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Adhesion property of asphalt binder

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Abstract: Moisture-induced damage in asphalt concrete pavements has a significant negative impact on the service life and structural durability of road surfaces. One of the most common manifestations of such damage is the loss of adhesion between the aggregate (materials) and the asphalt binder, as well as a reduction in the cohesive strength of the binder itself. As a result, defects such as cracking, raveling, delamination, and deformation develop within the asphalt concrete layer. This study provides an in-depth analysis of the adhesive bonding mechanism between asphalt binders and aggregate materials, and identifies the key factors influencing this interaction. In particular, the effects of aggregate mineralogical composition, surface texture, porosity, as well as the chemical composition and rheological properties of the asphalt binder are examined. Additionally, environmental factors such as moisture and temperature are considered. Throughout the study, adhesion and cohesion processes are evaluated from a physicochemical perspective, and the mechanisms of moisture-induced degradation are identified. The effectiveness of interactions among the components of asphalt mixtures is also analyzed. Furthermore, modern approaches and technological solutions aimed at improving the moisture resistance of asphalt concrete pavements are discussed.

Keywords: asphalt binder, bitumen, mineral materials, aggregates, adhesion, asphalt concrete, bond strength, moisture effect

1. Introduction

Infrastructure for modern road transportation is regarded as one of the main drivers of economic growth. The adhesion characteristics between bitumen and aggregates are the main factors influencing the long-term performance of asphalt concrete pavements. The selective adsorption of bitumen molecules onto the aggregate surface is an important part of this multiscale adhesion process.

The quality of asphalt concrete mixtures directly

affects the strength and longevity of road surfaces. The main ingredients of these combinations are mineral aggregates and asphalt binder (bitumen).

Bituminous mixes are used in the construction of a large percentage of road pavements worldwide. For the purpose of building flexible pavements, a bituminous mixture is a composite material made up of bitumen binder, aggregates, and mineral filler in particular ratios. Additives are sometimes added to asphalt mixtures to improve their performance.

The mechanical strength, moisture resistance, and deformation resistance of asphalt pavements are guaranteed by the adhesive bond between the aggregates and the asphalt binder. Defects like cracks and potholes may appear in the pavement if the asphalt binder does not sufficiently adhere to the aggregate surface.

The adhesion process is associated with molecular attractive forces, surface energy, and adsorption phenomena. Polar components within the bitumen are adsorbed onto the aggregate surface, forming a strong bond. Therefore, the investigation of the chemical and mineralogical composition of both the asphalt binder and aggregates is of significant importance.

2. Research methodology

The mechanical strength, moisture resistance, and deformation resistance of asphalt pavements are guaranteed by the adhesive bond between the aggregates and the asphalt binder. Defects like cracks and potholes may appear in the pavement if the asphalt binder does not sufficiently adhere to the aggregate surface [1].

Adsorption phenomena, surface energy, and molecule attractive forces are related to the adhesion process. Strong bonds are formed when polar bitumen components are adsorbed onto the aggregate surface. Thus, it is crucial to look into the chemical and mineralogical makeup of aggregates and asphalt binder [2].

The presence of moisture, high temperature, high air void content, and high stress are the four primary variables that promote stripping, according to Kandhal and Rickards (2001) [3]. The tiny separation of bitumen films from the surface of aggregates caused by moisture without a visible break in the bitumen films is known as detachment. An analysis of reversible moisture damage in asphalt mixtures was conducted by Apeagyei, Grenfell, and Airey (2014). Stiffness often decreased with conditioning time, according to research. Mannan, Ahmad, and Tarefder (2017) state that moisture conditioning has an impact on the binder's healing rate [1].

The actual mechanism of moisture-induced damage is, however, not completely understood but the phenomenon is believed to be governed in part by the physico-chemical interactions between mastic and aggregates, in the presence of water. The build-up of an interfacial water layer several monolayers thick (35–45 nm) at the aggregate–bitumen interface has been cited as a major cause of adhesion loss [2]. It has been shown (Airey et al., 2007) that the mineralogical and chemical composition of aggregates may play a

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fundamental and more significant role in the generation of moisture damage, than bitumen properties such as penetration grade, acid number, and molecular size distribution [4].

From claims that a loss of adhesion and subsequent debonding result from the reverse emulsification of moisture within bitumen. Displacement, detachment, pore pressure, spontaneous emulsification, and hydraulic scouring are some of the mechanisms of stripping that have been found [4]. The breakdown of the adhesive link between the aggregate and the bitumen binder is known as stripping, according to Kennedy and Ping [5].

As was already mentioned, the primary adhesive that holds the aggregates in a mix together is asphalt mastic. Therefore, it is crucial to comprehend some of the principles underlying the adhesion and debonding processes in order to better understand the moisture damage issue. In the past, a number of adhesion ideas have been put forth. Physical adsorption, diffusion, chemical bonding, electrostatic interactions, mechanical interlocking, and weak boundary layer theories are among them [6]. As will be covered next, the first two ideas may be the most pertinent to asphalt mixtures.

An irreversible decrease of bond strength is one sign of damage to a bond with a negative work of adhesion in the presence of water. Physical adsorption theory-based approaches are currently the most used approach for asphalt mixes [7]. This could be explained by the fact that during mixing, thin layers of asphalt and aggregates come into close contact to form the link between bitumen and aggregate.

In the ESEM-EDS test, the interface between bitumen and minerals at a micro level will be observed, and the adsorption of different elements in bitumen by the mineral surface will be detected. The ESEMEDS measurement is undertaken on cross-sections of the composite bitumen–mineral samples. As the 'footprint' molecules, polar molecules with in the bitumen layer are adsorbed to varying degrees on the surface of different minerals. In this study, the ratio of element carbon to element oxygen (C/O) is used as an indicator. The content variation of this indicator at different distances from the surface of the mineral reflects the differences in the adsorption of polar substances at various mineral surfaces [8].

As was previously mentioned, the susceptibility of asphalt mixtures to moisture damage is thought to be significantly influenced by the mineralogical composition of aggregates. A Mineral Liberation Analyzer (FEI Quanta 600 SEM) was used to characterize the aggregates' mineralogical compositions. The apparatus generates quantitative mineralogy measurements by combining an automated scanning electron microscope, several energy-dispersive X-ray detectors, and cutting-edge analysis software. The findings were utilized to pinpoint important mineral phases and their impact on the deterioration of aggregate-mastic adhesive strength caused by moisture [11].

Another important parameter that influences moisture-induced damage in asphalt mixtures is the rate and amount of water absorption of the aggregates. Moisture absorption tests were conducted to simulate moisture transport in the aggregate substrates using a total water immersion method at a temperature of 20◦C. The approach involved submerging uncoated aggregates disks with nominal dimensions 23mm diameter by 15mm thick in deionised water and measuring moisture uptake using a sensitive microbalance (0.1µg resolution) [11].

3. Research results

The results show that the adsorption of bitumen molecules is directly influenced by the mineralogical and chemical composition of aggregates. Bitumen components with polar functional groups, in particular, adhere more strongly to the aggregate surface, increasing adhesion strength.

The ability of aggregates and asphalt mastics to absorb moisture differs significantly. Granite aggregates have been found to absorb more moisture than limestone aggregates based on dynamic vapor sorption studies. The presence of hydrophilic minerals like quartz and feldspar in granite's mineralogical makeup is responsible for this tendency.

Additionally, bitumen's composition changes over time due to the phenomena of selective adsorption, which has an impact on asphalt pavements' moisture susceptibility and aging behavior. Additionally, laboratory test findings showed that the type of aggregate and testing conditions determine the degree of adhesive bonding between the asphalt binder and aggregates [4].

Using ESEM–EDS testing, the actual adhesion interface between bitumen and various mineral surfaces was observed at the microscopic level. Samples prepared using the freeze-fracture method enabled the formation of a smooth and well-defined cross-section at the bitumen–mineral interface. This, in turn, provided the necessary conditions for a reliable analysis of elemental distribution [8].

The results of EDS line scanning clearly confirmed the phenomenon of selective adsorption of polar components of bitumen onto the mineral surface. The sharp variation in the carbon-to-oxygen (C/O) ratio in the region near the interface indicates that bitumen molecules are not uniformly distributed on the aggregate surface, and that highly polar substances tend to accumulate at the interface [8].

Aggregates can be classified as acidic or basic (alkaline) based on their chemical nature. According to the studies by Hefer, acidic materials tend to form stronger chemical bonds with basic materials, while basic materials interact more effectively with acidic ones. In the bitumen–aggregate system, the formation of a strong chemical bond occurs, for instance, when a basic aggregate such as limestone reacts favorably with the acidic components present in bitumen [9].

Calcium carbonate ($CaCO_3$) present in limestone forms strong bonds with carboxylic acids in bitumen. In contrast, siliceous (silicate-based) aggregates exhibit an acidic nature, while bitumen itself is also considered a weakly acidic material. Therefore, the adhesion strength between bitumen and such aggregates is relatively low [9].

Kennedy and Ping (1991) defined stripping as the loss of adhesion between bitumen and aggregates under the influence of water [5]. Kandhal and Rickards (2001) identified the primary factors that promote stripping as the presence of moisture, high temperature, a high air void content, and elevated stress levels [3].

Studies have shown that asphalt mixtures that have lost up to 80% of their initial stiffness can fully recover upon drying. Kim et al. demonstrated that the use of hydrated lime ($Ca(OH)_2$) is effective in mitigating moisture-induced damage and improving the bond between bitumen and aggregates [10].

It has also been observed that when the bitumen penetration grade is increased from 60/70 to 80/100, the bond strength decreases by approximately 9.73%. Furthermore, under dry conditions, nearly 90% of the initial bond strength is developed within the first 24 hours. Subsequent increases in strength occur at a much slower rate [10].

The technique involved exposing aggregate samples to varying concentrations (partial vapour pressures) of carefully selected probe liquids and measuring the mass gain with time using a sensitive microbalance (0.1µg). The probe liquids used included chloroform, ethyl acetate, and octane. Detailed discussion of the sorption technique is provided elsewhere. The results were used to generate a series of sorption isotherms from which the Brunauer, Emmett and Teller (BET)-specific surface area and SFE components of the aggregates were estimated. The results were also used to estimate the relative porosity of the aggregates, and the thermodynamic work of adhesion and debonding of the aggregate–bitumen bond.

[11] The results showing better resistance to moisture-induced damage for aggregate bonds containing limestone mastic than granite mastics is in agreement with previous studies [1] on more involved asphalt mixture testing. On this basis, it is reasonable to state that the butt-joint test set-up presented in this study offers a promising approach to evaluate moisture sensitivity of asphalt mixtures.

The obtained results indicate that the adhesion process between the asphalt binder and aggregates depends on a number of factors. First, the mineral composition of aggregates plays a significant role. Alkaline aggregates exhibit better adhesion with bitumen, whereas acidic aggregates are more susceptible to moisture.

Second, the composition of the bitumen is also of great importance. Modified bitumens form stronger adhesive bonds with aggregates [3].

Third, environmental conditions, particularly moisture and temperature, have a significant impact on the service life of asphalt pavements. Therefore, in the design of asphalt mixtures, it is essential to select an appropriate combination of asphalt binder and aggregates.

4. Conclusion

The study's findings show that the strength and long-term functionality of asphalt concrete pavements are significantly influenced by the adhesive bonding between the aggregate and asphalt binder. Therefore, in the design of asphalt mixtures, selecting a compatible combination of asphalt binder and aggregates, as well as improving their adhesive properties, is of significant scientific and practical importance for enhancing the performance characteristics of asphalt pavements.

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