

## ABSTRACT

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Recent advancements in pavement research have increasingly focused on lowering production and compaction temperatures to improve the environmental and economic sustainability of hot mix asphalt (HMA) while maintaining its workability, durability, and performance. Warm mix asphalt (WMA) technology offers substantial environmental benefits and economic gains by reducing production temperatures (typically by 20–40°C), leading to lower emissions, energy consumption, and construction costs. WMA technologies are broadly categorized into organic, chemical, and foaming-based types. Although several proprietary technologies have been successfully implemented in the field, challenges remain in evaluating the workability, defining appropriate production temperatures, and assessing the impact of temperature reductions on pavement performance.

Guidelines for determining the production temperatures of asphalt binders are typically found in ASTM D2493 which recommends the equi-viscous method. This approach relies on measuring binder viscosity using a rotational viscometer (RV) and selecting temperatures corresponding to standard viscosity thresholds (e.g.,  $0.17 \pm 0.02$  Pa·s for mixing and  $0.28 \pm 0.03$  Pa·s for compaction). While this method has been widely used especially for unmodified, it often yields unrealistically high production temperatures for polymer-modified and WMA-modified binders. These elevated temperatures can result in excessive emissions and degradation of binder properties. Consequently, alternative methods have been proposed, such as those documented in the NCHRP Report 648, including high and low shear rate viscosity, zero shear viscosity (ZSV), simplified ZSV, steady shear flow, and phase angle-based approaches. While these methods offer improved predictions, their application remains limited, and none have been standardized for WMA-modified binders.

Traditionally, the reduction in production temperatures has been attributed to decreased binder viscosity. However, this assumption does not fully capture the complexity of binder behaviour in WMA modified binders. Although viscosity is a critical parameter influencing workability, WMA technologies often involve physical, chemical, or combined mechanisms that alter binder-aggregate interactions beyond viscosity modification. These include surface tension changes, foaming behaviour, adhesion promotions and time-temperature dependent rheological shifts which are not fully captured by conventional viscosity measurements alone. Hence, relying solely on viscosity can lead to inaccurate estimation of production temperatures, potentially affecting the compactibility, coating, and long-term performance of mixtures. Recent studies have proposed that frictional behaviour between binder and aggregate may serve as an additional or alternative indicator of workability. The improved lubricating effect of WMA binders attributed to reduced friction can enhance mix workability and compaction at lower temperatures. Hence, it is important to understand frictional mechanisms contributing to temperature reduction and define the constructability of WMA mixes accordingly. This understanding of frictional mechanisms can be studied using science of tribology. Also, the benefits and risks associated with the performance of WMA modified binders in terms of resistance to distress (rutting and fatigue cracking) and moisture damage have to be studied for optimizing the amount of additive dosage to be used for satisfactory results.

The main highlight of this thesis work is to carry out the tribological and performance assessment of WMA modified binders to determine their production temperatures and to understand the impact of reduced production temperature on performance of WMA modified binders. For this research work, two base asphalt binders, viscosity graded (VG), VG30, and polymer modified binder (PMB), PMB40 have been considered for preparation of WMA modified binders. Four different WMA additives: two organic-based (Sasobit and Asphaltan A) and two chemical-based (Rediset and Iterlow) additives have been used in the present study.

Five aggregate types from different sources: Granite, Dolomite, Dolerite, Basalt, and Sandstone have been used in the study to understand effect of WMA additives on moisture sensitivity of WMA modified binders. Among five different aggregates, Granite and Dolerite have been considered to understand the tribological and workability characteristics of WMA modified binders. After finalising various materials in the study, the four aspects of WMA technology have been critically evaluated in this study: First, the tribological assessment of WMA modified binders. Second, the performance of WMA modified binder at reduced aging level. Third, evaluation of moisture sensitivity of WMA modified binders by considering various aggregate types. Fourth, the dosage optimisation and selection of WMA according to the performance requirements of specific locations. The following paragraphs provide a concise discussion of these aspects, their corresponding results, and the implications that arise from them.

#### ***Tribological assessment of WMA modified binders***

In this study, ball on three plates tribology test has been performed on WMA modified binder by considering Steel, Granite and Dolerite plates. The ball-on-three-plates tribology test has been used to propose an approach for evaluating the mixing and compaction temperatures of asphalt binder. The ball-on-the-three-plate test was performed using different normal loads (1N, 3N, 5N, and 10N) and sliding speeds (0.05 m/sec, 0.1 m/sec, and 0.3 m/sec). The results are compared with various viscosity-based methods and phase angle method. To validate the mixing and compaction temperatures obtained from the tribology approach, workability, coating ability, and compactibility tests were performed. Workability assessment was carried out using a torque tester, where workability was measured by the torque required to rotate asphalt mixtures. The equi-torque concept was applied to determine the mixing and compaction temperatures which were then compared with those derived from the tribology test. Coating ability was tested to validate the mixing temperature, where image processing techniques were

employed to assess the coating ability of the mixture, with the normalized coating index serving as the parameter. Compactibility was assessed through air voids in Marshall-compacted specimens and was used to validate the compaction temperature. Viscosity based methods and phase angle method were found to be inappropriate in the quantification of the production temperatures of WMA binders. Results of the tribology study showed that the normal load of 1N and 0.3 m/sec was suitable for evaluating the production temperatures. Adding WMA additives resulted in a lower coefficient of friction (CoF) indicating better lubricating behaviour, whereas PMB showed higher CoF than viscosity grade binder. The effect of plate type (Granite, Dolerite, and steel) on the values of CoF was found to be insignificant, and the use of steel plates was recommended. Tribology test results indicated that reduction in mixing and compaction temperatures is a function of the type of warm mix additive, dosages used, and aggregate source. The results of tribology and workability were in good agreement with each other. The results of tribology test were well validated using workability test, coating ability test, and compactibility test. All WMA modified binders showed better or similar coatability and compactibility at lower temperatures (obtained from tribology approach) as compared to base asphalt binder. Temperature ranges corresponding to the CoF of  $0.26\pm 0.021$  and  $0.33\pm 0.023$  were proposed for assessing the mixing and compaction temperatures, respectively.

#### ***Performance assessment of WMA modified binders***

Warm mix asphalt (WMA) technology has proved to be a substitute for the production of asphalt pavements due to its lower mixing and compaction temperatures. However, one of the concerns associated with WMA technology is the effect of reduced aging on the performance of asphalt binders. This study investigates the impact of reduced aging temperature on the performance of WMA modified binders. Fourier transform infrared spectroscopy (FTIR) has been conducted to check changes in the chemical composition of the asphalt binder due to aging. Performance of the warm mix (WM) modified asphalt binders was assessed using linear

amplitude sweep test (LAS), multiple stress creep and recovery (MSCR) test. FTIR analysis showed that the addition of WMA additives increases the aging resistance of asphalt binders indicating lower aging potential of WMA modified binders. Performance test results revealed that the application of chemical WMA additives enhanced the fatigue performance compared to base binder and organic additives. On the other hand, organic additives decreased the non-recoverable creep compliance (J<sub>nr</sub>) and increased the percent recovery (%R) indicating better rutting performance, whereas the contrary trend was observed with the addition of the chemical additives. However, the use of chemical WMA additives in polymer modified binder showed excellent performance against rutting. Aging, rutting, and fatigue cracking performance of WMA additives have been amplified when blended with polymer modified binders.

#### ***Evaluation of moisture sensitivity of WMA modified binders***

Increased moisture susceptibility is a key challenge for Warm Mix Asphalt (WMA) technology. To better understand the moisture damage mechanism, evaluating the bond strength between aggregate and asphalt binder is crucial. Conventional moisture damage tests, such as the tensile strength ratio (AASHTO T 283) and boiling water test (ASTM D3625), often fail to replicate real field conditions, particularly the combined effects of tire movement and moisture. To address this limitation, this study employed the Pneumatic Adhesion Test (PAT), a binder-level method that provides a more realistic assessment of moisture-induced bond failure. The bond strength was evaluated using pull-off tensile strength (POTS) which measures the force required to break the bond between aggregate and asphalt binder. Moisture susceptibility was determined using the Bond Strength Ratio (BSR), defined as the ratio of pull-out tensile strength under wet conditions to that under dry conditions. This study examined the impact of various aggregates and four WMA additives on bond strength. Results showed that the bonding between aggregate and asphalt binder relies on the aggregate type, base binder, WMA additives and their dosages. Since PAT was carried out on both wet and dry-conditioned

samples, it was found that the conditioning state (wet and dry) also affects the interfacial bonding of the asphalt-aggregate matrix. Wet-conditioned samples tend to exhibit lower POTS values than dry-conditioned samples. Organic additives increased the bond strength due to the crystallization effect of the wax, whereas chemical additives showed negligible change, probably due to the emulsifying and surfactant action. The BSR values were found to be different for various aggregate-asphalt binder combinations. The threshold of BSR was found to be 0.82, corresponding to 93.2% reliability. This value can be used as a pass/fail criterion for moisture damage assessment at the binder level.

### ***Dosage optimisation and selection of WMA additives***

The dosages of WMA additives become very crucial while studying their effect on the performance of the asphalt binder. It is desirable to select the dosage that not only reduces the production temperature but also provides similar/better performance compared to conventional HMA (like base asphalt binders). Therefore, the dosage should be optimized by satisfying the performance characteristics of asphalt binder, which are highly dependent on the production temperatures. In this study, ranking methodology has been used to determine the optimum dosages of WMA additives based on their performance parameters. Optimum dosage determined was found to be different for both the base binders, as the interaction of base binders was found to be different with WMA additives. Finally, the selection of WMA additives was performed using various performance parameters for distresses such as rutting, fatigue cracking, low temperature cracking, and moisture damage. Ranking was employed in the study to rank the WMA additives for their selection corresponding to the types of distress. Ranking analysis showed that the WMA additives demonstrated varying rankings for different types of distresses. Organic additives are more effective in mitigating rutting, as evidenced by their higher rankings in scenarios where rutting is the primary concern. Conversely, chemical additives demonstrate superior performance in addressing fatigue cracking, achieving higher

rankings in such concerns. Regarding moisture damage, WMA additives with anti-stripping properties are ranked highest, indicating their enhanced efficacy in preventing moisture-induced distress.

**Keywords: WMA Technology, Tribology, Workability, Reduced aging, Performance, Dosage optimisation**