CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Preamble

This study investigated the influence of glass powder, Kota stone dust and glass - hydrated lime composite fillers on the performance of bituminous mastics and bituminous concrete mixes, when added in varying quantities. The comparison of aforesaid mastics and mixes was made with stone dust as conventional filler. The investigation was conducted in six phases each of which encountered a specific objective of the study. Salient conclusions devised after investigation are stated in subsequent sections.

10.2 Conclusions

10.2.1 Characterization of Various Fillers

- All materials fulfilled the requirements of filler as per Indian specifications (MoRTH, 2013). SD was found to be coarsest filler followed by GP, KS, and HL. KS and SD were the least porous fillers, while GP and HL had the highest porosity. GP had predominance of silica in its composition in form of quartz. KS, HL, and SD had large quantities of calcite, Portlandite and dolomite respectively in their composition which promotes bitumen-aggregate adhesion.
- A good relationship between void contents of fillers and their German filler values was observed. Similarly strong relationship between the oxide contents (SiO_2 and CaO) in fillers and pH value of filler-water suspension was found. Hence, German filler and pH tests are recommended for inclusion in current Indian guidelines to facilitate better characterization of fillers.

10.2.2 Design and Analysis of Bituminous Concrete Mixes

- The bituminous concrete mixes were designed at four different filler contents (4, 5.5, 7, and 8.5% by weight) using Marshall mix design method. With an exception of GL 8.5 mix (marginally lower VMA than required), all mixes fulfilled the Marshall and volumetric requirements of MoRTH (2013).
- The Marshall stability of bituminous mixes was found to increase with the filler content up to 7% (glass and glass - hydrated lime composite mixes) and 8.5% (stone dust and Kota stone mixes). In general glass - hydrated lime mixes displayed highest Marshall stability. Waste filler mixes prepared at lower filler contents (4 and 5.5%) displayed higher Marshall stability than conventional mixes. Fineness, porosity, and mineralogy of fillers seemed to influence Marshall stability of mixes.
- OBC and VMA of all mixes decreased with the increase in filler content due to the bitumen extender action of fillers. GL and KS mixes displayed lowest OBC followed by GP and SD mixes. OBC of mixes were influenced by the fineness, porosity and the specific gravity of the fillers. Lower OBC of mixes with waste fillers demonstrate their efficacy for economy.

10.2.3 Analysis of Bituminous Mastics

- The linear viscoelastic (LVE) limit of mastics was found to decrease with the increase in filler content and decrease in temperature. The mastics having higher stiffening (GL and GP) exhibited lower LVE limits and vice versa.
- The increase in complex modulus and decrease in phase angle was observed with the increase in filler content at each loading frequency. The stiffness of

bitumen and mastics was also increased with the decrease in temperature and increase in frequency.

- For all mastics, the rate of increase in complex modulus with frequency was found to increase with the testing temperature. It inferred that the mastics become more susceptible to frequency at higher temperature. At the same temperature, mastics with higher stiffness exhibited lower rate of growth in complex modulus.
- At the same frequency (10 rad/s), GL mastics displayed highest complex modulus and lowest phase angle followed by GP, KS, and SD. The increase in complex modulus was influenced by the porosity, filler volume fraction and angular particle shape of filler.
- All mastics (especially GL and GP mastics) displayed steady growth in complex modulus up to 5.5% filler concentration and then experienced a relatively rapid growth (higher slope) at higher concentration (7 and 8.5%).
- The rutting resistance of short-term aged mastics was found to increase with increase in filler content and decrease in temperatures as determined from Superpave rutting parameter and MSCR test. GL mastics displayed highest rutting resistance followed by GP, KS, and SD mastics. Barring few exceptions (GP 8.5, GL 7, and GL 8.5), stress sensitivity of mastics was found to increase with the increase in temperature.
- The fatigue resistance of long-term aged mastics at 25°C decreased with the increase in filler content as determined using Superpave fatigue parameter and LAS test. In general, SD mastics displayed highest fatigue resistance followed by KS, GP, and GL mastics. LAS test also suggested that fatigue life of mastics decreased with the increase in applied strain.

- Fatigue resistance of bituminous mastics was also determined using a new approach based on its percentage recovery determined by MSCR test. This approach delivered almost inverse trend than two former methods and suggested that fatigue resistance of mastics rather improved with filler content.
- The ageing susceptibility of the mastics was determined at 25°C and 64°C by calculating the Ageing Index (AI) based on complex modulus of short and long-term aged mastics. AI was found to decrease with the increase in filler concentration. The ageing susceptibility was also found to increase with the increase in testing temperature. The filler volume fraction and physico-chemical interaction between bitumen and filler are two responsible parameters for ageing susceptibility of mastics. In general GL and SD mastics displayed highest and lowest ageing resistance respectively.

10.2.4 Analysis of Bituminous Mixes

- The rutting resistance of various mixes was determined using MQ and uni-axial unconfined static creep and recovery test. Rutting resistance of bituminous mixes increased with the filler content. The improvement in rutting resistance was attributed to the lowering of VMA and AFT of the mixes. The rutting parameters of bituminous mixes (MQ and permanent deformation) also followed the similar trend to that of mastics (Superpave rutting parameter and J_{nr} values). GL mixes had the highest rut resistance followed by GP, KS, and conventional SD mixes.
- The moisture resistance of bituminous mixes was analyzed using modified Lottman and retained Marshall stability test. The moisture resistance of the bituminous mixes decreased with the increase in filler content due to the

simultaneous lowering of AFT. The SD and KS mixes fillers exhibited superior performance against moisture due to presence of minerals like dolomite and calcite.

- Mixes containing GP failed to fulfill the minimum criteria of tensile strength ratio. However it was observed that up to 5% of GP can be used as filler after addition of 2% hydrated lime. Hydrated lime inhibited the moisture sensitive nature of GP and mixes having 7% GL (5% GP+ 2% lime) as filler delivered satisfactory moisture resistance. Active and passive adhesion of mixes was also found to decrease with the increase in filler contents.
- Cracking resistance of mixes at 0°C and 25°C found to increase with increase in filler content. In general, GL mixes displayed highest ITS followed by KS, GP, and SD mixes. Fineness of fillers and their specific gravity influence the ITS of the mixes.
- The fatigue life of mixes was determined at 25°C with ITFT and they were found to increase with filler content. GL mixes showed highest fatigue life followed by GP, KS, and SD mixes. No correlation was found between the fatigue life of mixes and mastics computed using Superpave fatigue parameter and LAS tests. However fatigue life of mixes followed the similar trend as that of percent recovery values obtained using MSCR test. It suggested that mode of testing influence the fatigue behavior of mastic and mixes.
- Ravelling resistance of mixes was determined using Cantabro test (standard and wet). Ravelling resistance in wet condition was found to decrease with the increase in filler content. However in the case of standard testing, ravelling resistance was found to improve up to a certain filler content and then slight decrease in resistance was observed. GP mixes also displayed low Cantabro

loss in case of standard testing, which suggested that GP might be satisfactorily used in arid climates.

- Long-term ageing sensitivity of mixes was determined using Ageing Index corresponding to Marshall stability, MQ, ITS, TSR, and CL. In majority of the cases, the ageing sensitivity of bituminous mixes was found to increase with increase in filler content. Bituminous mixes displayed highest ageing sensitivity against MQ and CL. Overall, GL and SD mixes displayed highest and lowest sensitivity towards ageing respectively.
- Resilient modulus of mixes was determined at 25°C and 35°C. GL mixes displayed highest resilient modulus followed by KS, GP, and SD mixes. The resilient modulus was also found to decrease with the increase in testing temperatures. A good correlation between the resilient modulus and permanent deformation was also observed.

10.2.5 Pavement Design and Economical Analysis

- The flexible pavements with granular base and subbase were designed by utilizing various mixes as surface course to support similar traffic loading. Filler content increase in bituminous mixes tends to increase their stiffness and reduce the required thickness of surface layer for all mixes.
- GL mixes required minimum layer thickness to support the intended traffic followed by KS, GP, and SD mixes. It was observed that the replacement of SD with various waste fillers can result in up to 24% reduction in thickness.
- The cost of surface course made with mixes having waste fillers was found to be significantly lower than that of conventional mixes. Surface courses having KS mixes were most economical followed by GL, GP, and SD mixes.

- Replacement of SD mixes with the waste fillers at optimum proportion was resulted in considerable saving of up to 39% of surface layer cost.

10.2.6 Ranking of Bituminous Mixes

- This novel ranking method based on the experimental properties of the mixes and priorities assigned by the designer was proposed to assess overall suitability of bituminous mixes.
- Mixes prepared with KS and GL at higher filler contents delivered much superior performance than conventional SD mixes. On the other hand, GP mixes displayed overall poor performance.
- KS mixes prepared at 8.5% filler exhibited overall "better" performance, while GP mixes prepared at 4% filler exhibited overall "poor" performance.

10.3 Contributions of the Study

- This study analyzed the suitability of two industrial wastes (glass powder and Kota stone dust) as fillers by conducting their comprehensive physical and chemical characterization. It also proposed two filler characterization test methods for the improvement of present Indian pavement design guideline.
- It proposed the use of composite filler (made with glass powder and hydrated lime), which will not only maximize the use of glass powder without excessive moisture failure, but also improve performance of mixes.
- This study also explored the influence of characterization properties of waste and composite fillers on the rheological properties of bituminous mastics at various combinations of temperature and loading frequencies. It also assessed the performance of bituminous mastics in linear viscoelastic and non linear

viscoelastic domain against rutting, fatigue and long-term ageing. It also proposed another approach to determine the fatigue resistance of mastics.

- This study explored the influence of properties of studied fillers on the performance of bituminous mixes in terms of their Marshall, volumetric properties and performance against various distresses (rutting, fatigue cracking, low temperature cracking, ravelling, moisture sensitivity and long-term ageing), when added to four different filler contents in the mix.
- Design of flexible pavements utilizing studied mixes as their surface course for similar traffic condition was done as per IRC 37 (2018) guidelines. Cost analysis of materials needed to construct 1 km of surface layer for such pavements is also done and saving in material cost was assessed.
- A novel ranking method was also proposed to analyze overall suitability of the bituminous mixes.

10.4 Limitations of the Study

- The present study has explored the potential of studied fillers in the bituminous concrete mix made with aggregates and bitumen from a single source. The gradation of aggregates is also kept constant throughout the study.

10.5 Recommendations for Future Study

- While, this study explored the influence of studied fillers on the performance of bituminous mixes using comprehensive laboratory investigation; validation of the same from field performance studies can be helpful to understand the long-term effectiveness of using these fillers.

- Adhesion failure between bituminous mastics & aggregates can also be explored using PATTI (Pneumatic Adhesion Tensile Testing Instrument) test & surface free energy methods.
- Rutting resistance of various mixes can be explored at different temperature and wheel loads using standard and Hamburg wheel rut tester.
- Fatigue analysis of bituminous mixes can be conducted at strain controlled mode using methods like four point beam bending test and its relationship with Superpave fatigue parameter and fatigue life (LAS) test can be explored.
- This study analyzed the performance of silica-based (glass powder) and calcium-based (Kota stone) waste fillers. It would be interesting to observe the performance of industrial wastes such as Bauxite residue and Jarosite which have predominance of alumina and iron oxides.
- The potential of the studied wastes can be explored in gap graded mixes like Stone matrix asphalt.