CHAPTER 1. INTRODUCTION

1.1 Need for recycling

Road transportation is one of the major contributing sector to economy that constitutes around 3.6 percentage of gross domestic product (GDP) of India, as of 2022 [1]. Connectivity between the states, urban and rural areas helps in the movement of passenger traffic as well as freight, which is essential for the economic growth of a country [2]. Therefore, with the objective of road network development, fund allocations increased constantly and different initiatives has been taken by the government of India [3]. As a result, road network (national highways) increased by 60% in 2024 as compared to 2014 [4]. India is the second largest country in terms of road network with 1.46 million kilometres of national highways, as of December 2024 [5]. Around 98% of total road network in India are flexible pavement, which comprises of asphalt mixture in the surface course [6,7]. Asphalt mixture generally consists of graded mineral aggregates mixed with hot bitumen or asphalt binder to produce a dense wearing (surface) course. This asphalt mixture is referred to as hot mix asphalt (HMA).

Non-renewable natural sources such as virgin aggregates and asphalt binder are continuously depleting with the construction and maintenance activities of flexible pavements. Construction of one kilometre of highway would require around 15,000 tonnes of virgin aggregates [8]. This has put a lot of pressure on government bodies, as quarrying or mining the huge quantities of virgin aggregates has increased environmental, energy and economic concerns. Mining involves drilling and blasting the hard rock formations of different origins with explosives and heavy machinery and further crushing process [9]. Negative impacts of quarrying are air pollution (due to dust), noise pollution (due to heavy machinery and explosives), destruction of ecosystem (depletes earth cover and harms flora and fauna), acidic mine drainage and health and climate issues (co_2 emissions and dust) [10–12]. Quarrying is unavoidable as the huge quantities of virgin aggregates are necessary to meet the needs of rapid infrastructure requirement. Intensity of environmental effects that results due to quarrying varies depending on the geological characteristics of aggregate deposits [13].

Asphalt binder is a dark brown or black cementitious material produced by processing the residue obtained from the fractional distillation of crude oil in petroleum refineries [14,15]. Formation of crude oil takes place over a long period of time after subjecting the animal and plant remains (that lay at a great depths below the layers of sand, silt and rock) to heat and pressure [16]. As the crude oil is a natural or non-renewable resource, quantity of the reserves to meet the growing demand is a concern. And more than half of the crude oil reserves are located in five gulf countries [17–19]. In 1967, Arab oil embargo came into effect in the month of October to achieve political and economic advantage [20,21]. It leads to drastic increase in the cost of petroleum products. Thus in the light of declining rates of crude oil sources in addition with the chance of political agendas and their consequences, search for the alternative sources to asphalt binder has been going on over a long period of time.

On the other hand, resurfacing, reconstruction or rehabilitation operations involve the removal of existing asphalt pavement materials. This produces an enormous quantity of discarded waste, which devours landfill space [22]. The current huge network of pavements is also in need of repair owing to the distresses that resulted due to growing traffic and overdue maintenance. Repairing and maintenance activities requires huge amount of capitals. But a shortage of funds and economic constraints has prompted engineers to search for innovative approaches to reduce the use of virgin materials and replace with alternative materials. Even after their service life and at any point in time during their service, materials in old asphalt pavements have an absolute value [23]. Thus recycling the asphalt pavement materials will reduce the demand on the virgin aggregates and asphalt binder.

1.2 Recycled asphalt pavement (RAP)

Recycling of asphalt pavements is one of the oldest technology that dates back nearly a century. It provides a feasible and efficient solution to almost all the aforementioned concerns. Recycled Asphalt Pavement (RAP) materials, which are defined as the 'removed or reprocessed pavement materials containing asphalt and aggregates,' can replace high quality and expensive virgin aggregates and asphalt binder depending on the needs [24]. RAP is acquired by removing the existing flexible pavement either by milling (using a milling machine) or ripping and breaking process (using conventional constructional equipment) [25,26]. In milling, asphalt pavement is broken to required depth using a milling machine (see Figure 1-1) and the removed material is discharged into a truck. Milling machines are comprised of a rotating drum with easily replaceable tungsten carbide teeth (see Figure 1-2) in which spacing or pattern of the teeth can be altered to collect the anticipated size RAP [27–29].

Figure 1-1 Milling Machine [30]

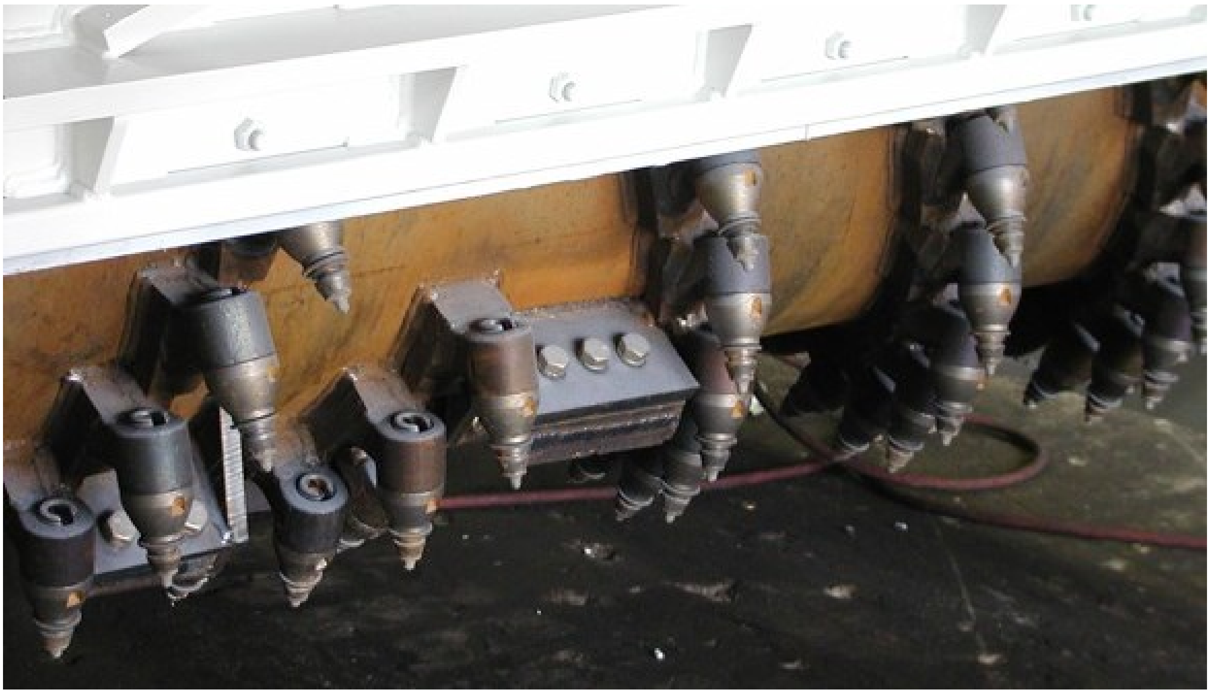

Figure 1-2 Teeth on rotating drum of milling machine [31]

The quality of RAP also depends on the milling apparatus, depth of milling and milling machine speed (slow forward rate and fast drum rotation increase fines) [32]. Material obtained using milling has gradation somewhat similar to original gradation [26]. Milling is preferably used in maintenance works where geometrics of pavement has to be maintained [27]. In the ripping process, conventional constructional equipment such as bulldozers, vibratory compactors, gird rollers, rippers, etc., are employed to remove the asphalt pavement [29,33,34]. This process is mainly used to reclaim the full depth of the bituminous layer. Materials are obtained in the form of large lumps and are needed to be crushed before stockpiling [42,45,48]. Consequently, crushing may result in the accumulation of undesirable fines that need to be removed [34].

1.3 Advantages and challenges of recycling

Savings from the usage of RAP in terms of materials, greenhouse gas emissions, landfill area and waste disposal costs for the year 2019 in Unites States of America (USA), as per the survey conducted by National Asphalt Pavement Association (NAPA) [36], are presented in Table

1-1. These multi-fold advantages prompt government agencies involved in the construction sector, to incorporate RAP in hot mix asphalt (HMA). As can be seen from Figure 1-3, the amount of RAP used in the asphalt mixture increased from 2009 to 2019 in the united states.

Table 1-1 Savings from the use of reclaimed asphalt pavement in 2019 [36]

Source	**Benefit**
Asphalt binder	4.5 million tons
Aggregates	84 million tons
Reduced greenhouse gas emissions	2.4 million metric tons of CO_2
Landfill space	58.9 million cubic yards
Gate fee for landfill disposal	5.3 billion dollars

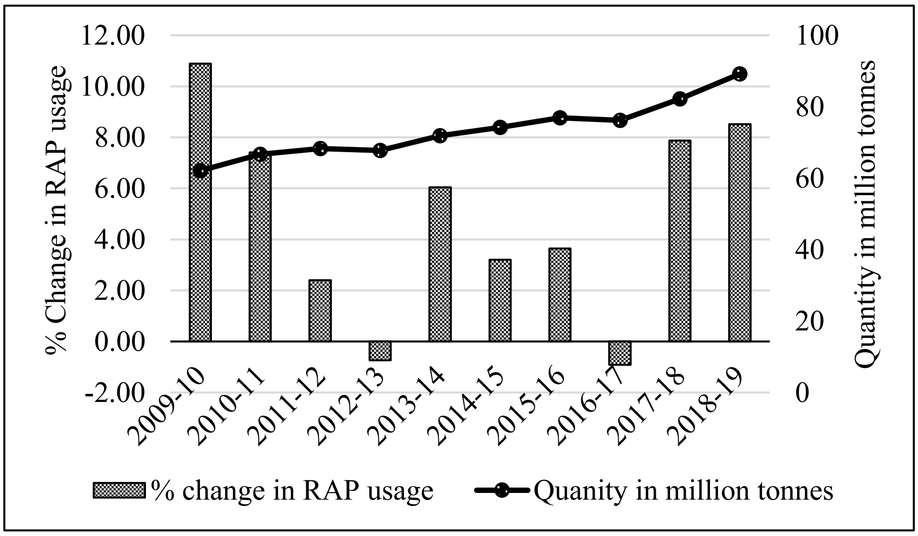

Figure 1-3 Usage of reclaimed asphalt pavement in asphalt mixtures over the years in the united states [36]

The vast road network of India will likely take a steep rise in the future due to rapid urbanization and construction activities. Ministry of road transport and highways (MoRTH), government of India lately acknowledged the value of reclaimed materials (RAP) and allowed its use in the new pavements [37,38]. Thus recycling, becoming a practice in recent times, will play a key role in the country's sustainable development. Currently, in India, not more than 50%, although the general practice of 30% is allowed for recycling in hot mix plants as per IRC 120-2015 [39]. Some of the factors that restricts or inhibits the usage of high percentages of RAP in HIMA are production complications, lack of guidelines for mix design, and stiff aged binder. Owing to these limitations, RAP was initially practiced in low volume roads, unbound layers, road shoulders, hot or cold in-place recycling, and in HMA at low percentages. With time, considerable knowledge has been gained regarding RAP.

The considerable amount of work done in pavements with the utilization of RAP led to a better knowledge of health-related hazards, which also helps reduce health-associated risks considerably [24]. Some modifications to the current hot mix plants can easily aid in incorporating RAP [29]. National Cooperative Highway Research Program (NCHRP) synthesis 54 and NCHRP report 224 included information about recycled materials, recycling procedures, structural design considerations, and construction specifications. Nevertheless, in the late 1990s, after the development of the Superpave mix design, the emphasis was given to coarse-graded mixes, and there was no provision for the inclusion of RAP [22,40]. High fine content and complications in evaluating volumetric restricted the utilization of RAP. It made agencies reluctant to use RAP in the Superpave mix design method. NCHRP project 9-12 addressed these problems, and the project's findings resulted in the development of NCHRP 253 guidelines for including RAP in Superpave mix design. Issues related to maximizing the use of RAP were addressed by NCHRP project 9-46, and the findings are summarized in report 752. NCHRP 752 developed mix design methodologies and evaluation procedures that are anticipated to result in satisfactory long-term performance, even with high RAP content.

As the Superpave mix design methods allows mixes with low binder contents, as compared to Marshall mix design method, fatigue and thermal cracking was primarily observed in the asphalt pavements [41]. As the inclusion of RAP further amplifies these distresses, there is a need for alternate approaches to replace the volumetric based mix design and to ensure long term performance. As a result, balanced mix design (BMD) approach has been developed along with different practical and low cost testing methodologies to asses rutting and fatigue performance. In this context, department of transportation (DOT) of different states of USA are trying to establish specific performance thresholds for rutting and fatigue performance. Appreciable effort has been done by Maine, Connecticut, Virginia and Oregon DOT's. Few important suggestions or findings are to subject asphalt mixes to long term aging to assess cracking performance [42], threshold for rutting along the wheel path and use of percentage of cracking over the surface of pavement as a baseline for threshold [43], thresholds of rutting value of less than 8.0 mm (8,000 passes) and a CT Index value of more than 70 [44], to adopt design levels to establish thresholds for BMD implementation [45], to increase binder content by less than 0.5% or one-grade bumping if same binder content is need to be adopted will result in satisfactory performance of high RAP mixtures (30 and 40% RAP) [46] etc.

Yet, stiff binder layer over aggregates is a major concern. The asphalt binder layer gets oxidized due to the loss of volatiles and change in its molecular structure during its in-service life [47–49]. This results in cracking and leads to potential adhesion loss and coating at the binder aggregate interface [50]. This negative impact increases with the increase in the percentage of RAP. High binder content or softer virgin binder or rejuvenators aids in increasing the cracking resistance and fatigue life of the recycled mixtures, considering other factors such as aggregate gradation, volumetric, binder content, film thickness are met. Among the available options, rejuvenators are found to be more reliable, especially for high RAP contents (above 30%).

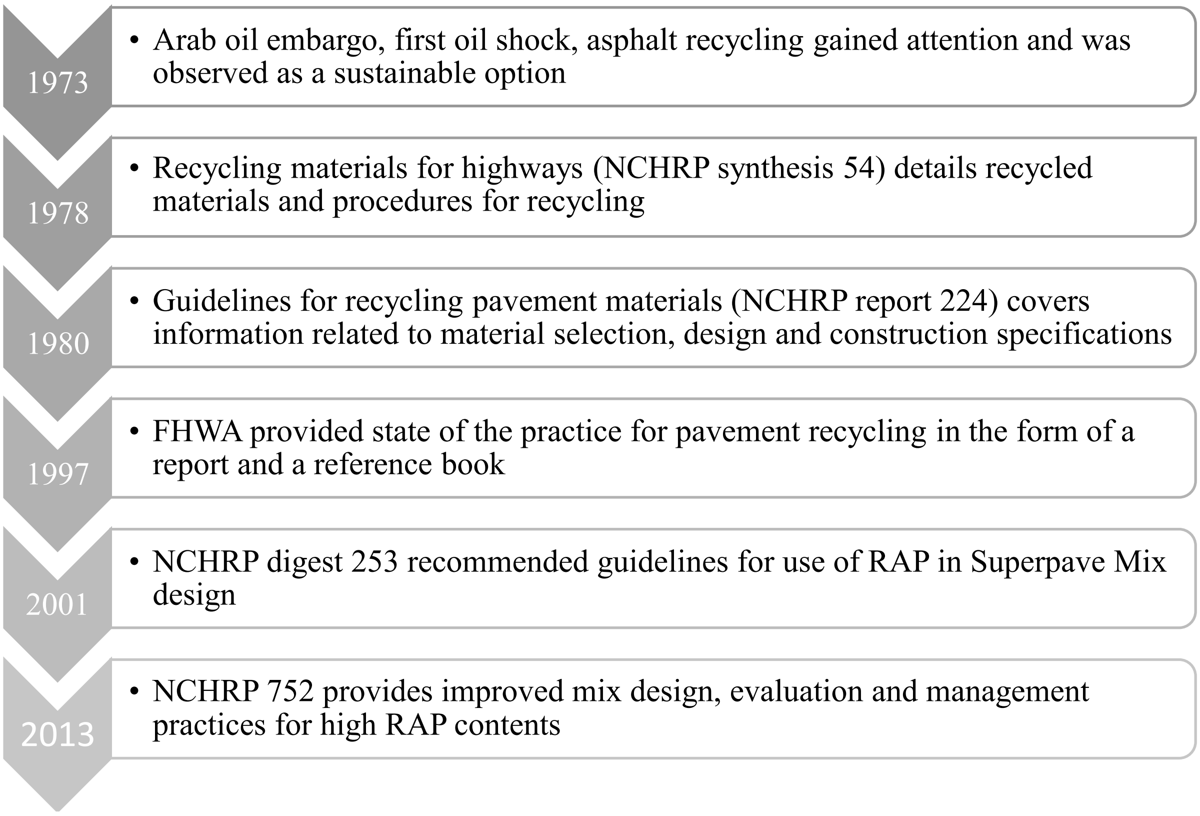

Figure 1-4 Key development related to the use of reclaimed asphalt pavement in hot mix asphalt

1.4 Rejuvenators

A rejuvenator is an additive of desired chemical composition and physical characteristics that can restore the aged RAP binder's degraded properties by prolonging the recycled materials' life [51]. In general, rejuvenators aid in incorporating the high RAP percentages and alleviate the problems linked with these increased percentages. Rejuvenator should also impart the required consistency and durability to the aged binder such that recycled mixes exhibit good engineering properties. Some products, such as lube stock, lubricating oil, asphalt flux oils, etc., only reduce the aged binder's viscosity and are termed softening agents. But the main focus of this study is only on the rejuvenators because they can restore the RAP binder's chemical composition and physical properties.

Rejuvenators improve the fatigue performance of recycled mixes and the effectiveness is mainly observed at high RAP percentages [52–54]. At low temperatures, bitumen becomes too stiff, and sometimes the role of the rejuvenator may not be observed. Still, reducing stiffness by rejuvenator can help relax the stresses at low temperatures [55]. At the same time, rejuvenators may reduce the rutting resistance of recycled mixes at different RAP percentages but performance should be either better than or comparable with the control virgin mix. It translates to the requirement that the impact of RAP should be more than softening effect of the rejuvenator and it was observed in previous studies also [56–62]. Interface cohesion between aged RAP binder and aggregate increases due to the addition of a rejuvenator resulting in enhanced moisture resistance [63]. As rejuvenators reduce the stiffness imparted by the aged RAP binder, modulus values are tend to decrease [64]. Overall, rejuvenators help in improving the performance of recycled mixes especially at high percentages of RAP.

1.5 Research Gaps

Application of rejuvenators for hot mix recycling is not a new technology. However, durability of rejuvenators, more specifically aging performance, is a major concern that has not been studied with enough rigor. Few studies [65–68] highlighted that rejuvenated binders age differently and faster than virgin binders and hence are susceptible to aging. It is also observed that rejuvenated mixes are even prone to cracking at later stages despite of having better cracking resistance initially. Aging performance of rejuvenated recycled mixes should be considered and the performance either needs to be better or similar to that of virgin mixes to confidently implement the rejuvenators in the field.

Another most important aspect of rejuvenators is the optimum dosage. It should be understood that any rejuvenator can successfully restore aged binder properties at a specific (optimised) dosage. But using a very high dosage may affect the optimum binder content and reduce the cohesion and adhesion properties, increases moisture susceptibility and pavement deformation. Besides, flushing, i.e., oils migrating to the surface, may also severely affect pavement performance due to reduced friction [32,69]. On the other hand, a low dosage does not confirm rejuvenation. So dosage has to be selected cautiously. Also dosage of the rejuvenator varies depending on the type of property or parameter used. Hence, an extensive evaluation needs to be done.

Properties such as thermal stability and viscosity of rejuvenators and their correlation with performance has not been explored earlier. Other physical properties such as specific gravity and flash point, which are standard basic properties are also not studied. These type of correlations can help select a better performing rejuvenator among different available options with minimum testing possible.

1.6 Objectives of the Research

The present study is aimed at comprehensively evaluating rejuvenators for hot mix asphalt recycling. The specific objectives are:

- To investigate the suitability of the standard aging protocol of AASHTO (American Association of State Highway and Transportation Officials) R30.
- To evaluate the difference in performance between a blend of used engine oils and WEO obtained from a single uniform source.
- To examine the effectiveness of different tests in characterizing a range of rejuvenators and to identify the rejuvenator properties that correlate best with the performance of recycled mixes.
- To determine the most appropriate parameter for evaluating the optimum dosage of rejuvenators.
- To assess the durability of rejuvenators based on the performance of recycled mixes in comparison with virgin mixes across different aging periods.

1.7 Organisation of Thesis

The thesis is organised into eight chapters and brief summary of the contents of each chapter is presented as follows:

Chapter 1: In this chapter a brief introduction to the recycling is provided. Necessity of recycling, definition of RAP and collection methods, advantages and challenges of the implementation of hot mix asphalt recycling along with need of rejuvenators has been discussed in this chapter. Research gaps in the field of rejuvenators are identified and discussed. The objectives of this study is to address the research gap along with the tasks of each objective is also provided in this chapter.

Chapter 2: This chapter provides the state-of-the-art information related to the rejuvenators associated with the study. A detailed description of the requirements of rejuvenators considering the changes that happens in the asphalt binder during the course of aging is specified. The section thoroughly discusses the classification of rejuvenators and methods used in the literature for tracking and optimising the rejuvenators. A comprehensive discussion on performance of recycled mixes with different rejuvenators is also provided. Also, the rationale for selecting the artificial aged binder in this study are mentioned.

Chapter 3: This chapter describes the materials (asphalt binder, aggregates and rejuvenators) used in the present study. A summary of the research methodology of this study is presented in the form of flow charts. The results of basic characteristics of materials are presented as well.

Chapter 4: This chapter assess the suitability of AASHTO R 30 aging protocol. The detailed performance in terms of Marshall stability, rutting, fatigue, moisture resistance and resislient modulus of virgin mixes at different aging periods are studied. Sensitivity of different performance parameters to aging are analysed.

Chapter 5: This chapter examines the difference between the waste engine oils obtained from a single uniform source and blended engine oils. Fourier Transformed Infrared (FTIR) spectra and performance of recycled mixes in terms of rutting and fatigue are studied for both waste engine oils. Statistical analysis is also conducted to examine the influence of source.

Chapter 6: Characterisation of rejuvenators is presented in this chapter. The comprehensive evaluation of optimum dosage of each rejuvenator considering multiple tests and parameters has been provided in this chapter. A simple ranking protocol is adopted to rank different rejuvenators based on their experimental results and to select a parameter for selecting a rejuvenator that would result in better performance.

Chapter 7: This chapter deals with the durability of rejuvenators in comparison with the virgin mixes. The effect of different aging periods on the performance of recycled mixes are presented. Prominence of different performance parameters in the context of durability are discussed in detail.

Chapter 8: The primary conclusions satisfying the objectives of the study are summarised in this chapter. The novelty of the work highlighting the contribution has also been outlined. Future scope and recommendations of the study are also emphasized.