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ENHANCEMENT AND UPGRADE OF POLYMER MODIFIED BITUMEN FOR DURABLE ASPHALT PAVEMENT: „MULTIFUNCTIONAL ADDITIVE“ – A NEW APPROACH

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Abstract

New multifunctional modifiers have recently been introduced that enhance bitumen properties. These additives serve various purposes, including anti-stripping, workability enhancement, and as warm mix asphalt additives, contributing to CO_2 savings and increased use of Reclaimed Asphalt (RA). These reactive additives can be easily integrated into the wet mixing process at asphalt plants, simplifying implementation. Given the rising mechanical and thermal stresses on roadways, upgrading asphalt binders to improve their engineering properties is essential for extending the lifespan of asphalt layers and supporting sustainability initiatives. Reactive isocyanatebased polymeric modifiers provide a pathway to upgrade polymermodified bitumen (PmB) to reconcile enhanced pavement performance with higher recycled content. This paper presents laboratory characterization and two field applications for an isocyanatebased reactive additive (AS P101) applied to commercially available PmB. Rheological testing (BTSV, MSCR, elastic recovery) and mix performance (rutting/track formation) demonstrate substantial increases in hightemperature stiffness and deformation resistance while maintaining excellent lowtemperature behavior. One paving trial, a highdemand logistics/manufacturing site (Dingolfing, Germany), demonstrates practical workability, storage stability and compatibility with long transport and up to 50% reclaimed asphalt pavement (RAP). This paper also discusses limitations of current specification frameworks (with a specific reference to elastic recovery's bias toward SBS) and expands on SBSrelated drawbacks with practical mitigation strategies. The findings support operational use of reactive isocyanate modifiers to deliver durable, long-lasting and lowercarbon asphalt pavements, subject to continued field validation.

Keywords: reactive modifier, polymeric isocyanate, polymermodified bitumen, rutting resistance

1 Introduction

Reactive polymeric modifiers (epoxy or isocyanatefunctional systems) offer a complementary strategy to SBS modification. By chemically bonding with polar bitumen fractions (e.g. asphaltenes), they change the colloidal balance and form dispersed insitu networks that improve hightemperature rigidity, storage stability and ageing resistance without relying on elastomeric domains (figure 1). Isocyanatebased modification thus enhances resistance to permanent deformation but does not produce the large elastic recoveries characteristic of SBS; consequently, elasticrecovery alone is an inadequate universal metric. Given increasing thermal loads and higher RAP contents, specification frameworks should move to multimetric, performancebased evaluation (i.e. rheology, Multiple Stress Creep Recovery, fatigue master curves and field validation),

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so reactive chemistries can be assessed and deployed on equal footing. Despite its widespread use, SBS has practical and performance limitations that merit consideration. Key issues include:

- Environmental ageing: SBS is vulnerable to UVinduced photooxidation and thermal oxidation, which cause chain scission, embrittlement and loss of flexibility over time.
- Thermal cycling sensitivity: Repeated expansion/contraction promotes microfatigue and can accelerate cracking, particularly under large diurnal or seasonal temperature swings.
- Storage and processing constraints: High polymer dosages increase binder viscosity, complicating mixing, pumping and plant operations and raising storagestability concerns.
- Compatibility with high RA: Achieving target performance with high recycled content can require higher SBS loads or additional compatibilizers, increasing cost and viscosity challenges.
- Specification bias and procurement effects: Normative emphasis on elastic recovery favors SBS and can exclude alternative modifiers that improve durability by different mechanisms.
- Cost and lifecycle tradeoffs: Higher polymer contents and additional mitigation measures (antioxidants, vulcanization, fillers) raise material and processing costs and may shift environmental tradeoffs unless balanced by demonstrable lifespan gains.

Combining SBS with reactive modifiers or using hybrid formulations can exploit complementary strengths. Recoverable elasticity from SBS and stiffness/ageing resistance from reactive chemistries, while mitigating the individual limitations of each approach, might be complimentary taking advantages of both type of modifications: elastomeric and plastomeric.

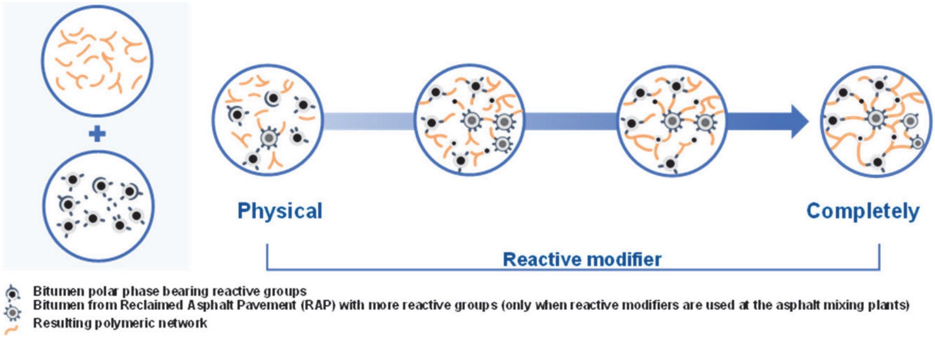

Figure 1 Schematic representation of reactive modification of bitumen by multifunctional isocyanate polymer and polymeric network formation (conceptual), source: BASF

Reactive modifiers reported in the literature include epoxyfunctional ethylenebased polymers and isocyanateterminated polymers [1–13]. Their classification as modifier of bitumen and/or asphalt mixes depends on dosage and points of application (premanufacture into readymade bitumen or direct addition at the asphalt plant). In practice, polymeric isocyanatebased additives act simultaneously as polymer modifiers, chemical additives, adhesion promoters/antistripping agents, compatibilizers for high RAP contents, odor suppressants (e.g. H_2S scavengers) and viscosity/workability aids that enable warmmix production. A substantial work demonstrates that isocyanatebased reactive polymers can raise binder viscosity, improve storage stability and enhance rutting resistance at elevated temperatures [5–13]; Carrera et al. first described insitu crosslinking of bitumen constituents using polymeric isocyanates [13]. Through appropriate processing, these modifiers can be used to produce binders and mixes at reduced production and laydown temperatures, supporting lowerenergy practices. To address rising thermal loads and the growing use of reclaimed asphalt, a pragmatic strategy is hybrid modification: combining SBS elastomers (for recoverable elasticity) with reactive polymeric modifiers (for stiffness, compatibility and ageing resistance) to exploit complementary mechanisms. This paper presents one paving trial that apply this approach: a highdemand logistics/ manufacturing site in Dingolfing (Germany), illustrating practical implementation and performance.

2 Materials and methods

2.1 Materials

PmBs 10/40-65 and 25/55-55 (EN 14023), commercially available, were purchased from different bitumen suppliers or collected directly at the asphalt mixing plant. Those PMBs were modified with a reactive modifying additive, based on a specific polymeric isocyanate (AS P101) obtained from BASF SE, or the modified bitumen binder was extracted from the asphalt mix produced on site. The main properties of the additive (AS P101) are listed in table 1.

Table 1 Main properties of additive AS P101 (composition, density, physical form)

Properties AS P101	
Chemical composition	isocyanate-based
Density (25°C)	1.2 g/cm^3
Physical form	Black liquid

2.2 Methods

European bitumen specification still relies on penetrationgrade criteria (EN 13924, EN 12591), typically expressed by needle penetration and Ring & Ball softening point. New rheological methods (for example BTSV: "Bitumen Test Schnell Verfahren" – Binder-Fast-Characterization-test) are being introduced to better characterize modern binders; however, BTSV correlations validated for unmodified bitumen do not always translate directly to polymermodified binders such as SBSPmB. All rheological tests were performed on Anton Paar DSR instruments (MCR 702 Multidrive and SmartPave 101) using 25 mm plate–plate geometry and within the linear viscoelastic range unless stated otherwise:

- BTSV (BinderFastCharacterizationTest) [14]: The complex shear modulus and phase angle were recorded while temperature was ramped from 20°C to 90°C at 1.2 K·min1, at 10 rad·s1 and a stress of 500 Pa (stresscontrolled mode). The temperature at which $|G^*| = 15$ kPa ($T(G^* = 15$ kPa)) and the corresponding phase angle $\delta(G^* = 15$ kPa) were taken as rheological softening indicators. δBTSV serves as a qualitative indicator of modification level; literature thresholds classify binders as unmodified (δBTSV › 75°), moderately modified (65° ‹ δBTSV ‹ 75°) or highly modified (δBTSV ‹ 65°) [22].
- MSCR (Multiple Stress Creep and Recovery, DIN EN 16659) [15, 16]. Tests were run at 60°C with 25 mm plates and a 1 mm gap. Each cycle comprises 1 s creep under 3.2 kPa shear stress and 9 s recovery, for ten cycles. The reported metrics are mean% recovery (R) and mean nonrecoverable creep compliance (Jnr). These parameters characterize binder susceptibility to permanent deformation and correlate well with mixture rutting [15, 16].

Conventional indicators Ring & Ball softening point was measured by standard procedure and reported alongside rheological metrics. Elastic recovery (DIN EN 13398) was used to classify PmB binders: specimens cast in molds were conditioned 90 min at 25°C, stretched to 200 mm at 50 mm·min^{-1} and cut. The distance between the two threads after 30 minutes yields elastic recovery as a percentage of extension. If failure occurs before 200 mm, the actual extension is used. Elastic recovery remains a common specification metric for SBStype modification.

Mixture production and performance testing Laboratory mixes and field cores (AC 8 DS, AC 16 BS / AC 16 DS) were produced with the specified PmB variants and comodified binders. RAP was incorporated up to 50% and binder dosages adjusted accordingly. Rutting (track formation) tests were performed at an elevated test temperature (up to 70°C) to assess deformation resistance; workability and compactability were recorded during production and storage trials.

2.3 Paving project

Dingolfing logistics site (2024) was a project involving a repaving of bus and truck lanes using 1500 tons of AC 16 DS with 50% RAP based on PmB 10/4065 modified with 2.0% AS P101. The mix travelled ~120 km from plant to site and was stored for 4–5 hours before laydown; laydown temperature was at about 160°C.

3 Results

3.1 Laboratory results

The initial laboratory work focused on multimodifying an asphalt mix to increase deformation resistance under high temperatures and heavy loads typical of bus stations and logistic areas. Adding a reactive modifier to a readytouse PmB 25/5555 A produced a clear rheological shift in the base binder toward properties associated with deformationresistant pavements. Several key indicators exceed those of a typical PmB (table 2). For comparison, a PmB 10/4065, presumed to contain a higher SBS content, was also evaluated as a reference binder.

Table 2 Bitumen binder test results (lab trials)

	R&B [°C]	**T (G* = 15 kPa) BTSV [°C]**	**Phase angle δ (G* = 15 kPa) - BTSV [°]**	**Elastic Recovery [%]**
10/40-65	72.2	66.6	66.4	69
25/55-55	61.0	61.2	69.2	75
25/55-55 + 2.5 M.-% (AS P101)	81.4	71.5	55.7	77

3.2 Logistic site of a large auto maker (Dingolfing, Germany, June 2024)

A major automotive manufacturing site in Germany sought to upgrade its onsite pavement and agreed to trial the reactive modifier to improve the PmB typically used there. The project included repaving large busstation areas and renewing a truck delivery lane at the Dingolfing site. For this work, 1, 500 tonnes of AC 16 DS containing 50% reclaimed asphalt (RAP) and based on a PmB 10/4065 were modified with 2.0% AS P101. The plant-tosite distance was about 120 km and the mix was held in storage for 4–5 hours before placement; despite this, laydown at approximately 160°C delivered excellent workability and compaction. Extracted binder results show a marked increase in softening point, corroborated by higher T(G* = 15 kPa) and a reduced phase angle δ(G* = 15 kPa), indicating an elevated degree of modification (table 3). MSCR tests further confirm that the modified binder meets the demands of very heavy traffic and higher load conditions.

Table 3 Bitumen binder test results (extracted bitumen from production trials)

Parameters of extracted bitumen		**PmB 10/40-65 + 50% RA**	**PmB 10/40-65 + 50% RA + 2% AS P101**
Softening point	T [°C]	64.4	86.0
BTSV (G* = 15kPa)	T [°C]	59.72	72.4
	δ [°]	71.71	60.9
MSCR Test (at 60°C and 3.2 kPa)	Recovery [%]	33.2	81.6
	J_{nr} [1/kPa]	0.821	0.018

Further testing at the mixture level confirmed that multimodification markedly increased the asphalt's resistance to deformation at elevated temperatures. Notably, the trackformation tests conducted at an adjusted temperature of 70°C showed pronounced reductions in permanent deformation (figure 2).

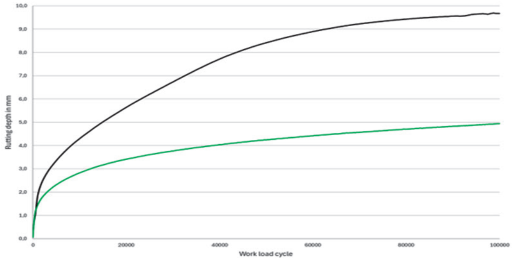

Figure 2 Rutting comparison for AC 16 BS: reference with PmB 10/4065 versus the same mix comodified with AS P101, showing reduced permanent deformation for the comodified material

4 Conclusion

Current binder specification systems in Europe have evolved around dominant technologies, notably SBS, and frequently treat elastic recovery as a primary quality metric. While elastic recovery is a valid control for elastomeric (SBS) behavior, its elevation to a prescriptive acceptance criterion can unintentionally exclude alternative chemistries that deliver equivalent or superior inservice performance by different mechanisms. Reactive isocyanate-based modifiers such as AS P101 typically do not produce the high elastic-recovery values characteristic of SBS, yet they improve high-temperature stiffness, rutting resistance and durability. To enable meaningful innovation, specification practice should shift from singlemetric pass/fail tests to performance-based frameworks that combine rheological and performance indicators (for example BTSV/T(G*), δ(G*), MSCR, fatigue master curves and mechanistic-empirical predictions) together with field validation pathways for novel additives. SBSbased modification remains effective when new, but it is vulnerable to environmental ageing through UV photodegradation, oxidation and repeated temperature cycling. These processes induce chain scission, increased binder polarity, embrittlement and interfacial degradation, which accelerate cracking and loss of fatigue resistance. Practical mitigation measures that slow SBS degradation include antioxidants and UV stabilizers, controlled sulphur crosslinking or compatibilizers, hydrophobic or nanotreated fillers, surface protective overlays, thermal and structural design measures to moderate peak pavement temperatures, and timely maintenance.

Hybrid strategies that combine elastomeric polymers (to provide recoverable elasticity) with reactive modifiers (to enhance stiffness, RA compatibility and ageing resistance) can exploit complementary mechanisms and deliver more balanced performance across the service temperature range.

This study demonstrates that multimodification, exemplified by AS P101 added to commercially available PmB (table 2), produces a clear rheological shift toward deformation-resistant behavior and yields marked reductions in track formation in field trials under demanding traffic and storage conditions. Reactive modification acts through insitu chemical network formation with polar bitumen fractions and therefore improves high-temperature rigidity and resistance to permanent deformation in ways not captured by elastic-recovery tests alone. Reported ancillary benefits include improved antistripping performance on some aggregates (e.g. granite and basalt) and reductions in certain VOC emissions during hotmix production.

For practical adoption, several conditions must be met. Specification frameworks should allow alternative compliance routes based on a suite of performance indicators and validated field outcomes. Continued field monitoring is essential to confirm laboratory-predicted service-life advantages under diverse climates and traffic regimes. Transparent lifec-ycle and supplychain data for additives will strengthen confidence in procurement decisions. Finally, occupational-health co-benefits resulting from lower production temperatures and reduced emissions should be considered in tender evaluations.

In summary, a performancefocused, multimodification strategy that integrates reactive isocyanatebased additives with standard elastomeric approaches offers a robust route to more durable, circular and workably producible pavements under rising thermal loads and higher recycledcontent demands. Implementing such solutions will require specification reform, rigorous field validation and clear lifecycle transparency to ensure reliable, long-term benefits.

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