ABSTRACT

Cold recycling using foamed bitumen (FB) has become a common method of rehabilitation for flexible pavements due to its potentially fast, cost-effective, and environment-friendly construction procedure. With the increased adoption of this technology by road agencies, considerable experience has been gained by engineers and researchers in the recent past with the construction of pavements incorporating foamed bitumen stabilised mixes (FBSMs). Based on this experience, different agencies developed mix design guidelines for FBSMs. Despite these efforts, there is a significant knowledge gap concerning some of the mix design considerations. This is primarily due to the distinct nature of these mixes in terms of their composition, structure, and mechanical characteristics compared to the conventional hot mix asphalt. With this view, the present study was taken up to contribute to the improvement of the mix design approach of FBSMs, particularly in the Indian context, through experimental investigation on various mix design considerations. Accordingly, the objective of the present study is to understand the mechanism involved in three major considerations of the mix design process of FBSMs, namely (1) characteristics of FB, (2) moisture susceptibility of FBSMs, and (3) moisture conditioning of FBSMs.

The foam characteristics of bitumen, such as maximum expansion ratio (ER_m) and half-life (HL), that are used to assess the quality of FB, are conventionally measured manually using a dipstick and stopwatch. Considering the related safety concerns and high variability of such measurements, the present study attempted to improve the process of determining the foam characteristics during the foaming process. This was accomplished by developing an ultrasonic sensor system that is capable of automatic non-contact measurement of bitumen foam characteristics. The repeatability of the developed system was evaluated and compared with that of the manual method. The study results indicate that the ultrasonic sensor system is very promising in terms of its ability to capture the entire expansion-decay profile of the FB with time. The developed system showed a noteworthy improvement in the accuracy of the measurement of FB characteristics with high repeatability compared to the conventional manual method. In addition to the precise measurement of FB Characteristics, the developed system also addressed most of the safety issues associated with the manual measurement.

The study also investigated how the intrinsic properties of bitumen control its foaming potential. For this, the influence of physical properties (such as penetration, softening point, and viscosity),

chemical properties [in terms of SARA (acronym of saturates, aromatics, resins, and asphaltenes) components and Fourier transform infrared spectroscopy (FTIR) indices], as well as physicochemical characteristics of bitumen [in terms of surface free energy (SFE)] on foam characteristics were investigated. The correlation analysis between the intrinsic properties of bitumen and foam characteristics of ten bitumen types from two different sources indicated that the physical properties of bitumen alone generally fail to explain the foaming potential of different grades of bitumen. The study results also revealed that the chemical compositions and SFE of bitumen can explain the variability associated with the foaming potential of different bitumen types in terms of ER_m and foam Index (FI), provided, they belong to the same source. In general, the intrinsic properties of bitumen were unable to explain the variability in the HL of FB, even when the bitumen types are from the same source.

Considering moisture susceptibility as the critical performance characteristic of FBSMs, the present study intended to better understand the influence of various factors on FBSM moisture susceptibility. Factors, such as bitumen physical properties (viscosity), foam characteristics, as well as their interaction effect, were evaluated with an aim to propose recommendations for bitumen selection and develop performance-based (moisture damage resistance) threshold limits of foam characteristics so that a satisfactory mix in terms of moisture damage resistance can be prepared. The study was carried out on FBSMs prepared with three bitumen types and 70% reclaimed asphalt pavement (RAP) mixes. The detailed laboratory investigation suggests that the physical properties of bitumen have a pronounced effect on the moisture susceptibility of FBSMs. However, the influence of FB characteristics and their interaction effect with the physical properties of bitumen were found to be equally significant. Findings suggest that the selection of bitumen for FBSMs should be based on physical properties as well as the FB characteristics. In this study, a strong positive correlation was noted for the product of ER_m and bitumen viscosity (viscosity at 60°C × ER_m) with the moisture damage resistance of FBSMs in terms of the wet indirect tensile strength (ITS-wet). Therefore, it is suggested that the product of ER_m and bitumen viscosity can be considered as a bitumen selection parameter for FBSMs where the bitumen with a higher value of the product should be selected. The study also found that between the two most widely considered foam characteristics i.e. ER_m and HL, ER_m has a relatively more dominant effect on the moisture susceptibility of FBSMs. The effect of HL is supplementary to the effect of ER_m. The study also proposed performance-based minimum threshold limits for ER_m and HL based on

the Receiver Operation Characteristics (ROC) analysis on the retained tensile strength (TSR) results obtained for the FBSMs prepared at varying foam characteristics. Based on the analysis, the study recommended that the FBSMs should be prepared with a minimum ER_m of 6 and HL of 4 secs to achieve a TSR level of more than 70%. To achieve a TSR level of more than 50%, a minimum ER_m of 4 and HL of 3 secs may be sufficient. The proposed threshold values were validated based on tests on mixes that are not part of the original analysis.

Conditioning the FBSM specimens prior to their evaluation for moisture damage resistance is one of the most important processes of the mix design. Therefore, selecting an appropriate laboratory moisture conditioning method that represents the key failure mechanisms of FBSMs is of utmost importance. In this regard, the present study also conducted a comprehensive investigation of the moisture conditioning of FBSMs. The effectiveness of three different moisture conditioning methods that are commonly used for moisture susceptibility evaluation of FBSMs, such as the conventional 24 hours of water soaking, vacuum saturation as per the AASHTO T283, and ASTM D7870 conditioning (hydrostatic pore pressure) were evaluated. For moisture conditioning of FBSMs as per ASTM D7870 standard, a moisture conditioning system that can apply cyclic hydrostatic pressure on the specimens was developed. It was observed that the ASTM D7870 moisture conditioning method could distinguish between moisture-resistant and moisture-susceptible mixes more accurately compared to the existing 24 hours of water soaking. Detailed analysis of the results suggests that the ASTM D7870 conditioning can potentially be a more suitable conditioning method than the existing 24 hours of water soaking for moisture susceptibility evaluation of FBSMs. The study also recommended threshold moisture susceptibility criteria in terms of TSR for the ASTM D7870 conditioning method based on the existing moisture susceptibility criteria for 24 hours of water soaking by performing ROC analysis on the TSR results. For different TSR criteria of 80%, 70%, and 60% for 24 hours of water soaking, the equivalent TSR threshold for ASTM D7870 conditioning is recommended as 60%, 55%, and 50% respectively.

Keywords: Foamed bitumen, foamed bitumen stabilised mixes, mix design considerations, foamed bitumen characteristics, moisture susceptibility, moisture conditioning