained shrinkage stresses and maintain structural integrity under severe mechanical loading.

1.3 Spray Application Challenges

Despite the overwhelming mechanical advantages of Engineered Cementitious Composites, their widespread adoption for large-scale infrastructure rehabilitation has been limited by practical application challenges. Manual troweling and formwork-based casting are labor-intensive, time-consuming, and often unfeasible for repairing complex geometries, vertical facades, or overhead structural elements [13]. Spray application, or shotcreting, offers a highly efficient, versatile, and rapid alternative. However, the transition from cast-in-place to spray-applied composites introduces a complex set of rheological and processing difficulties. The material must navigate a conflicting set of fluid properties during the application process [14]. Initially, the fresh composite must be sufficiently fluid to be pumped through long delivery hoses without causing blockages or requiring excessive pumping pressures, a property broadly defined as pumpability. Upon exiting the nozzle and impacting the repair substrate, the material must undergo an instantaneous transformation, transitioning from a fluid state to a semi-solid state capable of adhering to the surface and supporting its own weight without sagging or dripping, a property known as shootability. This transition is further complicated by the presence of high-volume fractions of reinforcing fibers, which tend to entangle and form clumps during pumping and can cause significant rebound upon substrate impact if the matrix viscosity is not precisely controlled. Furthermore, for overhead repairs, the density of the composite becomes a critical factor; heavy materials are prone to detachment under gravity. Therefore, the development of a lightweight, sprayable composite necessitates a profound understanding and active manipulation of the material's rheology.

2. Background and Literature Review

The successful development of a rheology-guided, spray-applied lightweight Engineered Cementitious Composite requires the synthesis of knowledge from multiple disciplines, including cement chemistry, fluid dynamics, micromechanics, and materials engineering. A comprehensive review of the existing literature provides the foundational context for the methodologies and analytical frameworks utilized in this research.

2.1 Rheology of Cementitious Materials

Rheology, the study of the deformation and flow of matter, is the fundamental science governing the fresh state behavior of cementitious materials. The flow of concrete and mortar is commonly modeled using Bingham or Herschel-Bulkley fluid models [15]. These models characterize the material using two primary parameters: yield stress and plastic viscosity. Yield stress represents the minimum applied shear stress required to initiate flow; materials with high yield stress exhibit high resistance to initial deformation and are less prone to sagging when placed on vertical surfaces. Plastic viscosity, on the other hand, describes the material's resistance to flow once the yield stress has been exceeded and flow has commenced; it governs the ease of pumping and the velocity of the fluid within the delivery hoses [16]. For standard concrete casting, a low yield stress and moderate plastic viscosity are generally desired to ensure adequate self-consolidation and flowability. However, for spray application, the requirements are highly dynamic. The material must exhibit thixotropy, which is a time-dependent, shear-thinning property [17]. A highly thixotropic material will experience a dramatic reduction in apparent viscosity when subjected to the high shear rates experienced during pumping and spraying, facilitating efficient transport and atomization at the nozzle. Once the shear forces are removed upon impact with the substrate, the material must rapidly rebuild its internal microstructure, resulting in a sudden increase in yield stress that prevents the material from flowing down the wall or falling from the ceiling. Achieving this delicate balance requires the precise application of chemical admixtures, primarily high-range water reducers and viscosity modifying agents, which interact at the colloidal level to govern the dispersion and flocculation of cement particles [18].

2.2 Lightweight Aggregates in ECC

The incorporation of lightweight aggregates into cementitious matrices is a well-established method for reducing the density of structural elements, thereby minimizing dead loads and improving thermal insulation. In the context of structural repair, particularly for overhead applications, density reduction is crucial for maintaining the stability of the fresh repair layer and reducing the structural burden on the aging host structure. Traditional lightweight aggregates, such as expanded clay, shale, or pumice, often suffer from high water absorption and relatively low intrinsic strength, which can negatively impact the mechanical performance and workability of the composite [19]. To maintain the strict micromechanical criteria required for strain-hardening behavior in Engineered Cementitious Composites, more advanced lightweight fillers are necessary. Hollow glass microspheres and fly ash cenospheres have emerged as optimal candidates [20]. These microscopic, spherical particles possess closed-cell structures, providing ultra-low density while maintaining a relatively high hydrostatic compressive strength. Furthermore, their perfectly spherical morphology acts as miniature ball bearings within the fresh matrix, significantly reducing inter-particle friction and improving the overall flowability and pumpability of the composite [21]. However, replacing dense silica sand with lightweight microspheres alters the fracture toughness of the matrix and changes the interfacial bond properties between the matrix and the polymeric fibers. Extensive literature highlights the necessity of re-evaluating the micromechanical parameters when formulating lightweight composites to ensure that the criteria for steady-state flat crack propagation and multiple cracking are still satisfied [22]. The delicate balance between achieving the target density and maintaining acceptable tensile ductility represents a significant challenge in mixture formulation.

2.3 Existing Spray-Applied Repair Techniques

The construction industry predominantly utilizes two primary methods for spray-applied concrete, often referred to as shotcrete: the dry-mix process and the wet-mix process. In the dry-mix process, dry cement, aggregates, and fibers are conveyed pneumatically through a hose to the nozzle, where water is injected immediately prior to discharge. While this method allows for rapid early strength development and high ultimate strength, it is notorious for generating excessive dust and suffering from high rebound rates, where a significant portion of the material, particularly the costly reinforcing fibers, bounces off the substrate and is wasted [23]. The wet-mix process, conversely, involves mixing all ingredients, including water, into a fluid state before pumping the mixture to the nozzle, where compressed air is introduced to accelerate the material onto the receiving surface. The wet-mix process generally provides better quality control, more uniform mixing, and a safer working environment with reduced dust emissions. Therefore, the wet-mix process is almost exclusively preferred for the application of high-performance fiber-reinforced composites [24]. Nonetheless, the wet-mix spraying of heavily fiber-reinforced materials presents substantial difficulties. The high fiber volume fraction drastically increases the plastic viscosity and yield stress of the mixture, leading to high pumping pressures and potential equipment failure. Furthermore, the chaotic impact dynamics at the substrate can lead to poor fiber orientation, porosity, and reduced mechanical performance compared to cast specimens. Understanding the fluid dynamics at the nozzle and the kinetic energy transfer upon impact is essential for optimizing the spray process to enhance material consolidation and fiber alignment.

3. Methodology for Rheology-Guided Design

The development of the optimal spray-applied composite involves a systematic and iterative methodology, transitioning from fundamental material characterization to advanced rheological modification and ultimately large-scale application simulation. This section details the comprehensive approach utilized to bridge the gap between micromechanical design and practical spray application.

3.1 Material Selection and Proportioning

The foundational matrix of the lightweight composite is composed of Ordinary Portland Cement and supplementary cementitious materials, predominantly Class F fly ash. The high volume replacement of cement with fly ash serves multiple critical functions: it reduces the heat of hydration, mitigates the risk of thermal cracking, improves the long-term durability through pozzolanic reactions, and critically,

lowers the chemical bond strength between the polyvinyl alcohol fibers and the cementitious matrix, which is a fundamental requirement for preventing fiber rupture and enabling strain-hardening behavior [25]. To achieve the target density while maintaining matrix integrity, a combination of fly ash cenospheres and hollow glass microspheres is utilized as the primary fine aggregate, entirely replacing conventional silica sand. The specific gravity of these lightweight fillers ranges from zero point two to zero point seven, allowing for a substantial reduction in the composite's overall density. Polyvinyl alcohol fibers, with an average length of twelve millimeters and a diameter of thirty-nine micrometers, are incorporated at a volume fraction of two percent. The fiber surfaces are treated with a proprietary oil coating to further regulate the interfacial frictional stress. The water-to-binder ratio is kept strictly low, typically around zero point two five, to ensure high matrix strength and durability. To manage the workability at such low water contents, polycarboxylate ether-based high-range water-reducing admixtures are employed [26]. These admixtures function through steric hindrance, dispersing cement particles and releasing entrapped water, thereby significantly reducing the yield stress of the mixture. However, to prevent segregation of the lightweight aggregates and to control the thixotropic structural build-up, cellulosic viscosity modifying agents are also incorporated into the mixture design.

3.2 Rheological Modification Strategies

The central challenge of this research is engineering a rheological profile that satisfies the conflicting demands of pumping and spraying. This requires navigating a specific rheological window, balancing yield stress and plastic viscosity across varying shear rates. The strategy relies heavily on exploiting the thixotropic nature of the customized cementitious paste. During pumping, the material experiences continuous high shear, breaking down the flocculated structures within the cement paste. The high-range water reducer ensures that in this dynamic state, the plastic viscosity remains sufficiently low to allow flow with manageable pump pressures, avoiding the blockages typically associated with long fiber reinforcement [27].

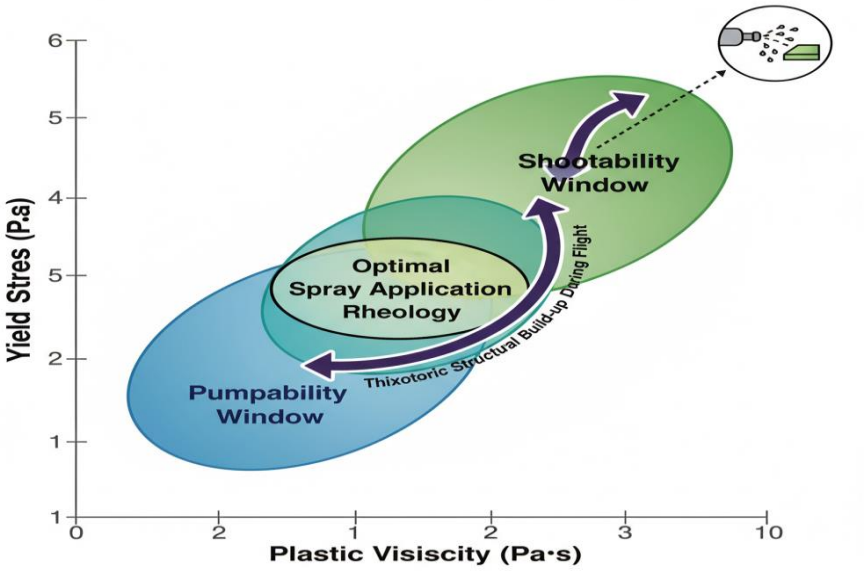


Figure 1: Rheological Window for Spray Application

Upon reaching the nozzle, the material is accelerated by compressed air, subjecting it to immense shear forces and atomization. Following impact with the substrate, the shear rate drops instantaneously to zero. At this critical juncture, the viscosity modifying agents play their essential role. They rapidly form cross-linked polymer networks within the interstitial water, facilitating immediate structural build-up and a massive, instantaneous increase in static yield stress. This rapid recovery prevents the material from flowing under gravitational forces, allowing the build-up of thick repair layers in a single pass without sagging [28]. The precise dosage and interaction between the polycarboxylate ether superplasticizer and the viscosity modifying agent are rigorously calibrated using advanced rotational rheometry,

continuously measuring the torque required to shear the material under varying rotational speeds to map the complete flow curve and calculate the Bingham parameters.

3.3 Evaluation of Sprayability and Pumpability

To validate the rheological design, a series of comprehensive tests simulating field conditions are conducted. Pumpability is initially assessed using a sliding pipe rheometer, which measures the pressure loss over a specific length of the delivery hose at various flow rates. This data allows for the calculation of the lubrication layer thickness and the dynamic flow resistance of the bulk material, ensuring that the necessary pumping pressure remains well below the operational limits of standard construction equipment [29]. Shootability is evaluated through direct vertical and overhead spraying trials onto standardized concrete test panels. The primary metrics for shootability include the maximum build-up thickness achievable in a single pass before failure due to sagging or sloughing occurs, and the quantification of material rebound. Rebound is meticulously measured by collecting and weighing all material that fails to adhere to the substrate during the spraying process. High rebound rates not only represent significant material waste but also alter the in-place composition of the composite, as larger particles and fibers are disproportionately rejected upon impact. The rheology-guided methodology aims to reduce the rebound rate to below ten percent, ensuring economic viability and structural consistency [30]. Furthermore, the consolidation of the sprayed material is evaluated through visual inspection of cross-sections and non-destructive testing to detect entrapped air voids and ensure adequate density uniformity across the repair profile.

4. Experimental Analysis and Structural Application

Following the successful formulation and rheological optimization of the composite, an extensive experimental campaign is executed to evaluate its mechanical performance and validate its efficacy as a structural repair material. The testing focuses on confirming that the transition from casting to spraying does not compromise the fundamental strain-hardening characteristics.

4.1 Mechanical Performance Assessment

The mechanical characterization of the sprayed composite is conducted on specimens directly extracted from large-scale sprayed panels. This approach ensures that the tested material accurately reflects the in-situ properties, accounting for the effects of high-velocity impact, compaction, and specific fiber orientation induced by the spray process. Uniaxial tensile testing is the most critical evaluation, as it directly measures the strain capacity and multiple cracking behavior. Dogbone-shaped specimens are cored and precision-cut from the sprayed panels and subjected to displacement-controlled tensile loading.

Table 1: Rheological and Mechanical Properties of the Optimized Lightweight ECC Mixtures

Mixture ID	Density (kg/m3)	Yield Stress (Pa)	Plastic Viscosity (Pa.s)	Tensile Strain Capacity (%)
LWECC-1	1450	120	15	2.5
LWECC-2	1380	145	18	3.1
LWECC-3	1250	180	25	2.8

The results indicate that the optimized mixtures not only achieve the targeted density reduction, falling well below the typical density of conventional concrete, but also maintain excellent tensile strain capacities exceeding two point five percent [31]. Furthermore, the compressive strength and elastic modulus are evaluated to ensure structural compatibility with typical host substrates. A crucial aspect of the mechanical assessment involves testing the interfacial bond strength between the sprayed composite and roughened concrete substrates. Direct tension pull-off tests and slant shear tests are employed to

quantify the bond integrity. The results demonstrate that the rheologically optimized material achieves exceptional intimate contact with the substrate profile upon impact, resulting in cohesive failure within the concrete substrate rather than adhesive failure at the interface, indicating a superior and durable bond.

4.2 Spray Process Optimization

The final phase of the analysis involves investigating the influence of operational spray parameters on the final material quality. The velocity of the material at impact, dictated by the compressed air pressure and the nozzle design, plays a dominant role in matrix compaction and fiber alignment. High-speed camera analysis reveals that optimal impact velocity results in a highly densified matrix, minimizing entrapped air voids that are common in viscous spray applications.

Figure 2: Spray Impact Dynamics and Fiber Alignment

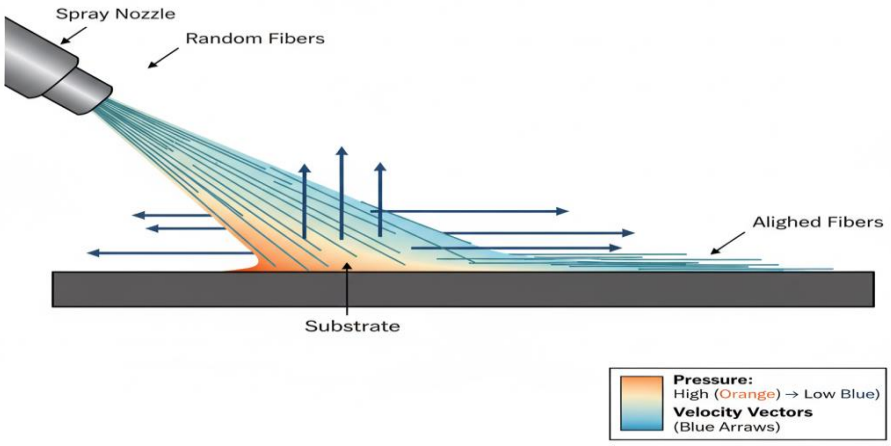


Figure 2: Spray Impact Dynamics and Fiber Alignment

More importantly, the kinetic energy of the impact forces the composite to flow radially outward from the point of impact. This localized, high-shear flow aligns the short polymeric fibers parallel to the substrate surface. In structural repair scenarios, tensile stresses are typically oriented parallel to the repair layer. Therefore, this two-dimensional fiber alignment, naturally induced by the optimized spray dynamics, acts to significantly enhance the tensile bridging efficiency of the fibers exactly in the direction where it is most required. This phenomenon explains why the sprayed specimens often exhibit comparable or even superior tensile strain capacity compared to traditionally cast specimens, provided the rheology is correctly calibrated to prevent fiber clumping during atomization. The standoff distance and the spray angle are also systematically varied to establish the standard operating procedures necessary to guarantee consistent quality in field applications.

5. Conclusion

This comprehensive study has successfully demonstrated the viability and superior performance of a rheology-guided, spray-applied lightweight Engineered Cementitious Composite for advanced structural repair. By meticulously tailoring the fresh state properties through the strategic combination of polycarboxylate ether superplasticizers, viscosity modifying agents, and lightweight microscopic aggregates, the historical paradox between material pumpability and shootability has been resolved. The developed composite exhibits a precisely engineered thixotropic behavior, allowing it to flow easily through long delivery systems under shear, yet instantaneously build sufficient structural rigidity upon substrate impact to prevent sagging, even in overhead applications. The substitution of normal-weight aggregates with fly ash cenospheres and hollow glass microspheres achieved significant density reductions, minimizing structural dead loads while maintaining the strict micromechanical parameters necessary for robust strain-hardening behavior. Experimental analysis confirmed that the material

preserves exceptional tensile ductility and tight crack width control, critical attributes for accommodating dimensional incompatibilities and preventing premature repair failure. Furthermore, the optimized spray process was shown to induce highly favorable, two-dimensional fiber alignment parallel to the substrate, maximizing the reinforcement efficiency against bending and tensile stresses [32]. The superior interfacial bond strength achieved through high-velocity impact ensures monolithic behavior with the existing structure. In conclusion, the integration of advanced rheological control and micromechanical design provides a highly scalable, efficient, and durable solution for the rehabilitation of aging civil infrastructure, offering a transformative approach to extending the service life of critical structural assets globally.

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