

Enhancing Mortar Mechanical Properties Using Bacterial Nanocellulose as an Additive: A Comparative Study of Electrolysis and Mechanical Production Methods

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ABSTRACT

This study aimed to assess the impact of Bacterial Nanocellulose (BNC) produced via electrolysis and mechanical methods on the mechanical properties of cement composites. The experimental research involved pulverizing cellulose using both mechanical and electrolysis methods. Flexural strength and compressive strength tests were conducted in accordance with the standards. The results showed that adding BNC at 0.05%, 0.1%, and 0.2% by weight of cement, regardless of the production method, reduced mortar flow by 1.21%-4.55% as the dosage increased. The nanocellulose's ability to retain water reduced the mortar's workability, decreasing specific gravity by 1.35%-5.35% compared to the control. Both production methods consistently increased the mortar's flexural strength as the additive dose increased. The highest flexural strength, 8.33 MPa, was achieved at 28 days with a 0.2% dosage of mechanical method nanocellulose, showing a 51.73% improvement over the control. Regarding compressive strength, the 0.05% dosage at 7 days increased it, whereas higher doses (0.1% and 0.2%) decreased it. However, at

28 days, the compressive strength improved linearly with increasing dosage, ranging from 3.76% to 15.75% higher than the control. Thus, BNC, particularly at a 0.2% dosage via the mechanical method, is a promising additive for enhancing mortar's mechanical properties. The novelty of this research lies in the direct comparison of BNC produced by electrolysis and mechanical methods as mortar additives, revealing distinct microstructural and mechanical outcomes that depend on the production method.

Keywords-bacterial nanocellulose; composite cement; mechanical properties

I. INTRODUCTION

Demand for building materials, particularly cement, rises due to rapid advances in the construction industry. Cement is the primary binding agent in concrete and mortar [1, 2]. According to Indonesian standards, several types of cement are widely used in construction, including white Portland cement, Portland Pozzolan Cement (PCC), mixed Portland cement, masonry cement, composite Portland cement, and Ordinary Portland Cement (OPC). The production of composite cement has seen various innovations, particularly through the incorporation of additives to improve material performance. Consequently, numerous studies have focused on enhancing cement quality by using additives and alternative materials as blended components in cement production [3, 17]. Nanotechnology, which involves manipulating materials at the molecular scale (below 100 nm), offers promising approaches for improving the performance of cementitious composites such as concrete and mortar [4, 6]. The inclusion of nanomaterials can refine the cement microstructure through pore-filling effects and accelerated hydration, leading to improved mechanical strength and durability [7-9]. Among the available nanomaterials, Bacterial Nanocellulose (BNC) has gained attention as a sustainable and high-performance additive, showing strong potential for the development of advanced composite cement materials [5]. BNC has a range of applications, including the manufacture of bioconcrete. In this study, BNC was derived from a sustainable source (fermented coconut water using *Acetobacter xylinum*) and utilized as an additive in mortar to enhance performance. To produce the nanocellulose additive for the composite cement, the bacterial cellulose (nata de coco) was crushed using two methods: mechanical and electrolysis. The purpose was to compare which method is more effective in producing cellulose in a form suitable for cement admixtures, given that the methods yield different particle characteristics. The electrolysis method breaks down the molecular structure of nata de coco into smaller fragments. In contrast, the mechanical method physically tears the nata de coco into longer fiber-like strands. The electrolysis process in the current study was performed by soaking nata de coco in an electrolyte solution (alum water, $KAl(SO_4)_2$) and applying a DC voltage of 12 V (0.2–0.4 A) using an aluminum plate electrode. Meanwhile, the mechanical method uses a standard laboratory blender to crush the nata de coco into a pulp. These distinct preparation routes result in finely dispersed nanofibrils in electrolysis-derived BNC, whereas mechanically pulverized BNC forms a web-like network of longer cellulose fibers. By employing and later comparing these two BNC preparation methods, this work examines how the production technique influences the microstructural and mechanical properties of BNC-modified mortar, a novelty not previously explored.

The efficacy of BNC in various forms and applications has been demonstrated. BNC can significantly improve mechanical properties when used as an additive [13-15], it can enhance the bond between natural fibers and cement [12], and even improve sulfate resistance [23]. These findings underscore the potential of BNC as a versatile and high-performance additive for cementitious composites. While the effectiveness of BNC in improving the mechanical properties of cement is well documented [10-12], as evidenced by increases in compressive and flexural strength, BNC is often treated as a generic material. A key variable that has been overlooked is the impact of the nanocellulose production technique on its final performance in a cement matrix. Existing research does not provide a direct comparison of different production methods, such as electrolysis and mechanical processing.

The core problem addressed in this research is the need for sustainable and effective additives to enhance the mechanical properties of cementitious materials. While nanomaterials like BNC show promise, the influence of their production method on mortar performance remains poorly understood. The novelty of the current research lies in its systematic comparison of BNC produced via electrolysis versus mechanical methods, aiming to correlate each production method with distinct microstructural outcomes and mechanical reinforcement mechanisms in mortar.

II. RESEARCH METHODOLOGY

This study employed an experimental research approach with a quantitative methodology. The primary data were obtained from laboratory experiments, while the secondary data were collected from scientific literature. The research was conducted at the Integrated Laboratory of Bioproducts (iLaB) of the Biomass and Bioproduct Research Center using OPC, standard sand, potable water, and BNC as primary materials. The BNC was produced via three steps: fermentation, electrolysis, and mechanical processing. First, a fermentation process using coconut water and *Acetobacter xylinum* (for 7–10 days) produced a gelatinous form of bacterial cellulose (traditionally known as nata de coco) [22].

Next, this raw bacterial cellulose was processed into nanocellulose using two methods. The electrolysis method utilizes an electrical voltage to break down the cellulose's structure into fine nanoscale fibrils. In contrast, the mechanical method involves cutting, pulverizing, bleaching, and washing the bacterial cellulose, and then drying it to obtain nano-cellulose powder with longer fiber strands. In the mix design, the BNC was added as an admixture (i.e., in addition to the cement, not replacing it) at dosages of 0.05%, 0.1%, and 0.2% by weight of cement. For clarity, each mixture is labeled according to BNC type and dosage: e.g., OPC E0.05 denotes OPC mortar with 0.05% electrolysis-produced BNC, and OPC M0.1 denotes

OPC mortar with 0.1% mechanically produced BNC. The mortar was prepared using a fixed proportion of cement, sand, and water (by weight) chosen to achieve a target flow consistency, following the recommendations in [18]. After thoroughly mixing the ingredients, the fresh mortar was tested for flow (workability) and then cast into molds. Specific gravity testing of the OPC cement was performed according to the Le Chatelier flask method [21], and the measured specific gravity was 3.15. Mortar specimens were cast in 4 cm × 4 cm × 4 cm cubes for compression tests and 4 cm × 4 cm × 16 cm prisms for flexural tests. All specimens were demolded after 24 h and cured under either sealed (plastic wrap) or immersion conditions, as required by the test program. The compressive strength test followed [19]: cube specimens were loaded to failure using a hydraulic compression testing machine (2000 kN capacity), and compressive strength values were calculated from the maximum load. The flexural strength test followed [20]: prism specimens were tested in three-point bending (using a standard flexural test apparatus with a 100 kN load cell) until fracture, and flexural strength was computed based on the span and fracture load. These tests were conducted at 7 and 28 days of curing for each mix, and the results were recorded for comparative analysis of the mortars with and without BNC.

A. Materials and Methods

The primary materials used included OPC, water, standard sand, and BNC. The specific gravity of the OPC was determined to be 3.15. The BNC was derived from nata de coco and processed using two distinct methods: electrolysis and mechanical disruption. The specimen notation used in this study is defined in Table I.

TABLE I. SPECIMEN NOTATION AND COMPOSITION

Specimen ID	BNC production method	BNC dosage (% by weight of cement)	Description
OPC K	-	-	Control specimen
OPC E0.05	Electrolysis	0.05	OPC with 0.05% electrolysis BNC
OPC E0.1	Electrolysis	0.1	OPC with 0.1% electrolysis BNC
OPC E0.2	Electrolysis	0.2	OPC with 0.2% electrolysis BNC
OPC M0.05	Mechanical	0.05	OPC with 0.05% mechanical BNC
OPC M0.1	Mechanical	0.1	OPC with 0.1% mechanical BNC
OPC M0.2	Mechanical	0.2	OPC with 0.2% mechanical BNC

B. Production of BNC

The BNC additive was produced using two different methods. In the electrolysis method, nata de coco was soaked in an electrolyte solution of alum water ($KAl(SO_4)_2$) and subjected to a 12-volt direct current from a DC power supply with a current range of 0.2 mA–0.4 mA using aluminum plates as electrodes. This electrochemical process breaks down the molecular structure of the cellulose into finer components. In contrast, the mechanical method involved physically pulverizing the nata de coco using a blender, producing a slurry composed of longer, fibrous cellulose strands. The electrolysis process was carried out using a 12 V DC power supply and a current of 0.2 A–0.4 A with aluminum electrodes in alum water ($KAl(SO_4)_2$). The mechanically produced BNC was blended and sieved to obtain fibers averaging 150 μ m–300 μ m in length. The nata de coco used as the raw material was sourced from certified local producers to ensure consistency and purity. In this study, the fermentation process was employed to obtain raw cellulose, with the two primary tested forms being electrolysis and mechanically produced BNC. The mixture labels are defined as follows: OPC K control, OPC E electrolysis-derived BNC, and OPC M mechanically derived BNC. Fermented (unprocessed) cellulose was not tested in this series.

C. Mortar Mix Proportion and Specimen Preparation

The mortar mix was designed in accordance with [18], using a weight ratio of 1:2.75:0.485 for cement, sand, and water, respectively. BNC was incorporated as an additive at dosages of 0.05%, 0.1%, and 0.2% by weight of cement. Two types of specimens were prepared: cube specimens measuring 4 cm × 4 cm × 4 cm for compressive strength testing and beam specimens measuring 4 cm × 4 cm × 16 cm for flexural strength testing. In total, 84 specimens were cast and cured until the designated testing ages of 7 and 28 days.

D. Testing Procedures and Instruments

The testing program was carried out in a structured sequence. Initially, the specific gravity of the cement was measured in accordance with [21] using the Le Chatelier method. Next, the fresh mortar properties were evaluated by assessing the flow of the freshly mixed mortar to determine its workability. Following these tests, the mechanical performance of the hardened mortar was examined. Compressive strength tests were performed at curing ages of 7 and 28 days using a Universal Testing Machine (UTM) in accordance with [19], with the maximum failure load recorded to calculate compressive strength. Flexural strength tests were conducted at curing ages of 7 and 28 days using a UTM equipped with a third-point loading configuration, in accordance with the procedure described in [20]. The flexural strength was calculated using the recorded failure load together with the specimen dimensions and support span. The results of these tests served as a basis for evaluating the mechanical performance of the BNC-modified mortar.

III. RESULTS AND DISCUSSION

A. Fresh Properties of Mortar

The mortar flow test results showed a reduction of 1.21% to 4.55% compared to the control mix, linearly correlating with the increase in BNC dosage, indicating an impact on workability. This reduction is attributed to the high-water retention capacity of the BNC fibers, which retain a portion of the mixing water, thereby reducing the fluidity of the fresh mixture. The mortar flow tests showed that incorporating BNC had a slight effect on workability. The reference OPC mortar (no BNC) exhibited a flow of 110% (flow table spread). In mixes with BNC, the flow decreased modestly: for example, with 0.2% BNC (electrolysis method), the flow was about 105%, and with 0.2% BNC (mechanical method), it was about 106%. This corresponds to a reduction in flow of roughly 4%–5% compared to the control. The decrease in flow is attributed to the BNC's ability to absorb water and form a gel-like network in the mix, which slightly reduces fluidity. However, all mixes still achieved an adequate flow for casting, indicating that workability remained within acceptable ranges. The addition of BNC slightly reduces mortar flow compared to the control. For example, at a 0.2% dosage, the flow decreased by approximately 4%–5%. This reduction is attributed to BNC's water-absorption capacity and gel-forming behavior. However, the reduction is not significant, and the mixtures maintained satisfactory workability for casting.

B. Mortar Specific Gravity

The results presented in Table II and Figure 1 indicate that the incorporation of BNC led to a slight reduction in the specific gravity of the mortar over time, irrespective of the BNC production method. This trend was observed in both the BNC-modified mixtures and the OPC K control mixture. As the BNC dosage increased from 0.05% to 0.2%, the mortar's specific gravity decreased by approximately 1.35%–5.35%. This reduction can be attributed to the low density and high water-retention capacity of nanocellulose fibers, which absorb and retain mixing water within their porous structure, thereby introducing additional microvoids into the matrix. As a result, the overall density of the hardened mortar is slightly reduced. The most pronounced decrease was observed in the mechanically produced BNC mixture at 0.2% dosage (OPC M0.2), which exhibited a specific gravity of 2097.66 kg/m³. This suggests that mechanically produced BNC, characterized by longer and more fibrous structures, tends to trap more water and air during mixing compared to the finer, more fragmented BNC produced by the electrolysis method.

Table II and Figure 1 illustrate that the incorporation of BNC resulted in a slight reduction in the hardened mortar's bulk density (specific gravity) for all mixtures. The control mixture (OPC K) exhibited an average dry density of 2216 kg/m³, whereas all BNC-modified mortars showed lower densities. As the BNC dosage increased from 0.05% to 0.2%, the specific gravity decreased by approximately 1.35%–5.35% relative to the control, regardless of the BNC production method. This behavior is primarily attributed to the inherently low density and high water-retention capacity of nanocellulose fibers, whose porous network introduces additional microvoids within the hardened matrix, resulting in a slightly lighter

mortar. The greatest reduction in density was observed for the mechanically produced BNC at a dosage of 0.2% (OPC M0.2), with a measured density of approximately 2098 kg/m³. This pronounced decrease is likely due to the longer, fibrous morphology of mechanically derived BNC, which tends to trap more water and air during mixing compared to the finer, more fragmented electrolysis-derived BNC. Although a lower specific gravity is often associated with reduced material strength, the results of this study indicate otherwise. Despite the slight increase in porosity, the BNC-modified mortars did not exhibit diminished mechanical performance. Instead, the water retained within the BNC pores contributed to internal curing, which helped sustain hydration and offset potential strength losses.

TABLE II. MORTAR SPECIFIC GRAVITY

Mix Id	Average specific gravity (kg/m ³)	Deviation
OPC K	2216.15	12.22
OPC E0.05	2173.18	11.59
OPC E0.1	2167.97	5.00
OPC E0.2	2160.16	34.77
OPC M0.05	2186.20	2.08
OPC M0.1	2144.53	3.61
OPC M0.2	2097.66	2.65

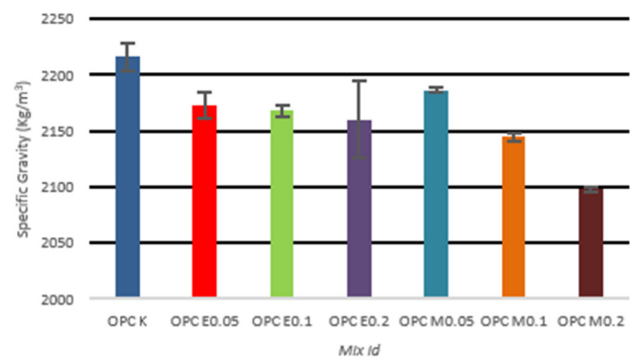


Fig. 1. Mortar specific gravity.

A lower specific gravity equals a weaker matrix. Still, in this study, the lower density was associated with higher flexural and compressive strengths at 28 days, rather than inferior mechanical performance. The BNC retains moisture, keeping unreacted cement particles wet over time. This means that the porosity contributed by BNC is not a negative thing; in fact, it may improve the microstructure by curing from the inside.

C. Flexural Strength of Mortar

The flexural strength results showed minimal improvement at 7 days but significant enhancement at 28 days. This is likely due to the delayed action of BNC as an internal curing agent. It retains water. It gradually releases it, improving hydration over time rather than at an early age. Consequently, the microstructure at 28 days is denser, and the fiber matrix interface is stronger, resulting in greater flexural strength. Similar trends have been reported in previous nanocellulose studies, supporting this interpretation. Both BNC produced by electrolysis and mechanical methods increased the flexural strength of mortar in a dose-dependent manner, as evidenced in

Table III and Figures 2-4. The mechanical method yielded the most significant improvement. Specifically, in the 28-day test, the mortar with a 0.2% addition of mechanically produced BNC exhibited the highest flexural strength of 8.33 MPa (Table III), representing a 51.73% increase over the control. This significant enhancement is likely attributable to the more fibrous, long-strand morphology of the mechanically produced BNC, which is more effective at bridging micro-cracks than the finer, more fragmented fibrils from the electrolysis method.

TABLE III. FLEXURAL STRENGTH OF MORTAR DAY 7

Mix Id	Flexural strength of mortar day 7			Standard deviation
	Mass	Flexural strength		
	g	MPa	Average	
OPC K	548	5.48	5.49	0.02
	542	5.48		
	516	5.51		
OPC E0.05	516	5.51	5.57	0.12
	570	5.48		
	576	5.7		
OPC E0.1	550	5.94	5.73	0.19
	552	5.67		
	510	5.58		
OPC E0.2	548	5.79	5.77	0.04
	542	5.73		
	516	5.79		
OPC M0.05	580	5.48	5.51	0.03
	570	5.55		
	552	5.51		
OPC M0.1	571	5.64	5.67	0.11
	555	5.58		
	540	5.79		
OPC M0.2	530	5.82	5.72	0.20
	554	5.48		
	562	5.85		

TABLE IV. FLEXURAL STRENGTH OF MORTAR DAY 28

Mix Id	Flexural strength of mortar day 28			Standard deviation
	Mass	Flexural strength		
	(g)	MPa	Average	
OPC K	554	6.4	6.45	0.09
	578	6.4		
	570	6.55		
OPC E0.05	544	7.98	7.42	0.68
	567	7.62		
	558	6.67		
OPC E0.1	555	7.98	7.56	0.59
	550	6.89		
	560	7.80		
OPC E0.2	513	7.56	7.60	0.05
	570	7.65		
	576	7.59		
OPC M0.05	559	6.89	6.65	0.28
	562	6.73		
	558	6.34		
OPC M0.1	550	7.31	7.07	0.32
	552	6.7		
	545	7.19		
OPC M0.2	536	8.44	8.33	0.17
	540	8.14		
	535	4.41		

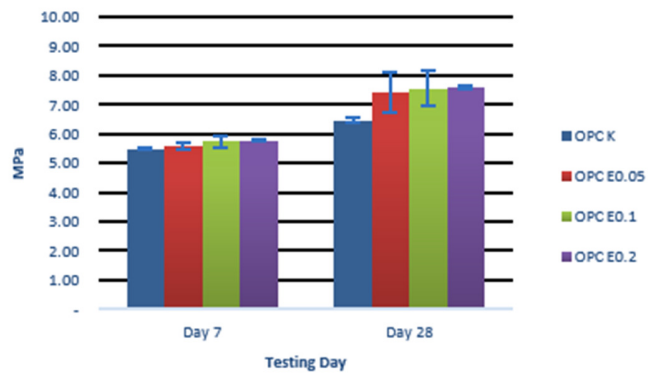


Fig. 2. Comparison chart of control flexural strength test with CP (electrolysis).

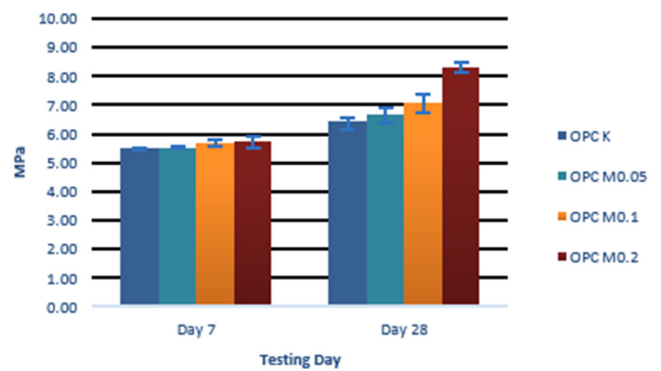


Fig. 3. Comparison chart of control flexural strength test with BC (mechanical production).

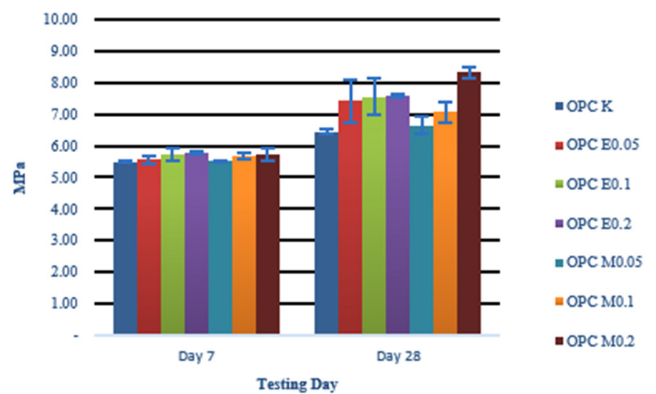


Fig. 4. Comparison chart of flexural strength test results.

Consistent with the findings in [15], the positive effect of nanocellulose on flexural strength was more pronounced than on compressive strength in this study. The positive impact of nanocellulose on the flexural strength of cement paste was much more significant than that observed in compressive strength. After 7 days of treatment, the flexural strength of cement paste containing 0.3% BC increased by almost 100%. In BC, higher dosage resulted in greater flexural strength. The addition of 0.3% BC increased the flexural strength by 57%. The positive effect confirmed that BC can act as a nano-

reinforcement to bridge micro-cracks in cement paste. In the experiment, after 7 days of treatment, the addition of 0.3% BC increased the flexural strength of the cement paste by almost 100%, demonstrating BC's effectiveness in improving the mechanical properties of cement. The higher the BC dosage, the greater the increase in flexural strength. Specifically, at a dosage of 0.3%, the increase in flexural strength reached 57%, indicating a direct relationship between BC concentration and improvements in cement mechanical performance. The primary mechanism of this improvement is believed to stem from BC's role as a nano reinforcement, which bridges microcracks in the cement paste. BNC has a nanofiber structure that can interact with the cement matrix, creating a denser network and improving internal cohesion. As such, BC can slow crack propagation, increase resistance to flexural stress, and reduce the likelihood of structural failure under loading. Additionally, the unique properties of BC, including its high surface area and ability to form hydrogen bonds with the cement matrix, enhance the cement's microstructure. The interaction between BC and cement hydration products increases the material's density and resistance to cyclic and dynamic loads. These improvements are particularly relevant for applications requiring high resistance to flexural cracking. From a sustainability perspective, the effectiveness of BNC as a nano reinforcement may also open the door to reducing the use of less eco-friendly additives in cementitious composites.

D. Compressive Strength of Mortar

The compressive strength results indicate that the effect of nanocellulose depends on both dosage and curing age. At 7 days, the addition of 0.05% nanocellulose increased the compressive strength compared to the control, whereas higher dosages of 0.1% and 0.2% led to a reduction in compressive strength at the same age. In contrast, at 28 days, the compressive strength of the mortar increased linearly with increasing nanocellulose content, with improvements ranging from 3.76% to 15.75%, relative to the control mixture. These findings suggest that nanocellulose contributes more effectively to long-term strength development than to early-age performance at higher dosages. Similar trends have been reported in previous studies, where nanocellulose increased the compressive strength of cement paste by nearly 30% after 7 days at a low dosage of 0.05%, and by approximately 10% after 90 days at a dosage of 0.1% [15]. Nanocellulose functions as an internal curing agent, retaining water within the cement matrix and promoting a more uniform and sustained hydration process. This internal curing effect leads to a denser microstructure in nanocellulose-modified systems compared to the control, resulting in enhanced compressive strength. However, at early ages, excessive nanocellulose content may cause a saturation effect, in which the overabundance of fibers disrupts cement particle packing or increases porosity, thereby reducing compressive strength at dosages of 0.1% and 0.2%.

At 28 days, the effect of nanocellulose on compressive strength showed a more stable and linear trend. As the nanocellulose dosage increased, the mortar's compressive strength increased gradually, ranging from 3.76% to 15.75% compared to the control. This suggests that nanocellulose

enhances the long-term durability of cement by interacting with hydration products that form progressively over time.

TABLE V. COMPRESSIVE STRENGTH OF MORTAR RESULT DAY 7

Compressive strength of mortar result day 7				
Mix Id	Mass	Compressive strength		Standard deviation
	g	MPa	Average	
OPC K	138	16.48	15.64	0.96
	138	15.85		
	136	14.59		
OPC E0.05	140	18.67	18.59	0.62
	140	17.94		
	138	19.17		
OPC E0.1	146	17.22	17.47	0.39
	144	17.27		
	136	17.92		
OPC E0.2	142	18.1	17.44	0.65
	140	16.81		
	138	17.43		
OPC M0.05	140	18.61	18.48	0.82
	142	17.61		
	146	19.23		
OPC M0.1	132	17.29	17.45	0.46
	146	17.1		
	148	17.98		
OPC M0.2	136	17.93	17.38	0.53
	136	16.86		
	138	17.36		

TABLE VI. COMPRESSIVE STRENGTH OF MORTAR RESULT DAY 28

Compressive strength of mortar result day 28				
Mix Id	Mass	Compressive strength		Standard deviation
	g	MPa	Average	
OPC K	134	27.85	27.69	1.5
	144	26.11		
	138	29.09		
OPC E0.05	140	29.54	30.83	1.55
	140	30.41		
	136	32.55		
OPC E0.1	144	30.53	31.84	1.58
	138	31.41		
	142	33.59		
OPC E0.2	130	31.08	32.05	1.61
	146	31.16		
	144	33.91		
OPC M0.05	138	28.53	28.73	0.41
	140	29.19		
	140	28.45		
OPC M0.1	146	29.93	29.51	0.66
	138	29.86		
	140	28.75		
OPC M0.2	136	30.16	30.38	0.55
	140	29.98		
	140	31		

Furthermore, after 90 days of treatment, the increase in compressive strength due to the addition of 0.1% BC reached about 10%. These results indicate that nanocellulose not only accelerates the initial development of compressive strength but also has long-term effects on material stability and strength. One of the main mechanisms contributing to this improvement is nanocellulose's role as an internal curing agent.

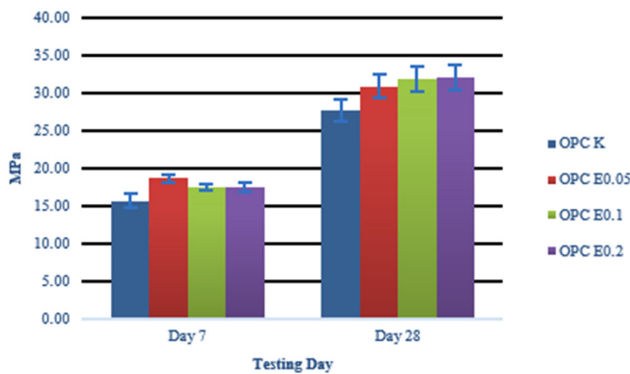


Fig. 5. Comparison chart of control compressive strength test with BC (electrolysis).

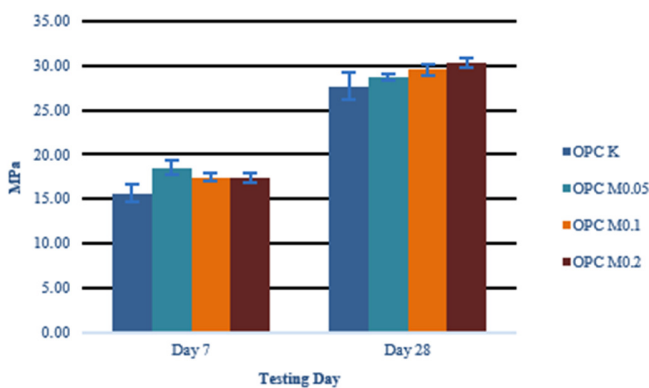


Fig. 6. Comparison chart of control compressive strength test with BC (mechanical production).

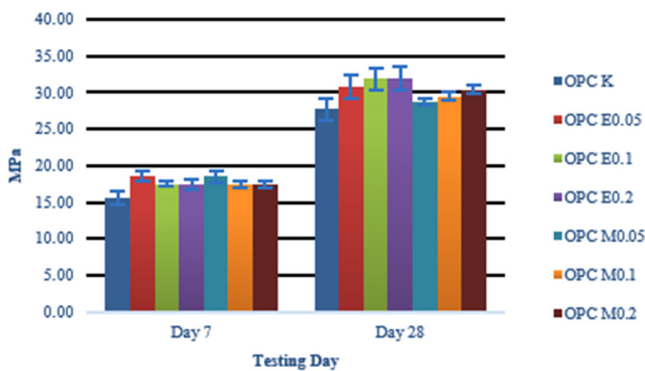


Fig. 7. Comparison chart of compressive strength test results.

As an internal curing agent, nanocellulose retains moisture within the cement matrix, enabling more efficient and uniform hydration. This optimized hydration process leads to the formation of a denser microstructure with fewer microcracks than the control mixture. The resulting densification directly enhances compressive strength by reducing structural weaknesses associated with porosity and material imperfections. Moreover, the high specific surface area of nanocellulose promotes stronger interactions with cement hydration products, particularly Calcium Silicate Hydrate (C-S-H), which plays a significant role in determining the

mechanical performance of cementitious materials. The presence of nanocellulose contributes to a more homogeneous distribution of C-S-H within the matrix, thereby strengthening particle bonding and improving overall cohesion of the mortar. These findings highlight the potential of nanocellulose to support the development of more efficient and environmentally sustainable construction materials [24]. By incorporating nanocellulose as an additive in composite cement, it is possible to achieve higher compressive strength, enhanced durability, and improved hydration efficiency, while reducing reliance on costly conventional reinforcing materials and promoting a more economical and sustainable solution.

E. Scanning Electron Microscope

The SEM micrographs in Figures 8 and 9 demonstrate apparent morphological differences between BNC produced by electrolysis and by mechanical methods. The electrolysis-derived BNC exhibits a highly fragmented, finely dispersed fibrillar network, indicating that the electrochemical process effectively breaks the cellulose into shorter nanofibers with increased surface roughness. This refined morphology enhances its interaction with hydration products, promoting a denser, more homogeneous cement microstructure by improving the nucleation and distribution of C-S-H.

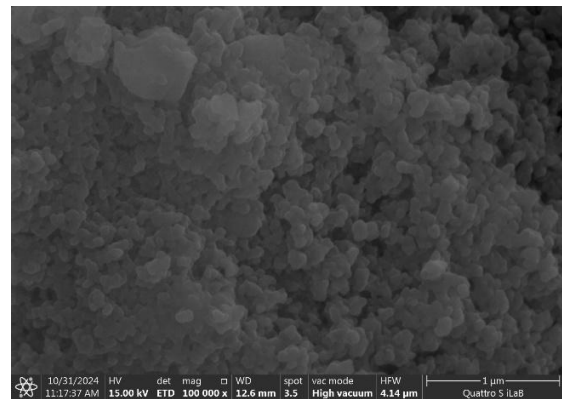


Fig. 8. SEM BNC (Electrolysis).

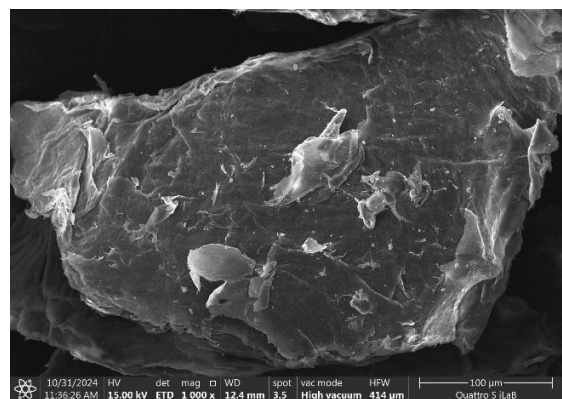


Fig. 9. SEM BNC (mechanical production).

In contrast, mechanically produced BNC exhibits a web-like network of longer, entangled fibers. This continuous

fibrous morphology provides an effective physical reinforcement mechanism within the mortar matrix by bridging microcracks and enhancing tensile load transfer. This crack-bridging capability explains the substantial increase in flexural strength observed at 28 days in mortars containing mechanically derived BNC. SEM observations further reveal that the electrolysis method produces finely fragmented fibrils that primarily promote matrix densification, whereas the mechanical method generates longer fibers that contribute to mechanical reinforcement through crack bridging. Based on these findings, a promising strategy for future research would be to combine both forms of BNC within a single mixture, thereby exploiting the synergistic benefits of matrix densification and fiber reinforcement to further enhance mechanical performance. Overall, the SEM results confirm that the BNC production method governs its microstructural function in cement composites. Electrolysis-derived BNC predominantly enhances matrix compactness and hydration efficiency, while mechanically derived BNC plays a more significant role in crack bridging and load redistribution. These complementary mechanisms account for the observed improvements in both compressive and flexural strength in the experimental results.

IV. CONCLUSIONS

This study systematically evaluated the effects of Bacterial Nanocellulose (BNC) produced via electrolysis and mechanical methods on the properties of mortar. The experimental results demonstrate that the BNC production method plays a critical role in determining its effectiveness as a mortar additive. The key findings of this study are:

- **Fresh Properties:** The incorporation of BNC, regardless of the production method, consistently reduced the mortar flow and specific gravity. This indicates that BNC affects the workability and density of the fresh mixture, primarily through its water-retention capacity.
- **Mechanical Performance:** Both types of BNC enhanced the mechanical properties of hardened mortar, but with distinct outcomes. **Flexural Strength:** The mechanical method produced BNC with superior performance in flexural strength. The highest flexural strength (8.33 MPa), representing a 29.15% increase over the control, was achieved with a 0.2% dosage of mechanically produced BNC at 28 days. This suggests that the longer, fibrous strands created by the mechanical method are more effective at bridging microcracks. **Compressive Strength:** The electrolysis method showed a more consistent and slightly superior improvement in compressive strength at later ages (28 days). The finer, more fragmented fibrils from electrolysis likely contribute to a denser microstructure, thereby enhancing compressive strength more effectively.
- **Methodology-Property Correlation:** The central finding of this research is that the production method governs the reinforcing mechanism of BNC. The mechanical process is better suited to applications requiring high flexural strength, while the electrolysis method is preferable for enhancing compressive strength.

Although the improvements in compressive and flexural strengths are moderate, the use of BNC presents additional potential benefits beyond mechanical performance. Its internal curing capacity, crack-bridging effect, and compatibility with the cement matrix suggest promising durability advantages. Nanocellulose can enhance the resistance of cementitious materials to alkali attack, carbonation, and chloride penetration, thereby improving their long-term durability. These aspects will be the focus of future research, which will build upon the findings of this study. In conclusion, BNC is a promising sustainable additive for mortar. The choice of production method allows tailoring mortar properties to meet specific application requirements. Future research should focus on the long-term durability, economic feasibility, and application of these BNC-modified mortars in full-scale structural elements.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no competing interests.

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DATA AVAILABILITY

The dataset analysed during the current study are available from the corresponding author reasonable request.

AI USE AND DECLARATION OF GENERATIVE AI USE

The authors used Quillbolt for grammar checking and language. The final content, interpretation, and conclusions are entirely the authors' own responsibility.

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