ASSESSING THE IMPACT OF PRODUCTION TEMPERATURES ON THE PERFORMANCE OF WARM MIX ASPHALT

वॉर्म मिक्स डामर के गुणों पर उत्पादन तापमान के प्रभाव का आकलन

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CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Preface

The present study assessed the influence of mixing and compaction temperatures on warm mix asphalt (WMA) performance. Two aggregate sources (granite and dolomite), two base asphalt binders (VG30 and PMB40), and five WMA additives categorized under organic, chemical, and foaming technologies were used to prepare WMA binders and mixtures. The performance of WMA was analyzed and compared with their respective base asphalt binders and mixtures through different experimental investigations. In addition, this study also assessed the energy consumption and resulting exposure to greenhouse gas (GHG) emissions during the production of asphalt mixtures, especially for WMA technologies. Six objectives were defined in this direction.

This chapter presents the conclusions drawn from different phases of the work, the main contributions, limitations, and applications of the study. The chapter also includes the scope and recommendations for future studies.

9.2 Conclusions

The following successive paragraphs present the conclusion drawn from different study phases.

9.2.1 Material Characterization

- Scanning electron microscopy (SEM) images confirmed that the adopted blending technique is appropriate for obtaining the homogeneous blend of WMA additive inclusive asphalt binder. All the WMA additives indicated a definite impact on the surface morphology of the base asphalt binders (VG30 and PMB40). However, due to the dominance of the polymeric network in the polymer-modified binder, the influence of WMA was relatively less significant in PMB40.
- FTIR results confirmed that the interaction between WMA additives and asphalt binders is purely physical. No new peaks were observed after the blending of WMA additives. However, a difference in the intensity of the absorbance peak was identified, depending on the base asphalt binder and WMA type.
- Sasobit Redux, Rediset, and Cecabase did not influence the physical characteristics (penetration, softening point, and viscosity) and high-temperature performance grade (PG). Incorporating Sasobit increased the softening point, viscosity, and true fail temperature and reduced the penetration value, irrespective of the base asphalt binder.

9.2.2 Production Temperatures of Asphalt Mixtures

- None of the test methods, which comprise testing the asphalt binder for evaluating production temperatures, were found to be appropriate. Therefore, the EQ method was found suitable only for VG30.
- Torque obtained in the workability approach was found to be inversely related to the temperature. However, the torque increment rate was higher for conventional HMA mixtures than for WMA mixtures. Workability analysis showed that the

mixing and compaction temperatures of all the warm mix-based asphalt mixtures were reduced by approximately 3-15% and 3-25%. The reduction in temperature is a function of warm mix technology, its type, and dosage. The maximum reduction in production temperatures was obtained for Sasobit Redux and Rediset.

- WMA mixtures prepared at reduced mixing temperature exhibited the same/better degree of coating than the HMA mixture. Chemical additives showed higher values of normalized coating index (CI_N), followed by organic and foaming-based technologies. Even at reduced compaction temperature, the air voids within WMA mixtures were consistent with the results obtained for conventional HMA mixtures. The proposed workability method for determining the production temperatures of WMA mixtures was found to be appropriate.
- Based on the coating and compactability results, the optimum dosage was found to vary with the change in base asphalt binder and aggregate source. The variation significantly depended on the WMA technology.

9.2.3 Performance of Asphalt Binders

- All the WMA binders acted as an anti-oxidant for base asphalt binders. Based on $I_{C=O}$ values, PMB40 exhibited higher ageing resistance compared to VG30. WMA additives with VG30 lowered the ageing susceptibility by 41-59% for STA and 24-65% for LTA, whereas a reduction of 23-38% for STA and 37-57% for LTA was observed in the case of PMB40.
- Incorporation of WMA additives imparted similar to better elasticity (based on percent recovery) with comparable (or even higher) rutting resistance (based on non-recoverable creep compliance) than base asphalt binders. In addition, the impact of WMA additives was observed to be more favorable for VG30 than

PMB40. Among different WMA additives, Sasobit imparted higher stiffness to the asphalt binder at all the test temperatures, resulting in excellent rutting performance.

- The addition of WMA additives with VG30 resulted in a relatively wider stress-strain curve, while a sharper curve was observed in the case of PMB40. Organic additives improved the peak stress, whereas higher failure strain was evident with chemical agents. The fatigue life (N_F) curves indicated that WMA binders did not deteriorate the long-term fatigue behavior of asphalt binders. A comparison of WMAs showed that chemical-based WMA binders outperformed other technologies at all strain amplitudes.
- WMA binders prepared with organic additives showed higher bond strength (BS) values than their respective base asphalt binders, while the effect of chemical agents was insignificant. However, chemical-based WMA binders exhibited a higher bond strength ratio (BSR), indicating an improvement of 3-12% in moisture resistance. The relative improvement with organic additives was 0-7%, depending on the type of aggregate substrate and base asphalt binder. The highest value of BSR was obtained with dolomite aggregates compared to granite, but the difference was relatively marginal. Besides, none of the WMA binders failed in adhesion, irrespective of the conditioning process.

9.2.4 Performance of Asphalt Mixtures

- Despite the reduced ageing temperature, all the WMA mixtures passed the termination criteria of 3600 loading cycles of 100 kPa at 60°C. Organic-based WMA additives performed better against rutting failure, followed by foaming and chemical agents. The rutting behavior of Sasobit with VG30 and granite aggregates was promising, while with PMB40, it showed higher creep modulus (or rutting resistance) with dolomite aggregates. However, the effect of WMA additives on the rutting resistance was slightly lower in the case of PMB40.

- Applying chemical-based WMA agents in VG30 and PMB40 leads to superior fatigue performance compared to organic and foaming-based additives. The combinations such as DPC, GPC, DR, and GR showed improved performance among their respective sample group. Even though the production temperatures of WMA mixtures were lower than HMA, the fatigue performance, indicated by Fatigue Index (FI), was comparable (or even better).
- Irrespective of the test method, WMA mixtures provided sufficient resistance against moisture damage. Rediset displayed superior performance against moisture damage among different WMA additives. However, the relative values between different samples were found to be in close proximity with no significant difference. Though the base binder's effect was not significant, dolomite aggregates showed higher resistance to moisture damage than granite.
- Results demonstrated appreciable correlations between the performance parameters of asphalt binders and mixtures. Non-recoverable creep compliance (J_{nr}) at 3.2 kPa offered the highest correlation (R^2 = 0.77) with the creep modulus. The rutting parameter of the asphalt binder and the creep modulus of the asphalt mixture exhibited a good correlation with an R^2 of 0.70. The correlation between FI and N_F tends to increase with an increase in strain level and stabilize at around 0.75 (ranging from 0.74-0.75), particularly after a 10% strain value. Considering moisture potential, a consistent correlation between BSR and tensile strength ratio (TSR) was found, ranging from 0.61 to 0.72.

9.2.5 Economic and Environmental Burdens

- The average maximum amount of heat energy was needed for heating the aggregates (60%), followed by water vaporization (25%), heating of asphalt binder (10%), heating water (4%), and removal of steam (1%). The application of WMA technologies lowered the production temperatures and thereby reduced the overall energy consumption by around 5-13% relative to HMA. In particular, reduction in energy consumption for organic, chemical, and foaming-based additives ranged from 6%-10%, 5%-13%, and 7%-13%, respectively.
- The heat energy required for producing asphalt mixtures was highest for coal-based plants, whereas it was the least when natural gas was the energy source. Although the amount of coal required to produce asphalt mixtures is the highest, the overall cost for producing asphalt mixtures using coal was considerably low due to the lower unit cost of coal relative to other fuels.
- The addition of Sasobit Redux and Rediset in VG30 and PMB40, respectively, and granite (i.e., GSR and GPR), indicated maximum cost savings. In the case of dolomite aggregates, using Aspha-Min, either with VG30 or PMB40 (i.e., DAm and DPAm), yielded more savings than other WMA additives. Irrespective of the fuel type, Cecabase with VG30 and dolomite aggregates could reduce the energy demand and considerably lower the construction cost. Using WMA additives with PMB40 and dolomite aggregates may not be cost-effective.
- WMA mixtures, irrespective of the aggregate source and base asphalt binder, reduced the GHG emissions compared to conventional HMA mixtures. Eventually, GHG emissions can further be minimized by adopting a cleaner energy source, such as natural gas. Shifting from coal, heavy oil, light diesel oil (LDO), furnace oil, low

sulphur heavy stock (LSHS), and diesel-based plants to natural gas reduces the environmental burden by a considerable amount ranging from 23-35%.

9.2.6 Ranking of WMA Additives

- Among different WMA binders, the use of Rediset with both VG30 and PMB40 showed the highest-ranking, except in the GVG group where Sasobit Redux outperformed.
- Based on the ranking of WMA mixtures, organic-based WMA additives exhibited a superior rank with VG30, whereas the chemical-based agents displayed better performance with PMB40. Organic based WMA additives generally reduces the viscosity of asphalt binder and hence influences the stiffness of the unmodified asphalt binder (here VG30). However, the presence of polymeric network in PMB confronts the impact of organic based WMA additives and thus the change in properties of PMB with organic based WMA additives was not noticeable. On the other hand, chemical-based WMA additives works on the principle of surface tension, which is primarily dependent on the interaction between aggregates and WMA binders. Thus, for PMB, the effect of chemical-based WMA additives was found to be more favorable in comparison to organic-based WMA additives.
- Based on average rank value (*ARV*), Sasobit, an organic-based WMA additive, attained the highest-ranking against rutting distress, whereas chemical agents, such as Cecabase and Rediset, indicated superior performance against fatigue and moisture damage. Global average ranking (*GAR*) showed that Rediset, a chemical-based WMA agent, is the best WMA additive in terms of mechanical performance and social and environmental aspects.

9.3 Contribution of the Study

The present study provides insight into the performance of WMA at reduced production temperatures. The significant contributions from the study are listed below:

- The current guideline, IRC SP 101-2019, on the use of warm mix asphalt (WMA), is also silent on rational quantification of mixing and compaction temperatures. In this study, a novel workability-based approach was proposed which can be successfully used to determine the production temperatures (mixing and compaction temperatures) for WMA. A workability apparatus was fabricated, and its applicability was demonstrated by testing HMA and WMA mixtures.
- It is recommended to use the procedure outlined in this study as a part of IRC SP 101 for the evaluation of production temperatures of WMA.
- The suitability of the workability apparatus for evaluating the production temperatures was addressed through two validation tests, including coating ability and compactability. In this direction, an image capturing device was built, and the coating of asphalt binder over the mineral aggregates was quantified by processing the images through an Android-based application. In addition, the compaction characteristics were validated using the air-void data of compacted asphalt mixtures.
- For a particular construction with fixed aggregate type and WMA technology, selecting/optimizing the appropriate dosage of WMA additive is critical for asphalt industrialists. Therefore, a criterion based on the coating and target air void range was proposed in this study to estimate the optimum warm mix dosage for the production of WMA.

- This study also detailed the influence of WMA additives against rutting, fatigue, and moisture sensitivity based on different test parameters at binder and mixture levels.
- The present study attempted to compile the data, in terms of energy consumption and GHG emissions, for constructing an eco-friendly and sustainable pavement.

9.4 Limitations of the Study

The present study intended to explore the impact of production temperatures on the performance of WMA binders and mixtures. The experimental work included the use of two aggregate sources (granite and dolomite), two base asphalt binders (VG30 and PMB40), and five WMA additives (Sasobit, Sasobit Redux, Cecabase, Rediset, and Aspha-Min). However, the aggregate gradation was kept constant throughout the research work.

9.5 Applications of the Research Output

- The results of the study can be directly used to revise the present Indian Roads Congress specification IRC SP 101-2019.
- Proposed limiting values of different parameters such as Creep Modulus, Fatigue Index, and Bond Strength Ratio can be used for the acceptance/rejection of asphalt mixtures.
- Results of the present study can be used to select appropriate WMA dosage for pavement construction, depending on the aggregate source and base asphalt binder.

9.6 Future Recommendations

The research outcomes of this study, considering the implementation of WMA technologies, are promising and encouraging. Nevertheless, there persists some scope for further investigation and analysis. The recommendations for additional research within this domain include:

- The effect of shear rate on torque values and production temperatures by testing the asphalt mixtures at varying speeds can be explored. Further, it is recommended to correlate the workability of asphalt mixtures with mix volumetric and performance-based test results.
- The present study evaluated the performance of WMA based on laboratory investigations. However, validation being a concern, a comprehensive field study is essential to understand the long-term effectiveness of WMA technologies.
- The economic concerns and environmental burdens may be further reduced by incorporating reclaimed asphalt pavement materials (RAPM) or other sustainable waste materials along with WMA technologies. Thus, future research can be done in this direction.
- Since energy consumption and GHG emissions were evaluated only by considering the production of asphalt mixtures, future expansion can be done by incorporating all the stages of life cycle assessment, from raw material extraction to the end of pavement life.