CHAPTER 3

RESEARCH METHODOLOGY

3.1 Preamble

This chapter summarizes the research methodology and experimental procedure involved in the study. The research methodology was designed to fulfil the objectives of investigating the suitability of glass powder, Kota stone dust, and glass - hydrated lime composite as fillers. The research methodology aimed to analyze the influence of the nature and quantity of waste and conventional fillers on the rheological properties of mastics as well as on the engineering properties and cost of bituminous mixes. Flow chart in Figure 3.1 describes the methodology adopted for the research work. This research methodology was further divided into six different sections as mentioned below and was described thereafter.

(a) Phase I: Material characterization

(b) Phase II: Design of bituminous concrete mixes

(c) Phase III: Rheological analysis of bituminous mastics

(d) Phase IV: Performance evaluation of bituminous mixes

(e) Phase V: Structural design and cost analysis of various mixes

(f) Phase VI: Ranking of various bituminous mixes

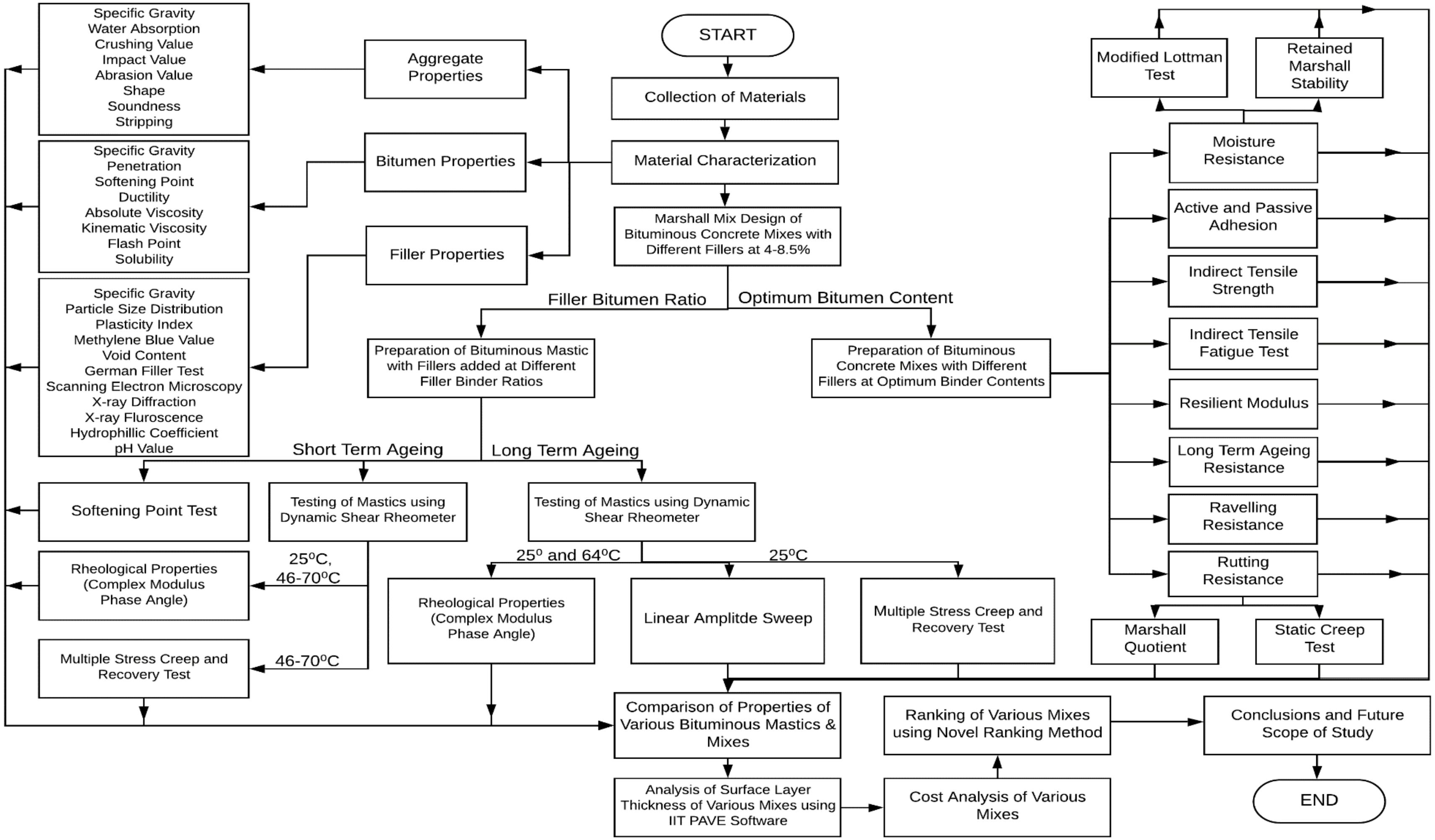

Figure 3.1 Flow chart showing methodology of the study

3.2 Phase I: Material Characterization

This section of the study concerns two significant aspects: (a) Collection of various ingredients (aggregates, bitumen, and fillers) used in the preparation of bituminous mastics and bituminous concrete mixes, and (b) Physical and chemical characterization of the ingredients. The experimental program followed in this phase is shown in Figure 3.2, and its details are presented in Chapter 4.

The coarse and fine dolomite aggregates were used in preparation of the bituminous mixes. Such aggregates are widely used in the preparation of bituminous mixes in the Northern regions of India. Stone dust was utilized as the conventional filler in study. The physical characteristics, strength, durability, and bitumen adherence of the aggregates were investigated in conformity with test specifications mentioned in Figure 3.2. Bitumen of VG 30 (VG: Viscosity Grade) confirming to IS: 73 (2013) is the most common type of refinery supplied unmodified bitumen used in pavement construction for wide range of climatic and traffic conditions in India (MoRTH, 2013). The Indian Road Congress specification (IRC 111, 2009) recommends usage of VG 30 bitumen for the construction of the dense bituminous mixes in places where the lowest daily mean air temperature is more than -10°C and highest daily mean air temperature is greater than 30°C. Hence VG 30 bitumen is used in the study and its physical and rheological properties were determined in compliance with the test methods mentioned in Figure 3.2.

Glass powder and Kota stone dust were two wastes fillers used in this study and were collected from dumping yard of their respective industries. In conformity with the objectives of this study, these wastes were utilized directly without any physical or chemical modification. They were oven-dried and passed through on 0.075 mm sieve, and apparently, being of very fine particle size the whole quantity qualified to be called finer than 75µm sieve size. Hydrated lime was also used in the study. It was manufactured in the laboratory by hydrating the quick lime in sufficient quantity of water. Based on the literature review and the methods specified in MoRTH, (2013), characterization of fillers was done using other relevant test methods like Rigden voids, German filler test, methylene blue value test, hydrophilic coefficient, and pH test as specified in European (EN 933-9, 1999; ISSA, 1989) and Chinese guidelines (JTG E42, 2005). Detailed physical and chemical analysis was done using Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and X-ray Fluorescence (XRF). Attempts were made to determine the relationship between the parameters like void content and German filler test values, as well as between XRF and pH. The void content and XRF analysis helps to determine the porosity and chemical composition of the fillers, respectively. XRF requires expensive and sophisticated instrumentation as well as expertise to perform, which may not be readily available on the field. German filler and pH on the contrary are simple to perform and involve inexpensive instrumentation, and therefore make a strong case for exploration of a good relationship, if it exists. The test procedures and the obtained results are discussed in detail in Chapter 4.

3.3 Phase II: Design of Bituminous Concrete Mixes

This phase concerns with two aspects: (a) Design of bituminous mixes with different fillers added in different quantities and calculation of their optimum bitumen content (OBC) and filler bitumen ratio, and (b) Analyze the influence of different fillers and their quantities on the Marshall stability, flow, and volumetric properties (air voids,

voids in mineral aggregates, and voids filled with bitumen) of the bituminous concrete (Grade II) mixes. A single type of gradation was chosen as per MoRTH (2013), and the Marshall mix design procedure was used as per MS-2 (Asphalt Institute, 2014). An adequate Apparent Film Thickness (AFT) of bitumen is responsible for ensuring satisfactory durability of mixes against moisture permeation and ageing. The AFT of all mixes were determined as per the NCHRP Report 567 and NCHRP Report 673 (Christensen and Bonaquist, 2006; NASEM, 2011). As per MoRTH (2013), the permissible range of filler for the stated type of mix is 4-10% by weight of aggregates. However, after the initial investigations, it was observed that mixes with more than 8.5% filler had failed to fulfill the volumetric requirements of voids in mineral aggregates (VMA). Hence a total of 16 different types of mixes were prepared with four types of fillers (stone dust, glass powder, Kota stone dust, and glass – hydrated lime composite) were added in four different proportions (4, 5.5, 7, and 8.5%). The glass - hydrated lime composite filler was prepared by fixing the proportion of hydrated lime at 2% in the respective filler proportion and assigning balance part to glass powder. While using this filler it was borne in mind to take reference from the literature suggesting that utilization of glass as a component tends to decrease the adhesion between bitumen and aggregates and reduce moisture resistance of mix (Wu et al., 2007). Hence, glass - hydrated lime composite as filler was prepared with an intention avoiding the possibility of formation of moisture-sensitive mix due to high silica content in glass powder by adding a nominal amount of hydrated lime as an anti-stripping agent. MoRTH has specified the permissible limit of hydrated lime at 2% in bituminous mix. Hence use of 2% of hydrated lime would envisage maximum utilization of glass powder without compromising with the moisture sensitivity of the bituminous mix.

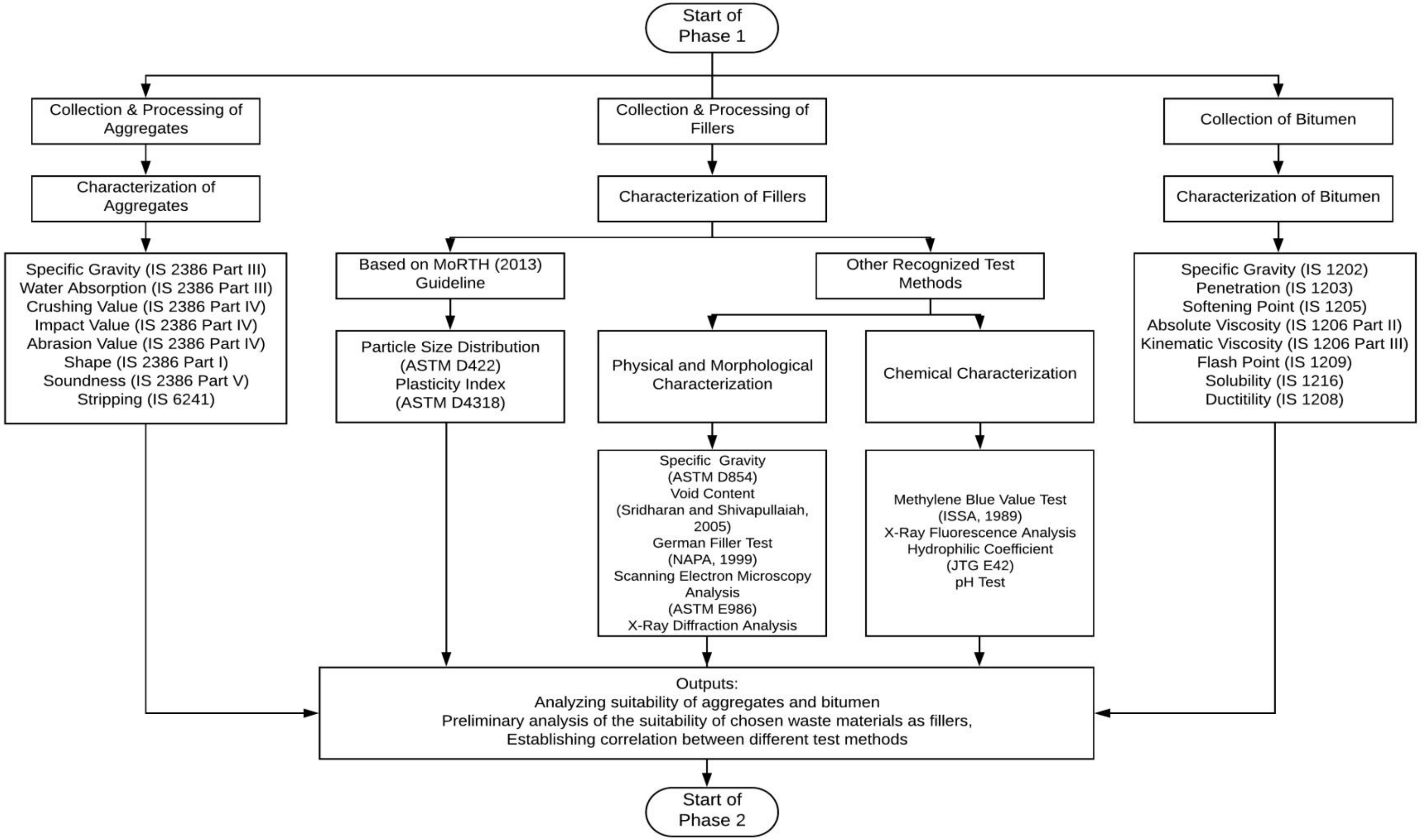

Figure 3.2 Flow chart showing experimental program of Phase 1

3.4 Phase III: Rheological Analysis of Bituminous Mastics

This section intended to explore rheological properties of various bituminous mastics and their performance against the rutting, fatigue, and ageing. The overview of the entire experimental program is highlighted in Figure 3.3 and explained in Chapter 6. Sixteen types of bituminous mastics were prepared by blending bitumen and fillers in proportion corresponding to the filler bitumen ratio determined at the end of Phase II. The two sets of same mastics were prepared. The first set of mastics was short-term aged in a thin-film oven as per ASTM D1754 (2014) protocol, while, the second set was subjected to short-term ageing followed by long-term ageing as per the protocol suggested by Behera et al., (2013) using standard draft oven as an alternative to the Pressure Ageing Vessel (PAV).

The softening point of bitumen and short-term aged mastics were determined as per IS 1205 (1978) guideline. Since bitumen and bituminous mastic are viscoelastic, their behavior gets influenced with the testing temperature and loading frequency. Hence viscoelastic behavior of bitumen and mastics was characterized at different temperatures and loading frequencies with the help of Dynamic Shear Rheometer (DSR). The performance grading of VG 30 bitumen determined using DSR as per ASTM D7175-15 (2015) and SP-1 (2003) guidelines came out to be PG 70-XX. Hence, the testing temperatures of bitumen and mastics were assigned in the range of 46-70^{o}C, along with 25^{o}C, which is the average intermittent temperature (SP-1, 2003). The testing frequencies were fixed in the range of 0.1-100 rad/s, which covers the entire spectrum of vehicular speed. Complex modulus and phase angle were determined at aforementioned temperatures and frequencies using frequency sweep test as per AASHTO T315 specification. However, frequency sweep analysis can only be done in the linear viscoelastic (LVE) region of the binders and mastics. The linear viscoelastic range of bitumen and mastics were determined at different temperatures using strain sweep test. The strain which falls within the LVE region of bitumen and mastics was determined for all mastics and bitumen, which was further used to conduct frequency sweep analysis and in the determination of rheological parameters.

The rutting susceptibility of bitumen and mastics were determined at 46-70°C according to rutting parameter (G*/sin δ) determined at 10 rad/s as per the Superpave guidelines (SP-1, 2003). But, inability of the rutting parameter to characterize the rutting behavior of bitumen and mastics have also been reported in previous studies due to non-linearity associated at higher temperature and stress levels (Dongre and D'Angelo, 2003; Li et al., 2019; Saboo and Kumar, 2016). Hence rutting resistance of bitumen and mastics were also determined by conducting the Multiple Stress Creep and Recovery (MSCR) test according to AASHTO T 350 guideline. Analysis of test results provided two parameters: non-recoverable creep compliance (J_{nr}) and percentage recovery, which are associated with the rutting susceptibility of the bitumen and mastics.

The rheological properties of long-term aged bitumen and mastics were determined at 25°C and 64°C using DSR according to ASTM D7175-15 (2015) specification. Long-term ageing of bitumen and mastic resulted in the loss of volatile compounds from the bitumen, which imparts stiffening to it. This may result in the generation of fatigue cracking at intermediate temperature (25°C). Hence fatigue resistance of the bitumen and mastics were analyzed within linear viscoelastic region using fatigue parameter (G*sinδ) determined according to Superpave guideline (SP-1, 2003) at a fixed frequency of 10 rad/s. Fatigue resistance of bitumen and mastics was also determined in non-linear viscoelastic region at different strain levels using linear amplitude sweep test performed as per AASHTO TP 101-14 specification. Other than these two methods, fatigue resistance of bitumen and mastics was also assessed based on percent recovery parameter determined according to MSCR analysis as per AASHTO T 350 specification.

The rheological properties of long-term aged bitumen and mastic were also determined at 64^{o}C. The complex modulus determined at this temperature was compared with that of their short-term aged counterparts. The ratio of complex modulus of long-term and short-term aged mastics is determined as the ageing index, which is helpful to study the ageing susceptibility of the bitumen and mastics. Higher the ageing index, more ageing susceptible the mastic will be. The relationship between different test parameters and between the filler characteristics and mastic properties are also analyzed, whose details are given in Chapter 6.

3.5 Phase IV: Performance Evaluation of Bituminous Mixes

This section investigated the effect of type and quantity of fillers on the performance of bituminous mixes subjected to various pavement distresses. The experimental scheme is shown in Figure 3.4 and explained in Chapter 7. Bituminous mixes are prepared at their respective OBC determined in Phase II. There is no well-defined procedure in MoRTH (2013) to determine the rutting resistance of mix. It has suggested determining the stiffness of the mixes based on their Marshall quotient values. The bituminous mix possessing higher Marshall quotient value displays superior stiffness as well as better load distribution capability, which ultimately results in its improved resistance against creep or rutting. In this study, the rutting resistance of bituminous mixes was also determined using a uni-axial unconfined static creep test as per the BS 598-111 (1995) specification. Static creep test was used by several researchers to determine the rutting resistance of bituminous mixes (Arabani et al., 2017; Bostancioğlu and Oruç, 2016; Chandra and Choudhary, 2013; Kuity et al., 2014).

Moisture sensitivity of the mixes was determined using modified Lottman test as per AASHTO T 283 and retained Marshall stability test as per ASTM D 1075-11 (2011). Modified Lottman test in MoRTH, (2013) to test moisture sensitivity of the mix, while retained Marshall stability was part of the previous edition of MoRTH (2001). However, retained Marshall stability test is relatively simple and less time consuming than its counterpart; and it was of interest to compare the results of both methods. Excellent adhesion between bitumen and aggregates in the bituminous mix in a dry state, as well as in the presence of water is crucial for its satisfactory performance and durability (Bhasin and Little, 2009) which are generally named as active and passive adhesion. The bitumen’s ability to completely cover the aggregates during the mixing operation of bituminous mixes can be termed as its active adhesion. The effect of various fillers on the active adhesion was analyzed by measuring the time required by the aggregates in the mix to get uniformly coated with the bitumen. Passive adhesion can be defined as the ability of bitumen to remain on the aggregate surface when it is subjected to external agents like traffic and moisture (Cui et al., 2019; Pasandin and Perez, 2015). Analysis of passive adhesion for loose mixes was carried out using the Texas boiling water test as per ASTM D3625-12 (2012) guidelines.

The temperature-sensitive nature of bituminous mixes led to the formation of thermal cracks (low-temperature cracking and fatigue cracking), which deteriorate the performance of pavements. The anti-cracking behavior of bituminous mixes has been widely analyzed using indirect tensile strength test (Bennart et al., 2018; Christensen and Bonaquist, 2004; Si et al., 2016). In this study, the cracking resistance of each mix was determined by comparing the average indirect tensile strength (ITS), which was determined at 0^{o} and 25^{o}C, according to ASTM D6931-17 (2017) guidelines. Similarly, the resistance of bituminous mixes against fatigue was determined at 25^{o}C using indirect tensile fatigue test performed according to EN 12697: Part 24 guideline. The influence of temperature on ITS of various mixes is compared.

Resilient modulus (M_r) is the most critical input in flexible pavement design methodology because it signifies the capability of pavement layers to dispense load among them. It measures the responses of bituminous pavement layers towards the applied stresses and their corresponding strains (Arabani et al., 2017; Karami et al., 2018). It influences the thickness of pavement layers to resist the load imposed on them. In this study, the resilient modulus was determined at 25^{o}C and 35^{o}C according to ASTM D4123-82 (1982) specification.

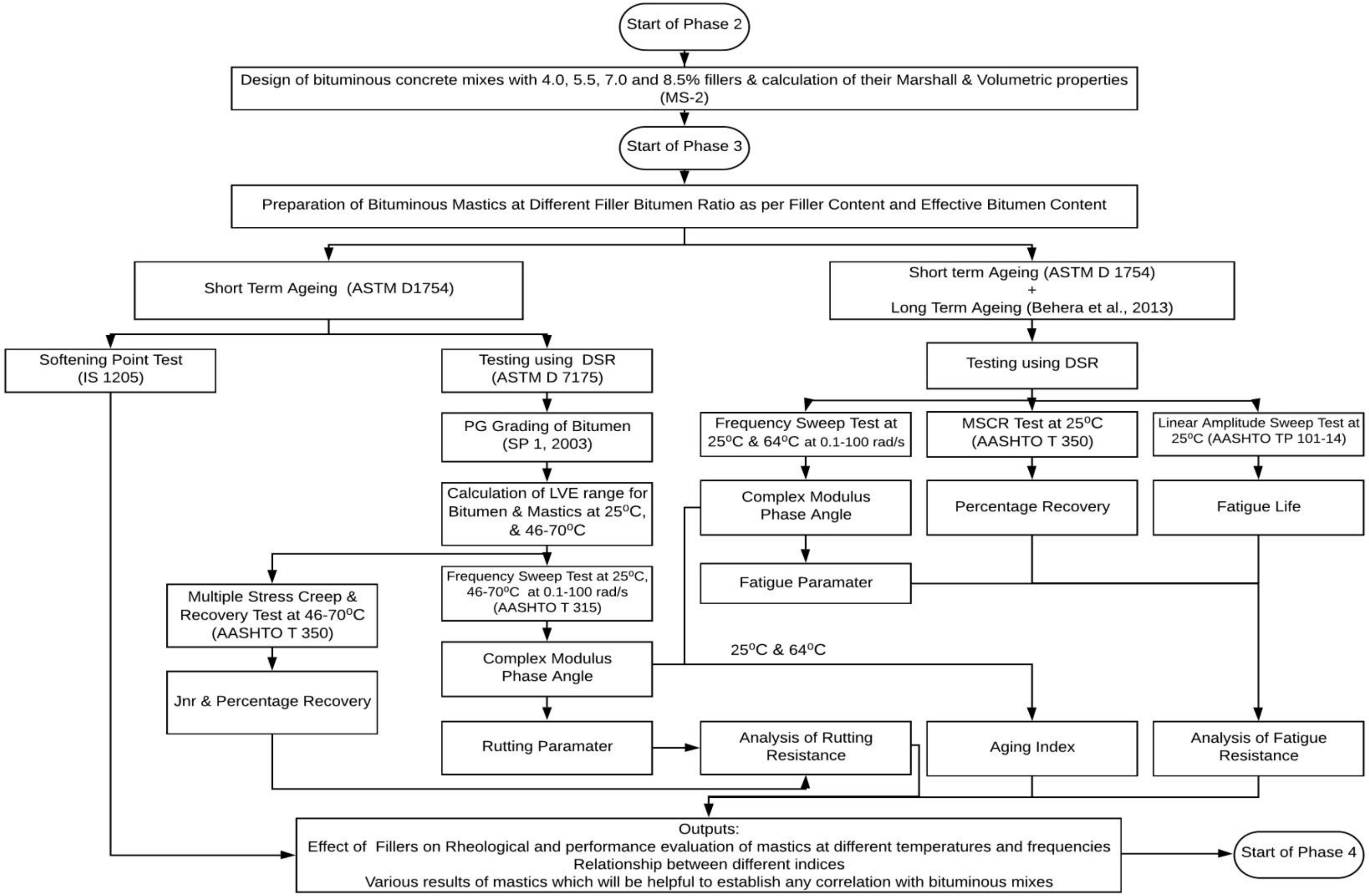

Figure 3.3 Flow chart showing experimental program of Phase 2 & 3

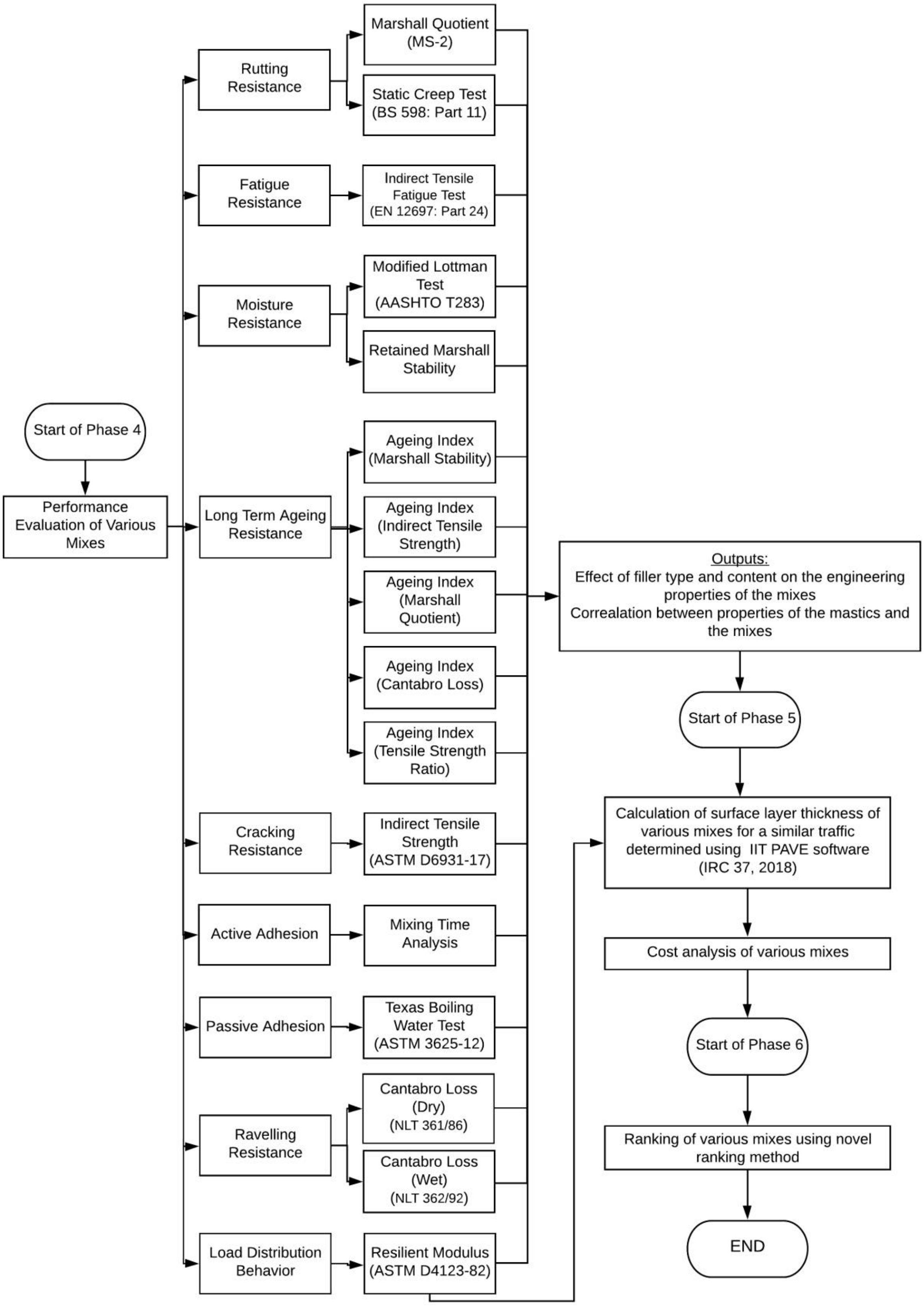

Figure 3.4 Flow chart showing experimental program of Phase 4,5, & 6 of the Study

Cantabro loss analysis was conducted in dry and after wet conditioning to investigate the ravelling resistance of bituminous mixes according to Spanish guidelines NLT 361/86 and NLT 361/92, respectively. Although Cantabro loss analysis is conducted on open-graded mixes, it is recently gaining popularity in dense graded mixes also due to their simplicity, low cost, and good efficiency (Cox et al., 2017; Doyle and Howard, 2016). This study is first of its kind to investigate the effect of filler type and content on the ravelling of dense graded bituminous concrete mixes.

Bituminous mixes after being exposed to their surrounding environment during their service life acquire brittleness due to various mechanisms discussed in Chapter 2. Although ageing couldn't directly be considered as distress, it influences the performance of the mixes in terms of other parameters such as stability, rutting resistance, ravelling resistance, moisture susceptibility, and cracking. There is no well-established protocol to compute the ageing resistance of bituminous mixes. Some studies have determined the ageing susceptibility of the bituminous mixes by determining the ageing index of various parameters, which is ratio of the value of the studied parameter of the mix after being aged to that of the same in the un-aged condition. The standard protocol to simulate the field aging in laboratory is conditioning the compacted Marshall specimen at a fixed temperature of 85°C for 5 days in accordance with AASHTO R30. In this study, five different parameters were analyzed to compute ageing indices which are: Marshall stability, Marshall quotient, ITS, Cantabro loss (dry), and tensile strength ratio. The mix having ageing index closer to the unity display lower ageing susceptibility and vice versa. All the test methods mentioned in this section, along with obtained results, are explained in Chapter 7.

3.6 Phase V: Structural Design and Cost Analysis of Bituminous Mixes

This section of the study has two primary objectives: (a) Determination of the minimum structural layer thickness of bituminous concrete as surface course made with different mixes to support standard traffic, and (b) comparison of the manufacturing cost of designed surface layers.

Firstly, the bituminous pavements were designed using IITPAVE software. IITPAVE is based on the mechanistic-empirical pavement design guidelines (MEPDG) as stated in IRC 37 (2018). For a given traffic volume, thickness of the surface layer made with all 16 types of mixes was worked out. In all cases, the thickness of binder, base, sub-base, and subgrade layers are kept constant, and only the surface layers were optimized. This was done by choosing thickness in such a manner (by trial and error) that the horizontal tensile strain at the bottom of bituminous layer and vertical compressive strain at the top of subgrade layer were less than the allowable critical strain. The input parameters (resilient modulus and Poisson ratio) for the binder, base, sub-base, and subgrade layers were chosen as per IRC 37 (2018) guidelines, while in case of the surface layer, the resilient modulus values calculated at 35°C in Phase IV was taken in consideration. All details are further explained in Chapter 8.

In second part of this section, the quantities of materials needed to prepare the bituminous surface layers were obtained. The current unit cost of different ingredients (coarse aggregates, fine aggregates, stone dust, hydrated lime, and bitumen) for the production of the mix was taken from schedule of rates of Central Public Works Department, India (CPWD, 2018). The other factors were assumed accordingly. The cost comparison of per km for a two-lane bituminous surface layer made with different mixes was made. The details are mentioned in Chapter 8.

3.7 Phase VI: Ranking of Various Bituminous Mixes

Various laboratory tests were done in previous sections to analyze the performance of bituminous mixes in different aspects. However, it is very difficult to identify the filler which should be considered “best” from the obtained set of test results. The term best is relative and is dependent on the location/test where the material is used (Saboo et al., 2018). The bituminous mix that gives the best performance against particular distress (e.g. rutting) does not necessarily delivera similar performance against another distress (e.g. fatigue). Hence, it is critical to identify the crucial distresses in every scenario, and then select the best filler which forms distress resistant mix. This section introduced a novel methodology to rank all 16 types of the bituminous mixes. This methodology not only ranks the bituminous mixes based on their stability, OBC, and their engineering properties, but also takes the priority assigned to the particular property (say, rutting) by the designer in the analysis. The properties of the mixes taken in the consideration are Marshall stability, OBC, Marshall quotient, tensile strength ratio, mixing time, bitumen coverage, indirect tensile strength, fatigue life, wet Cantabro loss, and dry Cantabro loss. The detailed explanation of the ranking method and the resultant ranking of various mixes are given in Chapter 9.

3.8 Summary

This chapter briefly explained the experimental program adopted to achieve objectives of the study. The entire methodology is divided into six phases. First phase concerns with the collection and characterization of various ingredients used in design of bituminous mastics and mixes. Emphasis is given to the physical and chemical characterization of various fillers on the basis of tests mentioned in the Indian specification i.e. MoRTH (2013), European standards, and tests mentioned in previously published relevant literatures. Phase II focused on designing of bituminous concrete mixes containing 4-8.5% fillers and determining their OBC, Marshall stability, volumetric properties, and filler bitumen ratio. Based on the obtained values of filler bitumen ratio and OBC of various mixes, author have prepared the bituminous mastics and mixes were prepared and analyzed their rheological and engineering properties respectively in the Phase III and IV of the study. The relationships amongst properties of the fillers, rheological properties of the mastics, and engineering properties of bituminous mixes were also analyzed. The structural design of pavement layer thickness and cost analysis for various mixes is done in Phase V. Finally a novel ranking method has been introduced to analyze the overall suitability of various mixes in the Phase VI.