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Determining the water damage resistance of nano-clay modified bitumens using the indirect tensile strength and surface free energy methods

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HIGHLIGHTS

- Both SFE and ITS tests results confirmed that nano-clay decreases the effect of water damage.
- Nano-clay has a high surface energy which improves the surface energy of modified bitumen.
- The nano-clay may be considered as anti-stripping material.

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ABSTRACT

Water infiltration into asphalt mixtures is one the serious distresses which lowers the performance of the top layer of road pavements. This problem is even worse in tropical countries which experience high temperature and heavy rainfalls. Therefore, this study aims to evaluate the effects of water infiltration on a 60/70 penetration grade bitumen vis-a-vis bitumen modified with 2 and 4% nano-clay. The Fourier Transform InfraRed (FTIR) test was done to identify any chemical changes that might occur in the nano-clay and the bitumen. The loose and compacted mixtures of the nano-clay modified bitumen were tested to determine their resistance to water damage. The loose mixture was tested by conducting the boiling water, the Vialit adhesion, and surface free energy (SFE) tests, while the compacted mixture was tested using the indirect tensile strength (ITS) test. Aging simulation was done for samples tested using SFE and ITS. The results of the tests show that adding nano-clay alters the mixtures' ability to resist water damage. The improvement in the samples varies depending on the type of binder as well as its aging stage. Unaged bitumen modified with 2% nano-clay show better ability to resist water damage compared to both the unmodified bitumen and the bitumen modified with 4% nano-clay. However, after being subjected to short-term aging (STA) and long-term aging (LTA), the results of both the ITS and SFE tests show that the addition of 4% nano-clay enhance the bitumen's resistance to water damage in comparison with the unmodified bitumen and the bitumen modified with 2% nano-clay. The addition of nano-clay reduces water's effect on the binder, hence indicating the benefit of using nano-clay as an additive to mitigate water effect.

1. Introduction

The performance, durability, and service period of pavements is dependent upon the degree to which the bitumen bonds and adheres to the aggregate surface under varying conditions. The bond between the bitumen and the aggregate surface is correlated

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with their physical and chemical properties; the bond weakens when water infiltrates into the bitumen system. The effect of water in reducing bitumen's ability to adhere to aggregate surface has been recognized since the early twentieth century [1–3]. Since then, a lot of effort has been made to identify the mechanism for water damage. It is crucial to understand the water infiltration process which causes stripping. This would allow for control and mitigation measures to be implemented to prevent stripping since stripping caused by adhesion failure could result in significant economic loss [4].

Several simple procedures can be used to evaluate water damage in asphalt mixtures, in which the effects of water infiltration into the bitumen-aggregate system is determined. One of the commonly used procedures is immersing the bitumen or bitumen coated aggregate in water. A more comprehensive study of water damage involves immersing different types of bitumen in water, either with or without chemical materials, for long periods of time, and also by subjecting the samples to rolling, agitation, boiling, and freeze-thaw cycles. Fromm [5] evaluated bitumen samples which have been immersed in water over a prolonged period of time and found that the water effect on these sample are more complicated. He concluded that water either enter the bitumen film through spontaneous emulsion formation or break the bitumen film at the air-water-bitumen interface. This is one of the simple procedures used to investigate the mechanism of water damage, and more effective methods were developed later. Amongst the special techniques used today are surface free-energy, SFE [6,7], and atomic force microscopy, AFM [8].

Subsequent to discovering that water affects the performance and durability of pavement during its service life, researchers began to study the water infiltration process which could alter the asphalt mixture system, hence causing damage. They found that there is more than one path to water damage, and that the most common path is when rain water enters pavement layer and flow through the connected macro-pores of the layer. Other effects occur when residual water remains in the mixture after rainfall, or when there is a wet subgrade under the pavement layer, or when the pavement is exposed to humid environment. In the case where water remains inside the aggregates after mixing [9], at least one molecular layer of water would still remain. In this case the mixture need to be heated to a temperature of about 1000 °C to completely remove water from the aggregate surface [10].

Many researchers have stated that water is the major cause of stripping even though some of mechanisms listed in this section have been observed. Occasionally, more than one mechanism were observed to occur simultaneously. The use of additives could delay these mechanisms, but they cannot fully prevent the mechanisms from occurring [5,11,12]. Some researchers have noted that several factors could accelerate the occurrence of stripping; amongst them are high air-void content, high temperature and humid environment, and high stress due to traffic load [11,13]. Five well-known mechanisms have been suggested to cause loss of adhesion and/ or cohesion, namely detachment, displacement, spontaneous emulsification, pore pressure, and hydraulic scouring.

Since water infiltration into the layers of road pavement cannot be prevented, pavement scientists and engineers have tried to improve the bonding strength of pavement mixtures by using different methods, initially by modifying the binders or the aggregate. However, some types of anti-stripping measures are found to be ineffective. Fromm [5] asserted that even though using some commercial anti-stripping additives with bitumen might result in better aggregate coating, it will not prevent or even delay subsequent stripping when samples are immersed in water. Hence, efforts are still being made to improve the general properties of bitumen [14,15]. Primary focus is given to improving the properties of unaged and aged asphalt mixtures. In recent years, focus has been shifted to using nano-materials to improve the properties of bitumen. Nano-material is a fairly recent development in which materials are measured in nano-meters, and it was introduced in science and education in the early 1990s [16].

Many studies have confirmed the benefits of using nano-materials as additives to binders. Amongst the nano-material commonly used as bitumen additive are nano-silica, titanium dioxide, nano-carbon, nano-hydrated lime, and nano-clay. Although these nano-materials are still being investigated, initial laboratory experiments have produced considerable improvement in the general properties of bitumen and mixtures. Yang and Tighe [17] listed many benefits of using nano-materials as additives. Additionally, several improvements, such as better rutting resistance and delayed Aging due to oxidation effect, have been achieved when nano-materials were used as additives. Adding nano-materials to bitumen has been shown to increase the mixture's resistance to UV light [18,19]. The addition of nano-clay and micro-carbon fibre to bitumen has been shown to significantly reduce the water susceptibility of the mixtures [20].

The addition of nano-clay produced significant improvement in binder's adhesion force (which was determined using the AFM technique which focus on improving the nano- and micro-structures of the modified binder) [8]. The surface free energy (SFE) technique was used to evaluate the effect of adding nano-clay to polymer-modified bitumen and results show improved water susceptibility of the modified bitumen [21]. Other studies have confirmed that asphalt mixtures show less water damage when nano-clay was added to the binder [16,22,23]. The tests conducted in these studies are the loose-mixture, compacted-mixture, and chemical tests. These studies were conducted using different materials and the applied wet condition in these studies was also varied. All studies concluded that the addition of the nano-clay improved the properties of the binders and these improvements were reflected in properties of the mixtures.

The main objective of this study is to investigate the effect of nano-clay on the adhesion property of asphalt mixtures under wet condition. Several tests could be used to evaluate water damage and the tests conducted in this study are due to their availability. The selected tests were classified into two groups: the first group is the loose mixture tests which is comprised of the boiling water test, the Vialit adhesion test, and SFE, while the second group is the compacted mixture test in which the indirect tensile strength (ITS) test was conducted. The effect of aging was also observed due to its role in facilitating water damage. It should be noted that the boiling water and the Vialit adhesion tests were conducted only on unaged samples and were used only as an indicator of any improvement that might occur in water damage resistance when nano-clay was added. The study focuses mainly on the results of the SFE and ITS tests. The correlations between SFE and ITS also were investigated under both dry and wet conditions. Any correlations that exist between the two tests imply the benefit of using nano-clay as an additive to bitumen and indicate an improvement in resistance to water damage.

2. Experimental design

2.1. Materials and sample preparation

2.1.1. Unmodified and modified binders

This study used a 60/70 penetration grade bitumen as the control sample. The physical properties of the control binder were determined using the penetration, softening point, and viscosity tests. The nano-clay used in this study is a halloysite nano-tube composed of double layers of alumina, silicon, hydrogen and