

Research Article

Sankaranarayanan Asvitha Valli* and Muthuswamy Saraswathi Ravi Kumar

Innovative approaches to enhancing crack repair: Performance optimization of biopolymer-infused CXT

<https://doi.org/10.1515/htmp-2024-0046>

received May 08, 2024; accepted July 14, 2024

Abstract: Biopolymer-modified cementitious repair material (CXT) is a composite material designed to enhance the properties of traditional cementitious materials through the incorporation of biopolymers. CXT is formed by blending cement (C) with biopolymers such as xanthan gum (XG) and additives like tartaric acid (TA), which improve the material's performance characteristics. This study investigates the effects of varying dosages of XG, TA contents, and curing durations on the performance characteristics of CXT. We evaluated key performance indicators, including the flowability, workability, setting time, compressive strength, and shrinkage. The optimal formulation XG 1:2 TA0.6 achieved a maximum compressive strength of $25 \text{ N}\cdot\text{mm}^{-2}$ and a flexural strength of $9.4 \text{ N}\cdot\text{mm}^{-2}$, with negligible shrinkage. The results showed rapid early strength development, with the material reaching over 77% of its final compressive strength within the first 14 days. These findings highlight the potential of CXT for crack-repair applications, offering improved workability, accelerated setting times, and reduced environmental impact compared to traditional repair materials. This study provides valuable insights for optimizing the formulation of CXT for enhanced performance in real-world applications.

Keywords: biopolymer repair material, crack sealing, sustainable construction materials, xanthan gum, tartaric acid

Nomenclature

C_3S	Tricalcium silicate
$\text{C}_3\text{S}_2\text{H}_3$, C–S–H	Calcium silicate hydrate
$\text{Ca}(\text{OH})_2$	Calcium hydroxide
CXT	Cementitious repair material made of cement, xanthan gum, and tartaric acid powder
SMF	Sulfonated melamine formaldehyde
TA	Tartaric acid
XG	Xanthan gum

1 Introduction

Cracks in concrete structures are a common issue that can significantly impact the integrity, safety, and esthetics of buildings. Various types of cracks, such as longitudinal, transverse, and diagonal cracks, can develop due to factors like structural loads, material properties, and construction processes [1,2]. These cracks can lead to corrosion, reduce the load-bearing capacity, and esthetic deterioration, highlighting the importance of timely detection and repair [3]. Advanced methods like image-based crack analysis using photogrammetry and deep learning techniques have been developed to accurately detect, quantify, and reconstruct cracks in concrete surfaces, ensuring precise measurements and assessments for effective maintenance and repair strategies [4]. Understanding the causes and effects of cracking is crucial for implementing appropriate preventive measures and repair techniques to address the diverse types of cracks that can occur in concrete structures [5].

To effectively manage these issues, traditional methods for repairing cracks involve a variety of techniques tailored to the specific type and severity of the crack. Common methods include the filling grouting method, surface repair method, and structural reinforcement method, each chosen based on the intended performance and economic considerations of the structure [6,7]. For instance, epoxy injection

* **Corresponding author: Sankaranarayanan Asvitha Valli**,
Department of Civil Engineering, Noorul Islam Centre for Higher
Education, Kanyakumari, Tamil Nadu 629180, India,
e-mail: spsasvitha@gmail.com

Muthuswamy Saraswathi Ravi Kumar: Department of Civil
Engineering, PSN Engineering College, Tirunelveli, Tamil Nadu 627152,
India, e-mail: ravikumar_ms@yahoo.com

is widely used for crack injection due to its effectiveness in restoring the structural integrity and protecting against environmental factors like carbonation and chloride ingress [8]. Additionally, traditional repair techniques have been applied to modern sustainable concretes, such as those containing recycled aggregates, proving their versatility and effectiveness in forming monolithic elements [9]. Electrochemical repair technology, often combined with traditional methods, has shown significant improvements in durability, especially in coastal environments where corrosion is a concern [10]. Moreover, advancements in microbial repair materials, such as those based on sodium alginate, offer promising alternatives by depositing calcium carbonate *in situ* to seal cracks, thereby enhancing the repair's durability and environmental friendliness [11]. The use of microbially induced calcite precipitation (MICP) has also been explored for its potential in repairing asphalt concrete cracks, demonstrating significant improvements in mechanical properties and resistance to permanent deformation [12]. For ancient ceramics, improved edge detection algorithms based on cluster analysis have enhanced the accuracy of crack repair, ensuring the preservation of cultural artifacts [13]. Overall, while traditional methods remain effective, integrating new technologies and materials can further enhance the longevity and performance of concrete repairs [14,15].

In the realm of sustainable materials science, the exploration of renewable resources like biopolymers from agro-wastes and aquaculture waste for innovative applications in construction materials is gaining momentum [16]. Biopolymers, such as xanthan gum (XG), have shown promise in enhancing the soil strength, reducing the water permeability, and improving the cohesion in concrete structures, making them a viable alternative for crack repair and sealing in construction materials [17]. Additionally, the development of Eco-Nanoseal, a sealant utilizing composite materials like graphene oxide and chitosan from aquaculture waste, showcases a sustainable approach to healing micro-cracks in concrete without external polymerizing agents, aligning with sustainability indices and offering an eco-friendly alternative to synthetic adhesives [18]. These advancements highlight the potential of biopolymer-modified materials, like CXT, to revolutionize the construction industry by improving the key properties through synergistic effects of biopolymer dosage and tartaric acid (TA) concentration.

Building upon this premise, the present study aims to investigate the synergistic effects of biopolymer dosage (specifically XG) and TA concentration on various key properties of biopolymer-modified cementitious repair materials, referred to as CXT. The specific objectives are as follows:

- Quantify the workability and set a time relationship of CXT modified with varying amounts of biopolymer (XG)

and TA using the slump cone and Marsh cone tests to determine the optimal mixture.

- Evaluate the mechanical properties, such as compressive strength and flexural strength, of the repair material CXT.

2 Materials and methods

The materials utilized in this research include cement, XG, TA powder, superplasticizer, and water. The characteristics of these materials and the reason behind choosing the specific quantities for each component in the presented CXT mix ratios are presented below.

2.1 Cement

The cement used to prepare CXT was Ordinary Portland Cement 43 grade conforming to ASTM C1019 specifications. This cement exhibited a fineness of $225 \text{ m}^2\cdot\text{kg}^{-1}$, a specific gravity of 3.15, and a soundness of 8 mm, ensuring suitability for its application as a repair material.

2.2 XG

XG was sourced from H R Chemicals, Mumbai – 400019, Maharashtra, India. XG is defined as a biopolymer with unique rheological properties derived from microbial fermentation. It is classified as a polysaccharide, consisting of repeating units of glucose, mannose, and glucuronic acid, and is produced by the bacterium *Xanthomonas campestris*. The molecular formula of XG is $(\text{C}_{35}\text{H}_{49}\text{O}_{29})_n$. Its chemical structure consists of a main-chain pentasaccharide repeat of linear β -1,4-D-glucose, with each molecule containing approximately 7,000 pentamers. These repeating units are composed of glucose, mannose, and glucuronic acid. The side chains of XG contain alternating glucose monomers with mannose and glucuronic acid, as well as pyruvic acid (Figure 1). This intricate structure gives XG its unique properties, such as high solubility in both hot and cold water and its ability to form highly viscous solutions at low concentrations [19].

The chemical structure of XG also imparts significant stability to the polymer. It remains stable over a wide range of temperatures and pH levels, and its viscosity is not significantly affected by changes in the temperature or pH. Additionally, XG exhibits excellent compatibility with various salts, enabling it to maintain its rheological

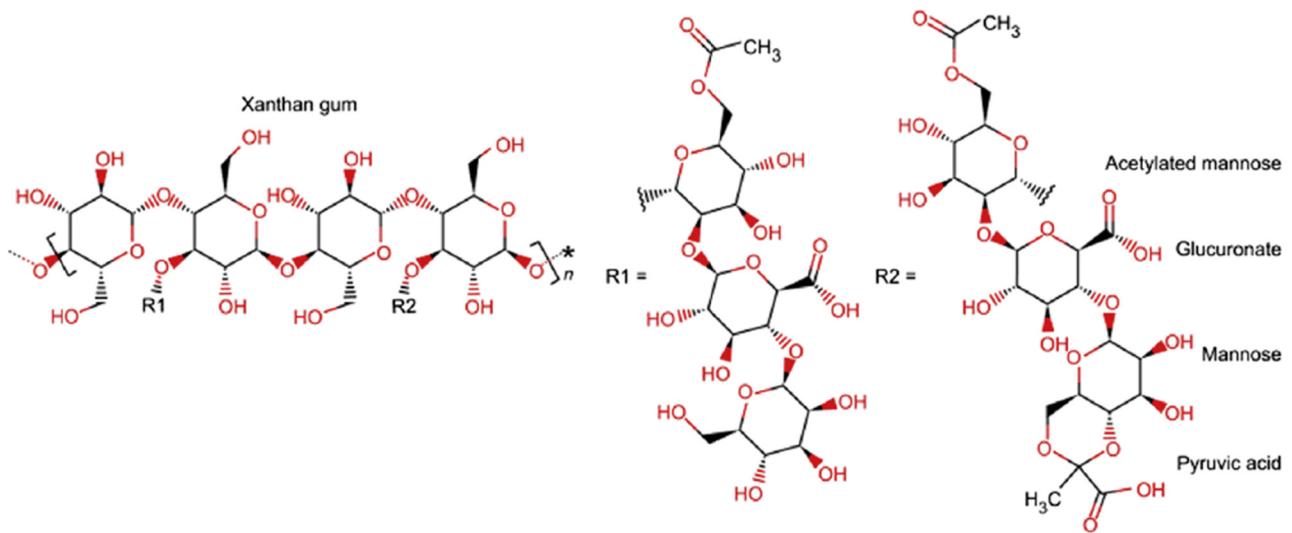


Figure 1: Chemical structure of XG [20].

properties even in the presence of high ionic strength environments.

This complex structure imparts unique rheological properties to XG, such as high viscosity and pseudoplasticity, which make it highly effective in enhancing the flowability and workability of cementitious materials. These properties are particularly advantageous in concrete applications, where XG helps improve the dispersion of particles, reduce the water content, and prevent washout. Additionally, XG remains stable in the presence of acids, alkalis, salts, and high temperatures, making it a robust additive in various industrial applications, including the petroleum sector where it is used extensively as a powerful viscosifier.

Furthermore, XG's ability to form strong, cohesive matrices with cement hydrates enhances the mechanical strength of the repair material, while its pseudoplastic behavior ensures that the material remains workable during application but becomes highly viscous once applied, reducing the risk of flow and washout.

2.3 TA powder

TA acts as a retarder in CXT by interfering with the early hydration reactions. Careful dosage is essential to prevent strength reduction and potential interactions with other admixtures. This study incorporates TA powder (0.2–0.6% by weight of cement) to explore its potential synergistic interactions with biopolymers. This dosage range was selected to investigate the potential effects of CXT while minimizing risks to the repair material's ultimate strength and durability.

2.4 Superplasticizer

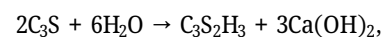
In this study, sulfonated melamine formaldehyde (SMF) served as a superplasticizer, effectively dispersing cement particles to enhance the workability and flow characteristics of sealant mixes. By reducing the water content while improving the fluidity, it contributes to the enhanced strength and durability of CXT.

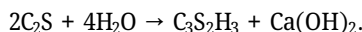
2.5 Water

A constant w/c ratio of 0.5 was initially maintained for all mixes to provide a consistent starting point for evaluating the effects of biopolymer and TA.

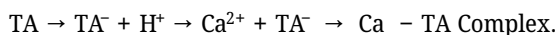
3 Strengthened properties of biopolymer-modified CXT

The chemical and ionic interactions within this biopolymer-modified CXT influence the key properties, such as the setting time and flowability. Cement hydration plays a fundamental role, with tricalcium silicate (C₃S) and dicalcium silicate (C₂S) dissolving to release calcium ions (Ca²⁺) and silicate ions (SiO₄⁴⁻). These ions are crucial for forming calcium silicate hydrate (C₃S₂H₃, C–S–H), the primary strength-giving compound in hardened cement. The reactions are represented as follows:





TA powder, introduced as a retarder, can dissociate and potentially form complexes with Ca^{2+} , represented as follows:



This interaction likely interferes with the rapid precipitation of solid hydration products, resulting in extended setting times. Simultaneously, SMF acts as a superplasticizer. The negatively charged SMF polymers are electrostatically attracted to positively charged cement particles:

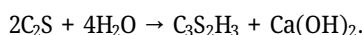
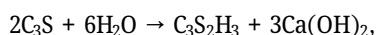
- Ca – TA Complex → Delayed Setting Time
- Better Particle Dispersion and Matrix Formation
- SMF[−] → Attracted to Cement Particles⁺
 - Steric Hindrance and Repulsion
 - Improved Dispersion and Workability.

Upon adsorption, SMF creates steric hindrance and repulsion between these particles, significantly improving the dispersion and sealant workability. Understanding these intertwined chemical and ionic mechanisms provides a foundation for optimizing this biopolymer sealant's formulation and tailoring its performance for specific crack-sealing applications.

3.1 Cement hydration (simplified)

In simplified cement hydration, C_3S and C_2S react with water to form $\text{C}_3\text{S}_2\text{H}_3$ and calcium hydroxide ($\text{Ca}(\text{OH})_2$).

The equations representing these reactions are the following:

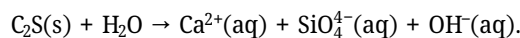
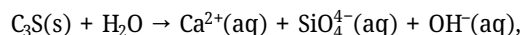


These reactions are crucial for the early stage of cement hydration, where C_3S and C_2S undergo dissolution and subsequent precipitation of hydration products. $\text{C}_3\text{S}_2\text{H}_3$ contributes to concrete strength and structure, while $\text{Ca}(\text{OH})_2$ provides pore solution alkalinity, aiding in corrosion protection and hydration of supplementary cementitious materials.

3.2 Dissolution of C_3S and C_2S

In biopolymer-modified CXT, the dissolution of C_3S and C_2S involves their reaction with water, resulting in the release of Ca^{2+} , SiO_4^{4-} , and hydroxide ions (OH^-) into solution. The

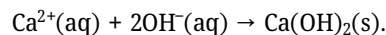
equations representing these dissolution reactions are the following:



These reactions are essential in the initial stages of cement hydration, where water penetrates the cementitious matrix, interacts with C_3S and C_2S particles, and triggers their dissolution. The released ions contribute to the formation of pore solution alkalinity and provide the necessary constituents for subsequent hydration reactions, ultimately leading to the development of hydrated cementitious phases and the setting and hardening of the repair material.

3.3 Formation of $\text{Ca}(\text{OH})_2$

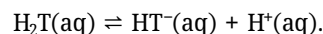
In the formation of $\text{Ca}(\text{OH})_2$, Ca^{2+} in aqueous solution react with OH^- to produce solid $\text{Ca}(\text{OH})_2$. The chemical equation representing this reaction is:



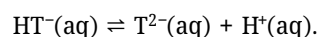
This reaction plays a crucial role in cement hydration, as $\text{Ca}(\text{OH})_2$ is a key hydration product. It contributes to the strength and durability of CXT.

3.4 TA dissociation

TA, represented as H_2T , undergoes dissociation in aqueous solution in two stages. Initially, it dissociates into a hydrogen tartrate ion (HT^-) and a hydrogen ion (H^+), as shown in the equation:



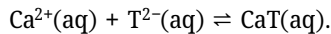
Subsequently, the HT^- further dissociates to yield a tartrate ion (T^{2-}) and another H^+ :



These dissociation reactions are essential in controlling the pH of solutions containing TA and play a crucial role in various chemical and industrial processes, including food production and pharmaceuticals.

3.5 Calcium–tartrate complex formation

In the formation of a calcium–tartrate complex (CaT), Ca^{2+} in an aqueous solution react with T^{2-} to produce a soluble CaT . The chemical equation representing this equilibrium reaction is as follows:



This reaction occurs in solution and involves the binding of Ca^{2+} with T^{2-} to form the complex.

4 Experimental part

To evaluate the initial properties, workability, flowability, and setting time, of a CXT developed for crack repairing applications, preliminary assessments were conducted using slump cone, Marsh cone, and Vicat needle tests. CXT formulations consisted of cement (C), XG, TA, superplasticizer, and water in varying trial mix ratios. The notations “XG” and “TA” will be used throughout, with the number following TA indicating the percentage of TA powder by weight of the total cement.

4.1 Optimization process of CXT

To optimize the formulation of the biopolymer-modified CXT, it is crucial to meticulously adjust the proportions of XG and TA. The concentration of XG was fine-tuned to achieve an optimal balance between workability and strength, as higher concentrations enhanced the viscosity but may impede the flowability. Similarly, the TA dosage was calibrated within a range of 0.2–0.6% by weight of cement to effectively control the setting time without compromising

the overall strength. Maintaining a consistent water–cement ratio of approximately 0.5 is essential, and incorporating a superplasticizer, such as SMF, significantly improves the flowability while reducing the water content.

Comprehensive workability tests, including slump cone and Marsh cone tests, were conducted to assess flow characteristics, while Vicat needle tests were performed to determine the initial and final setting times. Mechanical properties were evaluated through compressive and flexural strength tests at 7, 14, and 28 days to ensure long-term durability. Based on these test results, the proportions were iteratively adjusted to minimize the shrinkage and enhance the performance. The optimized formulation was validated through real-world crack repair applications and monitored for long-term performance to ensure its sustainability and robustness.

4.2 Slump cone test

The slump cone test, a widely recognized method for evaluating the workability of fresh concrete, was employed to investigate the effects of varying the XG to cement (XG:C) ratios and TA concentrations on the flow behavior of CXT. The slump values for the different trial mixes of CXT are shown in Figure 2. This test involved filling a metal cone, with a bottom diameter of 20 cm, a top diameter of 10 cm, and a height of 30 cm, with a fresh sealant in three layers.

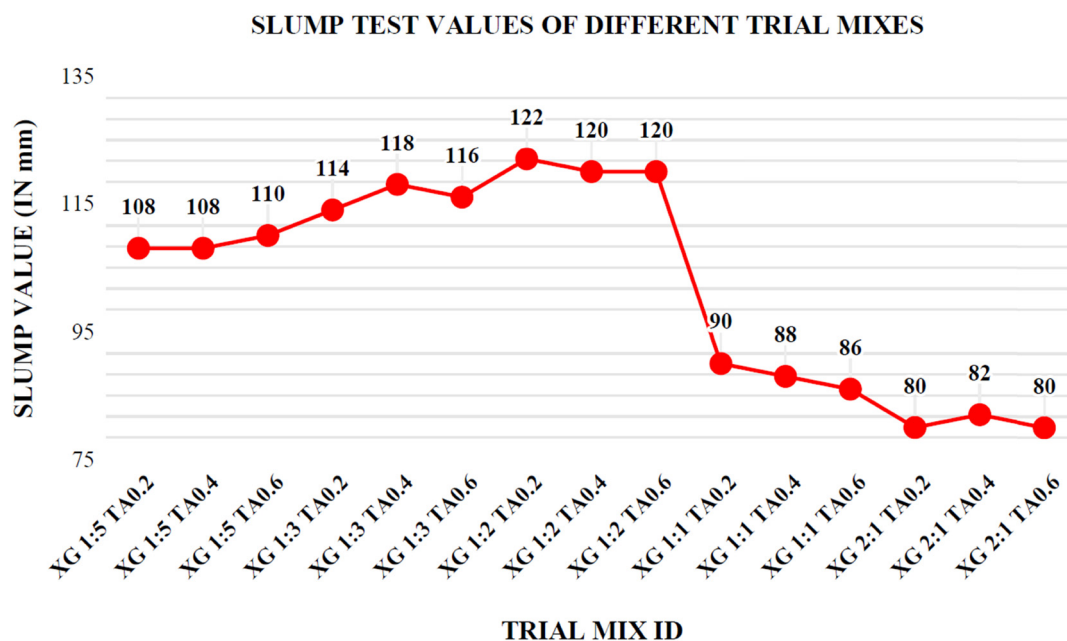


Figure 2: Graph representing the slump value for each trail.

Each layer was tamped 25 times, slightly deviating from the standard practice to ensure thorough compaction. After filling, the cone was carefully lifted vertically, allowing the sealant to slump. The vertical displacement of the sealant, known as the slump, was measured to assess its workability. This process was systematically repeated for each trial mix ratio to accurately determine their respective workability characteristics. By comparing the slump values, the influence of different XG:C ratios and TA concentrations on the flow behavior and workability of the CXT mixtures was comprehensively analyzed.

The results demonstrated a significant positive correlation between the XG:C ratio and the slump value. The 1:2 XG:C ratio consistently exhibited the highest slump values, indicating superior flowability compared to other ratios tested. This enhanced flow can be attributed to the thickening and viscosity-modifying properties of XG. Additionally, the inclusion of moderate amounts of TA (e.g., TA0.4–0.4% weight of cement) exhibited a synergistic effect, further increasing slump values. This is likely due to TA's retarding action, which delays cement hydration and extends the sealant's workable time.

While the 1:2 XG:C ratio with moderate TA addition demonstrated significant potential for crack-sealing applications, a comprehensive assessment necessitated further investigations which was performed next to slump tests. Supplementary tests to evaluate the setting time and mechanical strength are essential to ensure that the enhanced workability does not compromise the long-term repair performance. The slump value for each trail is tabulated in Table 1.

4.2.1 Enhanced flow properties

The enhanced flow of CXT can be attributed to the thickening and viscosity-modifying properties of XG. XG, a polysaccharide, is known for its ability to significantly increase the viscosity of aqueous solutions, even at low concentrations. This property is due to its complex molecular structure,

which consists of a cellulose backbone with side chains of mannose and glucuronic acid.

When XG was added to the CXT mixture, it increased the viscosity of the water phase, resulting in a more stable and homogenous mixture. This increased viscosity improved the dispersion of cement particles, reducing the likelihood of segregation and bleeding. Additionally, the pseudoplastic (shear-thinning) nature of XG allowed the mixture to flow more easily under shear stress during mixing and application while maintaining its shape and stability when at rest.

By modifying the viscosity and flow properties of the mixture, XG enhanced the workability of the CXT, making it easier to apply and ensuring better penetration into cracks and voids. This results in a more effective and durable repair material.

4.3 Marsh cone test

The Marsh cone is a standardized tool used to measure the flowability of repair material and similar cementitious mixes. It involves filling a metal cone with CXT and measuring the time it takes for a specific volume to flow out as shown in Figure 3.

Faster Marsh cone times indicated greater flowability. This simple test provides valuable insights into CXT's workability, making it relevant for applications like crack sealing where easy flow is essential. The Marsh cone values for different trail mixes of this biopolymer-modified CXT are shown in Figure 4, and the value for each trail is tabulated in Table 2.

The Marsh cone test results reveal a complex interplay between the XG concentration, TA inclusion, and CXT's flowability. XG emerges as the dominant factor driving flow enhancement, with increasing XG:C ratios consistently yielding lower Marsh cone values (indicating faster flow times). This can be attributed to XG's ability to thicken

Table 1: Slump value for each trail

Trial mix ID	Slump value (mm)	Trial mix ID	Slump value (mm)
CM (Control mix)	95	XG 1:2 TA0.4	130
XG 1:5 TA0.2	108	XG 1:2 TA0.6	132
XG 1:5 TA0.4	108	XG 1:1 TA0.2	90
XG 1:5 TA0.6	110	XG 1:1 TA0.4	88
XG 1:3 TA0.2	114	XG 1:1 TA0.6	86
XG 1:3 TA0.4	116	XG 2:1 TA0.2	80
XG 1:3 TA0.6	118	XG 2:1 TA0.4	82
XG 1:2 TA0.2	129	XG 2:1 TA0.6	80



Figure 3: Images representing the Marsh cone test.

the sealant, modifying its viscosity and promoting better flow behavior.

TA demonstrates a synergistic, yet more subtle effect. Within a selected XG:C trail ratio, increasing TA concentrations tend to result in slightly improved flowability. This aligns with TA’s known ability to retard cement hydration, extending the workable time of the repair material CXT and contributing to its flow characteristics. However, there is a crucial caveat: excessive XG concentrations, as demonstrated by the 2:1 ratio, appear to negate these flowability benefits. This highlights the need for a balanced formulation, as overly

high XG levels can increase the overall CXT viscosity to the point where the flow is hindered, even with TA present. For crack sealing applications, the 1:2 XG:C ratio, particularly with moderate TA levels, holds significant promise due to their demonstrated superior flow.

4.4 Setting time of CXT

The Vicat needle test (ASTM C191) is a standardized method for evaluating the setting time of cementitious materials. In

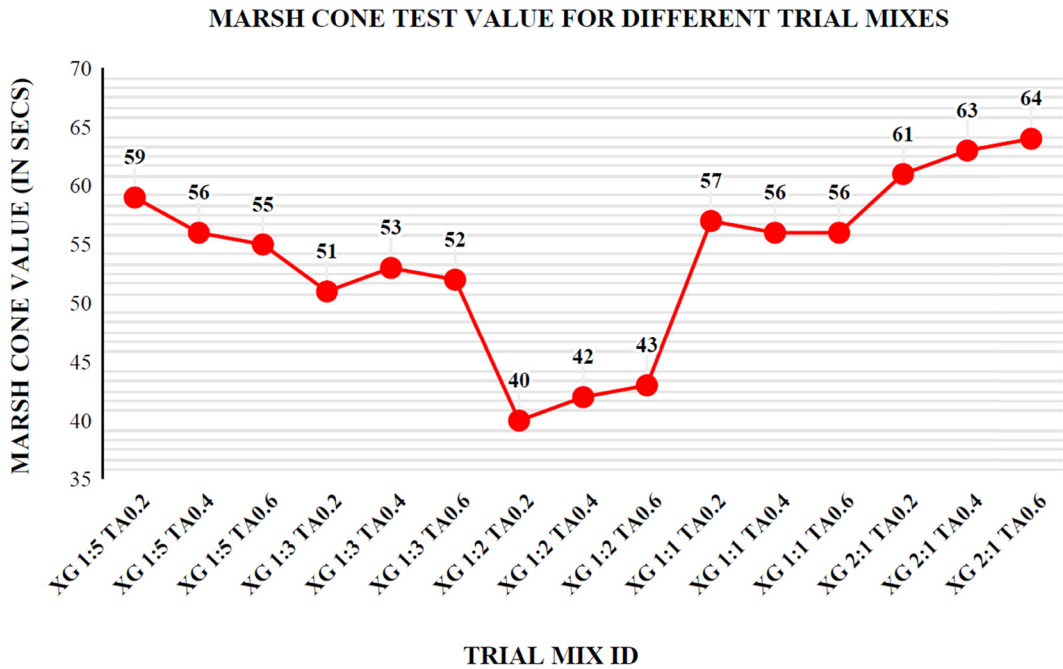


Figure 4: Marsh cone test values for each trail.

Table 2: Marsh cone values for each trail

Trial mix ID	Marsh cone value (s)	Trial mix ID	Marsh cone value (s)
CM (Control mix)	60	XG 1:2 TA0.4	42
XG 1:5 TA0.2	59	XG 1:2 TA0.6	43
XG 1:5 TA0.4	56	XG 1:1 TA0.2	57
XG 1:5 TA0.6	55	XG 1:1 TA0.4	56
XG 1:3 TA0.2	51	XG 1:1 TA0.6	56
XG 1:3 TA0.4	53	XG 2:1 TA0.2	61
XG 1:3 TA0.6	52	XG 2:1 TA0.4	63
XG 1:2 TA0.2	40	XG 2:1 TA0.6	64

this study, the Vicat needle test was performed with a load of 300 g to determine the initial setting time of the optimum mix ratio XG 1:2 by varying the TA powder concentration between 0.2 and 0.6% by weight of the cement biopolymer formulation. This test measures the penetration resistance of a standardized needle into the fresh sealant, providing insights into both initial and final setting times.

The initial setting time of the biopolymer-modified CXT was observed to be within the range of 21–23 min. Specifically, the initial setting time for the mix with 0.2% TA was 21 min, for 0.4% TA it was 22 min, and for 0.6% TA it was 23 min. This range indicates that the material remains workable for a sufficient period, allowing for adequate application and adjustments during the repair process.

The final setting time of the repair material CXT was observed between 24 and 27 h. The mix with 0.2% TA had a final setting time of 24 h, the mix with 0.4% TA had a final setting time of 26 h, and the mix with 0.6% TA had a final setting time of 27 h. This extended setting period ensures that the material undergoes a gradual hardening process, reducing the risk of cracking and ensuring a more durable

repair. The setting time values for different trail mixes of this biopolymer-modified CXT are shown in Figure 5, and the results are summarized in Table 3.

These findings indicate that the optimal mix (XG 1:2 with TA0.2/0.4/0.6) provides a balanced performance in terms of workability and setting times. The initial setting times ensure that the material can be easily applied and adjusted, while the final setting times allow for a thorough and gradual hardening process. This balance is essential for the durability of the repair, making the biopolymer-modified CXT with the optimal formulation of XG 1:2 and TA0.2–0.6 a promising solution for effective and durable crack repair in concrete structures.

Table 3: Results of setting time

Trial mix ID	Initial setting time (min)	Final setting time (h)
XG 1:2 TA0.2	21	24
XG 1:2 TA0.4	22	26
XG 1:2 TA0.6	23	27

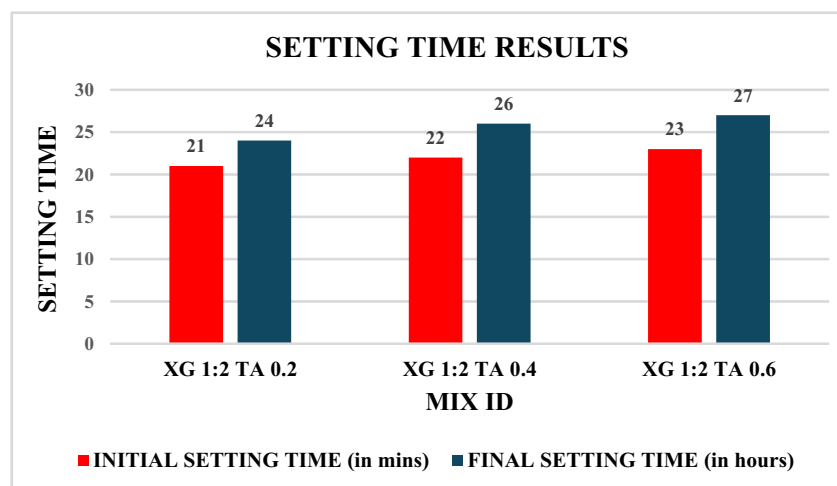
**Figure 5:** Setting time values for different trial mixes.

Table 4: Details of quantities of material corresponding to the optimum mix ratio

Mix ID	Cement (g)	Biopolymer (g)	Biopolymer:Cement ratio	TA (g)	Superplasticizer (mL)
XG 1:2 TA0.2	87.5	43.75	1:2	17.5	0.125
XG 1:2 TA0.4	87.5	43.75	1:2	35	0.125
XG 1:2 TA0.6	87.5	43.75	1:2	52.5	0.125

4.5 Casting of CXT cubes

CXT cubes (5 cm × 5 cm × 5 cm) were prepared using a mix ratio (outlined in Table 4) of XG:C (1:2), as this ratio was identified as optimal in previous experiments. To ensure accuracy, precise quantities of cement, biopolymer (XG), TA, and superplasticizer were calculated to yield the required CXT volume for each cube. The dry components (cement, XG, and TA) were meticulously mixed in a clean container for approximately 2 min to ensure complete homogenization. This mixing was performed using a low-speed mechanical mixer to facilitate consistency.

A stepwise addition of water and superplasticizer followed during the mixing process. Initially, roughly 70% of water was added, along with continuous mixing. The superplasticizer was then incorporated, and mixing was continued. The remaining water was gradually added, with

adjustments made as necessary to achieve a homogenous mixture with the desired workability. This mixing process typically lasted for 3–5 min, ensuring complete hydration of the cement, a uniform distribution of the biopolymer, and activation of the superplasticizer. This homogenous mixture was placed into cube molds as shown in Figure 6. After molding, the cubes were wrapped with a polythene sheet to prevent moisture loss and ensure proper curing, which is essential for achieving the desired mechanical properties.

4.6 Compressive strength

The compressive strength of CXT was assessed using standard cubes 5 cm × 5 cm × 5 cm, in accordance with the established procedure outlined in IS 4031 Part 7, and the results are tabulated in Table 5.

**Figure 6:** Preparation of CXT cubes.**Table 5:** Compressive strength values for 7, 14, and 28 days

Mix ratio	7 days (N·mm ⁻²)				14 days (N·mm ⁻²)				28 days (N·mm ⁻²)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
XG 1:2 TA0.2	11	11.8	11.4	11.4	18.4	18.9	17.2	18.2	22.6	22.2	22.2	22.3
XG 1:2 TA0.4	11.2	12.5	10.9	11.5	17.4	16.9	18.3	17.5	23.2	23.6	24	23.6
XG 1:2 TA0.6	12.6	12.5	12	12.4	18.8	19	17.2	18.3	25	24.8	24.6	24.8

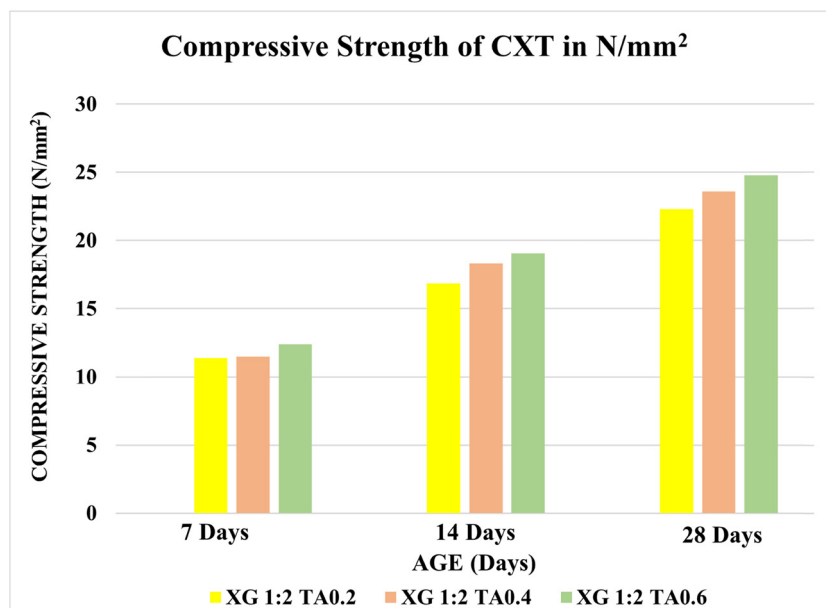


Figure 7: Compressive strength values for 7, 14, and 28 days.

The compressive strength analysis as shown in Figure 7 revealed a significant increase in strength for all CXT mixes over the 28-day curing period. The most rapid strength development occurred between 7 and 14 days, followed by a slower rate of gain from 14 to 28 days. This strength evolution pattern aligns with typical repair material behavior. Notably, mixes incorporating higher TA concentrations (XG 1:2 TA0.6) exhibited slightly greater increases in strength throughout the curing period.

Compressive strength analysis revealed a rapid strength development profile for the CXT formulation. Approximately 50% of its final compressive strength was achieved within the first 7 days. This accelerated early strength gain highlights the formulation's potential for applications requiring swift material setting. The majority of strength development occurred within the initial 14 days, with the repair material attaining over 77% of its final strength. A slight increase in strength was observed between 14 and 28 days, reaching its final strength; however, the rate of gain decreased progressively throughout this period.

The accelerated early strength gain of the biopolymer-modified CXT is a critical attribute for applications requiring rapid material setting and early load-bearing capacity. The primary mechanism underlying this accelerated early strength gain involves the modification of the hydration process by the biopolymer additives. XG and TA work synergistically to enhance the dispersion of cement particles, improve the hydration efficiency, and control the setting time. XG's high viscosity and pseudoplastic properties ensure a uniform distribution of cement particles, promoting more effective hydration. TA acts as a retarder, allowing sufficient time

for thorough mixing and application before the material begins to set.

As a result, the initial hydration reactions, particularly those involving C_3S , proceed more efficiently, leading to the rapid formation of C–S–H, which is the primary strength-giving compound in cementitious materials. This accelerated formation of C–S–H contributed to the early strength development of the repair material. Overall, these results suggest that the incorporation of biopolymer and TA into cement mixtures can positively influence compressive strength development over time. The varying percentages of strength achieved at different curing periods offer valuable insights for optimizing mixture designs tailored to crack sealing project requirements and performance expectations.

4.7 Flexural strength of CXT

The determination of the flexural strength of CXT followed the protocol outlined in the Indian standard IS:516. This involved studying the flexural strength using beam specimens measuring 40 mm × 40 mm × 160 mm, with an effective span of 120 mm, subjected to three-point loading. The beams were supported by two roller supports, each with a diameter of 10 mm, spaced 120 mm apart. The specimens were positioned on the roller supports on their bottom faces, with the third point loading applied symmetrically on the opposite and top faces using a third roller.

The two support rollers were set up in a simply supportive manner, facilitating unrestricted rotation of the

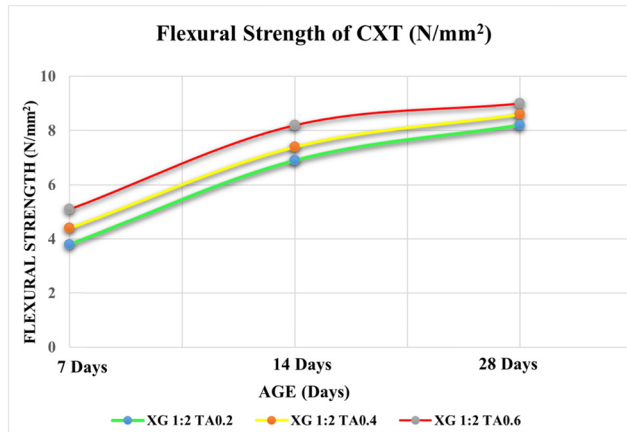


Figure 8: Flexural strength values for 7, 14, and 28 days.

beam around their line of contact to evenly distribute the line load across the width of the beam as a point load. The flexural tensile strength of the cement grout was determined as the average of three beam tests conducted at intervals of 3, 7, and 28 days. The variations in flexural tensile strength of the cement grout at different ages are depicted in Figure 8, and the results are tabulated in Table 6.

Flexural strength analysis demonstrated a rapid strength development profile for the CXT formulation. Within the first 7 days, the material achieved approximately 51% of its ultimate flexural strength. This accelerated early strength development signifies the potential applicability of the CXT formulation for scenarios demanding swift material setting. The majority of strength development transpired within the initial 14 days, with the repair material reaching over 87% of its final strength. Between 14 and 28 days, a slight increase in strength was observed, culminating in the achievement of material's final flexural strength. However, the rate of strength gain exhibited a progressive decline throughout this period. Overall, these findings indicate that biopolymer-modified CXT can have a beneficial impact on the development of flexural strength over time.

5 Limitations

While this study provides valuable insights into the performance of biopolymer-modified CXT, there are a few limitations that should be considered:

1. **Controlled laboratory conditions:** The experiments were performed under controlled laboratory conditions. Variations in environmental factors such as temperature and humidity were not considered. Future studies should investigate the performance of CXT in different environmental conditions to ensure its applicability in real-world scenarios.
2. **Long-term durability:** The long-term durability and performance of the biopolymer-modified CXT were not evaluated. Long-term studies are necessary to understand the material's behavior over extended periods, including its resistance to wear and weathering.

6 Results and discussion

This section presents the findings from various tests conducted on biopolymer-modified CXT, focusing on the workability, setting time, mechanical properties, shrinkage, and environmental impact.

6.1 Workability and flowability

- a. **Slump cone test:** The slump cone test results (Table 1) demonstrated that the optimal XG ratio was 1:2, with the addition of 0.6% TA, yielding the highest slump values (132 mm). This indicates superior flowability, attributable to the thickening and viscosity-modifying properties of XG. Similar enhancements in flow properties due to biopolymer modifications have been reported, showing significant improvements in the rheological properties of cementitious materials [21].

Table 6: Flexural strength values for 7, 14, and 28 days

Mix ratio	7 days (N-mm ⁻²)				14 days (N-mm ⁻²)				28 days (N-mm ⁻²)			
	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average	Trial 1	Trial 2	Trial 3	Average
XG 1:2 TA0.2	3.6	3.8	4	3.8	6.8	6.9	7.1	6.9	8.5	7.9	8.2	8.2
XG 1:2 TA0.4	4.4	4.2	4.6	4.4	7.5	7.4	7.4	7.4	8.9	8.4	8.4	8.6
XG 1:2 TA0.6	5.2	5	5.1	5.1	8.2	8.4	8	8.2	8.8	8.8	9.4	9.0

- b. Marsh cone test: Marsh cone test results (Table 2) corroborated with the slump test findings, with the 1:2 XG ratio and 0.6% TA showing the lowest flow times, indicating improved flowability. This aligns with findings that biopolymers enhance the flow characteristics of cementitious mixtures by reducing the water content and improving the particle dispersion [22].

6.2 Setting time

The Vicat needle test results indicated that the optimal formulation (XG 1:2 TA0.6) maintained an initial setting time within 21–24 min and a final setting time of 24–28 h. This delayed setting time provided sufficient workability without compromising early strength gain, consistent with studies showing that TA effectively extends the setting time of cementitious materials [23].

6.3 Mechanical properties

- a. Compressive strength: The compressive strength results (Table 5) showed a significant increase over the 28-day curing period, with the highest strength recorded for the XG 1:2 TA0.6 mix ($24.8 \text{ N}\cdot\text{mm}^{-2}$). The rapid early strength gain (77% of final strength within 14 days) observed in this study was supported by research indicating that the inclusion of biopolymers enhanced early-age strength by improving the hydration kinetics and matrix formation [24].
- b. Flexural strength: Flexural strength tests (Table 6) indicated that the XG 1:2 TA0.6 mix achieved a maximum strength of $9.4 \text{ N}\cdot\text{mm}^{-2}$ at 28 days. This result corroborates with findings that biopolymers improved the flexural performance by forming stronger cohesive matrices within the cement matrix [25].

7 Conclusions and implications

This study investigated the influence of varying dosages of biopolymer (XG) and TA on the performance characteristics of biopolymer-modified CXT. The optimal formulation, identified as XG 1:2 with 0.6% TA, demonstrated superior performance metrics, achieving a maximum compressive strength of $25 \text{ N}\cdot\text{mm}^{-2}$ and a flexural strength of $9.4 \text{ N}\cdot\text{mm}^{-2}$, along with minimal shrinkage.

The incorporation of XG significantly enhanced the workability of the CXT by increasing its viscosity and improving the dispersion of cement particles. This resulted in a more stable and homogenous mixture that is easier to apply and better at penetrating cracks. The pseudoplastic nature of XG allowed the mixture to flow under shear stress during application while maintaining its shape and stability when at rest. The formulation exhibited rapid early strength gain, achieving approximately 51% of its ultimate flexural strength within the first 7 days and over 77% of its final compressive strength within 14 days. This accelerated strength development is crucial for applications requiring swift setting and early load-bearing capacity.

Minimal shrinkage in the optimal formulation reduces the risk of crack formation and ensures the longevity of repairs, preventing the propagation of new cracks and maintaining the structural integrity. Additionally, the use of biopolymers in CXTs offers significant environmental benefits. Biopolymers, derived from renewable sources, lower the overall carbon footprint associated with cement production and contribute to more sustainable construction practices. Overall, the findings of this study suggest that the biopolymer-modified CXT, with the optimal formulation of XG 1:2 and TA 0.6, offers a promising solution for effective and durable crack repair in concrete structures, combining desirable mechanical properties with environmental sustainability.

8 Future scope

Building upon these results, future research could involve the following:

- Investigating the long-term durability of the XG 1:2 TA0.6 formulation under various environmental conditions relevant to field applications.
- Evaluating the performance of this optimized sealant formulation in real-world crack sealing scenarios.
- Exploring the potential for further enhancing the properties of biopolymer sealants through the incorporation of additional admixtures or alternative biopolymers.
- Conducting a lifecycle assessment of the biopolymer sealant compared to conventional sealants to quantify its environmental impact across production, application, and service life.

Acknowledgements: The authors would like to express their heartfelt gratitude to professors and parents for their unwavering support and encouragement throughout this research.

Funding information: The authors received no financial support for the research, authorship, and publication of this article.

Author contributions: Sankaranarayanan Asvitha Valli – responsible for the conceptualization of the study, conducting the investigation, and writing the original draft of the manuscript; Muthuswamy Saraswathi Ravi Kumar – provided supervision throughout the study, performed the formal analysis, and contributed to the review and editing of the manuscript.

Conflict of interest: The authors state no conflict of interest.

Data availability statement: Data will be made available on request.

References

- [1] Grzegorz, L. and L. Golewski. The phenomenon of cracking in cement concretes and reinforced concrete structures: The mechanism of cracks formation, causes of their initiation, types and places of occurrence, and methods of detection – a review. *Buildings*, Vol. 13, 2023, pp. 7–10.
- [2] Payab, M., R. Abbasina, and M. Khanzadi. A brief review and a new graph-based image analysis for concrete crack quantification. *Archives of Computational Methods in Engineering*, Vol. 26, 2019, pp. 347–365.
- [3] Pise, N., T. Meshram, Y. Doijad, R. Gathe, A. Bobade, A. Kutemate, et al. A brief study on causes of cracks, prevention and pattern of cracks on concrete. *International Journal of Scientific Research in Science, Engineering and Technology*, Vol. 8, No. 3, 2021, pp. 439–443.
- [4] Shokri, P., M. Shahbazi, D. Lichti, and J. Nielsen. Vision-based approaches for quantifying cracks in concrete structures. *ISPRS – International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 43, 2020, pp. 431167–1174.
- [5] Dung, T. M. and T. Q. Lam. Cracks in single-layer and multi-layer concrete beams. *Transportation Research Procedia*, Vol. 62, 2022, pp. 1–4.
- [6] Fan, L., J. Zheng, S. Peng, Z. Xun, and G. Chen. Experimental investigation on the influence of crack width of asphalt concrete on the repair effect of microbially induced calcite precipitation. *Materials*, Vol. 16, 2023, pp. 1–19.
- [7] Feng, F. Crack repair model of ancient ceramics based on digital image. *Scientific Programming*, Vol. 2022, 2022, id. 3.
- [8] Fan, W., J. Mao, W. Jin, J. Zhang, Q. Li, and F. Yuan. Repair effect of cracked reinforced concrete based on electrochemical rehabilitation technology. *Journal of Building Engineering*, Vol. 57, 2022, pp. 6–10.
- [9] ElKhatib, L. W., A. Elkordi, and J. Khatib. Methods and surface materials repair for concrete structures – a review. *BAU Journal – Science and Technology*, Vol. 4, No. 2, 2023, id. 7.
- [10] Hu, K., H. Rong, Y. Shi, G. Ma, and X. Zheng. Effect of microbial repair materials based on sodium alginate modification on mortar crack repair. *Magazine of Concrete Research*, Vol. 74, No. 22, 2022, pp. 4–12.
- [11] Kim, T. K. and J. S. Park. Performance evaluation of concrete structures using crack repair methods. *Sustainability*, Vol. 13, No. 6, 2021, pp. 4–7.
- [12] Bano, S., G. Jaiswal, R. Kumar, A. Tiwari, and M. Karthikeyan. Experimental study on the crack repair techniques of concrete structures: A case study. *IOP Conference Series: Materials Science and Engineering*, Vol. 1273, 2023, pp. 2–11.
- [13] De Belie, N., E. Gruyaert, A. Al-Tabbaa, P. Antonaci, C. Baera, D. Bajare, et al. A review of self-healing concrete for damage management of structures. *Advanced Materials Interfaces*, Vol. 5, No. 17, 2018, pp. 4–28.
- [14] Badr, A. Using standard repair methods on recycled aggregate concrete. *Magazine of Concrete Research*, Vol. 68, No. 1, 2016, pp. 6–40.
- [15] Huang, W. The research progress on cracks repair technology of concrete structure. *New Building Materials*, Vol. 41, No. 4, 2014, pp. 80–83.
- [16] Alaneme, G. U., K. A. Olonade, and E. Esenogho. Eco-friendly agro-waste based geopolymer-concrete: a systematic review. *Discover Materials*, Vol. 2023, 2023, pp. 1–19.
- [17] De Grave, L., J. R. Tenório Filho, D. Snoeck, S. Vynnytska, N. De Belie, K. V. Bernaerts, et al. Poly (aspartic acid) superabsorbent polymers as biobased and biodegradable additives for self-sealing of cementitious mortar. *Journal of Sustainable Cement-Based Materials*, Vol. 11, No. 6, 2022, pp. 2–16.
- [18] Kannan, U., S. A. Gafoor, S. Srivastava, M. Nithyadharan, S. Sen Gupta, and S. M. Maliyekkal. A waste-derived nanocomposite sealant for repairing micro-cracks in concrete. *Journal of Building Engineering*, Vol. 48, 2022, pp. 1–3.
- [19] Khatami, H. and B. C. O'Kelly. Prevention of bleeding of particulate grouts using biopolymers. *Construction and Building Materials*, Vol. 192, 2018, pp. 202–209.
- [20] Tusnim, J., M. E. Hoque, and M. C. Biswas. Biopolymers in building materials. *Advanced processing, properties, and applications of starch and other bio-based polymers*, Elsevier, Amsterdam, Netherlands, 2020, pp. 185–195.
- [21] Ivanov, V. and V. Stabnikov. Basic concepts on biopolymers and biotechnological admixtures for eco-efficient construction materials. In *Biopolymers and biotech admixtures for eco-efficient construction materials*, Vol. 2016, 2016, pp. 2–21.
- [22] Jia, D. X. Q. Incorporation of hybrid biopolymer/silicate-based microcapsules in cementitious mixtures for potential uses in self-healing technology with renewable materials. *RILEM Bookseries*, Vol. 2023, 2023, pp. 853–864.
- [23] Bishnoi, P. and K. Scrivener. Role of retarders in cementitious systems. *Cement and Concrete Research*, Vol. 39, 2009, pp. 849–860.
- [24] Khan, R. I., M. I. Haque, W. Ashraf, S. P. Shah, and N. Saleh. Role of biopolymers in enhancing multiscale characteristics of carbonation-cured cementitious composites. *Cement & Concrete Composites*, Vol. 132, 2022, id. 2022.
- [25] Mignon, A., D. Snoeck, P. Dubruel, L. Balcaen, F. Vanhaecke, S. Van Vlierberghe, et al. Biopolymers for self-sealing and -healing of mortar. *Presented at the Magnel Laboratory for Concrete Research*, Ghent University, Belgium, 2015.