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Effect of Freeze-Thaw Cycles on the Properties of Asphalt Pavements in Cold Regions: A Review

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Abstract

Asphalt pavements weaken over time due to the effect of environment and heavy traffic loading on paving constituents. Rutting, fatigue cracking and low temperature cracking are the major distresses responsible for degradation of the pavement and consequently leads to the failure of flexible pavement. Asphalt pavement is directly exposed to atmosphere and hence, suffers the effects of weather, environment and automobiles. Apparently, for a new asphalt pavement, even though there is no vehicle loading or other artificial activities, deterioration can also appear under climate and environment effects. In recent years, thermal cracks and low temperature distresses have become key concern for asphalt pavements in cold regions. In case of rutting of asphalt mixtures, aggregate characteristics play an important role, whereas, the properties of binder are more related to fatigue. Although the properties of asphalt binder can have a great influence on the performance of pavement, the role of aggregate gradation cannot be ignored in providing resistance to rutting and reducing permanent deformation. Gradation has significant effects on asphalt mixture's Freeze-Thaw (F-T) durability. This paper reviews research conducted on the various properties viz., fatigue, rutting, air voids, compressive strength, etc. of bituminous mixes which are under the influence of F-T cycles. This paper also discusses the effect of F-T cycles on stability of bituminous mixes.*

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1. Introduction

All civil infrastructures are facing the problem of deterioration and is being considered as a serious issue worldwide (Hong and Prozzi, 2006; Zhang and Damnjanović, 2006). Asphalt pavements are influenced by two main types of loading: mechanical loading especially due to heavy trucks, and, climatic effects as a result of moisture, temperature, and freeze-thaw cycle (Badeli et al., 2018). Asphalt Pavements are one of the key part of transportation infrastructure, which is exposed to atmosphere, suffering from environmental impact and the load of the vehicles directly (Huang, 2004). Asphalt is a thermoplastic material and is one of most important constituents of asphalt mixture. The flexible pavements are subjected to deterioration from seasonal freezing and thawing (Karen et al., 2005). Rutting, Fatigue cracking and cracking at low temperature are the main problems that cause the degradation of the paving materials and thus results in failure of flexible pavement (Lytton et al., 1983; Si et al., 2013; Vinson et al., 1989; Ziari et al., 2015). Low temperature cracking occurs when the thermal tensile stress in asphalt pavements exceeds its tensile strength (Huang, 2004). Numerous studies have concluded that distresses of the pavement has important relation with climate, the environment and loads (Feng et al., 2010; Huang, 2004; Si et al., 2013). Under the effects of repeated vehicle loading at elevated temperature, moisture changes, and low-temperature contractions, Asphalt Concrete (AC) mixtures are susceptible to damages caused due to rutting (permanent deformation), stripping (separation of asphalt from aggregates), and cracking (temperature contraction) (Huang, 2004). Water infiltration combined with the variation of temperatures deteriorates the adhesive bond between aggregates and binder (Gubler et al., 2005) .In the cold areas, the useful life of pavement decreases due to the Freeze-Thaw (F-T) cycles. During the F-T cycles, the ambient temperature repeatedly changes from positive to negative, and the pavement suffers from repeated thermal stresses and moisture influences. The compressive strength and resilient modulus of asphalt mix decreases when it is subjected to F-T cycles (Ma et al., 2015). In bituminous layers, a decreasing temperature has an effect on the binder, resulting in an increasing stiffness (Simonsen et al., 1997). From structural point of view, these changes in layer moduli are generally not critical, since the overall bearing capacity of the road structure is increased during freeze-up. However, the functional performance of the structure gets decreased due to uneven frost heave and thermally induced cracks (Simonsen and Isacsson, 1999). During spring thaw, the pavement structure can become saturated with thawing ice, and the bearing capacity is significantly reduced (Simonsen et al., 1997). Significant settlements can occur under such conditions, if the structure is exposed to heavy freight vehicles. The stability of Hot Mix Asphalt (HMA) pavements depends on the stiffness of the mixture, the bitumen content, the softening point of the bitumen, the viscosity of bitumen, the grading of aggregates, construction practice, traffic and climatic conditions (Cooper et al., 1974). The effect of varying temperature and exposure time on the stability of asphalt mixture using destructive and non-destructive methods was investigated. It has been found that the temperature of the environment considerably decreased the stability of asphalt concrete (AC) (Ozgan, 2007).

2. Engineering properties of HMA

Various studies have been carried to study the effect of F-T cycles on AC. The various properties affected are:

2.1. Thermal cracking and fatigue

Fatigue is a process in which the pavement deteriorates due to cracking because of irrecoverable strains that are built up over a period of time due to repeated loading (Sousa et al., 1991). Most of the past studies addressed fatigue damage under traffic load only. The cracks initiate at the bottom of the asphalt pavement when the tensile stresses and strains are highest, and these cracks mitigate towards the surface of the pavement (Jha et al., 2010). Fatigue cracking can also occur at the surface of flexible pavements due to extremely high tensile strains near the outer-edge of the vehicle tyre (Guercio et al., 2014). Thermal fatigue influences thermal cracking, fatigue cracking and permanent deformation resistance, and thermal fatigue due to thermal cycling is one of the reasons leading to degradation of pavement (Glaoui et al., 2011). Due to the large number of F-T cycles, the stresses in the asphalt mixture exceeds the critical value, resulting in the development of cracks and other apparent distresses (Feng et al., 2010). If the water comes into contact with the pavement, the bond between asphalt and aggregates weakens and there is a loss of adhesion, commonly called stripping. The F-T cycles result in an aggravation of the separation, which also leads to an increase in the voids in the asphalt mixture. This results in the development of various pavement distresses, such as cracking, raveling, flushing and bleeding. Environment factors such as repeated temperature fluctuations and F-T cycles in winter also cause a decrease in the stiffness of all the pavement layers, especially the surface layer, and this speed up the longitudinal and transverse top-down cracks. In addition, it accelerates fatigue damage due to traffic loading by causing an increase in the horizontal stress at the bottom of AC under traffic load. It was concluded that cracking and stripping increased with each F-T cycle. Based on the eight cycles of F-T conditioning, the splitting strength of asphalt decreases with an increase in the F-T cycle (Feng et al., 2009). Another study has shown that the initial stiffness and fatigue life of AC decreases with F-T conditioning (Barlas, 2013). At low temperature, when the water in the voids of AC material changes to ice, the AC mixture is subjected to ice-expanding force; At warmer temperature when the ice thaws, the AC structure loosens (Feng et al., 2010; Goh et al., 2011; Huang, 2004; Kettil et al., 2005; Si et al., 2013). Studies have shown that the asphalt-aggregate bonds are easily displaced by water, weakening the asphalt-aggregate binding, thereby leading to stripping phenomena (Feng et al., 2010; Goh et al., 2011; Huang, 2004; Si et al., 2013). Hence suggesting that asphalt pavements in colder areas are prone to more critical immature damage than general regions. It should be remembered that increasing the fatigue strength of a material can lead to other problems, such as a poor rut resistance. However, an improvement in fatigue resistance does not adversely affect the rut resistance of the mixes, with the exception of the cases where the softer grade of bitumen is used. A regression model for the initial stiffness and fatigue life of the asphalt samples for any number of freeze-thaw cycles when tested at 400με at 10Hz frequency and 20°C. is given by eq. 1 and eq. 2 respectively (Barlas, 2013).

$$S = 1000000e^{-0.008f} \tag{1}$$

$$L = 69270e^{-0.036f} \tag{2}$$

Where, S = stiffness (psi), L = number of cycles to failure and f = number of freeze-thaw cycles

eq. 1 and eq. 2 are used to predict the initial modulus and fatigue life of an asphalt sample for a particular freeze-thaw cycles.

2.2. Rutting

Two main mechanisms within the pavement materials that contribute to rutting are densification (compaction) and shear plastic deformation (Collop et al., 1995). These two mechanisms, each of which results from the repetitive application of wheel loads gives rise to permanent deformation in all layers of pavement. The researchers have found that if the pavement is well compacted during construction process, then it is likely that permanent deformation is due to shear flow only rather than by further densification (Eisenmann and Hilmer, 1987). Rutting not only reduces the useful life of the pavement but also creates consequential hazards for road users by affecting vehicle handling characteristics. The initial superficial type of rutting occurring in asphalt layer is densification compaction due to the load applied by the wheels of the vehicle (Eisenmann and Hilmer, 1987). This leads to formation of subsequent flow groove due to shear deformation of the pavement. The deformation causes the material to move laterally from under the wheels and, accumulates in the middle and next trajectories of the wheels. This phenomenon is clearly seen as rising of the pavement material adjacent to the rut (Olsson et al., 2000; Sousa et al., 1991). Due to the short-term amplitudes of load upon passing of automobiles, the stiffness of constituents gets reduced and a more number of load repetitions leads to a sudden reduction in the stiffness of the material and, subsequently over time its buildup can lead to total failure of the asphalt pavement (Benedetto et al., 2004). The dynamic modulus reliant on time and temperature is essential property of the bituminous material required to forecast pavement distresses, like permanent deformation and fatigue cracking (Witczak, 2008; Witczak et al., 2002). The inner arrangement of asphalt mixtures is critically damaged by F-T cycles in cold areas. Due to the repetitive cycle of freezing and thawing, voids in the mixture change and can progress in form of pavement distresses, such as loss of strength, rutting or groove formation, raveling and fatigue cracking (Amini and Tehrani, 2014). In the United Kingdom, one of the most frequent types of damage to flexible pavements is rutting in which the material that lies beneath the road of a truck wheel flows and compacts to form a groove or rut (Thrower, 1979). In case of flexible pavements, the wearing course is the top layer that is directly in contact with the tyre of the vehicles, therefore, is subjected to maximum pressure. This layer is also in contact with the atmosphere and, therefore, must resist the damage caused by the change in temperature. This layer must have the highest modulus of elasticity to withstand the high pressures and tensile stresses that develop due to traffic loads. This layer is highly susceptible to damage and generally consists of cracks in the surface, wheel ruts, deformations and potholes. Several types of distresses in flexible pavements develop due to the lower stability of the mix (Kalyoncuoglu and Tigdemir, 2004). Therefore, the stability of mixture plays a vital role to achieve a better pavement performance. Under the influence of repeated vehicle loading at high temperature, humidity cycles and low temperature contractions, asphalt mixtures are prone to permanent deformation (Huang, 2004). F-T cycles have negative effect on the performance of asphalt mixtures under vehicle loading. The internal structure of asphalt mixtures is severely damaged by F-T cycles in colder areas. The degree of conditioning effects depth of rutting and depth of wet rut is greater than dry rut in most preconditioning conditions. Saturation with F-T cycle does not result in larger wet rut depths. At the same F-T cycle, the wet rut depths of samples decreases with increasing saturation and at the same saturation, the wet rut depths of samples saturated only are usually greater than those saturated with F-T cycle (Wong et al., 2004).

2.3. Air voids

In general, it is accepted that the limits in the void content for dense mixtures are crucial for good road performance. A very low void content (sometimes called overfilling) can lead to premature rutting and a very high void content leads to reduced durability and, in most cases, to a poor resistance to rutting. Increasing the void content leads to lower fatigue performance. A 9% of expansion happens as the water phase turns to ice under normal environmental condition (Badeli et al., 2018). temperature of trapped water. As pore size decreases, the obliged temperature to freeze the water also lessens (Micah Hale et al., 2009). Size of pores plays an important role in defining the freezing temperature of trapped water In addition, the micro damage of the mixture slowly transforms into cracks and other apparent distresses (Qian and Chuang-jun, 2010; Ying-hao et al., 2008). At warmer temperatures, with melting of ice, the structure of the AC becomes loose mainly due to ice-expansion force (Feng et al., 2009; Goh et al., 2011; Huang, 2004; Kettil et al., 2005; Si et al., 2013). This expansion force results in micro-damage to mixture (Feng et al., 2010; Goh et al., 2011; Merbouh, 2012). During the thawing cycles, with the melting of the ice, more water fills the air voids and internal pores. Hence, the internal structure of mixture is severely damaged by freeze-thaw cycles in cold regions (Xu et al., 2015). It has been observed that air voids in asphalt mixtures exposed to the F-T cycles increase by 40 percent in 24 days (Özgan and Serin, 2013). In addition, air voids in open grade asphalt mixtures are more easily affected by F-T cycles than those in dense grade asphalt mixtures. The change in internal structure is attributed to three factors, that is, expansion of individual voids, coalescing of two separated air voids and formation of new voids (Xu et al., 2015). Use of various WMA technologies reduces the air voids in asphalt mixture which aids in better performance even after freeze thaw cycles (Sharma et al., 2018).

2.4. Compressive strength and resilient modulus

Asphalt pavement suffers from the impact of F-T cycles in cold regions and evaluating its influence on compressive characteristics becomes intimidating task (Feng et al., 2010; Goh et al., 2011; Merbouh, 2012).The compressive strength and the resilient modulus of the asphalt mixture tend to decrease with the increase in F-T cycles. The compression characteristics of the asphalt mixtures fall rapidly during the initial F-T cycles, whereas, the drop is soft after eight F-T cycles. (Si et al., 2015). Due to the repeated F-T cycles, the air voids in the mixture increases due to the change in volume by the expansion of water at low temperatures in the mixture. This expands the empty spaces of the internal composition and reduces the tensile strength of the mixture. The bond strength between aggregate and the asphalt is not strong. Under the considered temperature, load stress and F-T conditions, the structure of the mixture becomes loose, resulting in decrease in the compressive strength (Ai-ling et al., 2005; Chang-Xuan, 2011; Qian and Chuang-jun, 2010). The compressive strength decreases rapidly during the first few F -T cycles and the parabolic function can be used to reflect this tendency of variation. This rapid decrease in compressive strength during the first few F-T cycles is due to the expansion of the internal pores and the air gaps (Yan et al., 2008; Yi-qiu et al., 2011). This indicates that the F-T cycles during the first few years have an evident influence on the compressive strength of the asphalt mix. The inner apertures and the arrangement of the asphalt mixture fluctuates with the upsurge in the sum of F-T cycles and this has an adverse impression on the total aggregate meshing and leads to an intensification in the deformation (Yong and Li-jun, 2009; You-po et al., 2012). Consequently, the resilient modulus of AC has a declining tendency when the mix is exposed to the F -T cycles. In addition, the penetration of frozen water will destroy the structured asphalt of the aggregates, resulting in decrease in the cohesion between the aggregates and hence weakening of bond. The air pockets and the internal pores expand as the water freezes during the F -T cycles.

2.5. Viscoelastic behavior

The increasing number of freeze-thaw cycles deteriorates the viscosity of the asphalt binder, thereby reducing its ability to resist deformation. Asphalt mixture consists of asphalt binder and aggregates. Due to continuous freezing and thawing, the stability of the mixture gets reduced due to change in the structure of asphalt binder. Salt freeing cycles also has a significant influence on the viscoelastic properties of the asphalt mortar (Cui et al., 2017). Asphalt binder displays viscoelastic properties by showing viscous properties at elevated temperatures and elastic properties at low temperatures. Both, low temperature and high temperature are detrimental for asphalt, since low temperatures result in cracking whereas as high temperatures result in the formation of ruts. The permanent deformation in the asphalt occurs due to the viscous flow after it gets subjected to repetitive loading (Nicholls, 1998). The asphalt binder merely contributes to permanent deformation (15-20%) (Lavin, 2003). The quality and structure of the aggregates along with the proper mix design greatly impacts the rutting behavior of the pavement, and is responsible for rutting to a greater extent, that is, 80-85% (Kriech, 1994). The F-T cycles reduce the elastic behavior of the binder, thus resulting in increase in the deformation as well as higher chances of cracking.

3. Stability of mix

The main cause of damage to road pavements is the change in temperature and this change in temperature produces change in the stability of the asphalt mix. Several types of distresses in asphalt pavements develop due to the lower stability of the mixture (Tigdemir et al., 2002). Therefore, the stability of mixture plays an important role to achieve the better performance of the highway pavement. The Marshall Stability value decreased with the increase in F-T cycles. The stability value was reduced by 77.4% at the end of 24 days. Voids filled with bitumen values also showed a decreasing trend. Voids in mineral aggregate increased under the influence of F-T cycles and its value increased by to 7.4%, so freeze-thaw has a drastic negative effect on the performance of asphalt mixtures (Özgan and Serin, 2013). Low stability in asphalt pavement leads to several types of distress in asphalt pavements (Kalyoncuoglu and Tigdemir, 2004; Tigdemir et al., 2002). In case of WMA also, the application of F-T cycles damages the mixture adhesiveness and cohesive bonds, resulting in lower stability (Sharma et al., 2018). Use of natural asphalt at 8.33% by weight of mixture helps in achieving better performance in terms of improved resistance to stripping with successive F-T cycles, decreased susceptibility of mixture to permanent deformation and increased resistance to high loads (Kök et al., 2012).

4. Conclusion

Based on the literature review presented in this paper, the following main conclusions can be drawn

- Freezing and thawing can severely affect the physical and engineering properties of the asphalt pavement. The alteration is usually observed in the resilient modulus, the compressive strength, air voids, fatigue cracking and the rutting. Fatigue and rutting are distresses associated with flexible pavement that are more sensitive to climatic conditions. Use of WMA technologies and natural asphalt can aid in improving engineering properties of bituminous mixes subjected to freeze and thaw.
- The behaviour of bituminous mixture is mainly determined by the stiffness of the mix. The effect of freeze-thaw cycles is responsible for a lower stiffness value, which can affect the life of the mixture.
- The selection of the proper void content is essential for good pavement performance. Since too low void content can lead to premature rutting and too high can reduce the durability, therefore, great care must be taken when selecting the void content for the bituminous mix.

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