

**PERFORMANCE EVALUATION OF REJUVENATORS  
BASED ON AGING BEHAVIOR OF HOT RECYCLED  
ASPHALT MIXES**

**गर्म पुनर्चक्रित डामर मिश्रण के पुराने व्यवहार के आधार पर  
पुनर्जीवनकर्ताओं का प्रदर्शन मूल्यांकन**



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**Doctor of Philosophy**

By

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## **CHAPTER 8. CONCLUSIONS AND FUTURE RECOMENDATIONS**

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### **8.1 Preface**

This study is focused on multiple aspects of rejuvenators used for the hot recycled asphalt mixes. Effect of source of WEO on its behaviour as rejuvenator, suitability of AASHTO R 30 aging protocol for durability study, characterisation of rejuvenators, assessing the best suitable parameter for the evaluation of optimum dosage of rejuvenators and durability of recycles mixes in comparison with virgin mixes are the several objectives addressed in this study to provide insights into the rejuvenators. Four different type of rejuvenators: waste engine oil (E), waste vegetable oil (W), bio-oil based commercial rejuvenator (B) and compound type commercial rejuvenator (R) and two RAP contents: 40% and 80% are used in this study. Artificial aged VG-30 binder is used as RAP to avoid the influence of variability associated with field RAP and solvent in the recovered RAP binder on the test results. This chapter presents the conclusions and the main contributions from the multiple objectives of the study. Future recommendations based on the limitations of this study is also provided at the end of this chapter.

### **8.2 Conclusions**

#### ***8.2.1 Suitability of the existing aging protocol***

- Marshall stability, being empirical, showed little change with aging, indicating its limitation in capturing material property variations under environmental conditions.
- Asphalt flexibility ratio and peak load (IDEAL CT test), permanent strain (Dynamic creep test), tensile strength (ITS test) and recoverable strains (resilient modulus test) indicate that flexibility of the virgin asphalt mixes decreased and stiffness increased with the increase in the aging periods.

- Aging effects were significant between 45–100 h. Statistical analysis and aging index showed  $CT_{\text{index}}$  was most affected, followed by permanent strain and resilient modulus. The AASHTO R30 protocol adequately reflected performance changes, though aging impact varied with performance type.

### **8.2.2 *Effect of source of waste engine oil***

Difference between the two waste engine oils i.e. A - blend of multiple unknown used engine oils and B - WEO from a known single source, is evaluated based on the performance of recycled mixes at two RAP percentages (40 and 80%). The performance tests and two-way ANOVA results suggests that rejuvenator type (source of WEO) have significant influence only on rut depth but not on  $CT_{\text{index}}$  and TSR. Rather than rejuvenator type, dosage influence is more on the rut depth. From the overall performance, it can be said that source of WEO do not impact the performance of recycled mixes considerably i.e. uniform or single sourced WEO and blended WEO would perform similarly.

### **8.2.3 *Optimum dosage and evaluation of rejuvenators***

- All rejuvenators restored performance parameters but at different dosages, varying linearly with dosage. Blends with 80% RAP were more dosage-sensitive than 40% RAP blends. Dosage of bio-oil based rejuvenators (B and W) is more delicate compared to petroleum based (E) and compound (R) rejuvenators. Softening point, ZSV, and G-R gave unreliable dosages; overall, optimum dosage was  $PGI \pm 3.75\%$ .
- Despite similar physical properties, B-W and E-R differed in viscosity and aging resistance; WR were more stable than CR. All rejuvenators contained aliphatic and aromatic hydrocarbons like asphalt maltenes.
- From the global total rank values (GTRV), it is concluded that WR outperformed CR, with W ranking the highest, followed by E, B and R. RTFO weight change correlated

strongly with GTRV, making it a reliable criterion for rejuvenator selection over viscosity measures.

### 8.2.4 *Durability of recycled mixes*

- The rate of decrement of  $CT_{index}$  for recycled mixes is lower than virgin mixes, implying that  $CT_{index}$  values of recycled mixes are less effected by aging time compared to virgin mixes.
- $RT_{index}$  of recycled mixes is more sensitive to aging than virgin mixes. E4 and R8 mixes exhibited almost similar values and rate of increment as that of virgin mixes. All the remaining recycled mixes exhibited high rate of increments than virgin mixes.
- Moisture resistance showed two trends: in virgin, B4, E4, W4, and E8 mixes it decreased linearly with aging due to increase in functional groups that have high affinity to water, while in R4, B8, R8, and W8 it increased, likely from rejuvenator dominance, which consists of amines that enhanced bond strength.
- $M_R$  values of all mixes increased with time (except W8) but rate of increment for recycled mixes is very less than virgin mixes. Similar to  $CT_{index}$ , recycled mixes with RAP and rejuvenators are more durable than virgin mixes in terms of resilient modulus.

### 8.3 Summary

The study outcomes can be summarized as follows:

- AASHTO R 30 aging protocol indeed imparts changes in the performance of asphalt mixes (both virgin and recycled mixes) and can be used for a comparative study in the aspect of aging.
- Doesn't matter whether blended or a uniform sourced waste engine oil, it's behaviour as a rejuvenator remains the same.
- Weight change of rejuvenator after RTFO test can be used as a screening test for the selection of best performing rejuvenator.

- The optimum dosage of rejuvenators lies in the range of  $PGI \pm 3.75\%$ . Dosage to be implemented can be selected according to the performance requirements of project or location. Priority can be given to higher dosage ( $PGI+3.75\%$ ) when fatigue performance is of more importance. Similarly, lower dosage ( $PGI-3.75\%$ ) can be prioritized when rutting performance is of more importance.
- Durability is not an issue for the recycled mixes with higher RAP contents and rejuvenators. Focus should be on the rutting performance during the initial stages, given the selection and optimum dosage of rejuvenators are done properly.

#### **8.4 Future recommendations**

The recommendations for the future studies can be outlined as follows:

- The outcomes of this study are based on the neat binder (VG-30). Applicability of the results to the polymer modified binders (both virgin binder and RAP binder) needs to be studied further. Evolution of aging for recycled mixes with polymer modified binders and rejuvenators can be different and hence should be explored in-detail.
- Durability of the recycled mixes with rejuvenators and field RAP should be considered in the future, given the challenges associated with the field RAP, as specified in the chapter 2 and 3, are addressed.
- Exploring other aging protocols (different aging times, temperatures and approach) and establishing field performance correlation can further enhance the reliability of this study results.
- A Life Cycle Assessment study to quantify the environmental benefits of using rejuvenators would be beneficial.