Jurnal Kejuruteraan 38(1) 2026: 241-250
https://doi.org/10.17576/jkukm-2026-38(1)-23

Effect of Modified Styrene Butadiene Rubber on Mechanical and Durability Properties of Hybrid Fiber-Reinforced High-Performance Concrete with Fly Ash and Nano Silica

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Received 15 April 2025, Received in revised form 13 September 2025
Accepted 13 October 2025, Available online 30 January 2026

ABSTRACT

Concrete structures are frequently exposed to aggressive environments, particularly infrastructure applications located in coastal areas, saline clays, and acidic soils. These harsh conditions speed up deterioration, reduce durability, and lead to frequent, costly repairs. Conventional concrete often cannot handle these environments over time, especially when high performance is required. These challenges highlight the growing demand for advanced, durable, and sustainable concrete materials. Therefore, this study investigates the effect of modified Styrene Butadiene Rubber (SBR) on the mechanical and durability properties of high-performance concrete reinforced with hybrid fibers. The concrete mix included steel fibers, polypropylene fibers, high-volume fly ash, and nano silica. SBR was added at 0% to 15% by weight of cement, with 2.5% identified as the optimal dosage based on fresh and hardened performance. Results indicate that SBR significantly improved workability, increasing the slump from 20 mm (control) to 95 mm (15% SBR). At 2.5% SBR, compressive strength increased by 4.2% at 7 days and 3.3% at 28 days. Flexural strength improved by 34.8% at 7 days and 18.4% at 28 days, while tensile strength increased by 21% and 25%, respectively. Durability also improved, with chloride penetration reduced by 15.2%, water penetration by 35.6%, and water absorption by 66.7%. These enhancements confirm that modified SBR, in combination with hybrid fibers and supplementary cementitious materials, improves both mechanical and durability performance. The addition of 2.5% SBR enhances both mechanical and durability properties of concrete, demonstrating optimal performance at this concentration.

Keywords: Styrene butadiene rubber; high volume fly ash; nano silica; polypropylene fiber

INTRODUCTION

Concrete structures, particularly in infrastructure applications such as tunnels, marine structures, and underground foundations are often exposed to harsh environments like saltwater, acidic soils and saline clays. These harsh conditions compromise durability, reduce service life, and increase maintenance demands. As infrastructure demands evolve, the need for advanced, durable, and sustainable concrete materials becomes more critical.

This study proposes the development of an innovative concrete mix, high-strength high-volume fly ash nano-silica (HSHVFANS) concrete modified with Styrene Butadiene Rubber (SBR), steel fibres, and polypropylene fibres to improve durability, chemical resistance, and mechanical strength under severe environmental conditions. The incorporation of industrial by-products such as fly ash and nano-silica offers a sustainable approach to concrete production while enhancing its mechanical performance and microstructural integrity. Replacing a portion of cement with fly ash reduces the carbon footprint and improves workability and long-term durability. However, high-volume usage of fly ash can lead to reduced early-age strength. To mitigate this limitation, supplementary materials such as nano-silica, steel fibres, and polymer modifiers (e.g. Styrene Butadiene Rubber, SBR) are often introduced. Nano-silica, due to its high surface area and reactivity, significantly enhances the pozzolanic reaction, leading to improved microstructure, compressive strength, and durability, even at early ages. This makes it an ideal complement to fly ash in the development of sustainable, high-performance concrete. By accelerating pozzolanic activity and densifying the cement matrix, nano-silica plays a critical role in restoring and enhancing early-age strength (Ibrahim et al. 2012).

The addition of SBR into concrete has also garnered attention for its ability to improve flexibility, impermeability, and resistance to chemical attack. Idrees et al. (2021) evaluated the influence of varying SBR contents and found that SBR-modified concrete demonstrated enhanced flexural strength, adhesion, and impermeability. Soni and Joshi (2014) similarly reported improvements in compressive and flexural strength, with 15% SBR content yielding optimal performance. Moreover, SBR has been shown to significantly reduce chloride ion permeability (up to 67%), drying shrinkage (by 53%), and expansions due to alkali-silica reactions and sulphate attacks (by 57% and 73%, respectively) (Idrees et al. 2022). However, the effectiveness of SBR is dosage-sensitive. While moderate amounts contribute to performance enhancement, excessive SBR incorporation may reduce compressive strength. Essa and Hassan (2008) reported that increasing SBR content in cement mortar resulted in a decline in compressive strength and shortened setting times. Yao and Ge (2012) also found that while SBR improved impermeability, its influence on compressive strength was either minimal or negative. Thus, determining the optimal dosage is essential to balancing strength and chemical resistance.

To further strengthen the mechanical behaviour of concrete, steel fibres and polypropylene fibres are employed. These fibres are known to improve tensile strength, crack control, and impact resistance, features particularly important for tunnel lining segments which undergo stresses during manufacture, transport, and service life. Additionally, high-performance concrete systems, such as those containing HSHVFANS, have shown superior performance in high-temperature scenarios. Ibrahim et al. (2012) observed that concrete containing fly ash and nano-silica exhibited decreased pore sizes and enhanced residual strength at 700°C due to new binding phase formations. Alhawat et al. (2021) demonstrated that such high-strength concrete panels outperformed other formulations when exposed to tunnel fire temperatures up to 1100°C.

Considering these findings, the present study aims to optimize the mix design of high-strength high-volume fly ash nano-silica (HSHVFANS) concrete by incorporating Styrene Butadiene Rubber (SBR) to enhance both durability and mechanical performance. This work focuses on the development and characterization of SBR-modified HSHVFANS concrete tailored for infrastructure applications subjected to aggressive environmental conditions, such as tunnel linings exposed to acidic soils, coastal regions, and saline clays. The integration of these materials is expected to improve resistance to chemical attack and elevated temperatures while maintaining high compressive strength. This dual enhancement is critical for extending the service life and structural integrity of tunnel systems operating under harsh conditions.

In line with these objectives, the study evaluates the performance of SBR-enhanced HSHVFANS concrete incorporating hybrid fibres. Both fresh and hardened properties are assessed, including workability, compressive strength, splitting tensile strength, flexural strength, water absorption, water permeability, and chloride ion penetration resistance, to determine the suitability of the proposed mix for use in chemically and thermally aggressive environments.

METHODOLOGY

MATERIALS

The materials used in this study were carefully selected to produce high-performance concrete incorporating industrial by-products such as fly ash and nano-silica, polymeric modifiers like Styrene Butadiene Rubber (SBR), and reinforcement materials including steel fibres and polypropylene fibres. The primary binder was Portland Composite Cement (CEM I 52.5 N), supplied by YTL Cement Marketing Sdn. Bhd., which conformed to MS EN 197-1:2014 standards. This cement exhibited a fineness of 380 m^2/kg, a density of 3.82 g/cm^3, and setting times of 120 minutes (initial) and 180 minutes (final), making it well-suited for high-performance applications. Crushed granite with a particle size range of 4–20 mm was used as the coarse aggregate. Prior to use, the aggregates were thoroughly washed to remove surface impurities and oven-dried to ensure precise batching and optimal bonding with the cement matrix. Natural river sand, with a maximum particle size of 4.75 mm, served as the fine aggregate. Its grading was verified through sieve analysis in accordance with BS EN 933-1:2012, and it was also oven-dried to maintain consistency in the mix.

To enhance sustainability and improve long-term durability, Class F fly ash sourced from Kapar Stesen Jana Kuasa Letrik was used as a partial cement replacement. Additionally, nano-silica supplied by Levasil was incorporated to improve microstructural development and early-age performance. The nano-silica featured a SiO_2 content of 29.4–31.5 wt%, a specific surface area of 250 m^2/g, and a density between 1.200 and 1.216 g/cm^3. Its inclusion aims to refine the pore structure, enhance compressive strength, and reduce permeability, contributing to the overall durability of the concrete.

In addition, Styrene Butadiene Rubber (SBR) latex, obtained from BASF Malaysia (Styrofan D 623 na), was added as a polymer modifier. The SBR had a solid content of 50–52%, a pH value of 8.0–10.0, and a viscosity of approximately 70 mPa·s at 23°C. Known for enhancing tensile and flexural strength, reducing shrinkage, and improving resistance to acids, oils, and salts, SBR played a critical role in increasing the concrete's resilience under aggressive environmental conditions. The steel fibres and polypropylene fibres used in this study were commercially manufactured and purchased from industrial suppliers. These fibres were not sourced from recycled or waste materials, ensuring consistency in quality and compliance with standard specifications for concrete reinforcement.

CONCRETE MIX DESIGN

The proportions for the control high-volume fly ash nanosilica (HVFANS) mix were determined based on the approved patent of HVFANS concrete under file name MY-163281-A (Alhawat et al. 2021). This mix includes Portland cement content of 225.8 kg/m^3 which represent 45% of the mix, a water to cement ratio of 0.34, fly ash content of 278 kg/m^3 (52.5%), nanosilica content of 26.56 kg/m^3 (2.5%), polypropylene fiber at 1%, steel fiber at 1%, and a superplasticizer (SP) dosage ranging from 0.4-2% by mass of Portland Cement.

For other materials, the mix proportions align with those of the control HVFANS with the addition of Styrene Butadiene Rubber with different proportions (2.5%, 5%, 7.5%, 10%, 12.5% and 15%). The concrete mixing process was adhere to BS 1881-125:2013. Table 1 shows the details of the SFPFR-HVFANS-SBR concrete mix proportions, incorporating Styrene Butadiene Rubber.

TABLE 1. Mix Proportions of Concrete (kg/m^3)

Sample ID	Styrene Butadiene Rubber	Fly Ash	Nano Silica	Portland Cement	Steel Fiber	Polypropylene Fiber	Coarse Aggregate	Fine Aggregate	Water	SP
C0	0.0	278	26.56	225.8	78.5	1	942.6	682.01	138.0	6
C1	5.65	278	26.56	220.16	78.5	1	942.6	682.01	137.0	6
C2	11.29	278	26.56	214.51	78.5	1	942.6	682.01	136.0	6
C3	16.94	278	26.56	208.87	78.5	1	942.6	682.01	135.4	6
C4	22.58	278	26.56	203.22	78.5	1	942.6	682.01	134.5	6
C5	28.23	278	26.56	197.58	78.5	1	942.6	682.01	133.5	6
C6	33.87	278	26.56	191.93	78.5	1	942.6	682.01	130.2	6

SAMPLE PREPARATION AND TEST METHOD

Various experimental tests were conducted to assess the workability, mechanical strength and durability of the samples. The slump test, compressive strength test, tensile strength test, flexural strength test, rapid chloride penetration test, water penetration test and water absorption test are all included in these measures of concrete properties with incorporation of Styrene Butadiene Rubber. Six mix designs with varied Styrene Butadiene Rubber content of 2.5%, 5%, 7.5%, 10%, 12.5% and 15% were tested. The compressive strength and workability of the samples were first examined to determine the optimum SBR percentage that delivers the highest strength. Once the optimum SBR percentage was identified, additional tests like flexural strength, tensile splitting strength, rapid chloride penetration, water penetration, and water absorption were conducted to evaluate the mechanical and durability properties of the concrete. Table 2 shows the number of samples for each test conducted at 7 and 28 days of curing.

TABLE 2. Number of Samples for Each Test At 7 and 28 days of Curing

	Percentage of Styrene Butadiene Rubber (%)	Number of Samples	
		Curing Age (Days)	
		7 days	28 days
Compression Strength	0.0% (C0)	3	3
	2.5% (C1)	3	3
	5.0% (C2)	3	3
	7.5% (C3)	3	3
	10.0% (C4)	3	3
	12.5% (C5)	3	3
	15.0% (C6)	3	3
Split Tensile Strength	Control	3	3
	Optimum	3	3
Flexural Strength	Control	3	3
	Optimum	3	3
Rapid Chloride Penetration	Control	-	3
	Optimum	-	3
Water Penetration	Control	-	3
	Optimum	-	3
Water Absorption	Control	-	3
	Optimum	-	3

The workability of the concrete mix was assessed using the slump test in accordance with BS EN 12350-2:2019. The mechanical performance of the concrete was evaluated through compressive strength, split tensile strength, and flexural strength tests. Additionally, rapid chloride penetration, water penetration, and water absorption tests were conducted for durability assessment.

The compressive strength test assesses the mechanical characteristics of concrete containing Styrene Butadiene Rubber added in 2.5% to 15% proportions. Six mix designs were prepared, with three samples each, tested at 7 and 28 days which involved testing hardened concrete using 150 × 150 × 150 mm test cubes. Testing surfaces must be clean, and the load applied perpendicularly. Samples must be centered accurately, and a loading rate of 13.5 kN/s applied, recording the maximum load in kN. Table 2 shows the number of samples for compressive strength test.

The split tensile strength test, per BS EN 12390-6:2006, uses 100 mm diameter and 200 mm height cylindrical concrete Samples. Based on compressive strength results, the optimum mix for tensile testing is identified. Three samples each of control and optimum mixes are tested after 7 and 28 days of curing. Samples are marked for load application, ensuring alignment and cleanliness before testing. The load is applied centrally and parallel between the plates at a constant rate of 0.04 MPa/s to 0.06 MPa/s until failure.

The flexural strength test, as specified by the British Standard BS EN 12390-5:2019, using prism of 100 × 100 × 500 mm concrete beam samples. Based on compressive strength results, the optimum mix is identified for sample preparation. Tests are conducted after 7 and 28 days of curing. Three samples of each of the control and optimum mixes are prepared to determine average strength values. The test employs a three-point (center point) loading method as specified in the standard.

Rapid chloride penetration test (RCPT) is conducted to assess the permeability of concrete to chloride ions, following the guidelines of ASTM C1202. Concrete samples of 100 mm diameter and 50 mm thickness are used. The RCPT is performed by applying a voltage across the concrete sample and measuring the electrical charge passed through the sample, which helps determine its resistance to chloride ion penetration. The test is carried out at room temperature, and the maximum charge passed is recorded. The lower the charge, the better the resistance to chloride ingress, which is critical for concrete exposed to harsh environments.

The water penetration test is performed to evaluate the ability of concrete to resist water infiltration, following BS EN 12390-8:2009. In this test, concrete cubes of 150 mm dimensions are subjected to a constant water pressure for a set duration. The depth of water penetration is measured, with lower penetration depths indicating better resistance to water ingress. The sample is placed in a testing apparatus where water is applied to one side, and the depth of penetration into the concrete is recorded after a defined period.

The water absorption test is carried out to measure the ability of concrete to absorb water, as per BS 1881-122:2011 +A1:2020. Concrete cylinders of 75 mm diameter are immersed in water for a specified time, and the increase in mass is measured. The percentage of water absorbed is calculated based on the change in mass, and this data provides insight into the concrete's porosity and permeability. Lower absorption rates indicate better durability against environmental conditions.

RESULTS AND DISCUSSIONS

WORKABILITY

The experiment demonstrated a clear trend of increasing workability in concrete with higher SBR content as shown in Figure 1. The slump values for samples C0 to C6 increased from 20 mm (no SBR) to 95 mm (15% SBR), showing a steady improvement in consistency as the SBR percentage rose. For instance, C1 with 2.5% SBR had a slump of 25 mm, and C4 with 10% SBR reached 80 mm. The maximum slump of 95 mm occurred at 15% SBR in C6. These results align with studies by Qadri et al. (2020) and Shete (2014), which also observed increased slump values with higher SBR content, attributed to SBR's plasticizing effects that reduce internal friction and improve flowability. The study highlights the importance of optimizing SBR dosage for enhanced workability without compromising performance.

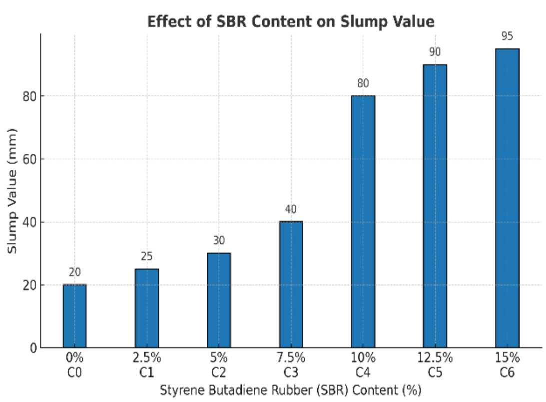

FIGURE 1. Slump Value with Varying SBR Content(%)

COMPRESSIVE STRENGTH

For compressive strength results with various percentage of Styrene Butadiene Rubber (SBR) ranges from 2.5% to 15% is shown in Figure 2. The results showed that with the increasing percentage of SBR reduced the compressive strength of concrete, especially at higher percentages. At 7 days, the C1 sample with 2.5% SBR had the highest strength of 58.15 MPa which surpass the compressive strength of control sample, while the sample with 15% SBR (C6) had the lowest at 17.96 MPa. This decline in early strength is consistent with the findings by Ang et al. (2022), who highlighted the impact of the polymer film formed by SBR in delaying the hydration process. This film reduces water availability for cement reactions, leading to lower compressive strength at early curing stages.

At 28 days, the compressive strength follows a similar trend, with the C1 samples recorded higest strength of 67.3 MPa and C6 dropping further to 26.22 MPa. This behavior aligns with the work of Kulsheshta and Rajnish (2022) and Yao and Ge (2012), who also observed reductions in compressive strength with higher SBR percentages. Moderate SBR content (2.5% and 5%) provided a balance, with C1 (2.5% SBR) achieving the highest strength at 67.3 MPa. This improvement is linked to SBR's ability to enhance the concrete's microstructure. However, SBR content above 5% resulted in a decrease in strength, as the negative effects of reduced density and stiffness took over. These findings align with previous research by Ang et al. (2022), Kulsheshta and Rajnish (2022), Yao and Ge (2012), and Qadri et al. (2020).

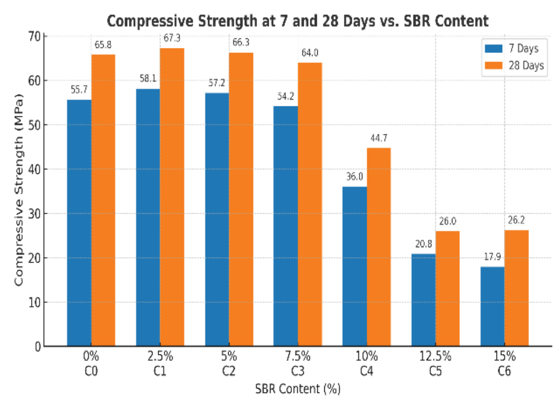

FIGURE 2. Compressive strength with Varying SBR Content (%)

The reduction in compressive strength at higher SBR percentages, such as 12.5% (C5) and 15% (C6), is attributed to the excessive polymer disrupting the concrete's matrix and weakening its structure. This aligns with findings by Palson and Vividelli (2020), that the compressive strength of concrete generally followed a decreasing trend with the increase of the latex dosage. The compressive strength at 28 days decreased at the latex content of 5%, 10%, and 15%. Careful optimization of SBR content is necessary to balance concrete properties without compromising structural integrity.

The optimum SBR content in this experiment is 2.5% (C1), which provided the highest compressive strength while enhancing the microstructure without excessive disruption. The results of compressive strength for further testing with 2.5% SBR is shown in Figure 3. At 7 days, modified samples with 2.5% SBR achieved 58.07 MPa, surpassing the control samples at 55.73 MPa. At 28 days, modifies samples reached 67.76 MPa, while the control sample had 65.57 MPa. These results confirm that 2.5% SBR improves compressive strength by enhancing the bonding within the concrete matrix, balancing strength and workability. These findings validate the use of SBR-modified concrete for structural applications and suggest further evaluation through additional tests like flexural strength and water absorption.

In addition to the influence of SBR, the integration of fly ash, nano-silica, and polypropylene fibres also contributed to the observed compressive strength performance. Fly ash enhanced the long-term strength through its pozzolanic reaction with calcium hydroxide, resulting in additional calcium silicate hydrate (C–S–H) formation and matrix refinement (Shaikh et. al. 2014; Supit & Shaikh, 2015). Nano-silica, due to its ultrafine particle size and high surface area, accelerated early hydration by acting as a nucleation site and micro-filler, improving both early and long-term strength (Tran & Phan, 2024). Polypropylene fibres, although not significantly influencing compressive strength directly, played an important role in mitigating plastic shrinkage cracking and enhancing the integrity of the concrete matrix, especially when used with steel fibres in a hybrid system (Alhozaimy et al. 1996).

The integration of these materials resulted in a concrete system that balanced both strength and durability performance. These materials worked synergistically with SBR to improve matrix cohesion and resistance to microcracking, contributing to the overall strength and durability performance. These combined effects align with the sustainability goals outlined in the study by reducing OPC content and promoting material efficiency.

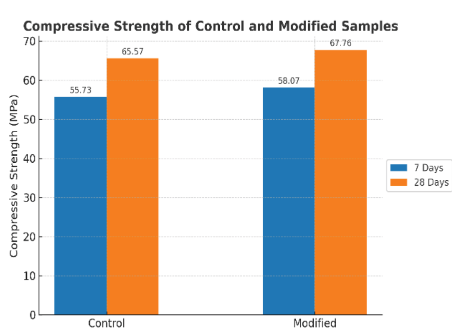

FIGURE 3. Compressive strength of Control and 2.5% SBR-Modified Samples

FLEXURAL STRENGTH

The results from the conducted tests on the flexural strength of beams modified with Styrene Butadiene Rubber (SBR) 2.5% is shown in Figure 4. From the test results, the control beam samples without SBR exhibited an average flexural strength of 9.24 MPa at 7 days, which increased to 12.28 MPa at 28 days. Meanwhile, the modified beam samples containing 2.5% SBR demonstrated a significant improvement, achieving an average flexural strength of 12.41 MPa at 7 days and further increasing to 14.53 MPa at 28 days. This confirms the trend observed in previous studies, where SBR incorporation enhanced the flexural strength of concrete due to its ability to improve tensile properties and bond strength.

Comparing these findings with the literature, the results are consistent with studies such as those by Ali et al. (2012) and Qadri et al. (2020). Ali et al. (2012) observed that flexural strength increased with the addition of moderate SBR content (up to 8%), but decreased beyond this level. This trend aligns with compressive strength results, which showed no significant reduction up to 7.5% SBR modification. While Qadri et al. (2020) reported an increase from 1.84 MPa to 2.52 MPa at 5% SBR replacement. Though the current test results do not include higher SBR percentages, they support the notion that even a small percentage of SBR, such as 2.5%, can significantly improve beam strength.

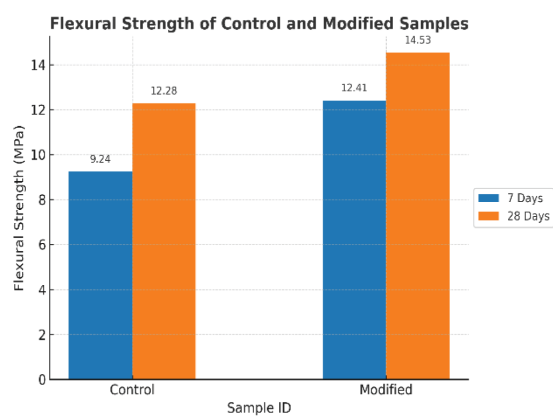

FIGURE 4. Flexural Strength of Control and 2.5% SBR-Modified Samples

However, it is also worth noting that some studies, such as those by Essa and Hassan (2008) and Essa et al. (2012), indicated that while moderate SBR additions improved flexural strength, excessive additions could lead to a decline. This reduction was likely due to an imbalance in the concrete mix, which affected its overall performance. Although the current test results do not cover this decline, they support the general understanding that adding SBR up to a certain level improves flexural strength. Overall, the results are consistent with previous studies showing that SBR enhances flexural strength by improving tensile properties and bond strength. Even at a relatively low percentage of 2.5%, the improvement in flexural strength is evident.

SPLIT TENSILE STRENGTH

The split tensile strength test results in Figure 5 shows that Styrene Butadiene Rubber (SBR) enhances concrete's ability to resist tensile forces. The control samples, without SBR, had an average tensile strength of 5.20 MPa at 7 days, increasing to 7.12 MPa at 28 days. In comparison, the samples with 2.5% SBR demonstrated improved tensile strength, reaching 6.29 MPa at 7 days and further increasing to 7.12 MPa at 28 days. These results align with literature, confirming that SBR improves tensile strength through its adhesive and microstructural bonding properties.

The literature review supports the enhancement of tensile strength with SBR. Qadri (2020) found that replacing 5% of cement with SBR increased tensile strength from 3.57 MPa to 4.3 MPa, with further increases at 10% and 15%. Khan et al. (2020) found that tensile strength increased with SBR content up to 15%, but started to decrease at 20%, suggesting that too much SBR can reduce tensile strength. The 2.5% SBR content used in the present test falls within this effective range, demonstrating a positive impact without reaching a diminishing point.

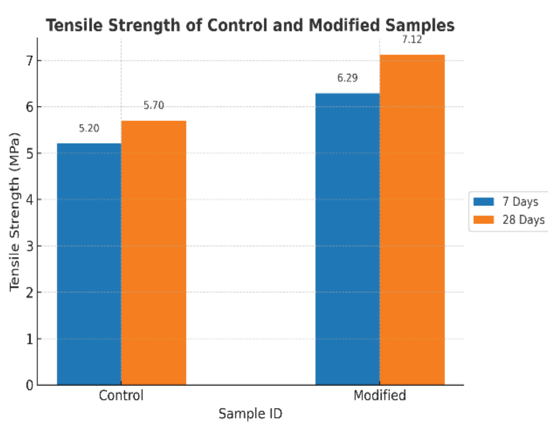

FIGURE 5. Split Tensile Strength of Control and 2.5% SBR-Modified Samples

The results also align with Qadri et al. (2020) observation's that tensile strength initially increases with SBR but then stabilizes at later curing stages. In this test, the modified samples shows a more significant strength gain between 7 and 28 days compared to the control samples, confirming that SBR enhances long-term performance by improving tensile stress resistance over time.

RAPID CHLORIDE PENETRATION

Figure 6 shows the Rapid Chloride Penetration Test (RCPT) results which provide insight into the durability of concrete concerning chloride ion permeability. The control samples exhibited an average charge passed of 2532 Coulombs, while the modified samples with 2.5% SBR showed a lower charge passed of 2148 Coulombs. This indicates that the SBR-modified concrete had reduced chloride permeability, which suggests an improvement in resistance to chloride ion penetration.

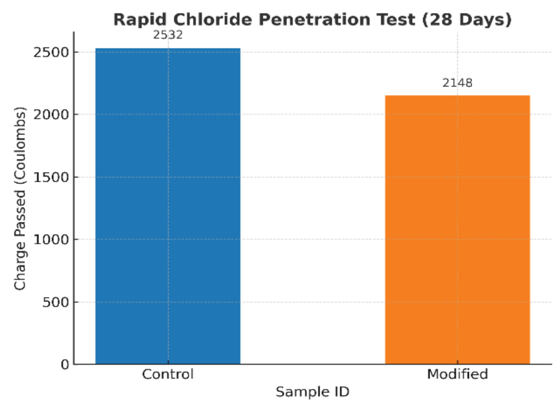

FIGURE 6. RCPT Results of Control and 2.5% SBR-Modified Samples

Despite the reduction in Coulomb values, both control and modified samples showed relatively high values, which may indicate increased conductivity or pore connectivity within the concrete. This could be due to the presence of steel fibers, which create conductive pathways, resulting in higher Coulomb readings during the Rapid Chloride Permeability Test (RCPT). These fibers might influence the electrical conductivity of the concrete, causing the charge passed to appear higher than expected, even if the actual permeability is lower.

The reduction in Coulomb values for the SBR-modified samples suggests that SBR enhances the concrete's microstructure, likely reducing capillary pore connectivity and improving resistance to chloride ion ingress. This is consistent with the known benefits of polymers in concrete, which help reduce permeability by filling voids and increasing cohesion. However, the steel fibers in both control and modified samples may have contributed to inflated readings, making it more challenging to interpret the chloride resistance accurately.

WATER PENETRATION

The 28-days water penetration test results reveal a significant reduction in water ingress with the incorporation of 2.5% Styrene Butadiene Rubber (SBR) in concrete as shown in Figure 7. The control samples recorded an average water penetration depth of 7.70 mm, whereas the treated samples with 2.5% SBR exhibited a reduced penetration depth of 4.93 mm. This 35.9% decrease in water permeability indicates that SBR enhances the waterproofing properties of concrete, making it more resistant to moisture ingress. This results is in agreement with Diab et al, (2013), stated that the incorporation of SBR latex significantly reduced water penetration depth in concrete. Specifically, the 90-day water penetration depth decreased by 72% and 84% with the addition of 10% and 20% SBR, respectively, compared to unmodified concrete.

The observed reduction in penetration depth can be attributed to the microstructural modifications caused by the addition of SBR. As a polymer, SBR improves the cohesion and bonding of cement particles, leading to a denser concrete matrix with fewer interconnected pores. This effect minimizes the pathways through which water can infiltrate the concrete, resulting in lower permeability and enhanced durability. Additionally, the penetration depths in the modified samples were more consistent (ranging from 4.62 mm to 5.31 mm) compared to the control samples (7.37 mm to 8.29 mm). This indicates that SBR not only reduces permeability but also improves the uniformity of concrete properties, potentially leading to greater reliability and performance in real-world applications.

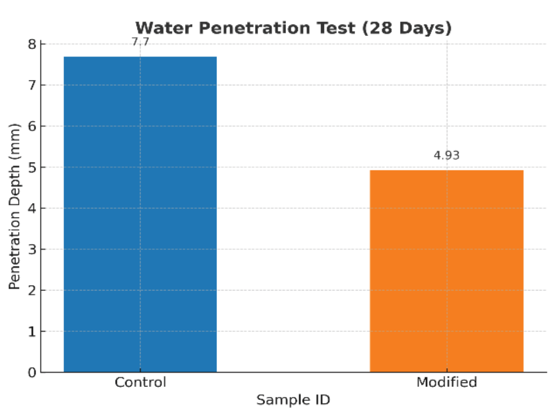

FIGURE 7. Water Penetration Results of Control and 2.5% SBR-Modified Samples

From a durability perspective, reducing water penetration is crucial in mitigating moisture-induced deterioration mechanisms, such as efflorescence, freeze-thaw damage, and reinforcement corrosion. Water ingress is a major contributor to chloride-induced steel corrosion, which compromises the structural integrity of reinforced concrete. The reduced penetration depth in the SBR-treated samples suggests improved resistance to such degradation processes, making the concrete better suited for environments exposed to moisture and aggressive chemicals.

WATER ABSORPTION

The 28-day water absorption test results demonstrate a significant reduction in water absorption with the inclusion of 2.5% Styrene Butadiene Rubber (SBR) in concrete shown in Figure 8. The control samples, which contained no SBR, recorded an average water absorption of 0.90%, while the modified samples with 2.5% SBR exhibited a much lower average absorption of 0.30%. This 66.7% reduction in water absorption highlights the enhanced impermeability of SBR-treated concrete, making it more resistant to water ingress and moisture-related deterioration. Hatungimana et al. (2020) reported that water sorptivity decreased by 6–48% in the SBR latex modified mixtures as compared to 0% SBR mixtures at the 28-day age. The significant decrease of the water sorptivity could be owing to the coagulated polymer filling of the pores, lowering of permeable pores and bridging of the microcracks propagating inside the matrix. The incorporation of SBR into concrete has been shown to decrease water absorption and porosity, thereby enhancing resistance to such degradation processes (Li et al. 2022).

The observed reduction in absorption is attributed to the modification of the concrete's pore structure due to the presence of SBR as a polymeric binder. SBR enhances cohesion within the cementitious matrix, reducing pore connectivity and capillary action that would otherwise facilitate water absorption.

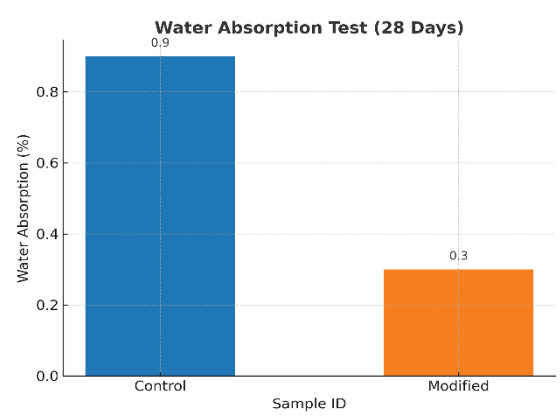

FIGURE 8. Water Absorption Results of Control and 2.5% SBR-Modified Samples

CONCLUSION

This research evaluated the impact of Styrene Butadiene Rubber (SBR) on the mechanical and durability properties of high-performance concrete reinforced with steel fibers, polypropylene fibers, high-volume fly ash, and nano silica. Key properties such as workability, compressive strength, flexural strength, split tensile strength, and durability were assessed.

The results showed that SBR significantly improved workability, with slump values increasing from 20 mm in the control sample to 95 mm at 15% SBR, though excessive SBR content led to bleeding issues. Moderate SBR content (2.5%-5%) enhanced compressive, flexural, and split tensile strengths, but higher SBR dosages (>10%) reduced compressive strength, likely due to disruption of the matrix. At 28 days, the 2.5% SBR-modified sample had the highest compressive strength (67.3 MPa), while 15% SBR resulted in the lowest (26.2 MPa). Flexural and tensile strength improved with 2.5% SBR, demonstrating better crack resistance and tensile stress resistance.

The incorporation of SBR significantly enhanced the durability properties of concrete. SBR-modified samples exhibited a 35.9% reduction in water penetration and a 66.7% decrease in water absorption. Chloride ion permeability was also reduced, with a lower charge passed compared to the unmodified samples. These results confirm that SBR improves concrete's workability, tensile performance, and resistance to moisture and chemical ingress, while preserving structural integrity at optimal dosage levels.

In conclusion, moderate SBR content (2.5%-5%) provides an optimal balance of workability, mechanical strength, and durability, making it ideal for self-compacting concrete and infrastructure applications like tunnel linings and marine structures. However, excessive SBR content should be avoided to prevent reductions in compressive strength and durability concerns.

ACKNOWLEDGEMENT

The authors express their gratitude to the Ministry of Higher Education Malaysia for the financial support through the Fundamental Research Grant (Grant No. FRGS/1/2023/TK01/UKM/01/1) and to the Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, for providing the laboratory facilities.

DECLARATION OF COMPETING INTEREST

None.

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