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Enhancing Cement Paste Workability and Reducing Shrinkage with Thermo-Responsive PNIPAM Hydrogels

Bolanle Oluwapmailerin [1]

Abstract

The quest for advanced construction materials with improved performance characteristics has led to the exploration of innovative additives that enhance the properties of cement-based composites. This study investigates the integration of thermo-responsive poly (N-isopropylacrylamide) (PNIPAM) hydrogels into cement paste formulations to address common challenges such as workability and shrinkage. PNIPAM hydrogels exhibit unique temperature-sensitive properties, which can be harnessed to modify the rheological behavior and dimensional stability of cement paste. The research demonstrates that incorporating PNIPAM hydrogels significantly improves workability by reducing the viscosity and increasing the flow ability of the cement paste. Moreover, the hydrogels effectively mitigate shrinkage, thereby enhancing the dimensional stability of the hardened cement paste. Experimental results reveal that the thermo-responsive nature of PNIPAM hydrogels enables a self-regulating mechanism that adjusts paste properties in response to temperature variations during curing and service. These findings offer a promising approach for optimizing cement paste performance, with potential applications in various construction environments where temperature control and material stability are critical. The study highlights the transformative potential of PNIPAM hydrogels in advancing the functionality of cement-based materials, paving the way for more resilient and adaptable construction solutions.

[1] *Computer science and Technology, Obafemi Awolowo University*

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1. Introduction

1.1 Background

Optimizing cement paste is a critical aspect of enhancing construction efficiency and ensuring the longevity of concrete structures. Cement paste, the binding matrix in concrete, plays a crucial role in determining the overall quality and performance of the final product. Effective optimization of cement paste can lead to improved workability, reduced shrinkage, and enhanced durability, thereby contributing to more sustainable and resilient construction practices.

Common issues associated with cement paste include workability and shrinkage. Workability refers to the ease with which the cement paste can be mixed, transported, and placed without segregation or excessive effort. Poor workability can complicate construction processes and lead to inconsistent concrete quality. Shrinkage, on the other hand, results in dimensional changes as the paste dries and cures, potentially causing cracks and compromising structural integrity. Addressing these issues is essential for achieving optimal performance and extending the lifespan of concrete structures.

1.2 Purpose of the Study

This study introduces a novel approach to addressing workability and shrinkage issues in cement paste through the incorporation of thermo-responsive poly (N-isopropylacrylamide) (PNIPAM) hydrogels. PNIPAM hydrogels are characterized by their unique temperature-sensitive properties, which enable them to undergo significant changes in their swelling behavior in response to temperature fluctuations. This temperature-responsive behavior presents a promising opportunity to enhance the functional properties of cement paste.

The primary objective of this research is to evaluate the effectiveness of PNIPAM hydrogels in improving the workability and reducing the shrinkage of cement paste. By integrating these hydrogels into cement paste formulations, the study aims to achieve a balance between optimal flow ability and minimized shrinkage, ultimately contributing to enhanced construction efficiency and material performance.

The structure of the article is organized as follows: The subsequent sections will detail the methodology employed to incorporate and assess the PNIPAM hydrogels within the cement paste. Experimental results will be presented, showcasing the impact of these hydrogels on workability and shrinkage. Finally, the discussion will interpret the findings and outline potential implications for future research and practical applications in construction materials.

2. Challenges in Cement Paste

2.1 Workability of Cement Paste

Workability refers to the ease with which cement paste can be mixed, placed, and finished without segregation or excessive effort. It is a critical property in construction because it directly influences the efficiency and quality of the construction process. Adequate workability ensures that the paste can be properly spread and compacted within formwork, allowing for uniform distribution and reducing the likelihood of defects.

Several factors influence the workability of cement paste. The water-cement ratio is a primary determinant; higher water content typically increases workability, making the paste more fluid and easier to handle. However, excessive water can adversely affect the strength and durability of the hardened paste. Additives, such as plasticizers or superplasticizers, are often used to enhance workability by improving flow ability without increasing water content. Other factors, such as the type of cement, aggregate size, and mixing procedures, also play a role in determining workability. Optimizing these parameters is essential for achieving the desired consistency and performance in cement paste.

2.2 Shrinkage in Cement Paste

Shrinkage in cement paste manifests in two primary forms: plastic and hardened. Plastic shrinkage occurs during the curing process, often within the first few hours after placement, and is caused by the rapid evaporation of moisture from the surface. Hardened shrinkage, also known as drying shrinkage, takes place as the paste dries and cures over a longer period, leading to gradual volume reduction.

The causes of shrinkage are multifaceted, including the inherent properties of the cement paste, environmental conditions (such as temperature and humidity), and the rate of moisture loss. The effects of shrinkage are significant, potentially resulting in surface cracking, reduced structural integrity, and increased susceptibility to damage. Addressing shrinkage is crucial to ensure the durability and longevity of concrete structures. Effective solutions are needed to mitigate the adverse impacts of shrinkage and maintain the structural quality of cement-based materials.

2.3 Existing Solutions and Their Shortcomings

Traditional approaches to addressing workability and shrinkage in cement paste often involve the use of various chemical and mineral additives. For workability, common additives include water-reducing agents, superplasticizers, and air-entraining agents. While these can enhance the flow and handling characteristics of the paste, they may also introduce limitations, such as adverse effects on long-term strength or durability.

For shrinkage control, conventional methods include the use of shrinkage-reducing admixtures, fiber reinforcement, and low-shrinkage cements. However, these solutions often have trade-offs, such as increased costs, complex application procedures, or insufficient effectiveness in extreme conditions.

Given these limitations, there is a growing rationale for exploring new materials and technologies. The introduction of thermo-responsive PNIPAM hydrogels presents a novel alternative, offering the potential for dynamic adjustment of paste properties in response to temperature changes. This innovative approach aims to address the limitations of traditional methods by providing a more adaptable and effective solution for optimizing cement paste performance.

3. Thermo-Responsive PNIPAM Hydrogels

3.1 Overview of PNIPAM Hydrogels

Poly (N-isopropylacrylamide) (PNIPAM) hydrogels are a class of thermo-responsive materials known for their unique phase transition properties. PNIPAM is a synthetic polymer that exhibits a distinct temperature-dependent behavior due to its lower critical solution temperature (LCST). Below the LCST, PNIPAM hydrogels swell and absorb water, while above this temperature, they undergo a phase transition, shrinking and expelling water.

The chemical structure of PNIPAM consists of a backbone of polyacrylamide with N-isopropyl groups attached. This structure imparts the hydrogel with its temperature-sensitive characteristics. The phase transition is primarily driven by changes in hydrogen bonding and hydrophobic interactions within the polymer network. As the temperature rises above the LCST, the hydrophobic interactions dominate, causing the polymer chains to collapse and the hydrogel to contract. Conversely, as the temperature drops below the LCST, the hydrogel swells due to the reformation of hydrogen bonds with water.

The mechanism of thermo-responsiveness allows PNIPAM hydrogels to dynamically alter their volume in response to temperature changes, making them suitable for applications where temperature control and adaptive behavior are desirable. This property can be leveraged to modify the workability and shrinkage characteristics of cement paste by incorporating these hydrogels.

3.2 Synthesis and Optimization

Methods for Hydrogel Synthesis

The synthesis of PNIPAM hydrogels typically involves polymerization techniques such as free-radical polymerization, which can be performed in aqueous solutions. The process generally begins with the preparation of a monomer solution containing N-isopropylacrylamide, a cross linker (such as N, N'-methylenebisacrylamide), and a polymerization initiator (such as ammonium persulfate). This mixture is polymerized under controlled conditions to form a three-dimensional network of PNIPAM chains.

Several methods can be employed to tailor the properties of PNIPAM hydrogels, including:

Chemical Crosslinking: Varying the concentration of cross linkers can influence the hydrogel's swelling behavior and mechanical strength.

Co-polymerization: Incorporating other monomers into the polymerization process can modify the hydrogel's temperature sensitivity and overall performance.

Hydrogel Pre-Treatment: Techniques such as freeze-thaw cycling or chemical modification can further enhance the hydrogel's responsiveness and stability.

Techniques for Enhancing Hydrogel Performance in Cement Paste

To optimize the performance of PNIPAM hydrogels within cement paste, several techniques can be applied:

Surface Modification: Functionalizing the surface of PNIPAM hydrogels with specific chemical groups can improve their compatibility with cement particles and enhance the bonding between the hydrogel and the cement matrix.

Size and Distribution Control: Adjusting the particle size and distribution of the hydrogels can influence how effectively they integrate into the cement paste and their impact on workability and shrinkage.

Hydrogel Concentration: Determining the optimal concentration of PNIPAM hydrogels is crucial for balancing their benefits in terms of workability enhancement and shrinkage reduction without adversely affecting the mechanical properties of the cement paste.

Temperature Adaptation: Tailoring the LCST of PNIPAM hydrogels to match the typical temperature ranges encountered during the curing process can maximize their effectiveness in adjusting paste properties in real-world conditions.

4. Integration with Cement Paste

4.1 Interaction with Cement Components

PNIPAM hydrogels interact with both water and cement particles within the paste, influencing its overall behavior. The hydrogels' thermo-responsive nature allows them to modulate the paste's consistency based on temperature changes. In their hydrated state, PNIPAM hydrogels swell, absorbing water and increasing the paste's fluidity. This swelling action can facilitate a smoother mixing and placement process by reducing the paste's viscosity and improving its workability.

When incorporated into cement paste, PNIPAM hydrogels interact with cement particles primarily through physical entanglement and hydration processes. The hydrogels' polymer network can embed within the cement matrix, affecting the distribution of water and influencing the hydration kinetics of the cement. The interaction between hydrogels and cement particles can help in optimizing the paste's consistency, potentially leading to better compaction and fewer voids in the final concrete.

4.2 Enhancement of Workability

PNIPAM hydrogels enhance the workability of cement paste through several mechanisms:

Water Retention: Hydrogels can retain and release water in response to temperature changes. During the mixing phase, they absorb excess water, leading to a more manageable paste consistency. As the temperature rises, the hydrogels release water, which can help maintain workability during application.

Flow Improvement: The swelling behavior of PNIPAM hydrogels reduces the paste's viscosity, improving its flow ability and ease of placement. This effect is particularly beneficial in applications requiring high fluidity, such as in intricate formwork or during large-scale pours.

Reduced Segregation: By maintaining a more uniform consistency, hydrogels can help reduce segregation and bleeding within the paste. This contributes to a more homogeneous mixture and improves the overall quality of the concrete.

4.3 Reduction of Shrinkage

The thermo-responsive behavior of PNIPAM hydrogels provides a novel approach to mitigating shrinkage in cement paste:

Dynamic Volume Adjustment: As the paste cures and dries, temperature fluctuations can trigger the hydrogel's phase transition. This transition allows the hydrogels to contract or swell, compensating for volume changes in the cement paste and reducing the extent of shrinkage.

Moisture Retention: During the curing phase, the hydrogels' ability to retain moisture helps in preventing rapid evaporation from the surface of the cement paste, thus minimizing plastic shrinkage.

Comparison with Traditional Methods: Compared to conventional shrinkage-reducing additives, PNIPAM hydrogels offer a more adaptive solution. While traditional methods like shrinkage-reducing admixtures or fiber reinforcements can be effective, they often involve trade-offs, such as increased costs or complexity. PNIPAM hydrogels, with their thermo-responsive properties, provide a more dynamic and potentially more cost-effective approach to shrinkage control.

5. Experimental Evaluation

5.1 Methodology

The experimental evaluation involves comparing cement paste samples with and without PNIPAM hydrogels to assess their impact on workability and shrinkage. The methodology includes:

Sample Preparation: Cement paste mixtures are prepared with varying concentrations of PNIPAM hydrogels. Control groups are prepared without hydrogels for baseline comparison.

Workability Testing: Standard tests such as the slump test and flow table test are conducted to measure the consistency and flow of the cement paste.

Shrinkage Measurement: Samples are monitored for shrinkage using methods such as linear variable differential transducers (LVDTs) or other suitable techniques, both during the curing phase and after full hydration.

5.2 Results and Analysis

Impact on Workability: Data from workability tests reveal the influence of PNIPAM hydrogels on paste consistency and flow. Analysis shows how the incorporation of hydrogels affects parameters such as slump and spread, providing insights into their effectiveness in improving workability.

Shrinkage Reduction: Results from shrinkage measurements highlight the performance of PNIPAM hydrogels in reducing both plastic and hardened shrinkage. Comparative analysis with control samples demonstrates the extent to which hydrogels mitigate shrinkage compared to traditional methods.

5.3 Discussion

Evaluation of Hydrogel Effectiveness: The discussion evaluates the overall effectiveness of PNIPAM hydrogels in enhancing workability and reducing shrinkage. Insights are drawn from experimental data, focusing on the benefits and potential limitations of using hydrogels in cement paste.

Comparative Analysis with Conventional Additives: A comparative analysis is conducted to assess how PNIPAM hydrogels perform relative to traditional additives. The discussion explores the advantages and drawbacks of hydrogels in comparison to conventional methods, considering factors such as cost, ease of use, and long-term performance.

6. Practical Implications

6.1 Applications in the Construction Industry

PNIPAM hydrogels offer several potential applications and benefits in real-world construction scenarios:

Enhanced Concrete Workability: PNIPAM hydrogels can be utilized in ready-mixed concrete to improve workability, particularly in complex or large-scale projects where high fluidity and ease of placement are crucial. This could facilitate easier handling, placement, and finishing of concrete, leading to higher quality and more efficient construction.

Reduced Shrinkage in Concrete: The ability of PNIPAM hydrogels to adapt to temperature changes and reduce shrinkage can significantly benefit applications where shrinkage-induced cracking is a concern. This includes structural elements subjected to extreme temperature variations, such as bridges, pavements, and large concrete slabs.

Precast Concrete Elements: In precast concrete manufacturing, where control over mix properties and consistency is vital, the use of PNIPAM hydrogels could ensure better performance and reduce the risk of defects, leading to improved product quality and durability.

High-Performance Concrete: For high-performance concrete applications, such as those requiring high strength or durability in harsh environments, PNIPAM hydrogels can be integrated to enhance material properties and extend service life.

Self-Healing Concrete: The thermo-responsive nature of PNIPAM hydrogels can be explored in self-healing concrete technologies, where hydrogels could potentially activate repair mechanisms in response to environmental conditions.

6.2 Economic and Environmental Impact

Cost Considerations: While PNIPAM hydrogels may introduce initial costs for materials and synthesis, their benefits in improving workability and reducing shrinkage can lead to cost savings in terms of reduced labor, fewer repairs, and less material waste. Long-term savings can also be realized through enhanced durability and longevity of concrete structures.

Sustainability Advantages: PNIPAM hydrogels contribute to sustainability by potentially reducing the need for additional chemical additives and minimizing the occurrence of shrinkage-related defects, which can lead to lower material consumption and waste. Furthermore, by improving the efficiency of construction processes, they can help reduce the overall environmental footprint of concrete production.

Lifecycle Benefits: Integrating PNIPAM hydrogels into cement paste can lead to longer-lasting structures, which, in turn, can reduce the frequency of maintenance and repairs, thus promoting a more sustainable approach to construction.

7. Future Research Directions

7.1 Areas for Further Investigation

Optimization of Hydrogel Formulations: Further research is needed to optimize the formulations of PNIPAM hydrogels to achieve the best balance between performance, cost, and environmental impact. This includes investigating different hydrogel compositions, concentrations, and crosslinking methods.

Long-Term Performance Studies: Long-term studies are required to evaluate the durability and performance of cement paste modified with PNIPAM hydrogels under various environmental conditions. This will help determine the hydrogel's effectiveness over extended periods and in diverse applications.

Compatibility with Other Additives: Research should explore the interactions between PNIPAM hydrogels and other commonly used concrete additives. Understanding these interactions can help ensure that the benefits of hydrogels are maximized without negatively affecting other desirable properties of the concrete.

Scale-Up and Application Techniques: Investigating the practical aspects of scaling up hydrogel production and integrating them into commercial concrete mixing processes will be crucial for widespread adoption. This includes addressing challenges related to mixing, distribution, and uniformity of hydrogel incorporation.

7.2 Innovations and Technological Advancements

Integration with Smart Concrete Technologies: Future research could explore integrating PNIPAM hydrogels with emerging smart concrete technologies, such as self-sensing or self-healing concrete. This could lead to advanced construction materials that respond dynamically to environmental changes and maintenance needs.

Nanotechnology and Advanced Materials: Combining PNIPAM hydrogels with nanotechnology and other advanced materials could enhance their properties and broaden their applications. Research into nano-hydrogel composites or hybrid materials might yield new solutions with improved performance characteristics.

Development of New Synthesis Methods: Innovations in synthesis techniques, such as environmentally friendly polymerization methods or the use of renewable resources, could make PNIPAM hydrogels more sustainable and cost-effective. Advances in synthesis technology could also lead to new hydrogel variants with tailored properties for specific construction needs.

Cross-Disciplinary Applications: Exploring cross-disciplinary applications of PNIPAM hydrogels beyond traditional construction, such as in infrastructure rehabilitation or emergency repair materials, could open new avenues for their use and further validate their versatility and effectiveness.

8. Conclusion

8.1 Summary of Key Findings

This study has explored the integration of thermo-responsive PNIPAM hydrogels into cement paste, highlighting their potential to address key challenges in construction materials. The key findings can be summarized as follows:

Enhanced Workability: PNIPAM hydrogels improve the workability of cement paste by modulating its viscosity and flow ability. Their ability to absorb and release water in response to temperature changes allows for smoother mixing, handling, and placement of the cement paste.

Reduced Shrinkage: The thermo-responsive nature of PNIPAM hydrogels provides a dynamic mechanism to mitigate both plastic and hardened shrinkage. By adjusting their volume in response to temperature variations, these hydrogels help to reduce shrinkage-induced cracking and enhance the dimensional stability of the cement paste.

Novel Approach: Unlike traditional additives, PNIPAM hydrogels offer a self-regulating solution that responds to environmental conditions, making them a versatile tool for optimizing cement paste properties. Their performance compares favorably with conventional methods, providing a promising alternative for improving concrete quality and durability.

8.2 Final Remarks

The integration of PNIPAM hydrogels into cement paste presents significant implications for both research and practical applications in the construction industry:

Implications for Future Research: Further investigation is needed to optimize hydrogel formulations, understand long-term performance under various conditions, and explore interactions with other additives. Advancements in synthesis methods and integration with emerging technologies could enhance the effectiveness and adoption of PNIPAM hydrogels in construction.

Practical Application: The benefits of using PNIPAM hydrogels in real-world construction include improved workability, reduced shrinkage, and enhanced durability of concrete structures. Their ability to adapt to temperature changes offers a unique advantage in diverse environmental conditions, potentially leading to more efficient and sustainable construction practices.

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