

Investigation on the Engineering Properties of Bituminous Pavements Incorporating (SBR) Latex

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Abstract - Flexible pavements are extensively used for road transportation, but conventional bituminous mixtures may experience premature deterioration under heavy traffic, temperature variation, moisture exposure and repeated loading. Polymer modification of bitumen is therefore an established approach for improving the balance between stiffness, flexibility, adhesion and resistance to deformation. The present study investigates the engineering performance of bituminous mixes incorporating Styrene-Butadiene Rubber (SBR) latex as an elastomeric modifier. The experimental programme was based on an 80/100 penetration-grade bitumen, coarse aggregate, fine aggregate and stone-dust filler. SBR latex was incorporated at 0%, 3%, 5%, 7% and 9% by weight of bitumen. Aggregate characterization included crushing value, impact value, gradation, shape characteristics, Los Angeles abrasion and specific gravity. Binder characterization included penetration, softening point, ductility and viscosity. The Marshall method was then used to evaluate stability, flow, air voids (Vv), voids in mineral aggregate (VMA) and voids filled with bitumen (VFB). The reported aggregate results indicate an aggregate crushing value of 18.43%, impact value of 24.17% in the consolidated test-results table, Los Angeles abrasion value of 24%, shape index value of 24.23%, and coarse aggregate specific gravity of 2.93. Fine aggregate and stone-dust specific gravities were 2.74 and 2.62, respectively. The base bitumen showed a penetration of 95.66 (0.1 mm), softening point of 48°C, ductility of 67.5 cm and viscosity of 3 s. Marshall stability increased from 8.9 kN for the unmodified mix to a maximum of 15.7 kN at 5% SBR, after which it decreased to 13.6 and 10.9 kN at 7% and 9% SBR, respectively. At 5% SBR, air voids reduced to 3.43%, VMA reached 15.2%, and VFB increased to 77.5%. The attached report identifies 5% SBR latex by weight of bitumen as the optimum content because it produced the most favorable combined Marshall response. The findings demonstrate that controlled SBR modification can substantially improve the load-carrying and volumetric characteristics of the investigated bituminous mixture, while excessive modifier content may adversely affect the balance of binder and aggregate interactions.

Keywords: SBR latex; bitumen; polymer-modified bitumen; Marshall stability; flow; air voids; VMA; VFB; flexible pavement.

1.INTRODUCTION

Road transportation is a major component of economic development and social connectivity, and flexible pavements form a substantial part of the road network. A flexible pavement generally consists of bituminous layers placed over granular pavement layers and a prepared subgrade. The performance of the surfacing is strongly governed by the interaction among aggregate structure, binder rheology, environmental conditions and traffic loading. The attached project report notes that conventional bituminous pavements may require repair and rehabilitation earlier than their intended service period, with heavy traffic and adverse climatic conditions contributing to cracking, rutting, raveling, undulations and shoving.

Bitumen is a viscoelastic material whose response depends on temperature and loading time. A pavement binder must therefore satisfy two apparently competing requirements: adequate stiffness and resistance to permanent deformation at high service temperatures, while retaining sufficient flexibility at low temperatures to reduce cracking. Conventional penetration-grade bitumen does not always provide this balance under increasing traffic demand. Consequently, modifiers such as polymers, synthetic rubber, natural rubber and chemical additives have been investigated to alter the physical and rheological response of bitumen.

Polymer modifiers are commonly discussed as plastomers and elastomers. Plastomers generally increase stiffness and viscosity, whereas elastomers contribute to elastic recovery and flexibility. SBR is an elastomeric synthetic rubber based on styrene and butadiene. The attached report describes SBR as a low-cost modifier used in liquid latex form and reports that it can improve wear resistance, bonding and resistance to cracking. When dispersed through bitumen, polymer chains can form an interconnected structure that modifies the binder response and consequently the engineering performance of the asphalt mixture.

1.2 Problem Statement

Increasing traffic intensity, axle loading and climatic variability place greater demands on conventional flexible pavements. Rutting, fatigue-related cracking, moisture-related deterioration and loss of surface integrity can develop when the

binder–aggregate system does not have sufficient stiffness, adhesion or elastic response. There is therefore a need to evaluate practical and economical modifiers that can enhance mixture performance without requiring major changes to conventional pavement construction practice. The present investigation addresses this requirement by examining SBR latex at several dosage levels and identifying the dosage that provides the most favorable Marshall characteristics.

1.3 Research Aim

The principal aim is to investigate the engineering properties of a bituminous mixture modified with different percentages of SBR latex and to determine the optimum SBR content on the basis of Marshall stability and associated volumetric and deformation characteristics.

1.4 Objectives

- To characterize the coarse aggregate, fine aggregate and filler used in the bituminous mixture.
- To evaluate the penetration, softening point, ductility and viscosity of the base bitumen.
- To prepare conventional and SBR-latex-modified bituminous mixtures containing 0%, 3%, 5%, 7% and 9% SBR by weight of bitumen.
- To determine Marshall stability and flow for each SBR dosage.
- To evaluate air voids, VMA and VFB and examine their variation with SBR content.
- To identify the optimum SBR latex dosage based on the combined Marshall response.

1.5 Significance and Scope

The study is significant because SBR is an elastomeric modifier capable of changing the viscoelastic response of bitumen and the load-transfer behavior of the mixture. The scope is intentionally focused on laboratory characterization and Marshall properties. The results support the selection of an optimum modifier dosage for the investigated materials and mixture proportions; they do not by themselves establish long-term field performance, fatigue life, moisture susceptibility or rutting life under actual traffic. Those aspects require additional testing and field validation.

2. Literature Review

Previous investigations summarized in the attached report demonstrate that polymer and rubber modification can improve the engineering response of bituminous materials. The literature is reviewed below with emphasis on polymer-modified binders, SBR, Marshall performance and related modifiers.

Pareek et al. (2012): A comparison of conventional 60/70 bitumen and PMB-70 was conducted using Marshall-designed bituminous concrete mixes at binder contents of 4.5%, 5.0% and 5.5%. The reported polymer-modified mixture showed improved rutting resistance, indirect tensile strength and resilient modulus, with a reported 27% increase in Marshall stability.

Dewi Sri Jayanthi et al. (2016): SBR was introduced into asphaltic concrete at 0%, 1%, 3% and 5% by mass. Marshall stability, abrasion loss, resilient modulus and dynamic creep were considered. The reported increase in stability from 0% to 5% SBR was 18.8%, while dynamic creep stiffness and resilient modulus also increased.

Martey et al. (2016): The study discussed asphalt rheology and polymer-binder strengthening using SBS. The reported benefits included improved fatigue-cracking resistance, rutting resistance, thermal stiffness, tension-cracking resistance and stripping resistance, particularly under more intense traffic loading.

Chopra (2019): Epoxy-modified bituminous mixtures were evaluated at several epoxy contents using Marshall stability, flow, air voids, VMA, VFB, penetration and softening-point tests. The modified mixtures were reported to show improved stability and flow relative to the conventional mixture.

Veena Raj et al. (2017): Synthetic polypropylene fiber and natural sisal fiber were investigated as bitumen modifiers. The reported optimum contents were 0.5% for polypropylene and 0.3% for sisal, with stability increasing as fiber content was introduced.

Yuanhang et al. (2007): An asphalt emulsion modified using epoxy resin and SBR latex was investigated using penetration, softening-point and ductility tests. The study reported increased softening point and improved mechanical behavior of the modified emulsion.

Upase et al. (2014): SBR latex was investigated in concrete at 10%, 15% and 20% by weight of cement. The reported results showed lower early-age compressive strength but improved later-age strength and reduced water absorption, illustrating the broader potential of SBR to modify cementitious material behavior.

K. V. R. Prasad et al. (2012): Waste plastic bottles were incorporated into 60/70 and 80/100 bituminous mixes. The optimum plastic content was reported as 8%, demonstrating that waste-derived modifiers can substantially alter Marshall stability.

Riara (2019): SBR, waterborne epoxy adhesive and colloidal silica were used individually and in combination in modified bitumen emulsion. Peak bonding strengths were reported at specific modifier dosages, emphasizing that modifier type and dosage must be selected together.

Miah et al. (2015): Different filler materials, including waste concrete dust and brick dust, were compared with conventional fine-sand and stone-dust filler. The results suggested that suitable waste fillers can achieve Marshall properties comparable with conventional filler systems.

Abedini et al. (2016): SBR-modified bitumen emulsion was evaluated at different SBR contents. The reported trends included changes in penetration, softening point and binder stiffness, with an observed performance increase at 6% SBR in that particular system.

Ramadhansyah Putra Jaya et al. (2016): 60/70 bitumen was modified with 0–5% SBR and evaluated for complex shear modulus, ageing, viscosity, penetration and softening point. Increasing SBR was reported to decrease penetration and increase softening point and viscosity, demonstrating the importance of dosage control.

2.1 Research Gap

The reviewed studies show that polymer modification generally improves selected strength, stiffness, adhesion and deformation characteristics, but the magnitude and direction of change depend strongly on binder grade, mixture composition, modifier type, modifier dosage and test method. The attached project specifically evaluates SBR latex at 0–9% in a single 80/100-grade bitumen system and combines binder characterization with aggregate characterization and Marshall volumetric analysis. This integrated evaluation provides a practical basis for identifying a dosage that balances stability, flow, and volumetric properties rather than relying on a single performance indicator.

3. Materials and Methodology

3.1 Experimental Programme

The experimental programme consisted of four main stages: (i) characterization of aggregates and filler, (ii) characterization of the base bitumen, (iii) preparation of conventional and SBR-modified mixtures, and (iv) Marshall testing followed by analysis of stability, flow and volumetric parameters. SBR latex contents of 0%, 3%, 5%, 7% and 9% by weight of bitumen were selected. The 0% mixture was treated as the control mixture.

3.2 Materials

3.2.1 Coarse Aggregate

The coarse aggregate was crushed stone satisfying the general requirements of cleanliness, strength, durability, shape and low porosity. The project used the fraction predominantly retained on the 4.75 mm IS sieve. Aggregate quality was assessed using crushing value, impact value, gradation, flakiness and elongation, abrasion and specific gravity tests. These properties are important because the aggregate skeleton controls load

transfer, packing, resistance to crushing and abrasion, and the volumetric structure of the bituminous mixture.

3.2.2 Fine Aggregate

Fine aggregate consisted of material passing the 2.36 mm sieve and retained on the 0.075 mm sieve. The report describes natural sand, crushed stone sand and crushed gravel sand as possible fine aggregate sources and specifies that the material should be clean, hard, durable, dry and free from organic matter. Particle-size distribution was determined using the IS 2386 (Part I) procedure.

3.2.3 Filler

Stone dust was selected as filler. Its function is to fill voids between coarse and fine aggregate particles, improve density and contribute to the mastic phase. The attached report specifies that filler should be inert and suitably fine, with the entire material passing 600 μm , at least 90% passing 150 μm and not less than 70% passing 75 μm .

3.2.4 Bitumen

80/100 penetration-grade bitumen was used as the binder. The control mixture contained 5% bitumen based on total mix mass. The binder was characterized using penetration, ductility, viscosity and ring-and-ball softening-point tests. These tests establish the basic consistency, temperature susceptibility, deformability and application characteristics of the binder.

3.2.5 SBR Latex

SBR latex was used in liquid form as the elastomeric modifier. The project describes SBR as a synthetic rubber based on styrene and butadiene and reports its use for improving cracking resistance, wear resistance and bond strength. The investigated dosages were 0%, 3%, 5%, 7% and 9% by weight of bitumen. The study therefore evaluates both moderate and relatively high modifier contents so that the point at which performance begins to decline can be observed.

3.3 Aggregate Testing

Aggregate crushing value was determined according to IS 2386 (Part IV) as a measure of resistance to crushing under gradually applied load. The impact value test was used to assess resistance to sudden impact or shock. Sieve analysis established particle-size distribution. Flakiness and elongation indices were used to evaluate particle shape, while Los Angeles abrasion quantified resistance to wear and degradation. Specific gravity was determined according to IS 2386 (Part III) and used subsequently in volumetric calculations.

3.4 Binder Testing

Penetration was measured at 25°C using a standard 100 g needle load and 5 s penetration period, following IS 1203–1978. Ductility was measured as the elongation distance before rupture, following IS 1208–1978. Viscosity was determined using the specified flow apparatus in accordance with IS 1206–

1978. Softening point was measured by the ring-and-ball method following IS 1205–1978. The project used these tests to establish the baseline properties of the 80/100 binder before Marshall mixture evaluation.

3.5 Mix Proportions

Table 1. Properties of Coarse Aggregate

Component	Percentage of total mix	Mass for 1200 g batch
Coarse aggregate	60%	720 g
Fine aggregate	20%	240 g
Filler	15%	180 g
Bitumen binder	5%	60 g
Total	100%	1200 g

For modified mixtures, SBR latex replaced a portion of the bitumen binder on a percentage-by-weight-of-bitumen basis. Thus, the nominal SBR dosage was 3%, 5%, 7% or 9% relative to the binder mass. The report describes the modified mixes as otherwise following the same aggregate and filler proportions as the control mixture.

3.6 Marshall Specimen Preparation

For each mixture, the aggregate, fine aggregate and filler were batched according to the specified proportions. The aggregates were heated before binder addition. The 80/100 bitumen was heated separately and combined with the heated aggregate. The mixing temperature reported in the project was approximately 150–155°C. The mould assembly was preheated and the mixture was compacted using 50 blows on each face. The compacted specimen thickness was approximately 63.5 mm. The same preparation approach was followed for the SBR-modified mixtures so that the effect of modifier content could be compared under nominally similar conditions.

3.7 Marshall Test Parameters

The Marshall test was used to quantify the maximum load sustained by the specimen and the associated deformation. The main response variables were Marshall stability and flow. Volumetric properties were then evaluated using the reported theoretical specific gravity, bulk density and constituent specific gravities. The project used the following relationships: air voids $V_v = 100(G_t - G_b)/G_t$; VMA = $V_v + V_b$; and VFB = $100(V_b/VMA)$, where G_t is theoretical specific gravity, G_b is bulk density and V_b is the volume of bitumen. These parameters were used collectively to assess mixture compactness and binder filling.

3.8 Standards Used

Table 2. Gradation of Coarse Aggregate

Test/Material	Standard reported in project
Aggregate crushing, impact, abrasion and shape	IS 2386 (Part IV)
Aggregate gradation	IS 2386 (Part I)
Aggregate specific gravity	IS 2386 (Part III)
Bitumen penetration	IS 1203–1978
Bitumen softening point	IS 1205–1978
Bitumen ductility	IS 1208–1978
Bitumen viscosity	IS 1206–1978
Paving bitumen specification	IS 73–2006
Bituminous concrete specification cited	IRC:29–1988

4. Results and Discussion

4.1 Aggregate Properties

The measured aggregate properties are summarized in Table 1. The crushing value was 18.43%, which is below the 30% value listed in the attached report. The consolidated test-results table reports an impact value of 24.17%, also below the listed 30% criterion. The Los Angeles abrasion value was 24% against a reported 40% limit. The combined shape-test value was reported as 24.23%, compared with a listed 40% criterion. The coarse aggregate specific gravity was 2.93, within the reported range of 2.5–3.0. These results indicate that the aggregate system had adequate resistance to crushing, impact and abrasion for the intended experimental programme.

Table 3. Gradation of Fine Aggregate

Property	Experimental value	Reported specification/reference
Aggregate crushing value	18.43%	30%
Aggregate impact value	24.17%	30%
Los Angeles abrasion	24%	40%
Shape test (combined)	24.23%	40%

Property	Experimental value	Reported specification/reference
reported value)		
Coarse aggregate specific gravity	2.93	2.5–3.0
Fine aggregate specific gravity	2.74	2.6–2.8
Stone dust specific gravity	2.62	Not stated

The detailed impact-test page elsewhere in the report records 23.34% from a test mass of 377 g and 88 g of fines, whereas the final consolidated Table 8 reports 24.17%. Because the two reported values are inconsistent, this paper uses 24.17% when reproducing the final consolidated results and flags the discrepancy rather than silently replacing one value with the other. For publication, the original laboratory sheet should be checked and one verified value should be retained.

4.2 Aggregate Gradation

Table 4. Properties of 80/100 Grade Bitumen

Coarse sieve (mm)	Mass retained (kg)	% retained	Cumulative % retained	Cumulative % passing
25	0.12	2.4	2.4	97.6
20	1.34	16.8	19.2	80.8
16	2.26	45.2	74.4	25.6
12.5	1.06	21.2	95.6	4.4
10	0.16	3.2	98.8	1.2
Pan	0.06	1.2	100	0

The coarse aggregate grading shows the largest retained fraction at the 16 mm sieve, where 45.2% of the sample was retained. The cumulative passing percentage falls from 80.8% at 20 mm to 25.6% at 16 mm and 4.4% at 12.5 mm. This grading forms the aggregate skeleton used in all mixture variants, thereby keeping the aggregate structure effectively constant while the SBR dosage is varied.

Table 5. Mix Proportions of the Bituminous Mixture

Fine sieve (mm)	Mass retained (kg)	% retained	Cumulative % retained	Cumulative % passing
4.75	0.012	1.2	1.2	98.8
2.36	0.033	3.3	4.5	95.5
1.18	0.133	13.3	17.8	82.2
0.60	0.272	27.2	45.0	55.0
0.30	0.405	40.5	85.5	14.5
0.15	0.130	13.0	98.5	1.5
0.075	0.010	1.0	99.5	0.5
Pan	0.005	0.5	100	0

The fine aggregate is concentrated around the 0.30–0.60 mm range, with 40.5% retained at 0.30 mm and 27.2% retained at 0.60 mm. Only 0.5% passed to the pan in the reported gradation test. The grading characteristics influence packing, VMA and binder demand, and therefore provide an important baseline for interpreting the Marshall volumetric results.

4.3 Base Bitumen Properties

Table 6. Standards Used for Experimental Investigation

Test	Experimental value	Reported specification
Penetration	95.66 (0.1 mm)	80/100 grade
Softening point	48°C	42–50°C
Ductility	67.5 cm	50–75 cm
Viscosity	3 s	3–5 s

The measured penetration of 95.66 (0.1 mm) is consistent with the reported 80/100 penetration grade. A softening point of 48°C lies within the reported 42–50°C range. Ductility of 67.5 cm lies within the stated 50–75 cm range, and viscosity of 3 s is at the lower end of the stated 3–5 s range. These values establish the reference binder condition against which the effect of SBR modification is evaluated.

4.4 Marshall Stability

Table 7. Marshall Test Results for SBR-Modified Bituminous Mixtures

SBR (%)	Air voids (%)	VMA (%)	VFB (%)	Stability (kN)	Flow (mm)
0	4.8	16.87	70.3	8.9	2.0
3	4.5	16.39	72.5	12.5	2.5
5	3.43	15.2	77.5	15.7	3.0
7	3.8	15.3	73.2	13.6	3.75
9	4.55	15.8	71.5	10.9	4.0

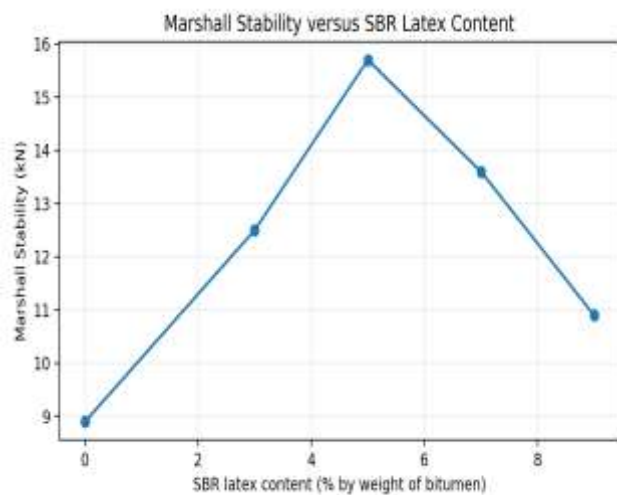


Figure 1. Marshall stability variation with SBR latex content.

Marshall stability increased from 8.9 kN for the control mixture to 12.5 kN at 3% SBR and reached a maximum of 15.7 kN at 5% SBR. Relative to the control, the 5% mixture therefore achieved an increase of approximately 76.4% in the reported stability. Beyond 5%, stability decreased to 13.6 kN at 7% and 10.9 kN at 9%. This rise-and-fall response is a central result of the investigation. Up to 5%, the elastomeric modifier appears to improve the binder–aggregate system sufficiently to increase load-carrying capacity. At higher dosage, the report attributes the reduction to decreased effective bitumen content/binding capacity. The exact physical mechanism should be confirmed by binder rheology or microscopy in future work, but the observed optimum within the tested range is unambiguous: 5% SBR produced the highest Marshall stability.

The stability trend also agrees qualitatively with the literature summarized in the report. Dewi Sri Jayanthi et al. reported increased stability up to 5% SBR, while Pareek et al. reported improved stability for polymer-modified bitumen. The present

results extend this observation for the particular 80/100-grade binder and mixture proportions used in the project.

4.5 Flow Value

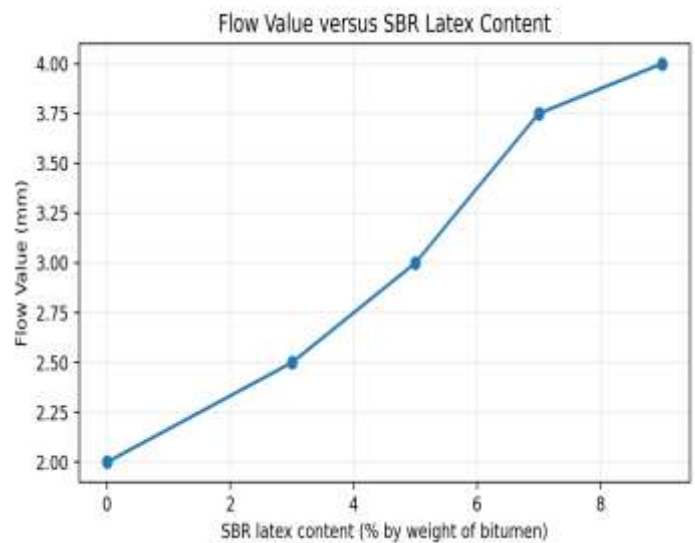


Figure 2. Flow value variation with SBR latex content.

The tabulated Marshall data show a progressive increase in flow from 2.0 mm at 0% SBR to 2.5 mm at 3%, 3.0 mm at 5%, 3.75 mm at 7% and 4.0 mm at 9%. The increase indicates a greater deformation response under the Marshall loading condition as SBR content increases. Within the reported MORTH limits of 2–4 mm, all tabulated values remain within the stated range, with the 9% mixture reaching the upper limit. The 5% mixture has a flow of 3.0 mm and therefore combines the maximum stability with an intermediate deformation response.

There is a textual inconsistency in the attached report: the discussion on page 67 states that the maximum flow value is 4 mm at 5% SBR, while the consolidated Marshall Table 11 gives 3.0 mm at 5% and 4.0 mm at 9%. For this paper, the numerical table is treated as the primary dataset, and the 5% flow value is reported as 3.0 mm. The inconsistency should be corrected against the original laboratory records before journal submission.

4.6 Air Voids

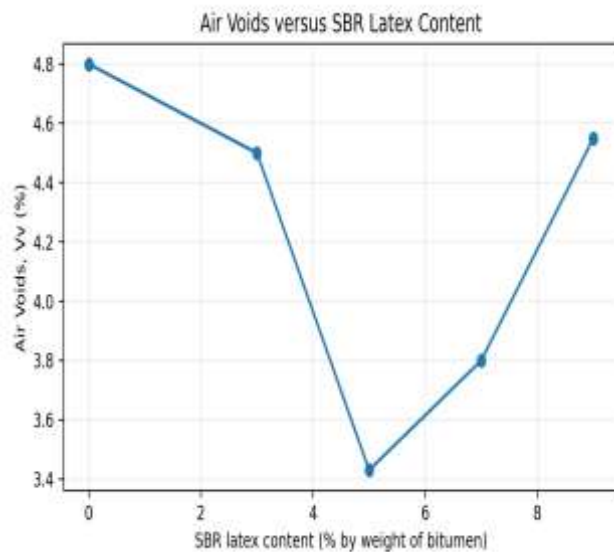


Figure 3. Air-void content versus SBR latex content.

Air voids decreased from 4.80% in the control mixture to 4.50% at 3% SBR and reached a minimum of 3.43% at 5% SBR. The value subsequently increased to 3.80% at 7% and 4.55% at 9%. The reduction from 4.80% to 3.43% corresponds to approximately 28.5%. The attached report interprets the lower air-void content as indicating reduced permeability and improved compactness. The subsequent increase at 7–9% suggests that excessive SBR may disturb the optimum packing/binder balance achieved at 5%.

The complete set of air-void values lies within the 3–6% range reported in the project's MORTH comparison row. Thus, the control and all modified mixtures satisfy the stated volumetric range, while the 5% mixture provides the lowest air-void content and therefore the most compact structure among the tested mixtures.

4.7 Voids in Mineral Aggregate (VMA)

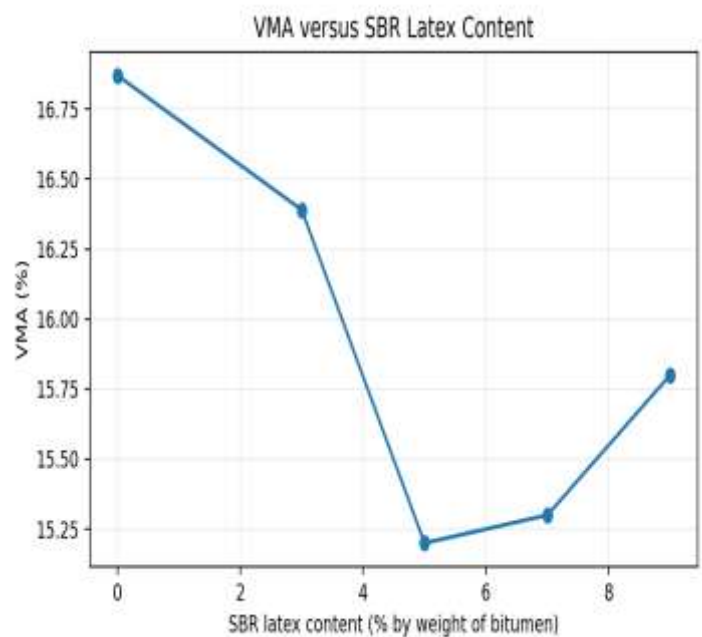


Figure 4. VMA variation with SBR latex content.

VMA decreased from 16.87% at 0% SBR to 16.39% at 3% and 15.20% at 5%, followed by slight increases to 15.30% and 15.80% at 7% and 9%, respectively. The 5% mixture therefore produced the minimum reported VMA. The report interprets the lower VMA as indicating fewer void spaces within the aggregate structure and a potentially thinner required asphalt film. In combination with the minimum air voids, the VMA trend supports the conclusion that 5% SBR produced the most compact volumetric arrangement within the tested dosage range.

It should be noted that VMA is a mixture-design parameter rather than a property for which the smallest possible value is universally optimal. The appropriate value depends on mixture type, nominal maximum aggregate size and applicable specification. Therefore, the result is interpreted here in the context of the project's reported comparison and not as a universal criterion that lower VMA is always better.

4.8 Voids Filled with Bitumen (VFB)

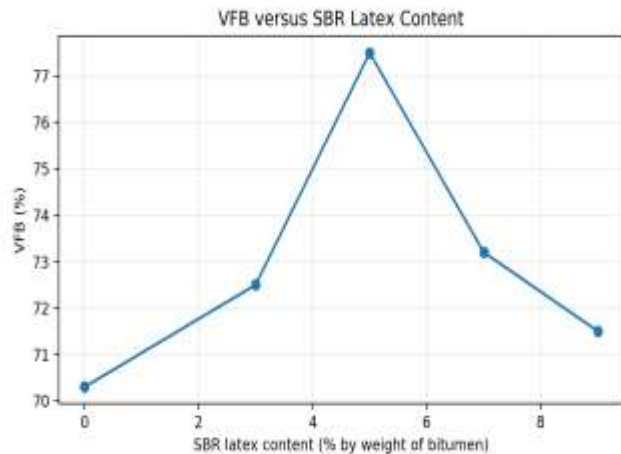


Figure 5. VFB variation with SBR latex content.

VFB increased from 70.3% for the control to 72.5% at 3% SBR and peaked at 77.5% at 5% SBR. It then decreased to 73.2% at 7% and 71.5% at 9%. The increase from 70.3% to 77.5% is approximately 10.2%. The result indicates that the 5% SBR mixture had the highest proportion of available aggregate void space filled by binder within the reported Marshall calculations. The subsequent reduction at higher SBR contents again indicates that the optimum binder–aggregate–modifier interaction was not maintained beyond 5%.

The project reports an MORTH comparison range of 65–80% for VFB. All five mixtures fall within this range, with the 5% SBR mixture near the upper part of the acceptable interval. This provides additional support for selecting 5% SBR rather than 7% or 9%.

4.9 Integrated Performance Assessment

The Marshall results demonstrate a consistent optimum region at 5% SBR. Stability, the principal load-bearing indicator in the Marshall test, is maximized at 5%. Air voids and VMA reach their minimum values at the same dosage, while VFB reaches its maximum. Flow is increased relative to the control but remains within the reported 2–4 mm comparison range. Thus, the optimum is not based on stability alone; it is supported by the simultaneous improvement of the principal volumetric indicators.

Table 8. Comparison of Marshall Stability and Flow Values

Parameter	0% SBR	5% SBR	Change at 5%
Marshall stability	8.9 kN	15.7 kN	+76.4%
Flow	2.0 mm	3.0 mm	+50.0%
Air voids	4.80%	3.43%	–28.5%

Parameter	0% SBR	5% SBR	Change at 5%
VMA	16.87%	15.20%	–9.9%
VFB	70.3%	77.5%	+10.2%

The percentage changes in Table 3 are calculated directly from the numerical values reported in Table 11 of the attached project. The flow change is not interpreted as an improvement in isolation; rather, it indicates greater deformation capacity, while the value remains below the upper bound reported in the project's comparison criteria.

4.10 Mechanism of Improvement

The observed behavior can be explained at a conceptual level by the elastomeric nature of SBR. At an appropriate dosage, polymer chains dispersed within the binder can contribute to a more continuous and resilient binder phase. This can enhance adhesion between binder and aggregate, improve stress transfer and increase resistance to deformation under the short-duration Marshall load. The attached report also describes the formation of an interconnected polymer matrix as a mechanism by which polymer additives modify physical properties. The maximum response at 5% suggests that the modifier concentration was sufficient to enhance the binder structure without excessively disturbing the effective binder balance of the mixture.

At dosages above 5%, the reduction in stability and VFB, together with the increase in air voids and VMA, indicates that the mixture no longer benefits proportionally from additional SBR. The project attributes the decline in stability to reduced bitumen content and a corresponding reduction in binding capacity. Since the experimental programme did not include detailed rheological, chemical or microscopic measurements, this explanation should be treated as an engineering interpretation rather than a directly measured mechanism.

5. Comparison with Previous Studies

The present results are broadly consistent with the literature summarized in the source report. The increase in Marshall stability up to an intermediate SBR dosage agrees with Dewi Sri Jayanthi et al., who reported an 18.8% increase in stability from 0% to 5% SBR. The magnitude of improvement in the present study is higher, at approximately 76.4% from 0% to 5%, which may be associated with differences in binder grade, aggregate gradation, mix design, SBR formulation, compaction and test conditions. Therefore, the numerical values should not be directly generalized across studies.

The reported optimum of 5% is also close to the upper end of the SBR range investigated by Ramadhansyah Putra Jaya et al., who studied 0–5% SBR and reported increasing viscosity and softening point with SBR addition. Martin Riara's study, as summarized in the source report, identified 4% SBR as a

critical dosage for peak bonding strength in a particular modified-emulsion system. Abedini et al. reported improved performance at 6% SBR in another emulsion system. These differences emphasize that optimum modifier content is system-dependent and should be established experimentally for each binder, aggregate and mixture design.

The current study contributes by combining aggregate quality, base-binder characterization and Marshall mixture response in one experimental sequence. The results also show that increasing SBR indefinitely is not beneficial: the stability peak and volumetric minima/maxima occur at 5%, after which the response reverses. This is important for practical dosage selection because excessive polymer addition can increase material cost and may adversely affect workability or mixture balance.

6. Engineering Implications

- The optimum 5% SBR dosage provides a substantial increase in Marshall stability compared with the conventional mixture. This suggests potential for improved resistance to load-induced deformation under conditions represented by the Marshall test.
- The reduction in air voids at 5% indicates a more compact mixture and, according to the project interpretation, potentially lower pathways for water and air movement.
- The increase in VFB at 5% indicates a larger fraction of the aggregate void structure filled with binder, supporting improved continuity of the binder phase.
- The flow value at 5% remains within the 2–4 mm comparison range reported in the project, suggesting that the increased stability was not obtained at the expense of an excessively high flow value.
- The decline in performance at 7% and 9% shows that modifier dosage must be optimized rather than maximized. This is relevant for economical pavement construction because unnecessary SBR addition may increase cost without improving mixture performance.
- The results are laboratory-specific. Field application should consider mixing and compaction temperature control, storage stability of the modified binder, ageing, moisture susceptibility, rutting, fatigue and low-temperature cracking before implementation.

7. Limitations and Future Research

The attached project is primarily a Marshall-based laboratory investigation. The following limitations should be recognized when converting the project into a journal research paper:

- Replicate-level Marshall data and standard deviations are not reported in the attached document; therefore statistical significance cannot be established.
- The SBR latex formulation, solids content and manufacturer-specific properties are not fully reported, which may affect reproducibility.
- Detailed rheological properties such as complex shear modulus, phase angle and elastic recovery were not measured in the reported experimental programme.
- Moisture susceptibility, wheel-tracking/rutting, fatigue, ageing and low-temperature cracking were not directly evaluated.
- Long-term field performance and life-cycle cost were not quantified.
- The source report contains a discrepancy in the reported aggregate impact value and a discrepancy between the flow discussion and the numerical Marshall table; these should be resolved from the laboratory records before final publication.

Future research should therefore include replicate specimens with standard deviation and confidence intervals, dynamic shear rheometer testing, ageing studies, indirect tensile strength or moisture susceptibility testing, wheel-tracking or dynamic creep, fatigue testing, and field trials. A statistically designed dosage programme around the observed optimum, for example 4%, 5% and 6%, would also help establish whether 5% is a statistically robust optimum or simply the best mean value among the five tested levels.

8. Conclusions

- The investigated coarse aggregate satisfied the reported quality criteria, with crushing value 18.43%, consolidated impact value 24.17%, Los Angeles abrasion value 24%, shape-test value 24.23% and specific gravity 2.93.
- The fine aggregate specific gravity was 2.74 and the stone-dust specific gravity was 2.62.
- The 80/100 penetration-grade bitumen showed penetration 95.66 (0.1 mm), softening point 48°C, ductility 67.5 cm and viscosity 3 s in the reported laboratory results.
- SBR latex contents of 0%, 3%, 5%, 7% and 9% by weight of bitumen were successfully incorporated into the investigated bituminous mixture.
- Marshall stability increased from 8.9 kN for the control to 15.7 kN at 5% SBR, corresponding to approximately

76.4% improvement relative to the control. Stability declined to 13.6 kN and 10.9 kN at 7% and 9%, respectively.

- Based on the numerical Marshall table, flow increased from 2.0 mm at 0% SBR to 3.0 mm at 5% and 4.0 mm at 9%. The 5% mixture remained within the reported MORTH comparison range.
- Air voids decreased from 4.80% to 3.43% at 5% SBR and then increased at higher dosages, indicating the most compact reported mixture at 5%.
- VMA decreased from 16.87% to 15.20% at 5% SBR and increased slightly at higher SBR contents.
- VFB increased from 70.3% to 77.5% at 5% SBR and subsequently decreased, indicating the most favorable binder-filling condition at the 5% dosage within the investigated range.
- Considering stability, flow and volumetric properties together, the attached project identifies 5% SBR latex by weight of bitumen as the optimum dosage for the investigated materials and mix proportions.
- The results support SBR latex as a promising elastomeric modifier for improving the Marshall performance of bituminous mixtures, but field-scale conclusions require additional durability, rheological, fatigue, rutting and ageing investigations.

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