CHAPTER 1

INTRODUCTION

1.1 Preface

The transportation system can be considered the lifeline of a nation, both in terms of passenger and freight, keeping in view its crucial role in economic development and social integration. Among the different modes of transportation, including road, railway, air, and water, road transportation is one of the most operated and preferred modes of transportation system. In India, the road transportation sector accompanies more than 90% of passenger traffic and approximately 70% of freight movement. Ministry of Road, Transport and Highways (MoRTH) [1] has constructed safer and more durable roads across the nation. Over the years, India's road network has achieved tremendous progress, and road transportation has become a focus of rapid development. As a result of major initiatives by the Government of India, the road network length has increased by more than 33% in the year 2021 compared to 2010. As of 2021, India stands in second place, after the United States, in terms of the road network, spanning over 6 million kilometers. Out of the total length of the road network, almost 80-90% length constitutes flexible pavements [2].

Most National and State highways in India are constructed with hot mix asphalt (HMA) as a surface layer. Producing HMA (a mixture of graded mineral aggregates, asphalt binder, and air voids) requires high heating temperatures (generally > 140 °C) [3,4]. The temperature monitoring during the production and compaction of asphalt mixtures is very critical as it facilitates coating of asphalt binder over the aggregates, densification at in-situ conditions, and eventually the mechanical performance of the compacted asphalt mixture. Overall, it can be stated that the production temperatures (generally referred to as mixing and compaction temperatures) influence the workability of asphalt mixtures and facilitates appropriate placement in the field. However, the high production temperatures increase concerns related to greenhouse gas (GHG) emissions and higher energy consumption [5]. Also, such elevated temperatures negatively affect the health of the workers, due to the emission of fumes containing volatile organic compounds (VOC), carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrogen oxide (NO_x).

Recently, the Government of India released a report on the country's comprehensive assessment of environmental conditions [6]. The report stated that an increase in GHG emissions (follows an exponential trend, as shown in Figure 1.1) shifts the climate to a warmer state and directly affects the country's human health, safety, social life, and economic development. These uncertainties will continue for decades and (even centuries) if mitigation strategies are not considered. In this context, the Government of India prohibits using HMA plants and burning fossil fuels (for road construction) in metropolitan cities, such as Kolkata, and Delhi, to curtail the increase in GHG emissions. In addition, the working of HMA plants in a few ozone non-attainment zones is restricted during the daytime, owing to ground-level ozone formation. The reason behind such restrictions is the elevated production temperatures of HMA mixtures. Over the decades, there have been constant efforts in the HMA industry to develop technologies that can reduce the production temperatures of HMA without conceding the performance and workability requirements [7,8]. Lower production temperatures result in the conservation of non-renewable resources, reduction in environmental pollution, and lower energy and fuel consumption. Use of cold mix asphalt (CMA) (0-30˚C); half-warm mix asphalt (HWMA) (60-100˚C); warm mix asphalt (WMA) (100-

150˚C) [9,10] are examples of such developed technologies. Figure 1.2 shows the arrangement of asphalt mixtures based on the production temperatures, energy consumption, and gas emissions.

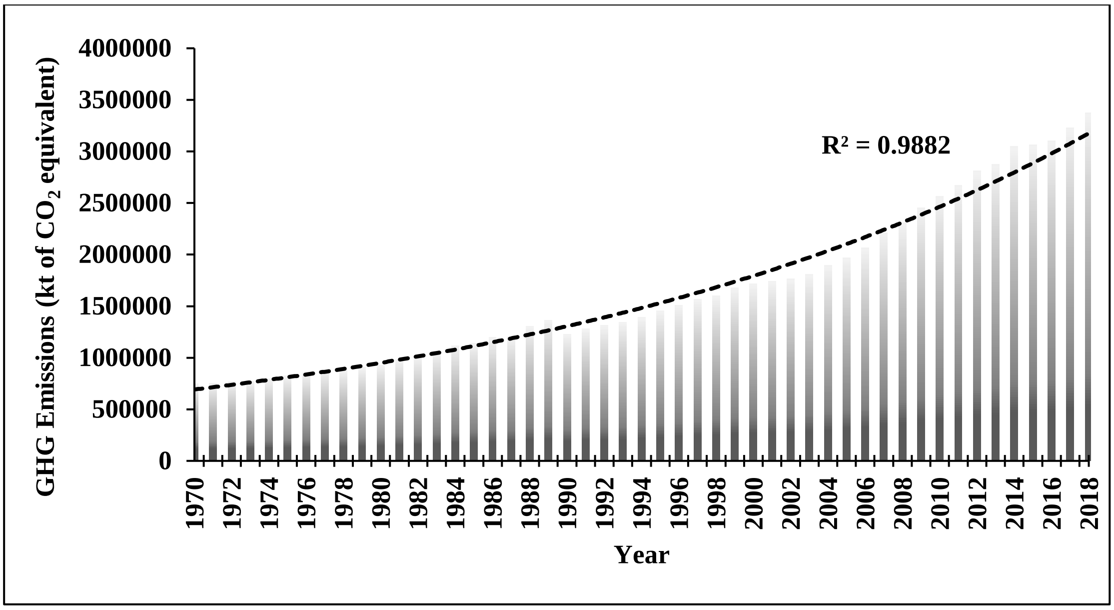

Figure 1.1. Year-wise variation of GHG emissions in India (kt indicates Kilotons) [11]

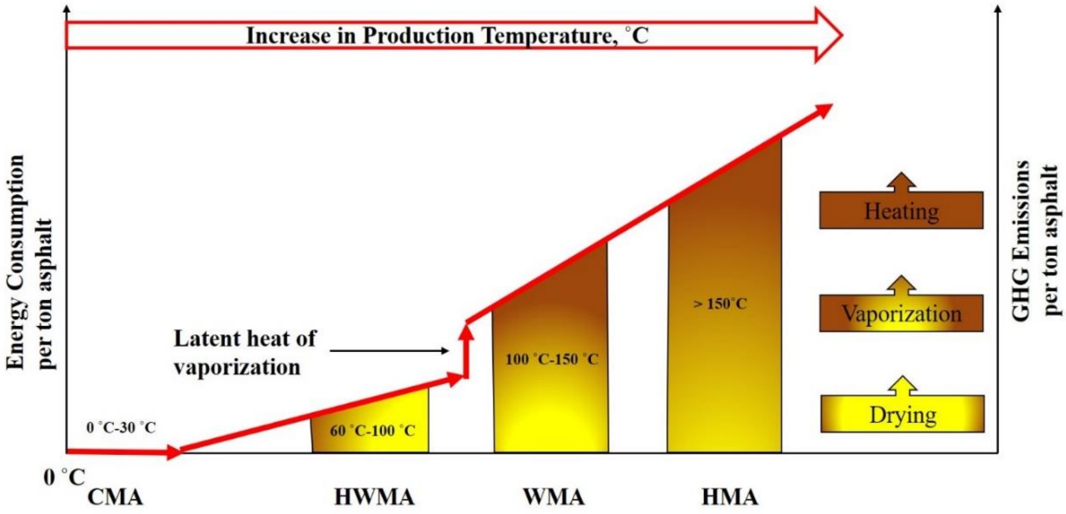

Figure 1.2. Classification of asphalt mixtures

Although CMA and HWMA technologies reduce production temperatures, previous studies [8,9] have shown that these technologies negatively affect the performance of the asphalt mixture. In addition, CMA has concerns regarding insufficient aggregate coating, higher air voids, and longer curing time. In contrast, HWMA deteriorates the workability and durability characteristics, owing to initial moisture within the aggregate particles [12,13]. WMA technology, on the other hand, can be produced and constructed at lower temperatures (100˚C -150˚C) when compared to HMA (150˚C - 170˚C) without compromising the performance of the mix [14–21]. WMA technology offers excellent technical, social, and economic benefits such as improved workability, reduced emissions, lower fuel consumption, improved working environment, and extended paving period [22,23].

1.2 History of WMA

In 1928, August Jacob first noticed and patented "Foamed Asphalt" in Germany [24]. Following its invention, many other products acquired patent rights and license to market in the USA for laboratory as well as for field experimentation [12]. In 1970, the interim mix design method for WMA mixtures was proposed. In mid 1995-1996, Kolo Veidekke and Shell led the first laboratory experiments on warm mix foaming technology in Europe [25]. The first large-scale field trial was executed and endorsed for public use in Norway (Europe) in the year 1997-1999 [26], United States (US) sanctioned the use of WMA technology (Aspha-Min) for field trials in 2004 in North Carolina and Florida [21]. In India, the first road stretch (400 meters) using WMA technology was constructed in an industrial area within Delhi in 2009 [27]. Since then, several field trials have been conducted throughout the country, as shown in Figure 1.3. Research on Aspha-Min, Sasobit, and Evotherm was published in 2006 by the National

Centre for Asphalt Technology (NCAT) [28–31]. Further, the National Cooperative Highway Research Program (NCHRP) initiated various projects to determine WMA's efficacy in pavement construction [32,33]. To date, various reports and published literature are available to justify the use of WMA based on performance, economic, and environmental aspects.

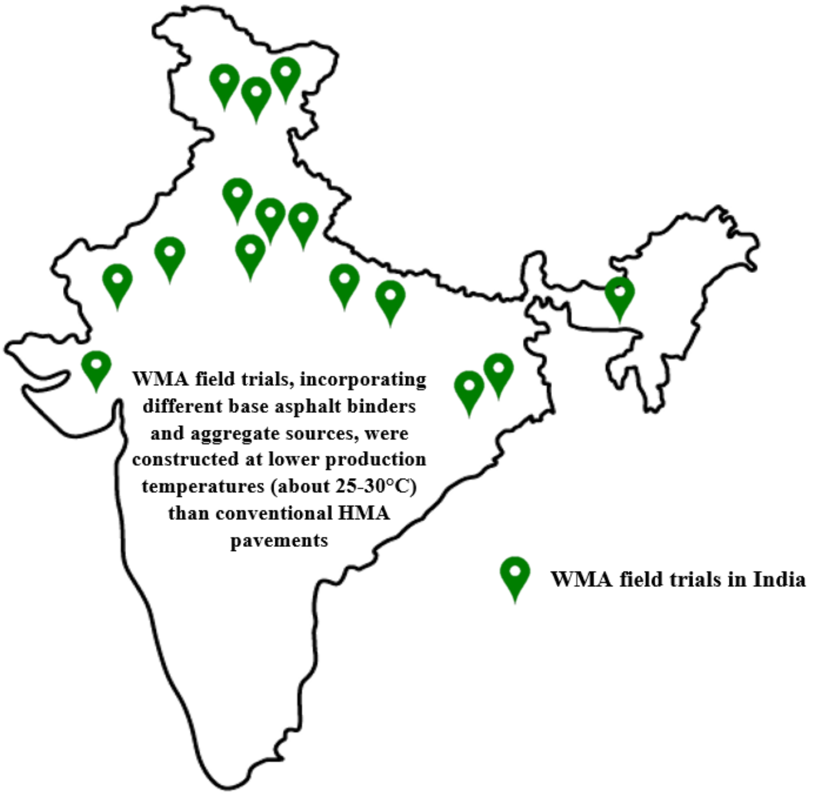

Figure 1.3. WMA field trials in India [27]

Over the years, various additives and foaming technologies have been developed under the domain of WMA. Selecting any of these technologies requires a careful assessment of multiple aspects before its use in infrastructure projects. WMA can be classified into three categories: foaming technology, organic additives, and chemical agents [34–38]. The following section gives a brief overview of these technologies.

1.3 Classification of WMA Technologies

In WMA mixture, the reduction in production temperatures can be achieved through three different processes: a) Use of foaming technology, b) Use of organic additives, and c) Use of chemical agents [39,40].

1.3.1 Foaming Technology

Foaming entails including a small amount of cold pulverized water, either added directly to the hot asphalt binder or injected into the mixing tank [41,42]. Subsequently, the water evaporates, and the hot steam is encapsulated within the asphalt binder, resulting in a temporary expansion of its volume along with a decrement in viscosity [43,44]. This phenomenon remarkably improves the workability and coating ability leading to a uniform distribution of asphalt binder over the aggregates [24,45,46]. In general, the expanded volume decays gradually with time; thus, the binder reverts to its original form after a certain period [14,47]. Foaming technology is subdivided into two groups based on their application process: direct foaming method (water-based technique) and indirect foaming method (water contained technique) [48,49]. In the former case, the water is injected through specific instruments, such as artificial nozzles, to produce foam within the asphalt binder, as shown in Figure 1.4. The indirect foaming method involves the intercalation of fine crushed synthetic zeolite directly to the asphalt mix. A zeolite is a crystalline hydrated aluminum silicate with approximately 20% water [50]. When these materials interact with the hot asphalt binder, they eventually discharge water, converted into steam at ambient pressure to manifest a foaming effect [51]. However, the volume of steam generated with zeolite is less than water-based technologies. Nevertheless, deciding the amount of water to be added is a big challenge. The quantity of water to be added should be adequate for expanding the binder phase without making the mix susceptible to moisture-induced damage (stripping). Van De Ven et al. [52] suggested incorporating adhesion or coating promoters to reduce asphalt mixtures' moisture sensitivity.

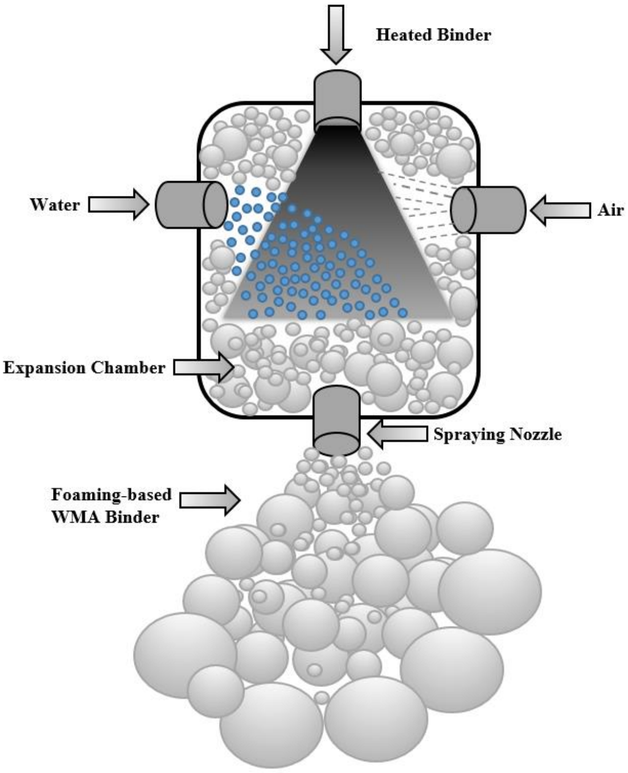

Figure 1.4. Direct method of foaming technology

1.3.2 Organic Additives

Organic additives function by reducing the viscosity of the base asphalt binder due to the presence of waxes. Several categories of organic additives have been presented in a plethora of literature that reduces the asphalt binder's viscosity, depending on their chemical composition [53–56]. In this technique, the additives can be blended either with the asphalt binder or directly with the asphalt mixture. Organic additives generally melt at about 80-120˚C and chemically modify the viscosity-temperature interaction of the asphalt binder [57,58]. Subsequently, when the asphalt binder cools, the additives crystallize and form a lattice structure with microscopically minute and uniformly dispersed particles [59]. This crystallization increases stiffness and improves resistance against permanent deformation. However, there is evidence of low-temperature cracking when using this technology [60–62]. The temperature at which the melting of additives occurs is directly related to the high molecular hydrocarbon chain of the additive. As per the investigation conducted by Ji and Xu [63], the wax commonly behaves like a Newtonian fluid above its melting point and non-Newtonian at intermediate and lower temperatures. From this perspective, the additive must be chosen carefully to ensure that the additive's expected melting point exceeds the pavement's service temperature and affords a solid structure at an in-service temperature [64].

1.3.3 Chemical Agents

Various chemical agents are available depending on their applications in pavement construction. These include surfactants, emulsifying agents, polymers, or a hybrid combination of additives. The chemical agents enhance the workability and compaction of the mixture and improve binder coating over the aggregates [65–68]. Chemical agents can be injected directly into the asphalt binder during the production process or used as an emulsified asphalt binder. In general, the working principle of chemical agents is entirely different from organic additives. Chemical agents primarily improve the coating of aggregates rather than reducing the viscosity [69,70]. These agents work on the microscopic interaction of asphalt binder and aggregate by reducing the interface's slip forces (i.e., surface tension). Consequently, this facilitates the smooth interaction of the binder-aggregate system, which results in lower production temperatures without altering the performance [14].

Some of the examples of WMA technologies are listed in Figure 1.5. More than 25 different WMA additives are categorized under three different WMA technologies. These processes or products can be pre-blended in the asphalt binder or directly added during the mixing of asphalt binder and aggregate within the asphalt mixer. Needless to say, the working mechanism of these additives may be different, but the primary aim is to lower the production temperatures of asphalt mixtures.

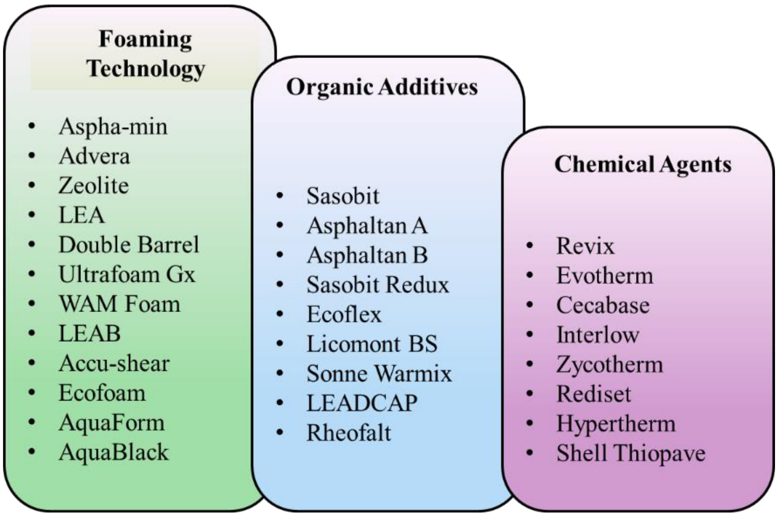

Figure 1.5. Examples of WMA technologies

1.4 Benefits and Drawbacks of WMA

WMA is a promising technique for constructing environmentally friendly and sustainable pavements [15,71,72]. WMA offers several benefits in addition to lowering the mixing and compaction temperature. This section compiles the positive and negative characteristics of employing WMA technologies over conventional HMA [73–79]. The positive impacts include:

- WMA technologies improve the workability, coating, and compaction of the mixes even at lower temperatures. However, the extent of improvement depends upon the technology adopted.

- Including WMA additives significantly reduces the oxidation of asphalt binder, which enhances the durability of WMA based asphaltic pavements.
- WMA offers an extended paving season due to the slower cooling rate than conventional HMA.
- WMA technologies tend to reduce the viscosity, allowing stiffer reclaimed asphalt pavement material (RAPM) binder and a higher dosage of RAPM in WMA mixtures. In addition, the increased RAPM content can alleviate the concerns of moisture susceptibility associated with WMA mixtures.
- WMA technologies reduce energy consumption depending on the energy used and its costs. The energy consumption for WMA is about 60-80% of HMA production.
- Inclusion of WMA additives aids in reducing CO_2 emissions. In addition, it reduces exposure to harmful fumes and toxic gaseous pollutants (CO, NO_X, SO_2), thus, allowing a better working environment for the workers at the construction site.

Overall, the implementation of WMA technology results in the improvement of technical, environmental, and economic aspects. Nevertheless, long term effectiveness and performance-related issues of WMA have been questioned [80–83]. The following concerns needs attention while using WMA technologies:

- Due to the lower ageing mechanism, during production, WMA becomes more susceptible to premature rutting.
- Owing to the heating of aggregates at lower temperatures, proper vaporization of aggregate moisture may not occur, thereby increasing the moisture sensitivity of warm mix modified asphalt pavements.
- There are some concerns related to the increase in initial cost as some technologies require additional equipment or plant modification. The specific increase/decrease

in the cost of WMA based-asphaltic pavements is rather dependent on the specific WMA type being considered.

- A complete quantitative environmental life cycle assessment (ELCA) is required to ascertain pavement sustainability over time. Furthermore, it allows the concerned agencies to quantify and compare different products and technologies considering their cradle to grave performance.

1.5 Problem Statement and Gaps

Since WMA is a relatively new technology, a comprehensive study is required to address the performance of WMA binders and mixtures based on rutting, fatigue and moisture characteristics. While exploring WMA technologies, several challenges and gaps were identified, which entails further investigation on WMA improvement and assessment.

1. Though standard methodologies are specified for determining the production temperatures of HMA, no standard approach is available to evaluate the mixing and compaction temperatures for WMA. In India, IRC SP 101-2019 [27] is available as a guideline on the use of WMA. In the present form, the guideline fails to describe a suitable procedure for assessing the mixing and compaction temperatures of asphalt mixtures produced using different WMA technologies. The guideline recommends producing asphalt mixtures at a 30 °C lower temperature than the conventional HMA mixture. Additionally, taking manufacturer’s recommendation is suggested to decide the appropriate reduction in the production temperature and optimum dosage of the WMA additives. This process is too iterative and lacks rational quantification of production temperatures, regardless of WMA technology.

2. Ageing is one of the critical factors affecting the viscoelastic properties, contributing to the premature failure of asphalt pavements. Nevertheless, no specifications/standards are available to select the ageing procedure for WMA, which can directly simulate the ageing that occurs on the field. Furthermore, the practice used for HMA is currently utilized to simulate ageing on WMA. Therefore, it is essential to underline a specific method to simulate the ageing of WMA at reduced temperatures.
3. Since WMA allows the production of asphalt mixtures at lower temperatures, the influence of ageing on WMA binders may be relatively lower than base asphalt binders. The reduction in ageing as well as the change in physical/chemical behaviour of asphalt binders with the addition of warm mix additives inherently affect the rheological properties. However, the influence of WMA additives on the rheological properties over a wide range of temperatures has not been studied with enough rigor and thus necessitates further investigation.
4. Ensuring satisfactory engineering performance of asphalt mixtures has a direct relation to in-situ characteristics. Considering the production of WMA mixtures at reduced temperatures, there are concerns regarding the resistance of asphalt mixtures to rutting, fatigue and moisture sensitivity. Hence, a comprehensive study is required to ascertain the mix design and performance of WMA mixtures with similar asphalt binder grade, aggregate type, gradation, and OBC as that of HMA mixtures.
5. Even though the application of WMA results in various environmental and economic benefits, it has not been examined and/or implemented, with enough rigor, for pavement construction. However, quantitative studies on economic and environmental benefits gained by using various WMA technologies (organic,

chemical and foaming based) are scanty. Hence, an ELCA of WMA, compared to HMA, would more comprehensively address the economic and environmental aspects.

Overall, a more systematic and complete comparative study between different WMA technologies relative to HMA is required for a better understanding and proper implementation of WMA technologies for pavement construction.

1.6 Key Research Queries

The key research queries that the present study anticipates to address are as follows:

1. What are the effects of WMA additives on the morphology and chemical behaviour of base asphalt binders?
2. All the WMA additives have different working mechanisms. Some are viscosity reducers, while others work on improving the aggregate coating by lowering the surface tension or by creating a foaming effect. So then, how can the traditional viscosity-based methods commonly adopted for HMA be used to evaluate the mixing and compaction temperatures of WMA mixtures? Are other proposed methods that can be adapted to appropriately determine the production temperatures of WMA mixtures based on their physiochemical mechanism?

   Since there are different methods to determine the mixing and compaction temperatures of WMA mixtures, how do we find the reliable/appropriate method among them? In addition, are there any validation checks that can be used to demonstrate the verification of forecasted mixing and compaction temperatures?

3. WMA technologies work on the principle of producing asphalt mixtures with similar workability levels to HMA at a reduced temperature range. But how is the workability of asphalt mixtures assessed?
4. What are the different performance characteristics of WMA binders and mixtures? Does the reduction in production temperatures impact the performance of asphalt binders and mixtures? Is there any possible correlation between the results of WMA binders and mixtures based on their performance predictors?
5. How does the reduction in production temperatures of asphalt mixtures, with the adoption of WMA technologies, affect the country's social integrity and economic development?
6. Which WMA additive is best for sustainable road construction, and how does their performance vary with the change in base asphalt binder and aggregate source?

1.7 Aim

The present study intends to rationalize the use of WMA technologies in asphalt binders and mixtures based on mechanical performance and economic and environmental aspects.

1.8 Objectives and Tasks

The present investigation focuses on the following five specific objectives:

1. To assess the change in base asphalt binders' morphological, chemical and physical characteristics with the addition of WMA additives.

   a. To analyse the morphological and chemical interactions of WMA technologies in base asphalt binders using Scanning electron microscopy (SEM) and Fourier-transform infrared spectroscopy (FTIR), respectively.
   b. To examine different basic characteristics, such as penetration value, softening point, viscosity, and high temperature performance grade along with true fail temperature.

2. To propose a rational method for assessing the mixing and compaction temperatures of WMA mixtures.
   a. To explore the use of available methods for predicting the production temperatures of WMA binders.
   b. To propose and validate a novel workability-based method that can be used to estimate the mixing and compaction temperatures of WMA mixtures.
   c. To determine the optimum dosage of WMA additives based on their production temperatures, pertaining to different technologies.
3. To explore and investigate the effect of different WMA technologies on the engineering performance of asphalt binders.
   a. To understand the effect of reduced ageing due to lower production temperatures of WMA binders.
   b. To study the rheological characteristics at high and intermediate test temperatures and moisture sensitivity of all the considered asphalt binders using Dynamic Shear Rheometer (DSR) and Pneumatic adhesion tensile testing instrument (PATTI), respectively.
4. To evaluate different mechanical performances of asphalt mixtures, such as rutting, fatigue and moisture characteristics.
   a. To characterize the asphalt mixtures based on different test conditions.

   b. To establish the correlation between asphalt binder and mixture characteristics based on the experimental test results.
   c. To determine the threshold values for rutting, fatigue and moisture characteristics incorporating different performance predictors.
5. To ascertain the environmental and economic impacts of WMA technologies compared to conventional HMA.
   a. To understand the extent of reduction in energy consumption with the incorporation of WMA additives during the production of asphalt mixtures.
   b. To find the change in greenhouse gas (GHG) emissions with the use of WMA technologies.
   c. To explore the effect of different fuel types/energy sources on the level of reduction in energy consumption and GHG emissions with the adoption of WMA technologies.
6. To rank different WMA additives based on their performance at asphalt binders and mixtures level.
   a. To rank different WMA additives, irrespective of aggregate type, individually, based on the test method.
   b. To find the global ranking of different combinations based on combined asphalt binder's and mixture's performance.

1.9 Scope of the Present Study

Two commonly used base binders (one viscosity graded asphalt binder (VG), VG30, and the other is a polymer modified asphalt binder (PMB), PMB40) are considered in the present study. Two aggregate sources, i.e., granite and dolomite, are acquired from different quarries to assess the effect of aggregate mineralogy on the properties of

WMA mixtures. Five WMA additives are chosen from different categories of WMA technologies, each with a unique working mechanism. Initially, the range of dosage(s) are selected based on the manufacturer recommendations. The aim and overall objectives of the present study are achieved through the following scope:

1. WMA binders (organic and chemical-based) are prepared using a high-shear mixer. For foaming-based technology, the additive is directly added during the production of the asphalt mixture. Therefore, the preparation of asphalt binder blend is not required in this case. The prepared asphalt binders are further scanned using SEM analysis to assess the change in morphology of the base asphalt binders with the addition of WMA additive. FTIR technique is performed on the prepared blends to understand the interaction between the base asphalt binders and WMA additives.
2. Evaluation of basic properties such as penetration value, softening point, and viscosity are done using conventional test methods. On the other hand, DSR is used to assess the influence of WMA additives on the high temperature performance grade of base asphalt binders.
3. The mixing and compaction temperatures of WMA binders are compared using different methods/approaches. First, a novel workability-based approach is developed for the rational evaluation of production temperatures, irrespective of base asphalt binder and aggregate source. After that, the obtained mixing and compaction temperatures are validated using different verification checks. Next, Coating Index (obtained by fabricating a new coating apparatus) and compaction ability (using impact compaction) checks are evaluated to validate the forecasted mixing and compaction temperatures, respectively. Finally, after the validation of production temperatures, all the asphalt mixtures are prepared at their respective mixing and compaction temperatures for further investigation.

These validation checks are also used to select the optimum WMA additives dosage for the base asphalt binders and aggregate sources. The optimum dosage of each WMA additive so obtained is further used for testing and analysis.

4. The rheological properties of all the selected asphalt binders are measured using DSR. Frequency Sweep (FS) test is carried out on a wider range of temperatures (10-70°C) and frequencies (0.1-100 rad/sec). FS is performed on unaged (UA), short term aged (STA) and long term aged (LTA) samples. Master curves were constructed at two reference temperatures of 20°C and 60°C, which are similar to the normal field temperatures at which fatigue and rutting, respectively, becomes dominant. The results of the FS test are further used to evaluate the change in ageing behaviour of asphalt binders with the addition of WMA additives.
5. Performance based accelerated tests such as multiple stress creep and recovery (MSCR), and Linear amplitude sweep test (LAST), Pneumatic adhesion test (PAT) are conducted to assess the efficacy of WMA additives against rutting, fatigue, and moisture resistance, respectively. MSCR is done on STA samples using a 25 mm diameter spindle and 1 mm gap setting at a temperature range of 40-70°C, while LAST is performed on LTA samples at three different temperatures, i.e., 10°C, 20°C, and 30°C, using 8 mm diameter spindle with 2 mm gap width.

   In this study, in addition to 0.1 kPa and 3.2 kPa, two additional stress levels, i.e., 5 kPa and 10 kPa, are also chosen to assess the response of asphalt binders at high-stress levels. Furthermore, since MSCR is conducted at different temperatures and stress levels, another parameter based on the Arrhenius equation, which combines the effect of temperature and stress level, is adopted to judge the rutting behaviour of the selected asphalt binders.

6. Engineering performance of HMA and WMA mixtures, such as rutting, fatigue, and moisture, are quantified. Rutting and fatigue characteristics are examined by carrying out a cyclic compression test at 60°C and an ideal cracking test at 20°C, respectively. These temperatures correspond to high temperature (60°C) and intermediate temperature (20°C), where rutting and fatigue, respectively, could be prominent distresses. Moisture sensitivity of the asphalt mixtures is evaluated by conducting three different tests, including a boiling water test, Retained Marshall stability test, and the Modified Lottman test. Possible correlations between the results obtained by testing asphalt binders and mixtures have been established, irrespective of the aggregate source and base asphalt binders for each test method. In the end, threshold/limiting values of all the performance parameters are assigned and proposed as a performance measure independent of aggregate source and base asphalt binder type. The limiting values of rutting and fatigue performance predictors are determined based on different traffic designations.
7. The economic and environmental impact of WMA mixtures over conventional HMA mixtures are determined through a theoretical life cycle assessment. In addition, different fuel/energy sources are incorporated to assess their influence on energy consumption and GHG emissions emitted during the production of asphalt mixtures. This assessment demonstrates the benefit of WMA technologies in producing asphalt mixtures considering financial savings and sustainable construction.
8. Since different asphalt binders (base and WMA binders) are tested in this study, it is essential to choose the asphalt binder with relatively higher performance than the other binder type, separately for each base binder. Thus, a simple ranking protocol

is adopted to select the best WMA additive based on the overall performance at the asphalt binders and mixtures level.

1.10 Organization of the Thesis

The thesis comprises a total of 9 chapters. A brief summary of the contents of each subsequent chapter is presented in Table 1.1.

Table 1.1**.** Chapter-wise layout of the thesis

Chapter 1	- This chapter provides a general description of the road network in India, construction technologies, and the background of the study. - The problems and gaps are identified. - Key research queries are also discussed. - The objectives and scope of the work are clearly defined, along with the organization of the thesis.
Chapter 2	- This chapter gives an overview of the previous works done on the use of WMA technologies in pavement construction. - A comprehensive review of the influence of WMA additives on the physical, chemical, and morphological characteristics of the asphalt binders is presented. - Emphasis is given to the effect of WMA technologies on the performance of asphalt binders and mixtures. - Mix design practices, field surveys and the interaction of WMA additives with different materials are also reviewed.

	- The variation in environmental and economic viability with WMA technologies is also discussed.
Chapter 3	- This chapter describes the materials used in the present study. - Information pertaining to the experimental framework and the methodology adopted are also presented. - The results of morphology, chemical, and physical characteristics are discussed as well.
Chapter 4	- This chapter compares the values of mixing and compaction temperatures obtained from different methods. - The description of the fabrication of a novel workability prototype and its working principle is emphasized. - The validation of mixing and compaction temperature, obtained through the workability approach, has been executed. - The optimum dosage of WMA additives is also determined in this chapter.
Chapter 5	- This chapter includes the various rheological aspects of the asphalt binders. - The inferences of master curves, constructed at different reference temperatures, are discussed. - Ageing behaviour of WMA binders has been studied, and the results are compared with the ageing characteristics of base asphalt binders.

	- The analysis of the MSCR test and LAST results at different temperatures and stress/strain levels have been discussed and presented. - The effect of WMA additives on moisture sensitivity is determined and compared with the results of base asphalt binders.
Chapter 6	- This chapter examines the performance of HMA and WMA mixtures in various aspects, such as rutting, fatigue and moisture resistance, through standard test protocols. - This chapter also outlines various test parameters adopted and the obtained experimental results. - Possible correlations between the test results of asphalt binders and mixtures, irrespective of base asphalt binders and aggregate sources, have been presented, and the limiting/threshold values for different parameters have been proposed.
Chapter 7	- This chapter deals with the impact of WMA technologies over the energy consumption and GHG emissions imparted during the production of asphalt mixtures. - The effect of different energy sources/fuel types on the economic and environmental burdens is also discussed.
Chapter 8	- This chapter outlines the discussion on the ranking of tested asphalt binders and mixtures.

	- A simple ranking protocol is adopted to rank different asphalt binders and mixtures based on their experimental results to select the best WMA additive, irrespective of the aggregate sources.
Chapter 9	- This chapter presents the significant conclusions drawn from different chapters of this study. - The contributions, limitations, and applications of the present study are discussed. - Future scope and recommendations of the study are highlighted as well.