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Natural Rubber Latex-Modified Concrete with Bottom Ash for Sustainable Rigid Pavements

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Abstract

This article investigates the viability of using natural rubber latex (NRL)-modified concrete with bottom ash (BA) as a partial replacement for river sand in sustainable rigid pavements. Concrete mixes with 10% and 20% BA replacement ratios and varying NRL dosages (0%, 1.0%, 1.5%, and 2.0% by weight of cement) were prepared and evaluated for their mechanical and microstructural characteristics. Results showed that BA substitution decreased the compressive strength of concrete. However, the addition of NRL at an optimal dosage of 1.0% significantly improved both the compressive and flexural strengths. The 10%BA+1.0%NRL and 20%BA+1.0%NRL mixes exhibited mechanical properties surpassing the control mix and meeting the minimum requirements for rigid pavement materials. However, excessive NRL content (1.5% and 2.0%) led to a reduction in mechanical strength. Scanning electron microscopy analysis exhibited a denser and more compact matrix in NRL-modified BA concrete, with NRL films enhancing the interfacial bonding and crack-bridging mechanism. Nonetheless, excessive NRL content resulted in the formation of abundant and thicker NRL films, which disrupted the continuity of the cement matrix and created weak zones. X-ray diffraction analysis confirmed the existence of crucial crystalline phases and their optimal balance in the 20%BA+1.0%NRL mix, contributing to its superior performance. Mixes with excessive NRL contents exhibited lower intensities of quartz, calcite, and portlandite peaks, indicating a disturbance in the proper formation and growth of essential crystalline phases. The findings demonstrated the potential of NRL-modified BA concrete as an eco-friendly and high-performance alternative for sustainable rigid pavements when using an optimal NRL dosage, promoting the employment of waste resources and reducing the environmental impact of the construction industry.

Keywords: Bottom Ash; Natural Rubber Latex; Sustainable Concrete Pavement; Microstructural Analysis; Compressive Strength; Flexural Strength.

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1. Introduction

Concrete, particularly Portland cement concrete, is commonly employed for rigid pavements due to its high strength, durability, and ability to withstand traffic loads without significant deformation. Rigid pavements distribute loads across a broad area of the subgrade, reducing the importance of subgrade preparation compared to flexible pavements. A key factor in rigid pavement design is the concrete's load-bearing capacity, with typical compressive strengths ranging from 28 to 35 MPa [1, 2].

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Despite their advantages, concrete pavements present several challenges. While the rigidity of concrete is beneficial for load distribution, it can also lead to reflective cracking if not properly managed through joints and reinforcement. Moreover, concrete requires precise construction techniques to avoid cracking and ensure longevity. Furthermore, the production of concrete has substantial environmental impacts, primarily due to the extensive consumption of natural resources, like sand and gravel, as well as the significant carbon emissions linked to cement manufacture [3]. Therefore, there is an increasing need for sustainable alternatives to conventional concrete that can reduce the environmental impact of concrete while maintaining its functional properties [4].

One promising approach to enhance the sustainability of concrete is the utilization of waste materials as partial replacements for natural aggregates. Bottom ash (BA), a by-product of coal combustion in thermal power stations, has been identified as a potential alternative to fine aggregate in concrete [5]. Utilizing BA in concrete not only decreases the use of natural resources but also provides a practical solution for the disposing of this waste material, which is frequently deposited in landfills, leading to adverse environmental effects. However, studies have found that increasing the BA content beyond moderate replacement ratios can lead to a decrease in engineering performance, especially compressive strength and flexural strength [6-10]. Furthermore, Mousa (2023) [11] investigated the feasibility of utilizing BA as a partial replacement for cement in concrete, demonstrating that BA can significantly improve compressive strength when used at optimal levels.

High concentrations of BA in concrete can result in a reduction of mechanical properties due to the porous characteristics of the ash particles and the presence of unburned carbon [12, 13]. Özkan & Yüksel (2007) [14] and Yüksel & Genç (2007) [15] examined the impact of substituting fine aggregate with BA and granulated blast furnace slag in concrete and found a reduction in compressive strength. Rafieizonooz et al. (2017) [16] performed an experiment in which sand was substituted with BA and cement was replaced with fly ash. The results indicated that the initial compressive strength of the material declined as the amount of BA increased. Despite the declined early compressive strength, the BA concrete mixtures exhibited comparable long-term compressive strength to normal concrete, while they had better resistance to sulfuric acid.

Kou & Poon (2009) [17] investigated the properties of concrete using various fine aggregates and two mixed-design approaches. It was found that when the concrete mixtures were designed based on a constant water-to-cement (w/c) ratio approach, using BA in concrete mixtures led to a decrease in both compressive strength and drying shrinkage of the concrete. Nevertheless, when the concrete mixtures were formulated according to a specific slump value, the inclusion of BA resulted in improved properties, including increased compressive strength, decreased shrinkage, and greater resistance to chloride-ion penetration. Kim & Lee (2011) [18] examined the employment of BA as both fine and coarse aggregates in high-strength concrete, observing that coarse BA reduced slump, while fine BA had minimal impact. They also found that BA significantly influenced flexural strength compared to compressive strength. Isa & Ayten (2007) reported lower flexural strength in concrete with BA in comparison to normal concrete. They also indicated a 10% decrease in tensile strength when compared to the control concrete, specifically when using 10% BA replacement. However, the tensile strength of BA concrete did not show significant changes at the higher BA substitution compared to the control concrete. Kurama & Kaya (2008) [19] investigated the flexural strength of BA concrete at various curing ages, finding similar flexural strength to that of the control mix at 28 days but higher strength at 56 days for all BA concrete mixes compared to the control mix.

In summary, substantial research has been conducted on utilizing BA as a substitute for fine aggregate in concrete, with outcomes varying based on replacement ratio, mix formulation method, and curing duration. Moderate replacement levels have shown promise in maintaining or even improving certain mechanical properties. Excessive replacement ratios have been associated with reduced compressive strength and increased shrinkage. To address these challenges, researchers have explored various additives to enhance the properties of BA-modified concrete.

Natural Rubber Latex (NRL) shows great potential in enhancing the mechanical and microstructural characteristics of concrete. Subash et al. (2021) [20] demonstrated that incorporating NRL into concrete as an additive could significantly improve mechanical characteristics, including compressive strength, flexural strength, and split tensile strength. The most effective dosage of NRL was determined to be 2% by weight of cement, though this inclusion also reduced workability, an important factor to consider in the mix design. NRL incorporation leads to a denser microstructure, improved water exclusion capacities, and enhanced resistance to acidic and sulfated environments [21]. Additionally, NRL-modified concrete exhibited better strength retention and reduced deterioration compared to normal concrete when exposed to aggressive conditions.

Tuffrey et al. (2024) [22] investigated the use of NRL in combination with waste paper pulp (WPP) to enhance the performance of cement composites. Their study revealed that NRL significantly reduced water absorption, improved flexural properties, and enhanced fire resistance of the composites. The optimal NRL content was found to be around 1.5% of the weight of ordinary Portland cement (OPC), which aligns with findings from previous studies in the field. Recent research has further emphasized the benefits of incorporating NRL into concrete mixtures [20]. Their study revealed that NRL can significantly enhance the compressive strength, flexural strength, and split tensile strength of concrete when used at optimal dosages. It was found that the optimal latex-to-water ratios ranged from 4% to 6%.

Yaowarat et al. (2021) [23] found that NRL-modified concrete pavements had better resistance to fatigue cracking and rutting when compared to traditional concrete pavements. Suddeepong et al. (2022) [24] proposed a mechanistic-empirical (ME) design approach that considered the enhanced mechanical characteristics and service life of NRL-modified concrete in the design process. This approach resulted in reduced pavement thicknesses compared to conventional concrete pavements, indicating potential cost savings and material efficiency. Further, Samingthong et al. (2023) [25] examined the synergistic application of NRL and recycled materials (PET and crumb rubber) in concrete to enhance the long-term sustainability of rigid pavements. The results demonstrated the capability of this approach to improve the mechanical properties, durability, and environmental efficiency of concrete pavements while promoting the utilization of recycled materials.

Despite the promising findings of these studies, there remain gaps in the current knowledge regarding the combination of BA and NRL affecting the properties of concrete. Most previous studies have focused on the individual effects of these materials, with limited exploration of their synergistic behavior when used together in concrete production. Furthermore, the potential application of NRL-modified BA concrete as a rigid pavement material has not been extensively studied, highlighting the need for comprehensive evaluations of its mechanical performance. This research aims to fill this gap by investigating the combined effects of BA and NRL on concrete, with the goal of developing sustainable and high-performance concrete for rigid pavement applications. Their strength development under compression and bending conditions was evaluated by compressive strength and flexural strength tests. Scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses were performed to examine their microstructural and mineralogical changes.

2. Materials and Methods

2.1. Materials

The coarse aggregate used in this study was crushed limestone with a maximum dimension of 19 mm, sourced from a local quarry. To ensure consistent size distribution and impurities removal, the limestone was washed and sieved. Table 1 shows the physical and mechanical characteristics of the coarse aggregate, which underwent testing in line with the appropriate ASTM standards [26, 27]. The limestone had a saturated surface dry specific gravity of 2.77, a dry specific gravity of 2.47, and a dry density of 1634 kg/m³. The limestone exhibited a water absorption of 1.86% and a moisture content of 0.98%. The coarse aggregate exhibited an abrasion loss of 22.4%, as determined by the Los Angeles abrasion test.

Table 1. Physical and engineering properties of coarse and fine aggregates

Properties	Coarse Aggregate	Fine Aggregate	
	Limestone	Sand	BA
Maximum size aggregate (mm)	19	4.75	4.75
Saturated surface dry specific gravity	2.77	2.62	2.30
Dry specific gravity	2.47	2.60	2.10
Dry density (kg/m^3)	1634	1613	1200
Water absorption (%)	1.86	0.70	1.50
Moisture content (%)	0.98	0.48	2.50
Abrasion loss (%)	22.4	-	-
Fineness modulus	-	2.75	3.00

This study used two types of fine aggregate: river sand and BA. The river sand was obtained from a local source, washed, and sieved to remove any organic matter and ensure a consistent size distribution. The physical parameters of the river sand were tested in accordance with the ASTM standard [28] as shown in Table 1. The river sand had a maximum size of 4.75 mm, a saturated surface dry specific gravity of 2.62, a dry specific gravity of 2.60, and a dry density of 1613 kg/m³. The water absorption, moisture content, and fineness modulus of the river sand were 0.70%, 0.48%, and 2.75, respectively.

The BA was sourced from the Mae Moh mine located in north of Thailand. It was first air-dried to remove the moisture. It was then sieved through a 4.75-mm sieve to remove any oversized particles and to ensure a consistent size distribution. The BA had a saturated surface-dry specific gravity of 2.30, a dry specific gravity of 2.10, and a dry density of 1200 kg/m³. The water absorption, moisture content, and fineness modulus of the BA were 1.50%, 2.50%, and 3.00, respectively. The composition of chemicals and mineralogy of the BA were investigated using XRF analysis and X-ray diffraction (XRD), respectively. The XRF results (Table 2) exposed that the BA had a high silicon dioxide content (59.50%), followed by aluminum oxide (25.70%), and iron oxide (6.07%). The XRD pattern of BA (Figure 1) revealed the existence of various crystalline phases, including gehlenite, ferroan diopside, ettringite, bassanite, and quartz.

Table 2. Chemical composition of OPC and BA

Components	OPC	BA
Silicon dioxide (SiO_2)	20.9	59.50
Aluminum oxide (Al_2O_3)	4.70	25.70
Iron oxide (Fe_2O_3)	3.40	6.07
Calcium oxide (CaO)	65.40	2.92
Magnesium oxide (MgO)	1.20	0.8
Sulfur trioxide (SO_3)	2.70	-
Loss on ignition (LOI)	0.90	2.20

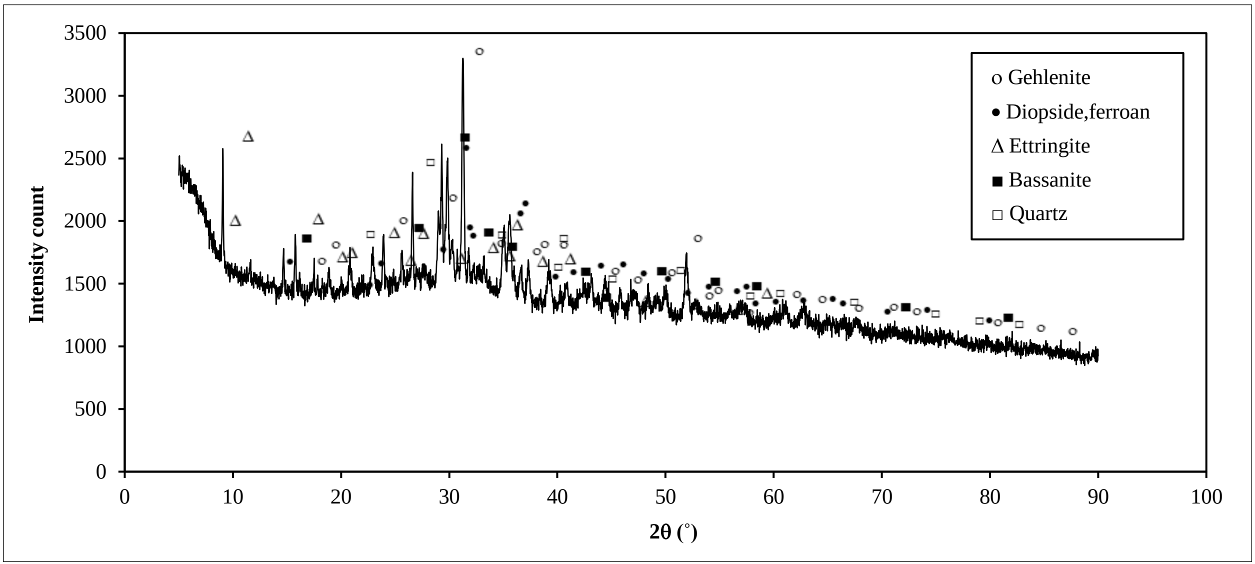


Figure 1. XRD pattern of BA

The gradation of the studied aggregates is presented in Figure 2, which shows that the combined gradations of limestone, sand, and BA at various replacement levels (0%, 10%, and 20%) fall within the boundaries for concrete aggregates [29].

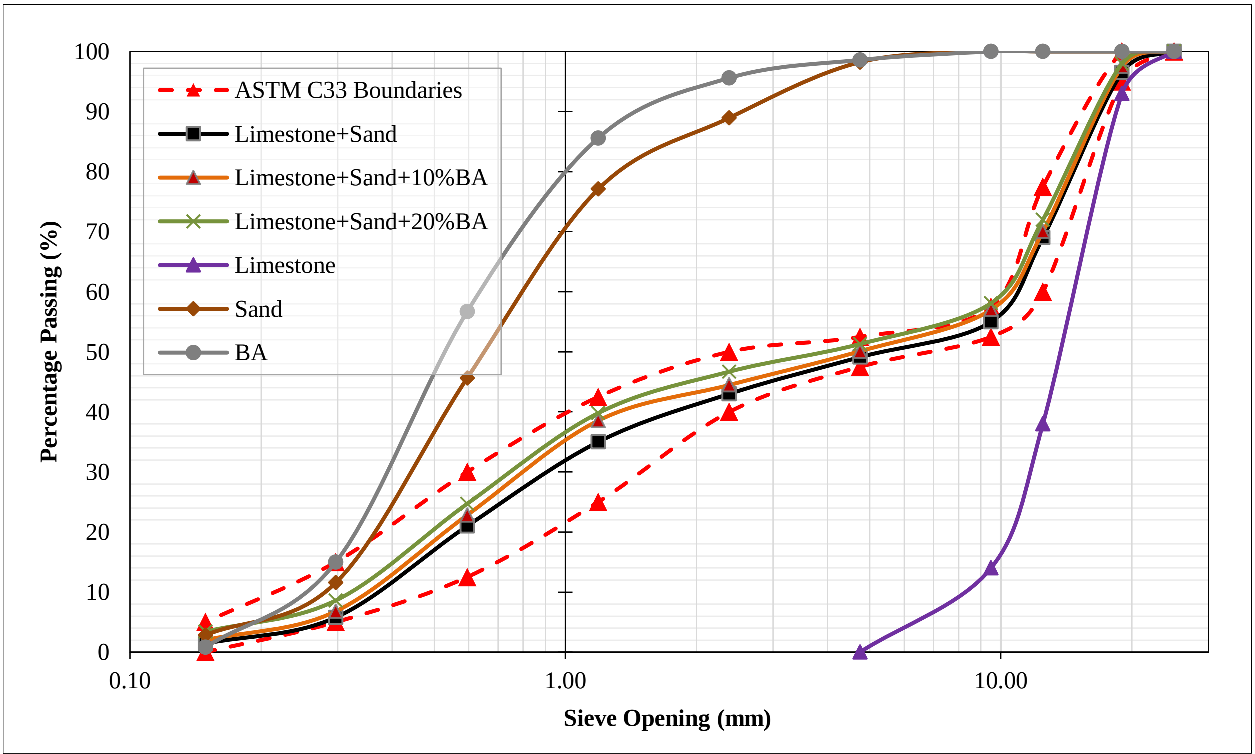


Figure 2. Gradation of studied aggregates

This study utilized Portland cement as the main cementing agent. The XRF analysis (Table 2) demonstrated that the Portland cement had a calcium oxide (CaO) content of 65.40%, a silicon dioxide (SiO_2) content of 20.9%, an aluminum oxide (Al_2O_3) content of 4.70%, and an iron oxide (Fe_2O_3) content of 3.40%.

This study utilized NRL sourced from the Rubber Authority of Thailand. The NRL was characterized by its total solid content (TSC), pH, and viscosity. The TSC was determined using the dry rubber content (DRC) method, while the pH and viscosity were assessed employing a pH meter and a Brookfield viscometer, respectively. The DRC of NRL was about 52%, while the water-soluble components constituted 47.35% of the total mass. The NRL had a pH value of 10.3, indicating its alkaline nature. The ammonia content of the NRL was 0.69%, which acted as a preservative and stabilizer in the latex. The viscosity of NRL was between 100 and 150 centipoises (cP), which is considered suitable for the modification of concrete properties.

2.2. Concrete Mix Design and Sample Preparation

The concrete mix designs utilized in this investigation are outlined in Table 3. A total of nine mixtures were formulated, including a control mix (normal concrete) and eight mixes incorporating BA as a partial substitute for river sand at volumes of 10% and 20% and NRL at varying ratios of 0, 1.0%, 1.5%, and 2.0% by weight of cement. The w/c ratio was set to be 0.5% for all mixes with a target slump of 75±5 mm to align with the concrete pavement specification established by DOH, Thailand. In addition, maintaining a consistent w/c ratio and slump ensures that the strength development of the concrete mixes can be directly ascribed to the varying levels of BA and NRL.

Table 3. Concrete mix designs in this study (slump = 75±5 mm)

Specimen ID	w/c	Portland Cement (kg/m³)	Coarse Aggregate Limestone (kg/m³)	Fine Aggregate		NRL		Water (kg/m³)
				Sand (kg/m³)	BA (kg/m³)	r/c ratio (%)	Solid (kg/m³)	
Normal Concrete (control mix)	0.5	370	1018	814	-	0	-	185
10%BA+0.0%NRL	0.5	370	1018	732.6	81.4	0	-	185
10%BA+1.0%NRL	0.5	370	1018	732.6	81.4	1.0	7.12	181.58
10%BA+1.5%NRL	0.5	370	1018	732.6	81.4	1.5	10.67	179.88
10%BA+2.0%NRL	0.5	370	1018	732.6	81.4	2.0	14.23	178.17
20%BA+0.0%NRL	0.5	370	1018	651.2	162.8	0	-	185
20%BA+1.0%NRL	0.5	370	1018	651.2	162.8	1.0	7.12	181.58
20%BA+1.5%NRL	0.5	370	1018	651.2	162.8	1.5	10.67	179.88
20%BA+2.0%NRL	0.5	370	1018	651.2	162.8	2.0	14.23	178.17

Note: r = dry rubber latex (solid content)

The mixing procedure was started by mixing the coarse and fine aggregates (river sand and/or BA) for about 1 minute. The cement was included into the mixture and mixed for an additional 1 minute. The remaining mixing water, along with NRL and Type F superplasticizer, was systematically included into the mixture and mixed for 2 minutes to ensure homogeneity and achieve the target slump. The slump of the fresh concrete was promptly measured after mixing to ensure compliance with the desired range.

For each mix, a total of 3 cylinders (with a diameter of 150 mm and a height of 300 mm height) and 3 prisms (measuring 100 × 100 × 500 mm) were created in order to measure the compressive strength and flexural strength, respectively. The molds were filled in 3 layers, with each layer being compacted by a tamping rod. This process was carried out to eliminate air voids and ensure proper consolidation. Following the casting process, the specimens were wrapped with plastic sheets and allowed to cure at ambient temperature (25±2°C) for 1 day. After that, they were removed from the molds and transferred to a water curing tank until they reached the ages of 7, 28, and 60 days, respectively, before undergoing mechanical testing.

2.3. Experimental Testing Program

An investigational testing program was carried out to assess the mechanical characteristics and benchmarked with the minimum strength criterion for rigid pavement designed by DOH, Thailand, while microstructural characteristics of the concrete mixes incorporating BA and NRL were performed in order to examine their strength development as summarized in Figure 3.

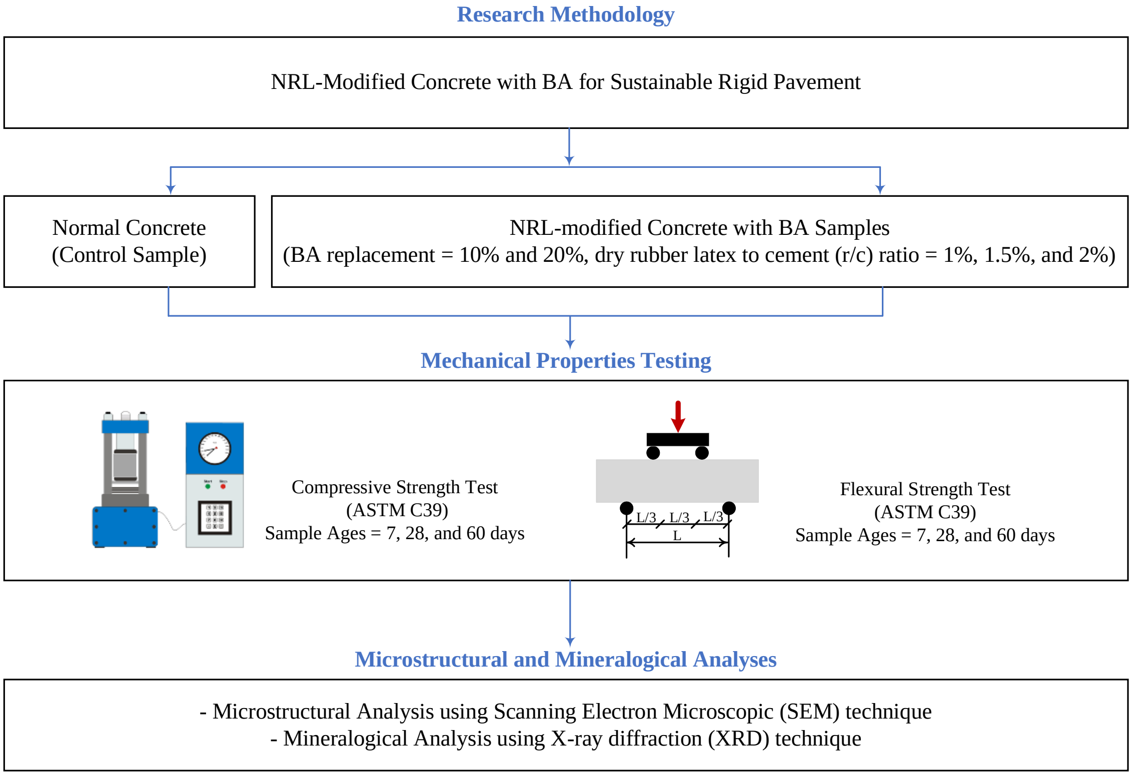


Figure 3. Flowchart of the experimental testing program

The concrete mixes' compressive strength was assessed following the guidelines of ASTM-C39 (2021) [30] at the ages of 7, 28, and 60 days. Three specimens were tested for each mix and testing age, and the average values were recorded. The specimens were subjected to a loading rate of 1 mm/min until they reached the point of failure. The highest amount of load that the specimen could sustain was then recorded.

The flexural strength of the concrete mixes was evaluated using ASTM-C78 (2009) [31], employing a simple beam under three-point loading condition. The tests were conducted on the prepared prismatic specimens at the ages of 7, 28, and 60 days. For each mix and testing age, 3 specimens were tested, and the average value was recorded. The specimens underwent three-point loading at a consistent rate of 0.02 mm/min until they failed. The highest load that the specimen sustained was documented.

Scanning electron microscopy (SEM) was employed to investigate the microstructure of the concrete mixes and to assess the interfacial interaction between the cement matrix, BA, and NRL. Surfaces of the concrete specimens were analyzed using a high-resolution scanning electron microscope, which was operated at an accelerating voltage of 1 kV. The specimens were coated with a thin layer of gold palladium to enhance their conductivity and to prevent charging effects during imaging.

X-ray diffraction (XRD) study was conducted to identify the crystalline phases present in the hydrated cement paste and to evaluate the influence of BA and NRL on the hydration products. Powder samples were prepared by grinding selected fragments of the concrete specimens of fine powder using a mortar and pestle. The powder samples were then analyzed using a Cu-Kα radiation X-ray diffractometer (wavelength of $\lambda = 1.5418$ Å), which operated at 40 kV and 30 mA. The XRD patterns were collected within a 2θ range of 10° to 90° using a step size of 0.02° and a dwell period of 1 second per step.

The results obtained from these experimental tests were utilized to assess the impact of BA and NRL on the mechanical characteristics and microstructure of the concrete mixes and to provide insights into the mechanisms governing the performance of these sustainable concrete materials.

3. Results and Discussion

3.1. Compressive Strength Results

The compressive strengths of the concrete specimens containing various BA and NRL contents after being cured for 7, 28, and 60 days are shown in Figure 4. Consistent with expectations, the compressive strength of all mixtures increased with increasing the curing age, which can be ascribed to the ongoing hydration of cement and the development of a denser microstructure over time. The effect of BA and NRL on the compressive strength development of concrete was assessed by comparing the performance of mixes with varying BA replacement levels and NRL dosages. The results were also benchmarked against the minimum requirement of 32 MPa for a rigid pavement material designated by the DOH, Thailand [32].

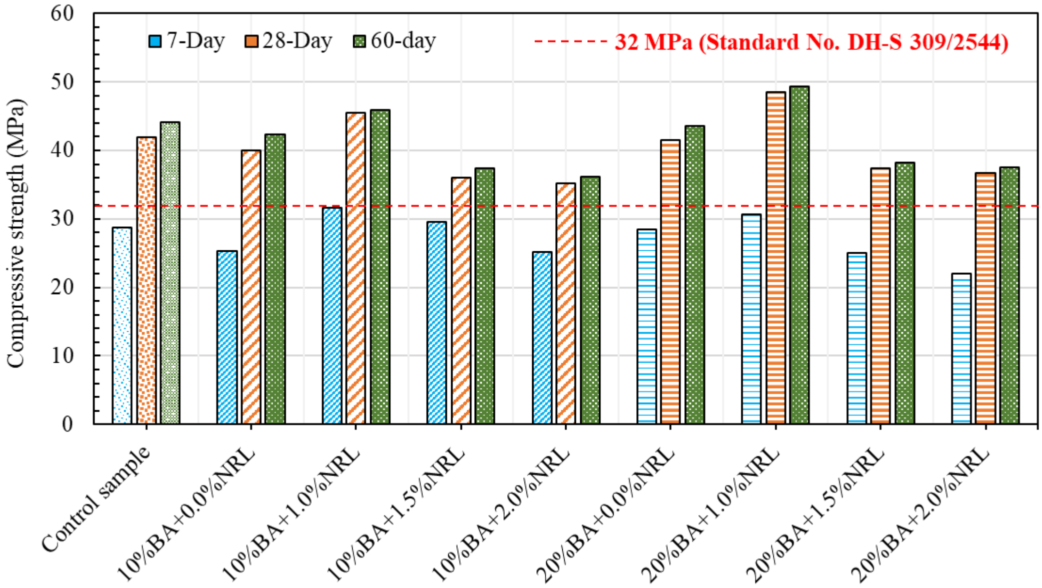


Figure 4. Compressive strength results of studied concrete samples with various BA and NRL contents cured at 7, 28, and 60 days

Replacing river sand with BA at 10% and 20% by volume, without the addition of NRL, resulted in decreased compressive strength compared to the control concrete at all curing ages. The compressive strength of concrete specimens with 10% and 20% BA substitution was reduced by 7.2% and 14.5%, respectively, compared to the control mix after 28 days. Previous studies have shown that incorporating BA in concrete generally results in a reduction of compressive strength due to the porous nature and lower density of BA particles, which weakens the interfacial adhesion between the BA particles and the cement matrix [5, 12, 13, 16]. This observation is consistent with the current findings where the 10% and 20% BA mixes exhibited lower compressive strength compared to the control mix. However, it is noteworthy to mention that the concrete's compressive strength with 10% BA substitution (36.2 MPa) still satisfied the minimum criterion of 32 MPa set by the DOH, Thailand, while the mix with 20% BA replacement (33.8 MPa) was slightly above the threshold.

The incorporation of NRL in BA concrete mixes resulted in varying effects on the compressive strength, depending on the NRL dosage. At 28 days, the compressive strength of concrete with 10% BA substitution and 1.0% NRL (10%BA+1.0%NRL) (43.68 MPa) was higher than the corresponding mix without NRL (10%BA+0.0%NRL) (39.96 MPa) and even surpassed the control mix (41.98 MPa). However, further increasing the NRL content to 1.5% and 2.0% in the 10% BA replacement mix reduced compressive strength compared to the mix with 1.0% NRL and lower than the control mix. Similarly, the mixes containing 20% BA replacement, with the addition of 1.0% NRL resulted in the highest compressive strength (42.20 MPa) among the NRL-modified mixes, while higher NRL dosages (1.5% and 2.0%) led to a strength reduction. The long-term strength development of the mixes was also evident from the 60-day compressive strength results, with most mixes showing an increase in strength compared to their 28-day values.

The enhancement in compressive strength with an addition of 1.0% NRL might be ascribed to the capacity of NRL characteristics to boost the stress dissipation and cracking-bridging mechanisms within the concrete matrix [23-25]. In addition, this improvement might be attributed to the film-forming property of NRL, which enhances the bonding between the cement matrix and aggregate particles, resulting in a denser and more cohesive microstructure [22]. The elastic nature of NRL particles helps absorb and dissipate the stresses within the concrete matrix, reducing the formation and propagation of microcracks. Furthermore, Subash et al. (2021) [20] reported that increasing the latex-to-water ratios made the concrete more viscous with more filled voids in the matrix, resulting in more cohesion and contributing to strength gain. However, this led to reducing the workability of the concrete mix.

The reduction in strength at higher NRL dosages (1.5% and 2.0%) implies that an optimal NRL content exists, beyond which excess NRL may introduce more voids and weaken the concrete matrix [21, 33]. Higher NRL content may lead to increased air entrainment and a more porous microstructure, adversely affecting compressive strength. Furthermore, the strength reduction is likely due to the excessive formation of rubber films, which can create weak zones within the matrix, disrupting the continuity of the cementitious phases [20]. These findings indicate that while NRL can significantly enhance the compressive strength of BA-modified concrete, its dosage must be carefully optimized to avoid negative effects.

3.2. Flexural Strength Results

Figure 5 illustrates the flexural strength of the concrete specimens with various BA and NRL contents cured at 7, 28, and 60 days. The impact of BA and NRL on the development of flexural strength was evaluated by comparing the performance of mixes with different BA replacement levels and NRL dosages. The results were also benchmarked against the minimum requirement of 4.2 MPa for the 28-day flexural strength of rigid pavement material, as specified by the DOH, Thailand [32].

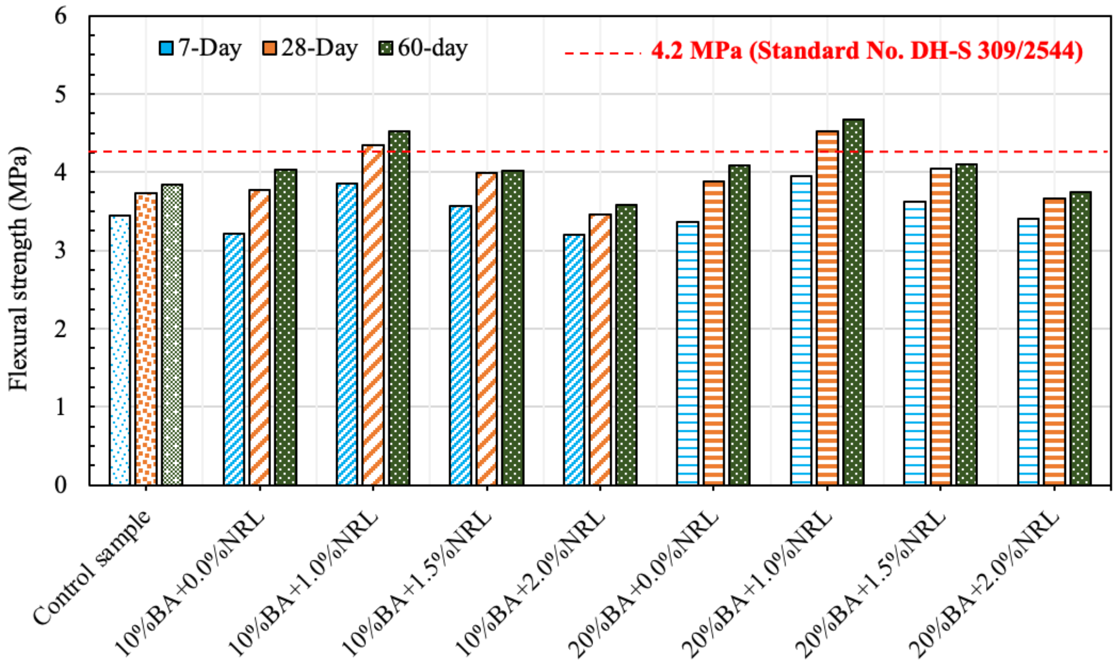


Figure 5. Flexural strength results of studied concrete samples with various BA and NRL contents cured at 7, 28, and 60 days

Similar to the compressive strength results, the inclusion of BA at 10% and 20% replacement levels led to a reduction in flexural strength compared to the control mix. The partial substitution of river sand with BA at 10% and 20% by volume, without NRL, caused effects on the flexural strength of the concrete at different curing ages. The flexural strength of concrete with 10% and 20% BA replacement was 3.21 MPa and 3.37 MPa, respectively, at 7 days. These values were lower than the flexural strength of the control mix, which was 3.45 MPa. However, at 28 and 60 days, the flexural strength of BA concrete surpassed that of the control mix. The mix with 10% BA replacement achieved flexural strengths of 3.77 MPa and 4.03 MPa at 28 and 60 days, respectively, while the mix with 20% BA replacement attained flexural strengths of 3.88 MPa and 4.09 MPa at the same curing ages. These values are higher than the control mix, which exhibited flexural strengths of 3.73 MPa and 3.85 MPa at 28 and 60 days, respectively. The improved flexural strength observed in later stages can be related to the pozzolanic reaction of BA, which causes the development of extra calcium silicate hydrate (C-S-H) gel, resulting in a denser microstructure and enhanced mechanical properties [34, 35]. In addition, the coarse surface texture and angular shape of BA may also contribute to better interlocking and improved flexural strength [5, 36].

The incorporation of NRL in BA concrete and the control mix resulted in significant improvements in flexural strength, with the enhancements being more pronounced at higher curing ages. At 7 days, the 10% and 20% BA replacement mixes with 1.0% NRL (10%BA+1.0%NRL and 20%+1.0%NRL) achieved flexural strengths of 3.85 MPa and 3.95 MPa, respectively, surpassing the BA concrete without NRL and the control mix.

At 28 and 60 days, the positive influence of NRL on flexural strength became more evident. The 10%BA+1.0%NRL mixes reached flexural strengths of 4.35 MPa and 4.53 MPa at 28 and 60 days, respectively. The 20%BA+1.0%NRL mixes had flexural strengths of 4.55 MPa at 28 days and 4.67 MPa at 60 days. These NRL-modified mixes exhibited better performance than their counterparts without NRL and surpassed the minimum criterion of 4.2 MPa set by the DOH, Thailand, for the 28-day flexural strength of rigid pavement materials.

The enhancement in flexural strength with the addition of NRL can be attributed to the capacity of NRL to facilitate the transmission of tensile stress and the crack-bridging mechanism within the concrete matrix. The elastic characteristic of NRL helps redistribute the tensile stresses and control the propagation of microcracks [37]. Moreover, the inclusion of NRL can enhance the interfacial bonding between the aggregates and the cement pastes, resulting in a more cohesive and resilient microstructure [38, 39].

However, similar to the compressive strength results, increasing the NRL content beyond 1.0% resulted in a decrease in flexural strength. It is worth mentioning that while higher NRL dosages (1.5% and 2.0%) also improved flexural strength compared to the mixes without NRL, the enhancements were not as significant as those observed with 1.0% NRL. This confirms the existence of an optimal NRL content, beyond which the benefits in flexural strength may decline. The improvement in flexural strength observed in the studied NRL-modified BA concrete mixes is consistent with the findings of Tuffrey et al. (2024) [22], reporting that NRL significantly enhanced the flexural properties of waste paper pulp-cement composites. They found that the optimal NRL content for achieving the best overall flexural properties was approximately 1.5% of the weight of OPC, which closely aligns with this research result. This consistency across different studies underscores the potential of NRL as a versatile additive for improving the mechanical properties of various types of cement-based composites.

In terms of strength development, while BA concrete without NRL exhibited compressive and flexural strength reduction with increasing BA content, the incorporation of NRL at an optimal dosage of 1.0% meaningfully enhanced the mechanical characteristics of BA concrete mixes. The 10%BA+1.0%NRL and 20%BA+1.0%NRL mixes not only compensated for the control mix but also met the stringent requirements for rigid pavement materials set by the DOH, Thailand. These findings highlight the potential of using NRL-modified BA concrete as a sustainable and high-performance alternative for pavement construction, contributing to the valorization of waste materials and the enhancement of environmentally conscious construction practices.

4. Microstructural Analysis

The microstructural characteristics of concrete are essential in defining its mechanical behavior and durability. The microstructural analysis conducted using SEM provides valuable insight into the internal structure of both regular concrete and NRL-modified BA concrete.

Figure 6 demonstrates the SEM image of the control mix, after being cured for 28 days. The microstructure of the control mix revealed the presence of hydration products, especially calcium silicate hydrate (C-S-H), calcium hydroxide ($Ca(OH)_2$), and ettringite. SEM image showed a dense, amorphous, and interconnected matrix, which enhanced the mechanical characteristics of the concrete. Ettringite, a needle-like crystal, plays a crucial function in the initial formation of strength in concrete and contributes to its setting and hardening processes. C-S-H occurs through the process of hydration involving the interaction between the cement particles and water. This reaction leads to the development of a strong and cohesive microstructure. $Ca(OH)_2$ or portlandite is another hydration product dispersed throughout the cement matrix, which can participate in a secondary reaction that forms additional C-S-H in the presence of pozzolanic materials [40].

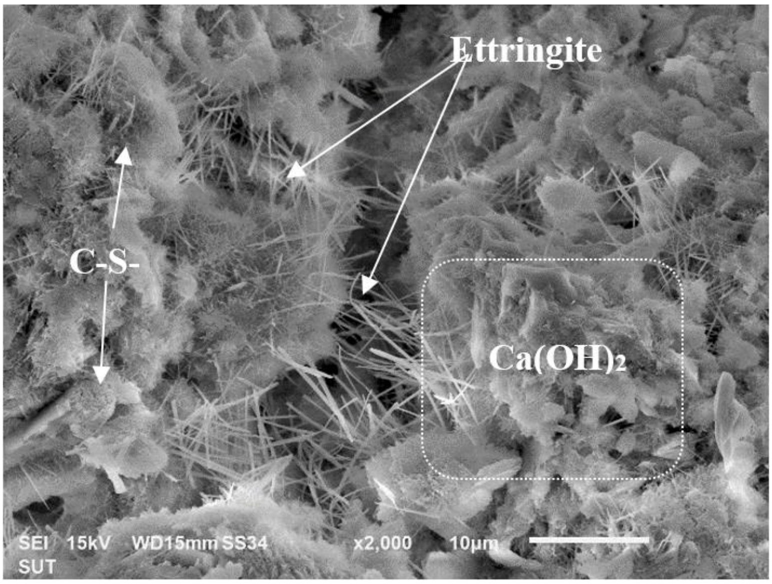
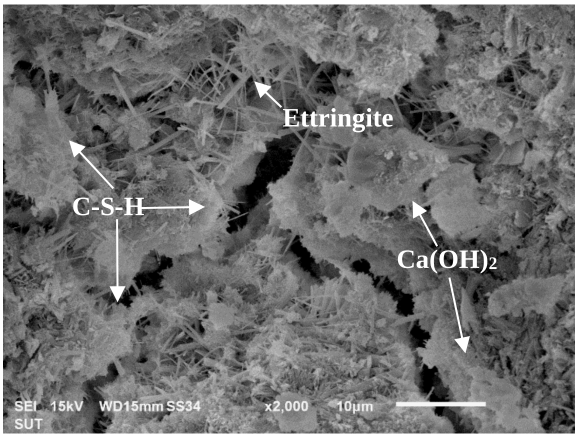
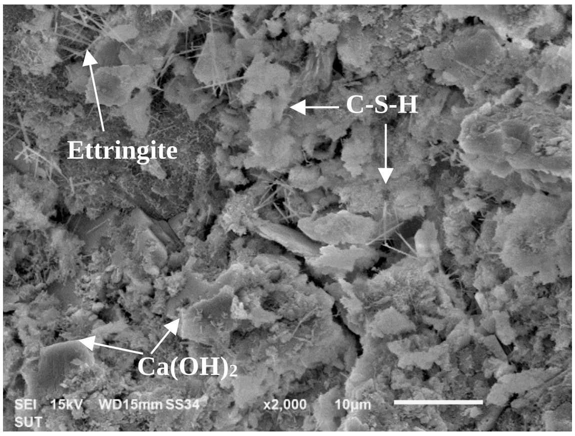


Figure 6. SEM image of a control sample

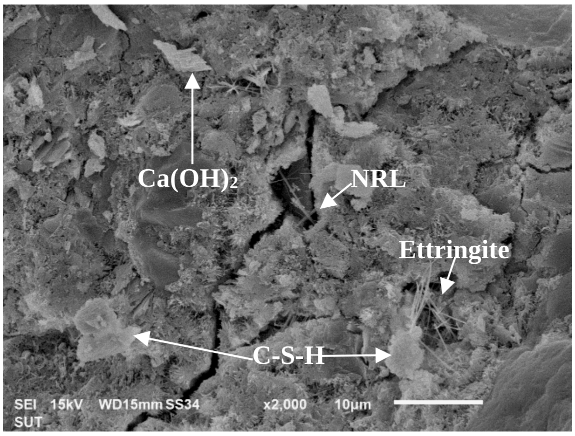
Figure 7 illustrates the SEM images of concrete mixes incorporating BA as a partial substitute for river sand at 10% and 20% by volume, with and without the addition of NRL at a dosage of 1.0% and 2.0% by weight of cement. These images provided valuable insight into the microstructural alterations caused by the incorporation of BA and NRL in the concrete matrix.



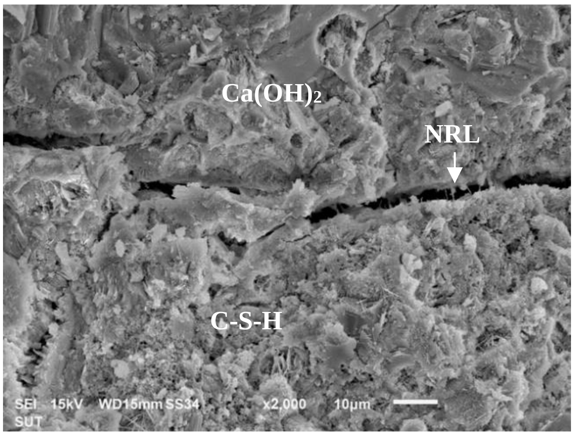
a) 10%BA+0.0%NRL sample



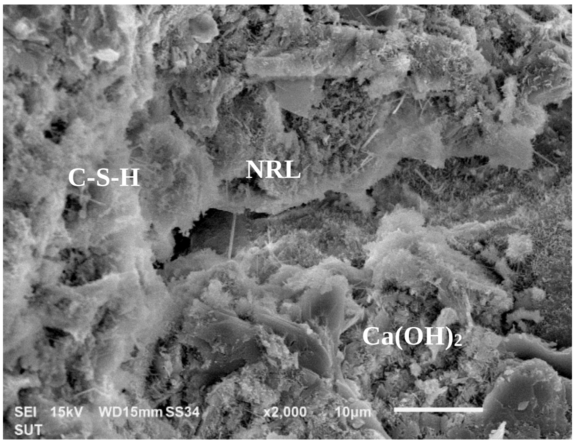
d) 20%BA+0.0%NRL sample



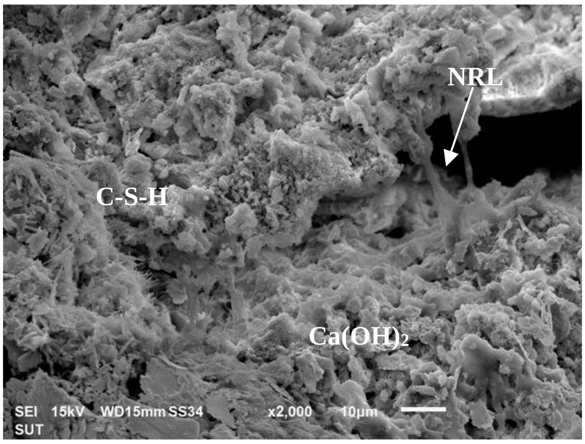
b) 10%BA+1.0%NRL sample



e) 20%BA+1.0%NRL sample



c) 10%BA+2.0%NRL sample



f) 20%BA+2.0%NRL sample

Figure 7. SEM images: a) 10%BA+0.0%NRL, b) 10%BA+1.0%NRL, c) 10%BA+2.0%NRL, d) 20%BA+0.0%NRL, e) 20%BA+1.0%NRL, f) 20%BA+2.0%NRL

The SEM images of BA concrete mixes without NRL (Figures 7-a and 7-d) revealed a microstructure that closely resembled that of the control mix, with the presence of C-S-H, $Ca(OH)_2$, and ettringite. However, the incorporation of BA appeared to have resulted in a slightly more porous and heterogeneous microstructure in comparison to the control mix. This phenomenon could be ascribed to the pozzolanic reaction occurring between BA and calcium hydroxide, resulting in the creation of extra C-S-H, which ultimately leads to a more heterogeneous microstructure. The more porous and heterogeneous microstructure observed in the BA concrete mixes without NRL contributed to a decrease in both compressive and flexural strengths, as depicted in Figures 4 and 5.

The SEM images of NRL-modified BA concrete mixes (Figures 7-b, 7-c, 7-e, and 7-f) exhibited significant microstructural changes compared to the BA concrete mixes (without NRL). The NRL-modified BA concrete mixes (10%BA+1.0%NRL and 20%BA+1.0%NRL) indicated a denser and more compact microstructure with reduced porosity compared to the BA concrete mixes. The formation of C-S-H appears to be more extensive and well-distributed compared to the BA concrete mixes without NRL. SEM observations of a denser and more compacted microstructure in NRL-modified BA concrete align with the findings of Tuffrey et al. (2024) [22], which reported similar microstructural enhancements in NRL-modified cement composites. They observed the formation of C-S-H crystals, which plays a crucial role in enhancing concrete strength and durability. In addition, Subash et al. (2021) [20] reported that the formation of a more refined pore structure and enhanced interfacial bonding between aggregates and the cement paste were detected by SEM analysis.

In addition, incorporating NRL in BA concrete mixes resulted in the formation of thin NRL films in the concrete matrix. These NRL films play a crucial role in improving the interfacial bonding between the BA particles and the cement paste, resulting in a more cohesive and compact microstructure. These findings were also reported in previous work on NRL-modified cement pastes [38, 39]. The enhanced interfacial bonding can be attributed to the chemical compatibility and attractive forces between the NRL films and the cement hydration products. The improved interfacial bonding and bridging mechanism in the aggregate and cement matrix enhanced mechanical properties such as compressive and flexural strengths (Figures 4 and 5) by providing a stronger and more cohesive network within the concrete.

Moreover, the NRL films act as stress-absorbing and crack-bridging media within the concrete matrix. When the concrete is subjected to loading, the NRL films can deform and stretch, absorbing the stresses and redistributing them across the matrix. This mechanism helps prevent the initiation and propagation of microcracks, leading to improved toughness and durability of the NRL-modified BA concrete, which provides benefits when used as rigid pavement material under cyclic loading.

Comparing the microstructure of 10%BA+1.0%NRL and 20%BA+1.0%NRL mixes (Figures 7-b and 7-e), it was observed that the 20%BA+1.0%NRL mix exhibited a slightly denser and more homogenous microstructure than the 10%BA+1.0%NRL mix. This observation was consistent with the slightly higher compressive and flexural strengths reported for the 20%BA+1.0%NRL mix compared to the 10%BA+1.0%NRL mix. The improved microstructure and mechanical properties of the 20%BA+1.0%NRL mix can be attributed to the optimized combination of BA and NRL, which synergistically affects the hydration process and the development of a strong and compact cement matrix.

While incorporating NRL at an optimal dosage (1.0% by weight of cement) enhanced the microstructure and mechanical characteristics of BA concrete mixes, excessive NRL content (2.0% by weight of cement) led to a reduction in strength. This strength reduction could be attributed to the formation of larger and more numerous NRL films in the cement matrix. Excessive NRL content can result in the agglomeration of NRL particles and the formation of thicker NRL films, which may disrupt the continuity of the cement matrix and create weak zones. These weaker regions can act as stress concentrations and potential sites for crack initiation, resulting in a decrease in the overall mechanical strength. These findings emphasize the importance of optimizing the NRL content to achieve the desired balance between microstructural enhancement and mechanical performance in NRL-modified BA concrete mixes when used as rigid pavement materials.

5. Mineralogical Analysis

The X-ray diffraction (XRD) analysis provides insights into details on the crystalline phases present in the cementitious materials, which are indicative of the chemical reactions occurring during the process of hydration and the subsequent aging of the concrete. The technique of XRD was employed to assess the crystalline phase compositions of the control mix and the NRL-modified concrete mixes with 10%BA and 20%BA and varying NRL content.

Figure 8 shows the XRD pattern of the control mix, after 28 days of curing. The XRD investigation detected considerable crystalline phases inside the cement matrix. The major peaks identified in the XRD pattern correspond to quartz (SiO_2), calcite ($CaCO_3$), and calcium hydroxide ($Ca(OH)_2$).

Quartz is a prevalent mineral found in natural aggregates, such as sand and gravel, which are used in the manufacture of concrete. The presence of quartz peaks observed in the XRD patterns of the control mix suggests that siliceous aggregates were included in the concrete mix design. Calcite is a crystalline form of calcium carbonate, and the presence of calcite peaks in the XRD pattern indicated that some degrees of carbonation may have occurred in the control mix during the curing process. Calcium hydroxide (portlandite) is a primary hydration product of Portland cement. The presence of calcium hydroxide peaks in the XRD pattern demonstrated the advancement of cement hydration, playing a role in the enhancement of strength of the control mix. The XRD pattern of the control mix serves as a benchmark for comparing the crystalline phases and their relative intensities with those of the NRL-modified BA concrete mixes.

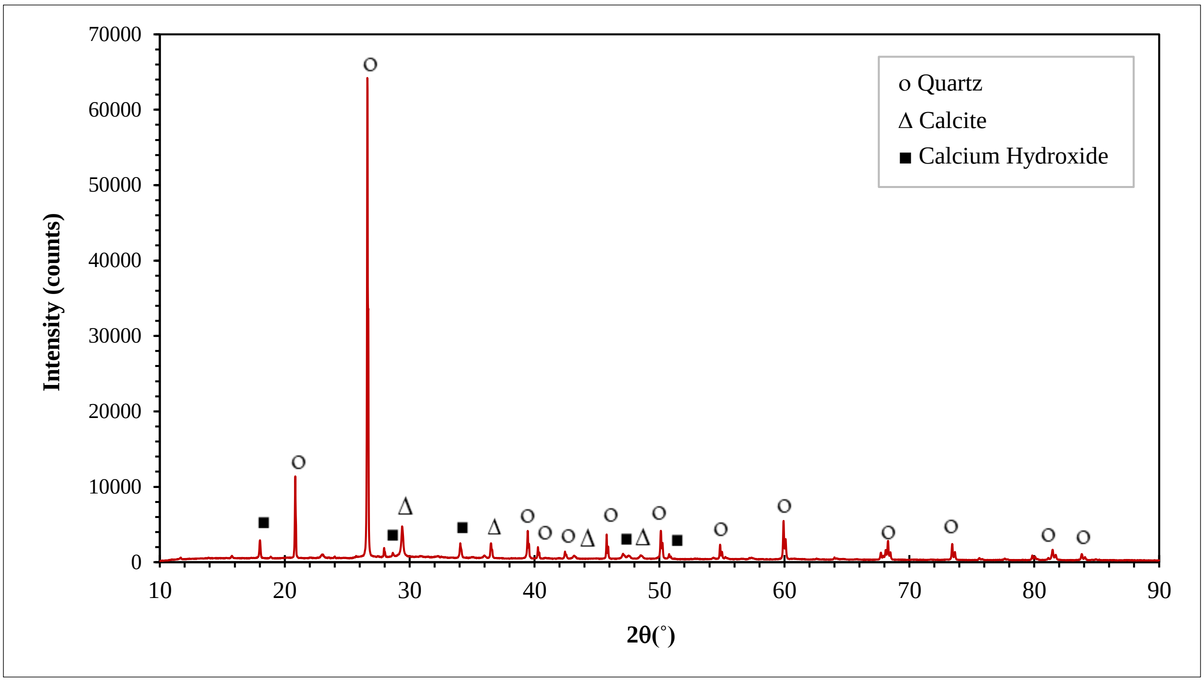
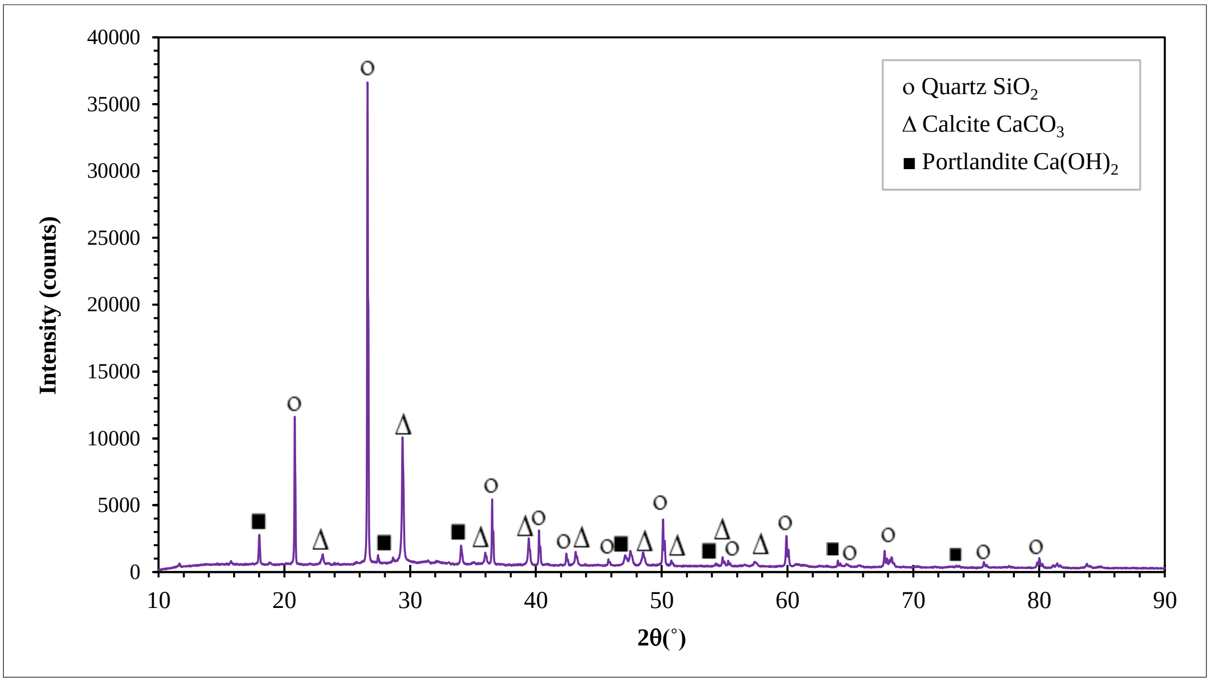
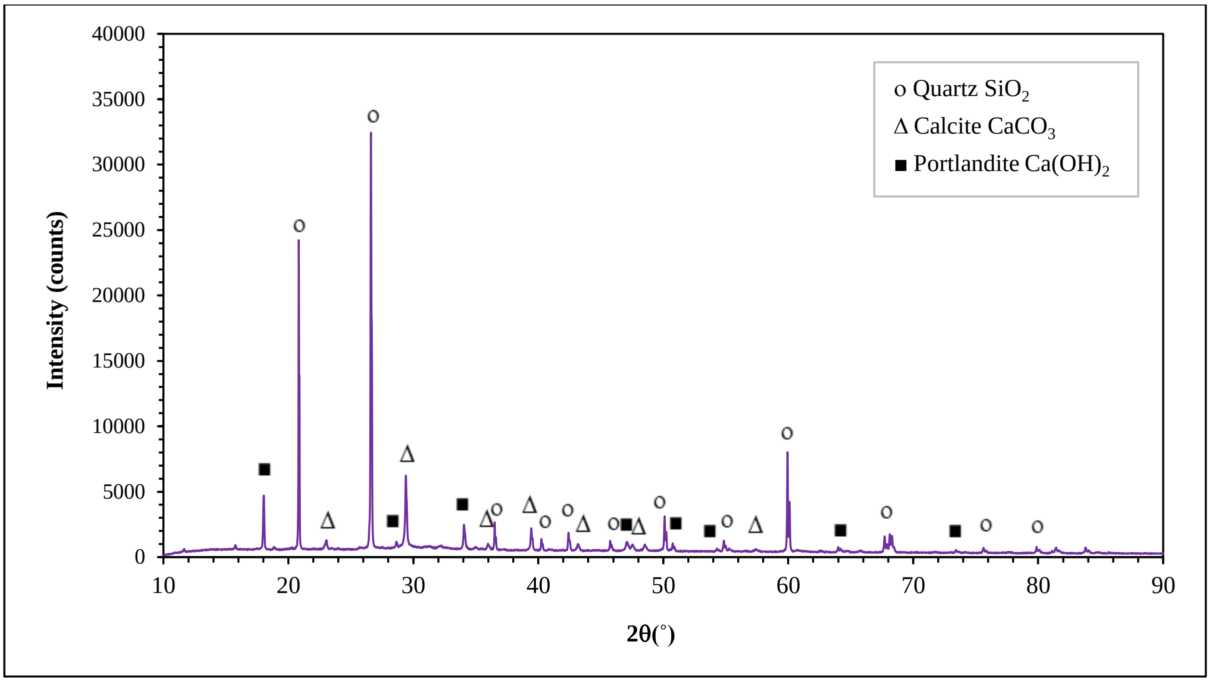


Figure 8. XRD pattern of a control sample

Figure 9 presents the XRD patterns of concrete mixes incorporating 10%BA as a partial substitute for river sand and the NRL at a dosage of 1.0% and 2.0% by weight of cement, respectively. The XRD patterns of 10%BA+1.0%NRL (Figure 9-a) and 10%BA+2.0%NRL (Figure 9-b) mixes exhibited crystalline phases similar to the control mix, including quartz, calcite, and portlandite. However, some differences in the relative magnitudes of the peaks could be observed.



(a)



(b)

Figure 9. XRD pattern of a) 10%BA+1.0%NRL sample, b) 10%BA+2.0%NRL sample

In the XRD pattern of the 10%BA+1.0%NRL mix (Figure 9-a), the intensity of the quartz peaks was considerably lower than that of the control mix. The decrease in quartz intensity could be related to the partial replacement of river sand with BA, which has a different mineralogical composition. The presence of BA in the mix may have diluted the quartz content, resulting in lower peak intensities.

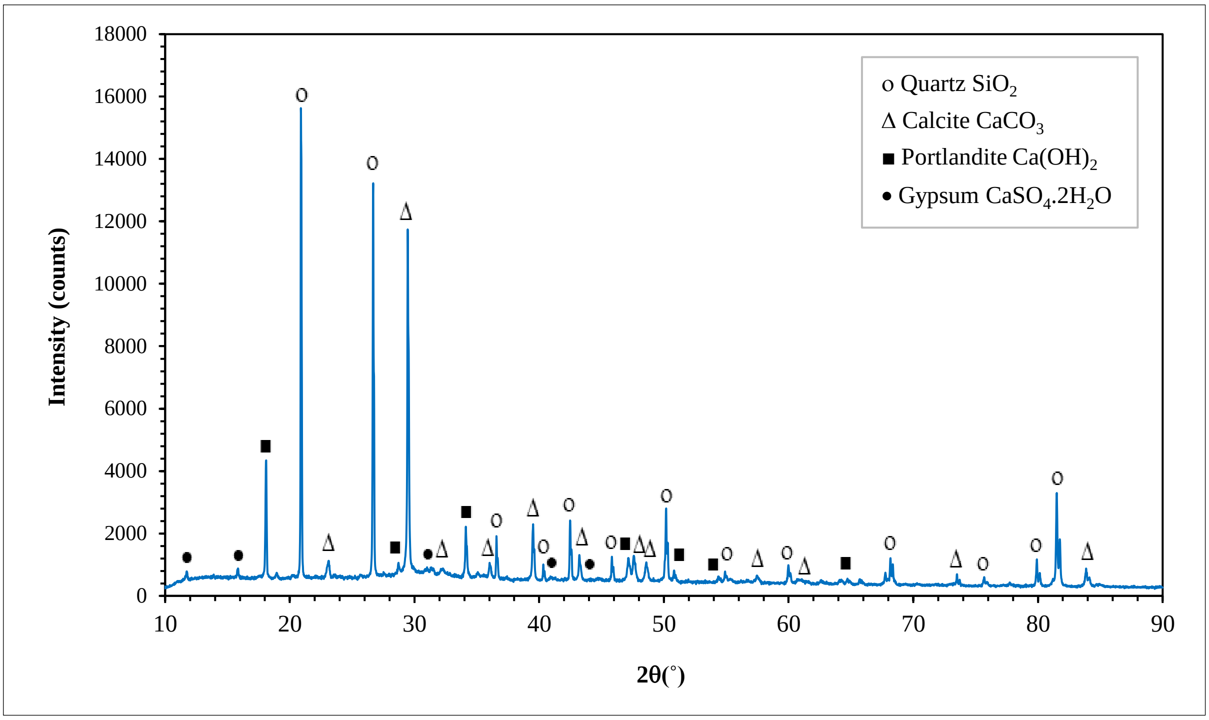
The calcite peaks in the 10%BA+1.0%NRL mix appeared to be slightly more intense compared to those in the control mix. This increase in calcite intensity may be due to the amount of calcium carbonate in the BA or the potential influence of cement hydration products, leading to the formation of additional calcite [41, 42]. The intensities of the portlandite peaks in the 10%BA+1.0%NRL were marginally altered compared to those in the control mixture, indicating that the incorporation of BA and NRL at these dosages slightly affected the formation of calcium hydroxide during cement hydration and hence strength development.

In the XRD patterns of the 10%BA+2.0%NRL (Figure 9-b), the intensities of the quartz, calcite, and portlandite peaks appeared to be lower compared to those of the 10%BA+1.0%NRL mix. This decrease in peak intensities may be ascribed to the increased dosage of NRL in the mix. The excess NRL content in the 2.0%NRL mix might disrupt the proper formation and growth of the crystalline phases, such as portlandite and calcite, which are essential for strength development.

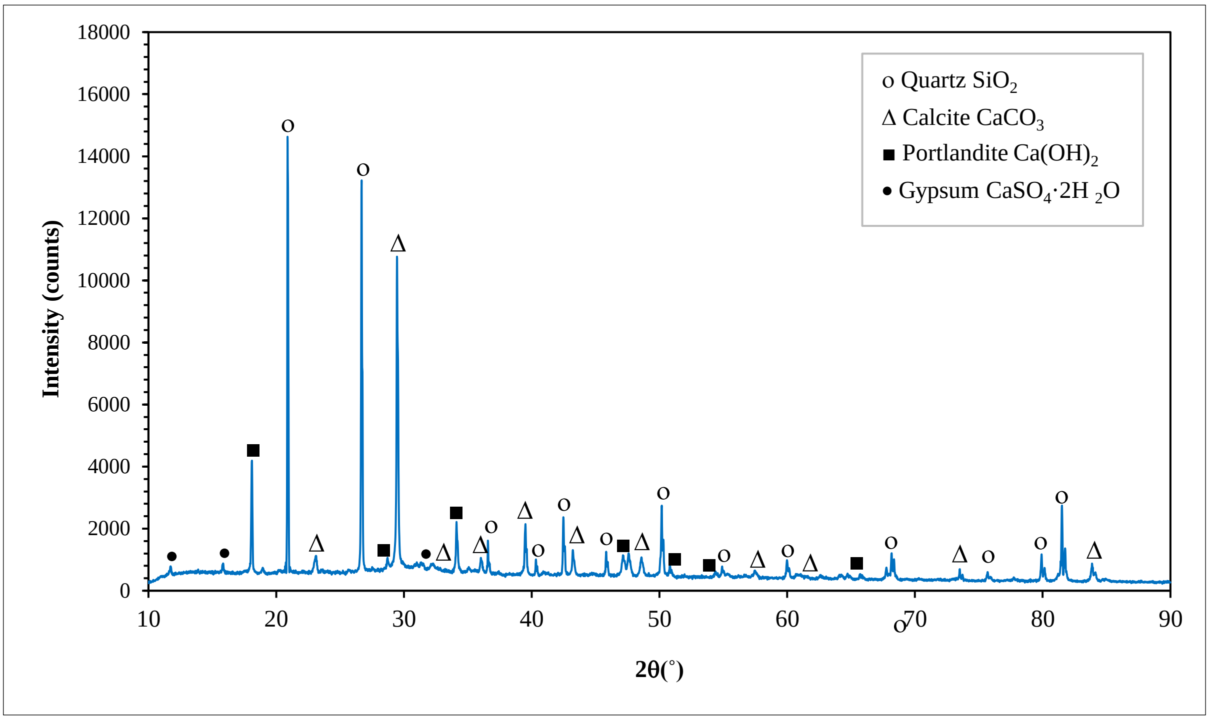
Figure 10 presents the XRD patterns of NRL-modified 20%BA concrete mixes at 1.0% and 2.0%NRL dosages. The gypsum peaks (CaSO4.2H20) were notably detected in the XRD patterns of the 20%BA mixes when compared to the 10%BA mixes. The presence of gypsum in the 20%BA mixes could be attributed to the higher proportion of BA replacement, which likely enhanced the presence of sulfates in the cement matrix [41, 43]. The presence of gypsum in the 20%BA+1.0%NRL mix (Figure 10-a) might contribute to the improved mechanical properties of the concrete.

The gypsum peaks in the 20%BA+1.0%NRL mix were more prominent compared to those in the 20%BA+2.0%NRL mix, indicating that the 1.0%NRL dosage might facilitate the formation of an optimal amount of gypsum, which could contribute to the enhanced strength properties. On the other hand, the XRD pattern of the 20%BA+2.0%NRL mix (Figure 10-b) showed lower intensities of quartz, calcite, and portlandite peaks compared to the 20%BA+1.0% mix. The decrease in peak intensities could be related to the disruptive impact of the excessive NRL content (beyond the optimal 1.0% NRL dosage) on the crystalline phases, as discussed earlier. As a result, the compressive and flexural strengths of the BA concrete mixes with a higher dosage of NRL were found to be reduced.

Comparing the 20%BA mixes with the 10%BA mixes, it was evident that the incorporation of a higher percentage of BA (20%) influenced the formation of gypsum, which was not present in the 10%BA mixes. The presence of gypsum in the 20%BA mixes, particularly in the 20%BA+1.0%NRL mix, might play a crucial role in the improved mechanical characteristics of the concrete. Furthermore, the XRD patterns of the 10%BA mixes showed a more pronounced reduction in peak intensities when the NRL dosage was increased from 1.0% to 2.0%, compared to the 20%BA mixes. This implied that the disruptive effect of excess NRL on the crystalline phases might be more significant in the 10%BA mixes, leading to a slightly higher decrease in strength properties when the NRL dosage was increased.



(a)



(b)

Figure 10. XRD pattern of a) 20%BA+1.0%NRL sample, b) 20%BA+2.0%NRL sample

From the microstructural and mineralogical analyses, the BA replacement and additional NRL content were found to be remarkable in influencing the microstructural and mechanical properties of the NRL-modified BA concrete. The optimal 1.0% NRL content was determined to yield the highest mechanical strength among the NRL dosages for both 10%BA and 20%BA mixtures. In addition, the optimal combination of BA replacement level (20%) and NRL dosage (1.0%) in the 20%BA+1.0%NRL mix has resulted in a well-developed microstructure, as evidenced by the dense matrix in the SEM image and balanced properties of key crystalline phases in the XRD patterns. These findings demonstrate the potential of optimizing the BA and NRL contents to achieve superior mechanical properties in NRL-modified BA concrete mixes.

6. Conclusions

This study investigated the effects of incorporating BA as a substitute for river sand and natural rubber latex (NRL) as a modifier on the mechanical and microstructural characteristics of concrete for sustainable rigid pavements. The results demonstrated the potential of using NRL-modified BA concrete as an environmentally sustainable and high-performing substitute to conventional concrete in pavement construction. The primary conclusions derived from this research can be succinctly outlined as follows:

- The compressive strength of BA concrete dropped with the amount of BA content increased, while incorporating NRL at an optimal dosage of 1.0% significantly improved the compressive strength of both 10%BA and 20%BA mixes. The addition of NRL further enhanced the flexural strength, with the 10%BA+1.0%NRL and 20%BA+1.0%NRL mixes exhibiting superior performance compared to their counterparts without NRL and the control mix. At the optimal 1.0%NRL dosage, the NRL-modified BA concrete mixes had mechanical strength surpassing the control mix and meeting the minimum requirement (compressive strength is greater than 32 MPa and flexural strength is greater than 4.2 MPa) for concrete pavement material set by the DOH, Thailand.
- SEM analysis exhibited that NRL-modified BA concrete had a denser and more compact microstructure compared to BA concrete (without NRL). The formation of thin NRL films enhanced the interfacial bonding between BA particles and the cement phase, leading to a more cohesive matrix. The NRL films also acted as stress-absorbing and crack-bridging agents, enhancing the toughness and durability of the concrete.
- XRD analysis demonstrated the presence of key crystalline phases, including quartz, calcite, and portlandite, in all mixes. The incorporation of BA and NRL influenced the relative intensities of these phases. The 20%BA+1.0%NRL mix exhibited an optimal balance of crystalline phases, contributing to its superior mechanical properties.
- Excessive NRL content led to the formation of larger and more numerous NRL films detected by SEM analysis, which disrupted the continuity of the cement matrix and created weak zones in the interfacial transition zone. XRD analysis also confirmed that the mixes with excessive NRL content led to lower intensities of quartz, calcite, and portlandite peaks, which might distribute the proper formation and growth of the essential crystalline phase and hence reduce the overall mechanical strength of the concrete.

This study provides crucial insights into the advancement of eco-friendly and high-performing concrete materials for sustainable rigid pavements. The incorporation of waste materials such as BA and natural modifiers like NRL offers an optimistic solution to reducing the environmental impact of the construction sector while still satisfying the increasing need for resilient and durable infrastructure.

7. Declarations

7.1. Author Contributions

Conceptualization, M.H. and S.H.; methodology, K.K., M.H., and S.H.; validation, A.S., A.B., T.W., and V.P.; formal analysis, K.K. and S.S.; investigation, K.K., S.S., and B.R.; resources, M.H., S.H., and A.S.; data curation, V.P.; writing—original draft preparation, K.K. and M.H..; writing—review and editing, S.H. and V.P.; visualization, A.S., A.B., T.W., and V.P.; supervision, M.H.; project administration, S.H.; funding acquisition, M.H. and S.H. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

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