CHAPTER 1. INTRODUCTION

1.1 Preamble

Enhancing the overall performance of asphalt mixtures has received a lot of attention over the last two decades, particularly to meet environmental and financial goals [1]. Recently, more focus has been placed on lowering energy usage during the production of asphalt mixtures without degrading their mechanical performance when used. Additionally, there is increasing worldwide pressure to reduce the usage of fossil fuels and the generation of GHGs like carbon dioxide (CO_2) [2]. Unfortunately, the procedure necessary to dry and heat the mineral aggregates and binder at temperatures exceeding 150°C contributes significantly to energy consumption and the release of polluting gases during the production of hot mix asphalt (HMA) [3,4]. The pavement industry has been advocating three techniques to try and lessen these difficulties. First, through the use of inexhaustible and clean new energy sources [5], second, through the substitution of conventional binders with synthetic adhesive binders [6,7], and third, through the development of new technologies to create environmentally friendly asphalt mixtures that can be built and compacted at lower temperatures without affecting their properties [1].

The use of warm mix asphalt (WMA) is one of the energy efficient technology, which produce asphalt mixture at temperatures below 140°C [2]. The reduction in production temperature can be achieved by using one of the warm mix technologies, either organic, chemical, or foaming). The use of such energy efficient technology (WMA) has replaced traditional hot mix asphalt (HMA), which requires mixing temperatures between 150°C and 180°C [1]. The implementation of such technology can lead to significant improvement in energy conservation and the release of pollutant gases. According to previous literatures [1,2,4,8,9], the use of WMA resulted in the following reductions in emissions across the various stages during the plant's production process: 30–40% for CO_2 (carbon dioxide) and SO_2 (sulphur dioxide), 50%

for volatile organic compounds, 10–30% for CO (carbon monoxide), 25–55% for dust, and 60–70% for NO_x (nitrous oxide). In addition, polycyclic aromatic hydrocarbons and asphalt aerosols/fumes have both seen reductions of between 30% and 50%. WMA was also found to use 30% less energy than conventional methods. Nevertheless, despite these significant advancements in the economy and environment, there is still doubt about their use due to a lack of information about their long-term performance, moisture susceptibility brought on by lower production temperatures, and issues with coating and bonding. This is because the lower temperatures in WMA may lead to incomplete drying of aggregates which can weaken coating quality and binder-aggregate adhesion making the mixture more prone to moisture damage [10]. The successful implementation of WMA technology depends on the accurate determination of production temperatures (mixing and compaction temperature). Past studies have shown that there are no standards available for the determination of production temperatures (mixing and compaction temperature) of WMA technology [11,12]. The use of equi-viscous criteria for determination of production temperatures in case of WMA technology may give unrealistic results [11,13,14]. This is because WMA additives improve the workability of binders through mechanisms such as enhanced lubrication and surfactant action which are not directly captured by viscosity measurements. As a result, equi-viscous methods may underestimate the effectiveness of WMA technologies at lower temperatures. The recent studies have demonstrated that the conventional viscosity criteria cannot be used for justification of reduced temperature in case of WMA technology [15]. Recent studies have also shown that the mechanism by which warm mix technologies reduce the production temperatures could be related to the reduction in friction at the contact zone of the mineral aggregates and asphalt binder [15–17]. This reduction in friction leads to improved workability in the asphalt mixture produced with WMA technology. The friction between mineral aggregate and asphalt binder can be studied using science of tribology [18].

Tribology can be defined as the study of lubrication, friction and contact zone between particles in relative motion [19]. The word “tribology” is derived from the Greek word, “tribo” meaning “to rub, ” and suffix “logia” meaning to “study or learning”[20]. Mixing and densification of asphalt mixtures follows such phenomena (reduction in friction), wherein mineral aggregate particles are in relative motion with a thin film of asphalt binder acting as the lubricating medium [15]. Being a new area of exploration, there are no guidelines available currently to explain the tribological characteristics of WMA technology. Because of such implications, in regards to lack of fundamental understanding, transportation agencies are unable to provide any standard guidelines for finding the most appropriate mixing and compaction temperature for WMA technology. Moreover, there is no criteria available for optimizing the dosage of different WMA additives to be used in the asphalt binders for achieving the most desirable performance.

While offering reduced production temperatures, WMA technology may result in inadequate drying of the mineral aggregates potentially leading to higher moisture retention [12,21]. This may further increase the moisture susceptibility of asphalt mixes leading to early failure of the mix. Many existing literatures has already cited the moisture susceptibility issue for mixes prepared using WMA. In order to understand the mechanism associated with the decrease in performance of such mixes, it is important to introduce and study specific moisture susceptibility test process while studying WMA. This will help in identifying the requirement of incorporating an adhesion test for selecting the type and amount of WMA additive to be used for a specific project. Additionally, reduced aging offered by the warm mix additives will tend to lower the stiffness of the mix, which in turn may impact the rutting susceptibility [21,22]. Though the primary aim of using WMA technology is to reduce the production temperature, it should be able to produce mixes with at least similar strength as given by a conventional hot asphalt mix. Hence it is important to ensure that the use of WMA technology shall not affect the rutting and fatigue performance of asphalt binders. Multiple stress creep and recovery (MSCR) and linear amplitude sweep (LAS) test can be used to study these performance characteristics of binders modified using warm mix additives.

The current school of thought in the pavement industry is that WMA can be used to facilitate the sustainable and green roadway infrastructure. For its successful implementations, it is necessary to conduct a detailed study on the use of WMA modified asphalt binders and develop understanding on the various mechanism associated with improved workability characteristics of WMA modified asphalt mixes. Further, it is also desired to design an optimized procedure which can help in selecting the right amount and type of WMA additive for achieving the most desirable properties (rut resistance, fatigue resistance, and moisture resistance) in the final mixture. This study will facilitate development of guidelines for determination of production temperature of WMA technology and for the effective use of WMA in the country promoting environmentally friendly and sustainable road infrastructure.

1.2 Status of WMA Technology In India

India has the second largest road network across the world spanning over 5.4 million km after United States. This road network transports more than 60 per cent of all goods in the country and 85 per cent of India’s total passenger traffic [23]. Road transportation has gradually increased over the years with the improvement in connectivity between cities, towns and villages in the country. Ministry of road transport and highways constructed national highways extending 10,331 kms during financial year 2022-2023 [23]. Overall road projects exceeding 64,000 km in length, costing more than Rs. 11 trillion, are in progress out of which work in respect of projects of more than 40,000 km length has been completed and in balance length of more than 24,000 km works are in progress. National Highways of 5,248 km length have been constructed in the first six months of FY 2023-24 at an average of 28.3 km per day [23]. The

Government of India has a target to develop 2 lakh km of national highway network by 2025. The Ministry of road transport and highway has decided to invest Rs 20.34 trillion (US$ 247.11 billion) for construction of new roads and highways over the period of 2020-2025. Out of the total length of road network, almost 80-90% length constitute of flexible pavements [24].

In India, majority of National and State highways 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) [25,26]. 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 affect 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. The high production temperatures increase concerns related to greenhouse gas (GHG) emissions and higher energy consumption [27,28]. 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) [29].

With the uptake of green highway policy in 2015, it is evident that Indian government is thriving for the development of sustainable green roadway infrastructure [30,31]. Many state and national highways have already adopted several technologies including cold mix technologies, warm mix technologies and plantation policies for environmental benefits. On the contrary, the loading in Indian highways has seen drastic changes in the past few years. New axle configurations, overloading and high traffic density requires effective strengthening of pavement. So, any green technology which is adopted for the construction of road should be able to produce mixes which are at least of similar strength as that of conventional hot mix asphalt. Out of the different green technologies, WMA technology promises such requirements. This is the reason that WMA technology has spread rapidly in India with many state highways and National Highways already being constructed using various WMA technology [32,33]. Central Road Research Institute (CRRI) is one of the initial institutes to have started working on WMA technology [32]. Many wax and chemical based WMA additives have been tried and implemented in different roadway projects. Roja et al. studied the use of Evotherm and Sasobit at high and intermediate temperatures [33]. In a comparative study Aniket et al. found that the fatigue and rutting behaviour of wax based WMA additive resulted in positive rutting and fatigue performance [34]. Rajiv et al., while comparing the rheological properties of different WMA modified asphalt binders incorporating polymers concluded that Sasobit is the most effective form of additive for PMB’s [35]. Aging characteristics of different WMA technologies has also been studied by few of the Indian researchers [36–38]. A brief review of use of WMA in various projects in India have been presented by Kumar and Chandra [39]. However, the performance observed for these mixes are not very consistent in terms of performance using similar type of additives.

1.3 Need for the Research

Indian government is actively promoting the development of sustainable green roadway infrastructure. Various state and national highways have adopted several green technologies to achieve environmental benefits [39]. Among these green technologies, warm mix asphalt (WMA) technology appears particularly promising in meeting the desired requirements. Very few state highways and national highways are already being constructed using various WMA technology. However, use of WMA technology indicates that the benefits gained by the reduced production temperatures is not yet supported by the underlying understanding about the mechanisms involved, which hinders the full exploitation of the benefits and implications involved with the use of WMA additives. In India, IRC SP 101-2019 is available as a guideline on use of WMA technology [40]. The present guidelines are silent on rational quantification of mixing and compaction temperatures. According to the guidelines, asphalt mixture should be produced at a temperature 30°C lower than the usual hot asphalt mixture. Most of the projects involving construction of roads using WMA technology still adopt manufacturer's recommendation for using the amount of WMA additive. There are no strict guidelines which are used for finding the mixing and compaction temperature for mixes prepared using WMA technology.

The traditional belief of considering reduction in viscosity offered by WMA additives cannot be completely used as a justification for reduction in mixing and compaction temperature of asphalt mixes produced using this technology [15]. Although viscosity is a critical parameter influencing workability, WMA technologies often involve physical, chemical, or combined mechanisms that alter binder-aggregate interactions beyond viscosity modification. These include surface tension changes, foaming behavior, adhesion promotions and time-temperature dependent rheological shifts which are not fully captured by conventional viscosity measurements alone. Hence, relying solely on viscosity can lead to inaccurate estimation of production temperatures, potentially affecting the compactability, coating, and long-term performance of mixtures. Hence it is important to understand the complexities related with WMA technology and define the mechanisms related to its constructability. In recent studies, the tribological properties of the asphalt binders has been hypothesized as a possible mechanism, in addition to the viscosity of the binders, associated with the improved workability and densification of the WMA modified asphalt mixes [41]. Tribology can be defined as the study of lubrication, friction and contact zone between particles in relative motion [18]. One of the fundamental tools used in tribological analysis is the Stribeck curve, which illustrates the relationship between the coefficient of friction and the lubrication regime, typically characterized by the Hersey number (a function of viscosity, speed, and load). It delineates three lubrication regimes: boundary, mixed, and hydrodynamic. A standard Stribeck curve has been successfully used to describe such mechanism in few of the recent studies [15,18]. Being a new area of exploration, there are no guidelines available currently to explain the tribological characteristics of WMA.

The development of warm asphalt technology began in Europe, and more recently, the India has seen an increase in research activity in this field [42]. The effectiveness of WMA has been the subject of in-depth studies. Although a lot of time and effort has gone into examining the performance of various warm technologies, more research needs to be done before it can be decided whether or not to switch from the existing HMA to WMA. Before implementation of WMA technology, the performance of WMA is one of the topics that needs to be looked into in more detail. Also the benefits and risks associated with the performance of WMA modified binders in terms of resistance to distresses (rutting and fatigue cracking) and moisture damage has to be studied for optimizing the amount of additive dosage to be used for satisfactory results [10,22,43].

Therefore, a complete fundamental understanding on the behaviour of WMA is required so as to optimize the dosage depending on the type of base binder used for modification, type of WMA technology employed. Furthermore, the reduction in production temperatures offered by the respective WMA additive needed to be understand in order to ensure better performance of the binder in terms of moisture damage, rutting resistance and fatigue life. The present study will pave the road for the development of guidelines for effective use of WMA in the country promoting sustainable and green roadway infrastructure. Therefore, the adoption of WMA technology is imperative for enhancing the sustainable infrastructure development efforts in country like India.

Finally, it is envisaged that the results of the study will bring out new guidelines for effective utilization of WMA technology in the country. The study will bring clarity, through fundamental understanding, on the processes involved in lowering of production temperatures of asphalt mixes prepared using WMA modified binders. This will help in selecting the most optimized dosage of WMA additive depending on the type of WMA technology, type of base binder and aggregate and the type of aggregate gradation.

In summary, the following aspects were taken into account when defining the study objectives in order to meet the goals stated in this chapter:

1. Even though extensive studies have focused on the determination of production temperatures for WMA based on existing guidelines, there is still no definitive approach for establishing the production temperatures of warm mix modified mixtures. Furthermore, the available methods are highly iterative and lack rational quantification of production temperatures, regardless of the specific WMA technology used.
2. The workability of asphalt mixture is most logical way to define production and placement of WMA modified mixture. But very limited research studies have used this approach for quantification of production temperature of WMA technology. Therefore, there is a need to address and investigate the effect of warm additives on workability of asphalt mixture and use this approach for determination of production temperature.
3. In paving industry, tribology is comparatively a young science, recently adopted to investigate warm mix asphalt (WMA) technologies. Tribology has been emerged as an effective tool for a complete fundamental understanding of the behaviour of WMA modified asphalt binder. However, there is currently no proper methodology that can be used to explain the tribological properties of WMA as this field of study is still being explored. In fact, there is a need for a methodology to accurately evaluate WMA technology using tribological approach.

4. Although the technology offer reduction in production temperatures with numerous benefits, but the implementation of the technology may create the potential issues. The most repeated concerns raised in the literature are related to reduced aging of WMA modified asphalt binders. Till date, there are no specifications that can be used to choose the aging method for WMA that can accurately mimic the aging that takes place on the field. Therefore, there is need to addresses and investigate the aging protocol for WMA modified binders.
5. The impact of aging on WMA binders may be less than base asphalt binders because WMA enables the production of asphalt mixtures at lower temperatures. Rheological properties of an asphalt binder are inevitably impacted by the use of warm mix additives because they reduce aging and alter the physical/chemical behaviour of asphalt binders. Therefore, the performance of asphalt binders should be even more difficult to characterise in WMA as the production temperature is lower than HMA; thus, another two factors or questions should be addressed. The first is that the performance of the asphalt binder is enhanced by warm mix additives or by the lower production temperature. The second is how much the temperature during production may be lowered without having a negative effect on the level of adhesion between the binder and the aggregate in asphalt mixtures. The current study carefully examines both of these issues. Although the numerous studies are available regarding performance of WMA modified asphalt binders. But studies are limited regarding the performance of WMA technology at reduced aging level. Therefore, there is a need of further exploration in this direction.
6. Due to reduction in production temperature, moisture may retain in the mineral aggregates due to incomplete drying. This may further increase the moisture susceptibility of asphalt mixes leading to an early failure of the mixture. Many existing

literatures have already cited the moisture susceptibility issue for mixes prepared using WMA. Few studies related to moisture damage in terms of the bond strength between aggregate and binder has been carried out to check the effectiveness of WMA additives. Recent studies have shown the extent of moisture damage is dependent on the type of WMA technology, type of aggregates, regional climatic conditions and loading conditions. However, the influence of WMA additives on the bond strength has not been studied with enough rigor and thus needs further exploration.

To this end, it is thus required to conduct a detailed study on the use of WMA modified asphalt binders and develop understanding on the various mechanism associated with improved workability characteristics of asphalt mixes. In order to achieve desirable properties in the final mix, it is also necessary to develop an optimised technique that can assist in choosing the suitable amount and type of WMA additives.

1.4 Significance of the Research

As previously noted, WMA can significantly lower the energy use and greenhouse gas emissions (GHG). A number of challenges must yet be addressed. The impact of production temperature on the functionality of WMA is one of these difficulties. Any considerations of lowering the production temperature should be prudently made without comprising the mixtures' properties because the production temperature has a significant impact on durability of asphalt mixture. It is necessary to further investigate the effect of production temperature on the performance of WMA in order to specify (for a highway agency) a minimum reduction in the production temperature to produce asphalt mixtures with an equal or better performance than HMA. With this we shall achieve great positive economic and environmental improvements. The reason for this is that, if the WMA is not as resilient as the HMA, maintenance costs may rise and, in extreme cases, the pavement may need to be rebuilt earlier than anticipated when the pavement structure was designed.

Although an effort was made to explore the workability of WMA mixture or asphalt mixture, so far, no research has been conducted which investigates in depth understanding of the workability of WMA mixtures. Understanding of workability behaviour of WMA mixture can contribute to accurately assessing the production temperature of the WMA asphalt mixture. In recent studies, researchers have started use of tribology for the assessment of WMA technology. Till date the literatures are insufficient to make firm comment about the behaviour of WMA technology. Furthermore, understanding the tribological behaviour of warm mix additives incorporated in an asphalt binder can contribute to establishing a technique for assessment of their production temperatures. A proper approach for determination of production temperature needs to be revised in the future if the WMA is to replace the HMA. Therefore, research is needed to determine how production temperature of different WMA additives affect performance, particularly at binder and mixture level.

In addition, a methodology to optimise the dosages are also required to give more confidence to pavement designers for the use of WMA technology in pavement structure. The implementation of such technology can promote to the economical, environmentally friendly and sustainable structures.

1.5 Goals and Objectives of the Research

The main objective of the study is to assess the allowable temperature reduction based on the tribological and performance characteristics of the WMA modified asphalt binders. In order to achieve these objectives, following sub objectives have been defined:

1. To assess the effect of WMA additives and its dosage on tribological characteristics of asphalt binder

- **Task 1:** To assess the production temperatures of WMA technology using viscosity-based method.
- **Task 2:** To study the effect of WMA technology and its dosage on frictional characteristics of asphalt binder using ball-on-three-plates fixture mounted on DSR.
- **Task 3:** To analyse the effect of different types of plates on frictional characteristics of asphalt binder.
- **Task 4:** To determine production temperatures of WMA modified asphalt binders using tribological approach.

2. To assess the effect of WMA additives and its dosages on workability characteristics of asphalt binder.
   - **Task 1:** To analyse the effect of WMA technology on workability characteristics of asphalt mixture made with different binder (VG 30 and PMB 40) and aggregates (Dolerite and Granite).
   - **Task 2:** To use workability-based method for determination of production temperatures of WMA technology.
   - **Task 3:** To correlate and validate tribology-based approach used for determination of MT and CT using workability method. To use coating ability test (to ensure better coating ability at mixing temperature) and compactibility test (to ensure sufficient air voids at compaction temperature) for validation tribology based approach.
3. To evaluate the effect of WMA additives and its dosages on performance characteristics of asphalt binders
   - **Task 1:** To determine aging resistance of WMA modified binders using FTIR test.
   - **Task 2:** To assess the rutting performance of WMA technology using MSCR test at reduced aging temperature.

- **Task 3:** To assess the fatigue performance of WMA technology using LAS test at reduced aging temperature.
- **Task 4:** To analyse the moisture sensitivity of different WMA technology using bitumen bond strength (BBS) test.

4. Development of guidelines for appropriate choice of WMA technology to be adopted in the country.
   - **Task 1:** To formulate the guidelines for determination of production temperatures of WMA technology.
   - **Task 2:** To formulate the guidelines for selection of WMA additives and their optimum dosages.

1.6 Scope of the Present Research

This research investigates the production temperature and performance characteristics of warm mix asphalt (WMA) modified asphalt binders. The study focuses on two types of binders: viscosity graded (VG) VG30 and polymer modified binder (PMB) 40. Each binder is modified with varying dosages of four WMA additives: Sasobit, Asphaltan A, Iterlow, and Rediset based on the manufacturer's recommendations. In addition to these, fourteen viscosity grade binders have been selected to determine the reference coefficient of friction (CoF) values for estimation of production temperatures using tribological approach. Furthermore, four polymer modified binders have been used to evaluate the suitability and applicability of the tribological approach in predicting production temperatures for polymer modified binders contaning WMA additives. To explore the impact of aggregate mineralogy on the workability of WMA asphalt mixtures, two types of aggregates: Dolerite and Granite are used in the mixture preparation. The study begins with binder characterization, including penetration, softening point, and performance grading (PG) using dynamic shear rheometer (DSR). The tribological behavior of the binders is studied using the ball-on-three-plate geometry attached to DSR. These tests are conducted across a wide temperature range (90°C to 160°C, at 10°C intervals) covering the operational temperature ranges of VG30, PMB40, and WMA-modified binders. Subsequent to the tribology study, workability tests on asphalt mixtures are conducted using a torque tester to analyze the impact of WMA additives and their dosages on mixture workability. The test temperatures are also varied within the practical operating range to provide robust data for optimization. After determination of production temperature using tribology and workability approach, the aging behavior of WMA modified asphalt is investigated at the mixing and compaction temperatures (MT and CT) determined from the tribology tests followed by Fourier Transform Infrared Spectroscopy (FTIR) analysis to evaluate the aging resistance of WMA technology. The performance properties of the binders are then tested using multiple stress creep and recovery (MSCR) tests at high temperatures (40-60°C) for rutting performance and linear amplitude sweep (LAS) tests at intermediate temperatures (10-30°C) for faigue cracking performance. Moisture sensitivity is studied using the bitumen bond strength (BBS) test by employing five aggregates (Basalt, Dolomite, Dolerite, Granite, and Sandstone) to investigate the effect of aggregate mineralogy on moisture sensitivity. Finally, Comprehensive data analysis will be conducted throughout the study for concluding in an optimization strategy for selecting the optimal WMA additive combinations and dosages to achieve desirable binder performance.

1.7 Organisation of Thesis

The thesis is organised into eight chapters. Chapters 1 and 8 are the introduction and conclusion respectively. The main body of the research is presented in chapters 2 to 8 and brief summary of the contents of each chapter is presented as follows:

Chapter 1: The first chapter is general introduction that provides a brief account about the emergence of tribology in WMA technologies. In addition, current status of WMA technology in India has been discussed in this chapter. A problem statement regarding the key research questions concerning the topic of this study is provided along with the research objectives. The scope of the current research work to achieve these objectives was briefly discussed.

Chapter 2: The state-of-the-art chapter reviews the available warm mix technologies with reference to the foaming, organic technology and chemical technology. This chapter also reviews the various methods available for the determination of MT and CT of WMA technology along with workability approaches. This chapter also reviews the hypotheses regarding the use of tribology for the assessment of WMA technology. This chapter also reviews the laboratory and field performance of WMA technology. Finally, the gaps in the literatures are identified and discussed in this chapter.

Chapter 3: This chapter provides the information regarding the materials used and methodology adopted in the present study. Information regarding the experimental framework used in the study for the characterization of WMA technology has been presented in this chapter. The results of physical properties of WMA modified binders are also discussed in this chapter.

Chapter 4: This chapter provides the information regarding the determination of MT and CT of WMA technology using various viscosity based methods and phase angle method. The results and discussions regarding these methods has also been discussed in this chapter. The drawbacks of these methods for determination of MT and CT of WMA technology have also been highlighted.

Chapter 5: This chapter provides the information regarding the tribological assessment of WMA technology using ball-on-three-plates test. The selection of appropriate combination of tribological parameters (sliding speed and normal force) for the characterization of WMA technology has been discussed in this chapter. The tribology based methodology for determination of MT and CT of WMA technology has also been presented. The results and discussion regarding this tribology based approach have been discussed in this chapter. Finally, the validation of this approach using workability, coating ability test, and compactibility test has been presented.

Chapter 6: This chapter provides the information regarding the various performance tests (frequency sweep, MSCR, LAS, and BBS) carried out on WMA modified binders to check their suitability. The aging resistance of WMA modified binder using FTIR test has also been discussed in this chapter. The results and discussions regarding these performance tests and FTIR test have been presented in this chapter.

Chapter 7: This chapter provides the framework regarding the selection of WMA technology based on their performance parameters. The selection of optimum dosage for each type of WMA technology corresponding to each base binder based on ranking has been discussed in this chapter.

Chapter 8: This chapter provides the important conclusions drawn from different chapters of this study. The contributions, limitations, and applications of the present study has also been highlighted in this chapter. Finally, the future scope and recommendations of the study been discussed in this chapter.