Chapter 8
CONCLUSIONS AND FUTURE SCOPE

8.1 Prologue

This work is focused on the fatigue characterization of asphalt mastics and asphalt mixtures incorporating waste fillers. The study involved six waste fillers from various sectors: industrial waste, dimensional stone waste, and quarry waste. In addition, two types of binders, i.e., unmodified (VG-30) and modified (PMB-40), were engaged for the preparation of mastics as well as the mixtures. The initial phase of the study included physical characterization of the materials, i.e., aggregates, fillers, and binders, with a series of tests. It was followed by the preparation of asphalt mastics at three filler volume concentrations of 10, 20, and 30% with respect to the binder. The mastics were long term aged as per the WRI method, and the corresponding LVE limits were determined using the amplitude sweep test. The next phase was to assess the efficacy of the LAS test as a surrogate fatigue testing protocol for the TS test. The failure point was determined using DE and PSE based approach in the LAS test and DER based approach in the TS test. Also, the suitability of hyperbolic geometry as an appropriate alternative to conventional cylindrical geometry was examined using the LAS test by studying the evolution of pseudostiffness as a function of applied shear strain. After selecting the adequate test and the geometry, the influence of major factors affecting the fatigue behavior of the asphalt mastics, such as temperature, type of filler, binder, filler content, applied strain, etc., was studied, followed by the investigation on the applicability of G-R parameter as a cracking indicator. The last section of the study focused on evaluating the fatigue resistance of the asphalt mixtures using the SCB test and comparing it with the results of asphalt mastics. The

SCB samples were fabricated at 7% air voids at two notch lengths, and the cracking resistance was quantified using the critical strain energy release rate known as the J_c parameter. The study concludes with a relationship between the optimum filler content and the parameter FSR/$|G^*|$.sinδ to allow the selection of filler dosage based on the properties of filler and the binder exhibiting superior fatigue performance and lower binder requirement.

8.2 Conclusions

The primary conclusions of the study can be outlined as follows:

8.2.1 Filler Characterization

The properties of the fillers were determined by various physical, chemical, and morphological tests.

- The particle size distribution from the hydrometer analysis showed Basalt as the coarsest filler, followed by Marble dust & Limestone, whereas Red mud and Quartz were the finest fillers which were also confirmed by the FM values.
- The RV values of the fillers complemented the FM, as evidenced by the exact opposite trend and strong correlation. The considerably higher RV values of RM (45.7%) filler indicated the higher optimum binder content of the corresponding mixes, which were later confirmed by the mix test results.
- The presence of harmful clays was within the permissible limits (<10 g/kg), as evidenced by the Methylene Blue Value test results.
- Silica and Calcite were the primary compounds in most fillers, as observed from X-Ray Diffractograms.

- The SEM images showed that the surface morphology of the fillers varied to a wide extent ranging from an agglomeration of round shaped particles of Red Mud to sharp and pointed edges in Quartz
- The BET test revealed that the SSA of Red Mud (27.825 m^2/g) was the highest, followed by Basalt (11.869 m^2/g). The higher SSA of Basalt, despite having coarser PSD showed that the FM and SSA are not substitutes for each other and hence cannot be used interchangeably.
- The high variation in SG of the fillers highlighted the importance of adding filler by volume rather than by weight to ensure uniform distribution of the filler particles inside the asphalt matrix.
- The higher FGC showed the well graded distribution of Red Mud (0.97) and Quartz (0.95) particles which was also confirmed by particle size distribution curves.
- The correlational analysis showed appreciable correlations between FM, FGC, D_{10}, and RV, out of which FM showed a strong correlation with all the filler properties.
- The correlation analysis can be used to find the common indicator for the filler characterization, but the primary filler properties affecting the behavior of the asphalt mastics can be determined only by actually conducting the rheological analysis.
- The obtained LVE limits for asphalt mastics were not complementary to those calculated from SHRP equations developed for the asphalt binder.

8.2.2 Selection of Alternate Fatigue Test

Despite being acknowledged as one of the most accurate existing binder fatigue tests, the longer testing duration in the TS test demands searching for an alternate test. The LAS test, an accelerated fatigue test, was selected to assess its suitability as an alternate fatigue test.

- The power law regression was found to be the best fitted model for correlation analysis between N_f from the TS test and other three variables, i.e., N_f from DE & PSE approach as well as $|G^*|.\sin\delta$ parameter.
- The TS test and LAS test (PSE approach) displayed the strongest correlation, followed by the DE approach and Superpave fatigue parameter, irrespective of the testing geometry and the binder. Also, the coefficient of determination between the TS test and $|G^*|.\sin\delta$ was poor ($R^2 < 0.4$) in all the cases, which ruled out the possibility of using it as an alternative.
- The ranking analysis showed that the LAS test using the PSE approach was able to rank the materials similarly to by TS test with the minimal discrepancy, as evident from the minimum deviation of data points from the line of equality. Hence, stronger goodness of fit (high R^2) and the lowest discrepancy between TS and LAS test results justified the use of the LAS test as a surrogate fatigue test, with hyperbolic geometry being preferable over cylindrical geometry for better simulation.

8.2.3 Assessment of Better Testing Geometry

The most common geometry used for the rheological testing of asphalt materials using DSR, i.e., cylindrical parallel plate geometry, has been reported with several lacunas, such as non-uniform stress distribution, adhesive failure, incompetency to accommodate large sized modifiers, etc. Therefore, an alternate geometry with higher accuracy can provide more accurate results than cylindrical geometry.

- The response of the materials against the fatigue testing was not alike in both the geometries, which shows that the effect/role of geometry is very prominent in the fatigue analysis of asphalt materials.

- The evolution of damage in the hyperbolic geometry was smoother and more gradual irrespective of the testing variables attributed to the predefined failure location, resulting in true cohesive failure.
- On the other hand, a similar damage rate was obtained in cylindrical geometry along with some inconsistencies in many cases, especially at higher filler content which can be attributed to the localized failure within the parallel plate. Therefore, one can opt for the hyperbolic geometry to obtain the true cohesive failure within the asphalt sample because the results of cylindrical geometry may or may not be that accurate, attributing to the uncertainty about the true failure in some cases.

8.2.4 Fatigue Analysis of Asphalt Mastics and Asphalt Binder

The material's fatigue behavior depends on several factors that act simultaneously and affect the testing results. The current work is a comprehensive study that integrates the majority of the variables that play a vital role in the performance of asphalt mastics.

- The effect of temperature was very straightforward, with higher temperature corresponding to better fatigue life irrespective of other variables.
- The addition of filler to the binder resulted in different behavior of the mastics owing to the characteristics of the filler. The fillers with lower FSR (RM, QZ) detriment the fatigue susceptibility of the binder, whereas MD & LS enhances the fatigue behavior. But, the effect of the F-B ratio was considerably different with PMB, where the fatigue life of mastics was higher than the binder for all the fillers.
- Among the mastics, the increase in filler volume concentration results in lower fatigue life irrespective of the type of filler and the binder.
- The MD and LS were found to be the top performing fillers, whereas the fatigue life of the asphalt mastics prepared using RM and QZ was lower while using an unmodified

binder. On the other hand, RM yielded the highest fatigue life in PMB based mastics, whereas the performance of other fillers was similar to with unmodified binder.

- The relative ranking between the mastics changed with the change in applied strain corresponding to LVE, NLVE, and failure domain, respectively, making the choice of strain a judicial decision while describing the fatigue test results. The strain rate of 5% was found to be suitable for comparing the fatigue results of asphalt materials.
- The fatigue life of asphalt binder and the asphalt mastics was higher with PMB compared to their VG-30 counterparts.
- The Glower-Rowe parameter was found to be unsuitable for accurately characterizing the fatigue behavior of asphalt mastics.
- The Fineness modulus, Specific surface area, and Rigden voids were found to be the three filler properties that played a prominent role in the behavior of asphalt mastics. Also, the newly introduced FSR parameter was able to successfully rank the fatigue performance of fillers identical to the ranking obtained by the fatigue testing; however, this was not valid with the polymer modified binder.

8.2.5 Performance Evaluation of Asphalt Mixtures

The fatigue testing results of the asphalt mastics were validated by the results of asphalt mixtures prepared with RM, MD, and LS fillers at three filler contents of 3, 5, and 7% by weight of the total aggregates and tested at 15°C temperature using the SCB test.

- The fatigue performance of the asphalt mixtures was found to be highest at 5% filler content, irrespective of the type of filler and the binder. Moreover, MD emerged as the best performing filler, followed by LS for both binders. On the other hand, the asphalt mixtures prepared with RM performed worst with the unmodified binder, whereas it was the best performing filler with PMB-40 binder. These results were exactly similar to the results of asphalt mastics.

- The OBC was found to be lowest at 5% filler content for all the fillers and both binders, out of which the RM based mixes yielded the highest OBC, whereas it was approximately similar in MD and LS incorporated mixes.
- The 7% filler content exhibit the worst fatigue performance as well as the highest OBC, which showed that the designer should not choose any random filler content within the specified limits just to satisfy the gradation, but a range of optimum filler content should be selected considering the output in terms of fatigue performance and lower binder requirement.
- The optimum filler content can be selected as the average of the filler content corresponding to highest critical strain energy release rate and lowest OBC for the asphalt mixtures with unmodified binder as well as the polymer modified binder.
- The correlation between the optimum filler content, which corresponds to higher J_c and lower OBC, and the parameter FSR/$|G^*|.\sin\delta$ was found to be excellent. This shows that the filler dosage in the asphalt mixtures can be obtained from the properties of fillers and binders, which will result in higher fatigue performance and lower optimum binder content.
- The ranking of the asphalt mixtures prepared with different fillers was found to be exactly similar to that obtained from the fatigue testing of asphalt mastics; however, the effect of filler addition was different from the mastics. This shows that the relative fatigue performance of the asphalt mixtures prepared with different fillers can be predicted from the LAS testing results of corresponding asphalt mastics using hyperbolic geometry.

8.3 Summary

The outcomes of the present study can be summarized as following:

- The fillers can be characterized by a variety of tests however, FM, SSA, and RV were found to be the most prominent filler parameters that influence the behavior of asphalt mastics/mixtures.
- The linear amplitude sweep can be a suitable alternative of time sweep test for the fatigue characterization of asphalt mastics.
- The damage accumulation is more steady and uniform in hyperbolic geometry owing to which it can be used as a surrogate of cylindrical geometry to obtain the true cohesive failure in the sample.
- The performance of asphalt mastics is influenced by several factors and hence the comprehensive study considering all the major factors can truly describe the fatigue behavior of asphalt mastics.
- The Glover-Rowe parameter cannot be used for the fatigue characterization of asphalt mastics.
- The filler dosage in the asphalt mixtures can be optimized by a methodology considering the properties of filler and the binder to achieve higher fatigue performance and lower optimum binder content.

8.4 Future Scope

The recommendations for future study can be outlined as follows:

- This study utilized different waste fillers for the fatigue characterization of asphalt mastics and asphalt mixtures. However, the domain of waste utilization is very wide due to the availability of several types of seldomly explored fine wastes such as sewage sludge ash, municipal solid waste incineration ash, kimberlite, zirconium tungstate, oil shale fly ash, zeolite catalyst, bagasse ash, jarosite, etc. which can be explored in future studies.

- The fatigue testing results of asphalt mastics were validated by conducting the SCB testing on asphalt mixtures prepared with a single source of aggregates, i.e., Dolomite. Hence, different types of aggregate sources, like granite, limestone, etc., can also be investigated for the same. In addition, other binder grades, such as VG-40, may also be employed for the performance assessment.
- The current research is a comprehensive study covering many variables to study their influence on the fatigue behavior of asphalt materials. It would be interesting to observe the rutting behavior as well for the aforementioned testing variables.
- The current study is limited to one bituminous mix which may not be enough to recommend the modifications in current standards. Although, the current research can be an initial step in the direction of optimizing the filler dosage in the asphalt mixtures. It can provide a path for the future studies to conduct research on a more extensive scale on the basis of which a universal methodology can be developed and implemented.
- The results obtained from the study should be validated by field performance studies to understand the long term effectiveness of the research outcomes.

8.5 Research Contribution

The current study is dedicated to the fatigue characterization of asphalt mastics and mixtures assimilating the waste fillers. The following list summarises the study's key contributions:

- This study has explored the wastes from three different sectors in the form of fillers by a wide variety of characterization tests. The study helps in identifying the major filler properties responsible for the fatigue behavior of asphalt mastics/mixtures.

- The outcomes of the study justified that the LAS test can be used as a surrogate of conventional TS test for the fatigue analysis of asphalt mastics as TS test is not considered feasible due to its longer testing durations. The results of this study will aid in the universal acceptance of the LAS test as a fatigue test provided that the PSE approach can be used for more accurate test results.
- The current study has extensively investigated the suitability of a recently introduced hyperbolic geometry as an alternative of conventional parallel geometry. The most common issue during the rheological testing of stiffer materials at intermediate i.e. adhesion failure can be solved by the use of hyperbolic geometry. This study will motivate the future researchers to explore the hyperbolic geometry in a more rigorous manner.
- The present work detailed the influence of the majority of variables that are responsible for the fatigue behavior of asphalt mastics. These variables were selected from every domain i.e. material based (filler, binder, filler-binder ratio), testing based (temperature, test type, strain), analysis based (failure criterion), and geometry based (cylindrical, hyperbolic).
- The suitability of the widely known Glover-Rowe parameter which is consider as the cracking indicator was investigated and validated through the ranking analysis. It is not recommended to utilize it for the accurate characterization of asphalt mastics.
- The selection of filler dosage is a vital step in the mix design process for asphalt professionals corresponding to a particular aggregate type and aggregate gradation. Hence, a criterion for estimating the optimum filler dosage for the design of asphalt mixtures was proposed in this study based on the filler and binder properties.

8.6 Practical Applications of the Study

- The current specifications considers only two criterias for the selection of filler i.e. particle size distribution and plasticity index. However, the current study showed that these are not sufficient and hence more tests are required to accurately characterize the fillers. Therefore, specific surface area and Rigden voids can also be included in the standards.
- The results of the present study can be used to screen the fillers before using in the pavement for achieving a fatigue resistant mixture. The results showed that the higher FSR value corresponds to the better fatigue resistance owing to which the fillers can be selected based on three tests namely particle size distribution, specific surface area, and Rigden voids.
- The proposed methodology can be used to choose appropriate filler dosage in the pavement construction depending on the type of filler and the base binder.