

## Analysis of failure mechanism of bitumen films

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### HIGHLIGHTS

- ▶ Using video recording and image processing, time evolution of bitumen film failure phenomena was studied.
- ▶ Five distinct binder film failure stages were identified and recorded.
- ▶ Behavioral distinctions between straight run bitumen and the polymer modified bitumen were identified.
- ▶ In tensile tests, bitumen flow is dominated by viscous effects, capillary forces play a role at later stages.

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### ABSTRACT

The failure phenomena of a viscoelastic thin film of bitumen and polymer modified bitumen under direct tension tests is investigated in detail, experimentally and theoretically. Using video recording and image processing techniques, the time evolution of failure and film disintegration and separation phenomena were studied. The following failure stages were identified and recorded: Initial (=stage 1), necking (=stage 2), filamentation with void nucleation (=stage 3) and separation (=stage 4). The technique allowed the identification of an additional failure stage for the pure bitumen than the four identified for binders, namely light transparent thinning before void nucleation. The determination of stages to final separation allowed behavioral distinction between the straight run bitumen and the polymer modified bitumen. As the direct tensile tests proceed, in addition to shear forces demonstrative of viscous effects, gravity and capillary forces act on the binder film. In order to understand the relative effect of these forces the order of magnitude of relevant dimensionless numbers, representing ratios of these forces is considered and discussed. The analysis of the above numbers confirms that the flow in bitumen is dominated by viscous effects although capillary forces do play a role at later stages of the experiment with negligible inertia and gravitational effects. The detailed analysis of micromechanical behavior of straight run bitumen and polymer modified bitumen provided further indication corroborating the superior field performance of polymer modified bitumen in porous asphalt.

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### 1. Introduction

Asphalt concrete is a three phase road material that consists of coarse and fine aggregates, bitumen and air voids. Porous asphalt (PA) is a special type of asphalt concrete with a high void content of ca. 20%. Bitumen is a viscoelastic material that is the residue obtained by distillation of crude oil. Its properties are highly temperature and time dependent [1]. Degradation of asphalt concrete occurs under static and dynamic mechanical loading as well as environmental exposure. This deterioration results from oxidation

of the binder due to contact with air resulting in photochemical deterioration at its surface and contact with water. Weakening of asphalt concrete is primarily due to the deterioration of the bituminous binder film which acts as glue and may fail by loss of cohesion within the binder and/or loss of adhesion between the binder and the aggregates. This deterioration can be also due to moisture infiltration that leads to loss of strength and durability and ultimately results in raveling and the stripping process. Material optimization can be done by changing mortar or bitumen properties and can result in a significant improvement on raveling resistance [2]. In order to improve the performance of asphalt concrete various additives are used such as fibers [3] and polymers [4]. The effect of moisture on the material has been studied extensively [5–7]. For example Cheng et al. [6] has investigated the diffusion of moisture vapor into various bituminous binders and has shown that this diffusion is binder dependent. Using a universal sorption device, two

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stages were observed. In the first stage absorption and adsorption occur simultaneously. During the second stage adsorption on the surface of the binder film reaches equilibrium whereas absorption (diffusion) continues until it eventually becomes constant due to saturation. Kim et al. [7] showed that moisture reduces stiffness, fatigue resistance and fatigue life of sand-asphalt.

As shown in the example of Fig. 1, bituminous binders in asphalt concrete exist in the form of thin films. Understanding the behavior of the material as thin films is essential in understanding its fundamental properties [8,9]. However, extensive conclusive research on thin binder films has not been performed so far. Recently, Harvey and Cebon [10,11] have investigated relatively thick bitumen films of 0.5–3 mm thickness at temperature range of  $-30$  to  $30$  °C and tension strain rates of  $0.03$ – $100$  s $^{-1}$ . Fracture properties of  $320$   $\mu$ m thin films of straight run bitumen were investigated by Hammoun et al. [12] who studied the evolution of crack size with numerical methods.

As apparent from Fig. 1, pure bitumen film does not exist in a real pavement environment, rather a combination of bitumen, filler and additives known as mastic. For the purpose of simplification and to unravel the fundamental aspects of the binder behavior in this study, as a first step no mineral fillers were used.

The tensile behavior of two types of bituminous films confined between mineral aggregates or stainless steel as adherends, was previously investigated in the brittle and ductile regimes [13]. Uniaxial, thin and slender specimens were fabricated employing a prototype set up allowing construction of micro-scale thin films and visualization of failure phenomena. The specimen preparation techniques are discussed in detail in [13]. The effect of key parameters, namely, temperature ( $23$  °C and  $-10$  °C), binder type (straight run and polymer modified), adherend type (stainless steel and mineral aggregate), and water conditioning and not, were investigated sequentially. The results showed that water sensitive aggregate-binder combinations in macro ( $150$  mm diameter) and mega (in service) scales also displayed reduced tensile strength in the microscale when water conditioned. At  $23$  °C ductile failure and at  $-10$  °C brittle fracture was observed. When using proper surface preparation procedures (surfaces free of oil and debris), all specimen investigated at  $23$  °C failed cohesively and at  $-10$  °C predominantly adhesive-cohesive failure were seen.

The direct tensile tests revealed failure mechanisms characterized by four stages for the binders investigated. At  $23$  °C, phenomena, such as formation of striations during tensile mechanical loading, void nucleation and growth, filamentation and large duc-

tile flow before fracture could be witnessed [13]. The significant behavioral distinctions seen in the binders that corroborated field performance warrant a closer look at the behavior of these materials at the local level. In this paper, these failure phenomena are investigated in depth and analyzed using video recording and image processing techniques enabling the study of time evolution of failure behavior. Furthermore, in order to understand the relative effect of the forces acting on the bitumen film, the order of magnitude of relevant dimensionless numbers, representing ratios of these forces is considered and discussed.

## 2. Binder materials

The binder materials in this study were chosen based on two different porous asphalt mixes with known field performance used in Switzerland in Cantons Aargau (AG1) and Vaud (VD4), referred to as binder A and binder B. Composition of these two materials differ firstly in the aggregate type and gradation and secondly in the type and content of the bituminous binder. The physical properties of the binders relevant for this investigation are listed in Table 2. Although bitumen with respect to its volume (ca. 6%) is a small part of the asphalt mixture, its properties are very important for the performance of the mix. Furthermore, the viscoelastic behavior of asphalt concrete and the strong dependency of its mechanical behavior on temperature are due to the bituminous binder. Binders affect the cohesion, adhesion and durability of the mix. Physically, bitumen can be understood as a colloidal suspension of asphaltene particles in an oily continuous matrix (maltenes) containing resin. Oils have the lowest molecular weight, resins intermediate and asphaltene particles the highest molecular weight in this mixture [14]. The addition of high molecular weight polymers to hot bitumen produces a chemical change due to the absorption of the maltenes by the polymer and its consequent swelling [1,15,16].

Two binders are investigated here; binder A straight run bitumen 55/70, which is based on AG1 and binder B modified with styrene butadiene styrene co-polymer (SBS), which is used in VD4. Polymer modification of the binder is known to improve the rheological properties of bitumen and is required by the current Swiss standards for porous asphalt [4,17]. SBS a block co-polymer is a thermoplastic elastomer which is a type of polymer that at ambient conditions, exhibits elastomeric (rubbery) behavior. However, the thermoplastic nature also means that they soften when heated and harden when cooled. In thermoplastic elastomers the melting-solidification process is reversible and repeatable. Upon melting the physical crosslinks disappear and upon re-solidification the crosslinks reform. The most important property in terms of mechanical behavior of thermoplastic elastomers is that they have a three dimensional network with a physical crosslinking and interpenetration of the molecules which gives them strength and elasticity. SBS consists of block segments of styrene, a hard and rigid mer and butadiene, a soft and flexible elastic mer. At ambient temperatures, the soft butadiene segments impart the rubbery elastomeric behavior to the material. At temperatures below the melting temperature of the hard styrene segments, hard chain end segments from adjacent chains aggregate together to form rigid domain regions. These domains are physical crosslinks that act as anchor points that restrict soft chain segment motion. The temperature range where the rigid domains and soft flexible domains are active lies between glass transition temperature of the soft component and melting temperature of the hard component. For SBS, this range is between  $-70$  °C and  $100$  °C. Characteristic thermoplastic behavior is that at temperatures above the glass transition temperature the polystyrene softens as the domains weaken and can also dissociate under stress allowing easy processing. Upon cooling, the domains re-associate restoring the strength

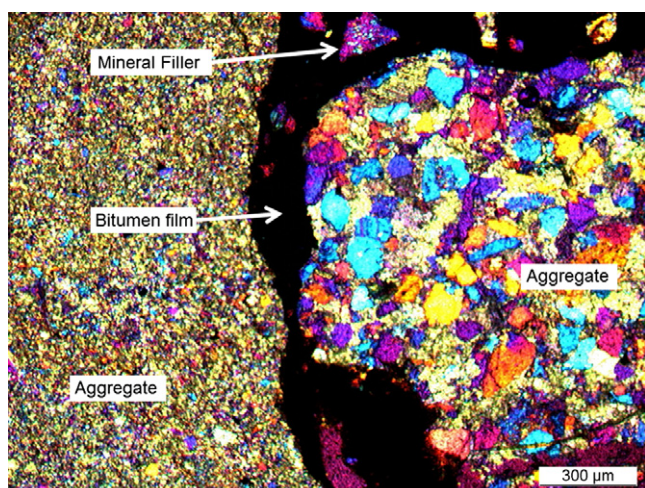


Fig. 1. Polarized optical micrograph showing microstructure of asphalt concrete: two mineral aggregates with their composition and mastic in between.

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