CHAPTER 2. WARM MIX TECHNOLOGY: STATE-OF-THE-ART

2.1 Preamble

In India, the asphalt mixture is generally produced using hot mix asphalt (HMA) technology. Hot mix asphalt (HMA) is a mixture of graded mineral aggregates and asphalt binder which conventionally used as a surface layer during the construction of flexible pavement. The production of hot mix asphalt mixtures requires high heating temperatures, generally > 140 °C to achieve the better workability and placement of asphalt mixtures. Modern days flexible pavement requires the use of polymer modified asphalt binder to carry out high traffic loading to ensure the better performance against rutting and fatigue cracking. Asphalt mixtures prepared using polymer modified asphalt binders are believed to be more difficult to work than unmodified binders. To improve the workability of polymer modified binders, the production and placement of polymer modified binder are generally done at higher production temperatures (> 160 °C). The high production temperatures (generally referred to as mixing and compaction temperatures) involved in HMA technology increase concerns related to greenhouse gas emissions and higher energy consumption. 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). With the goal of enhancing the benefits of hot mix asphalt (HMA) for the environment and economy without compromising the workability, durability, or performance of asphalt pavements, pavement researchers have directed more of their attention towards lowering production and compaction temperatures of HMA technology. Significant advancements in both environmental prosperity and performance of asphalt mixture will result from the introduction of energy efficient technologies in the form of warm mix asphalt (WMA) technology, which is one of the primary targets of future pavement technology initiatives.

Warm mix asphalt (WMA) is one of the energy efficient technologies that produce asphalt mixture at a temperature 20-40°C lower than that of HMA technology using one of the warm technologies such organic, chemical, and foaming. WMA technology offers excellent technical, social and economic benefits such as improved workability, reduced emissions, lower fuel consumption, improved working environment and extended paving time. Moreover, in order to maximise the benefits, the technology can be used with polymer modified binders to allow the development of more durable and sustainable pavement structure. It is anticipated that WMA technology should ensure similar or better performance as compared to the HMA technology. If this goal is not met, then all of the aforementioned advantages will be useless. The successful implementation of WMA technology greatly depends upon the proper production and placement of this technology. Till date majority of the previous literatures have shown that WMA perform same as that of HMA. But there are certain parameters where WMA production and its performance still needs to be enhanced. The current state-of-the-art chapter reviews the more common available warm mix technologies: organic technology (Sasobit and Asphaltan A), chemical technology (Rediset and Iterlow), and foaming technology (water based foaming technology and water bearing foaming technology). In addition, this chapter also reviews the various conventional methods available for the determination of mixing and compaction temperatures of WMA technology. To overcome the issues of conventional methods for determination of MT and CT, the use of tribology as a tool for assessment of WMA technology has also been reviewed in this chapter. The state of the art regarding the performance of WMA modified binders has also been discussed in this chapter.

2.2 History of Warm Mix Asphalt Development

Warm Mix Asphalt (WMA) additives and technologies enable asphalt to be mixed and laid down with mineral aggregates at temperatures that are 20 to 55°C (35 to 100°F) lower than those of conventional HMA [1]. This technology enables the entire coating of aggregate particles at lower temperatures by facilitating a decrease in the viscosity of the asphalt binder. The implementation of such technology can lead to significant reduction in energy consumption and the release of pollutant gases [2].

From a historical perspective, the idea of employing lower mixing and compaction temperatures is not entirely new. At Iowa State University, Professor Ladis Csanyi initiated research in 1956 by examining the possibility of using foamed bitumen as a soil binder [44,45]. In this foaming technique, using a specifically designed nozzle the saturated steam was introduced into heated asphalt binder at around 40 psi, resulting in the controlled creation of foam. The foam of asphalt enhanced the surface energy and decreased viscosity for better mixing with cold, wet aggregates or soils. It was mentioned that mixes used for stabilised foundation and pavement surfaces of Iowa state traffic roads was prepared with foamed asphalt. With this idea of foaming, the other nations have also developed effective foamed asphalt technology.

Nevertheless, even if the idea of adding steam to heated bitumen worked, the work was not feasible for in situ foaming processes. For this reason, Mobile Oil Australia modified the original method in 1968 by adding cold water to the hot bitumen instead of steam, and thereby acquired the patent rights for Csanyi's invention [46]. In this modified process, the foaming was carried out by substituting steam with 1-2% cold water and following the more extensive mixing process. The Mobil process, also known as Foamix, comprised the introduction of cold water under controlled flow and pressure into the heated asphalt binder in a specially developed foaming chamber. Consequently, the foamed asphalt is discharged into the cold, moist aggregate using spray bar nozzles.

Further advancement in this technology was introduced to the market in the USA as the Conoco product, which was evaluated as a base stabiliser in both the field and the laboratory [44]. In the early 1970s, new methodologies of pavement mixtures stabilised with emulsified asphalt were successfully developed by Chevron and published the Bitumuls Mix Manual as a practical guideline in 1977 [44].

In 1994, the Houeran and Maccarone examined cold-mixed asphalt-based foamed bitumen, which is produced at a temperature of roughly 20–49°C [44]. It was noted that cold mix was becoming more popular because of the lower emissions and increased energy efficiency of this system. In fact, it was said that "Cold technologies represent the future in road surfacing." Though cold asphalt mixes (CAMs) provide numerous advantageous qualities, hot mixes have not been replaced by CAMs. This was because of their need for curing time, which results in a lengthy wait before the road can be opened to traffic after laying. In addition, the inferior long-term performance of CAMs as compared to HMAs, CAMs cannot replace the HMAs as the major road surface materials [47]. However, rising fuel prices, global warming and more stringent environmental regulations have resulted in more demand to reduce production and compaction temperature. It is therefore necessary to heat the aggregate to at least above the ambient temperature so that appropriate coating occurs between the aggregate and the binder. From this idea, in 1999, Jenkins et al. introduced a new concept of half-warm foamed bitumen treatment, which can enhance mix cohesion, tensile strength and compaction [47].

With this thought process, a warm asphalt mixture process has been developed in Europe. Three significant asphalt companies from Norway, UK, and Netherlands participated in a number of road trials in Europe between 1996 and 1999 to evaluate the performance of warm mix in the field. The initial trials of warm mix asphalt and paving took place in Germany and Norway between 1995 and 1999 [42]. In 1996, the German Ministry of Labor and Social Affairs considered the implementation of regulations for workers exposed to asphalt fumes, including the reduction of production process temperatures for asphalt mixtures [48]. The initial experimentation involving Aspha-min zeolite for the purpose of foaming asphalt mixtures, was carried out in 1995 by a German company. Following this, in 1996, Norway conducted its earliest trials with WMA emulsion by making the advancement of WAM Foam and design one of the pioneering applications of foaming technology. In 1997, Hamburg implemented the initial use of warm mix asphalt incorporating a wax additive known as Sasobit [49]. Following experimentation in 1999, the trials of WMA utilizing foam asphalt and Aspha-min zeolite was studied in Norway and Germany, respectively [46]. Harrison and Christodulaki initially presented the findings of these trials at the First International Conference of Asphalt Pavement in Sydney, 2000 [2]. Subsequently, during the 2000 Eurobitume Congress, the Koenders et al. presented a more thorough and comprehensive report that detailed the innovative warm asphalt mixture and its performance based on lab testing and extensive field evaluation [50]. Therefore, it can be stated that certain warm asphalt technologies employed today originated from the innovative efforts of European researchers aiming to reduce the mixing and compaction temperatures of asphalt binder [10]. The introduction of WMA technology to the USA was happened in 2002 through a study conducted by the National Asphalt Pavement Association (NAPA) [51]. Between 2000 and 2015, progressively strict environmental regulations were implemented to mitigate the excessiveness of climate change effects. To overcome this, WMA additives were developed to reduce both the emission and energy consumption [49,52]. Subsequently, significant advancements in warm mix asphalt have been achieved through extensive research, resulting in the emergence of new warm mix technologies. In recent years, although the innovation of warm asphalt technologies remarkably started in Europe, the topic has gained lot of momentum in the USA and other countries [44]. To the date, the many countries along with India have started the use of warm mix technology and studied their laboratory and field performance as compared to conventional hot mix technology. In India, the Central Road Research Institute (CRRI) is one of the initial institutes to have started working on WMA technology. Many warm mix additives have been tried and implemented in few road projects in India. It was found that there have not been any adverse reviews on effectiveness of WMA in the field.

2.3 Various WMA Technologies

The construction of flexible pavement generally involves the production and placement of mixture consisting of aggregate and asphalt binder at high temperatures (140℃ -190℃). The technology used for production and placement of asphalt mixture at such high temperature is generally referred as hot mix asphalt (HMA) [53]. In fact, heating is the major cornerstone for the construction of HMA. However, the technology requires more energy in the production and placement of asphalt mixtures. Besides more energy consumption, this also causes increase in carbon footprint due to emission of the harmful greenhouse gases that have an adverse effect on climate change. The increasing environmental concerns and economic consideration shifted the interest of pavement researchers in development of energy efficient and sustainable technologies. The new technologies must be capable of producing mixes at lower temperature without deteriorating the level of mechanical performance. Based on reduction in production and placement temperature, several technologies were developed over the passage of time. Figure 2-1 shows the ranking of different technologies with respect to their production temperature. Based on temperature involved in production of asphalt mixture, the technology are classified as: Hot Mix Asphalt or HMA (190^{o}C - 150^{o}C); Warm Mix Asphalt or WMA (100 ^{o}C-140^{o}C); Half-Warm Mix Asphalt or HWMA (60 ^{o}C-100^{o}C); and cold mixes (0^{o}C- 40^{o}C) technology [2,54] .

Out of the above-mentioned technologies, CMA and HWMA is mostly suitable for low to medium traffic condition [55]. WMA is one of the energy-efficient technology that enables the production and placement of asphalt mixtures at lower temperatures than HMA without conceding the performance. The reduction in temperature merely depends on different types of

WMA technologies. WMA technology offers promising reduction in harmful emission and burning of fossil fuels which roughly showed 60-80% reduction in energy consumption [1]. Various technologies are available for development of warm mix asphalt mixture and many more are under development. WMA technology can be broadly divided into categories: Foaming technology, Wax/Organic additives and Chemical additives [56].

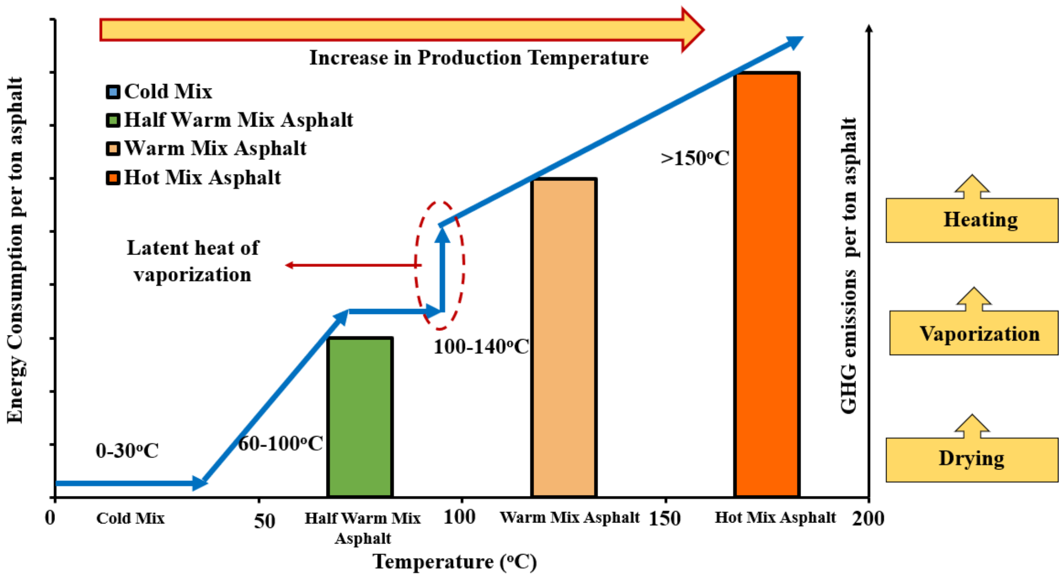


Figure 2-1. Production temperatures of asphalt mixtures technologies

Foaming technology is further sub-divided into two processes: water bearing and water based. Water bearing additives usually contain synthetic zeolites composed of silicates of aluminium and alkali metals [57]. At temperatures >100 ℃, the synthetic zeolites release the crystalline water and creates foam in the binder, increasing its volume and reducing the viscosity. On the other hand, water based process involves spraying of cold pulverized water with the help of artificial nozzles. The water from nozzles mixed with hot bitumen and a large amount of steam is generated which indirectly increases the foaming effect. The increase in foam improves the coating of asphalt binder on the aggregates. It is noteworthy that the amount of steam generated in water based technologies is more than water bearing additives [57]. Table 2-1 shows the description about some of the available foaming based technologies [1,2,4,10,42].

Table 2-1. Foaming technologies used for temperature reduction

Technology	Product/ Additive	Company	Description	Dosage of Additive	Production Temperature or (Reduction Range)
Water-containing	Advera WMA	PQ Corporation	A foaming process with synthetic zeolite	0.25% w/m	(10-30 ˚C)
Water-containing	Aspha-Min	Eurovia and MHI	A foaming process with synthetic zeolite	0.3% w/m	(20-30 ˚C)
Water-based	Double Barrel Green	Astec	Multi nozzle device to microscopically foam the asphalt binder with water	2.0% w/b	116-135 ˚C
Water-based	LEAB	Royal Bam Group	Direct foam with binder additive with the mixing of aggregates below water boiling point	0.1% w/b	90 ˚C
Water-based	Accu-Shear	Stansteel asphalt production product	Variable speed colloidal mill for the intermixing of water or other liquid additives	Depends on the additive type	120-160 ˚C
Water-based	AquaFoam	AquaFoam, LLC	Two fan nozzles mounted 180˚ to each other and perpendicular to asphalt stream	Water addition 1.5% w/m	100-120 ˚C
Water-based	Eco-Foam II	AESCO/MADSEN	Inline vortex mixer based on the principle of shear zone turbulence to enhance foaming	1.0%-2.0% w/b	-
Water-based	WAM-Foam	Shell and Kolo-Veidekke	Two-stage addition of asphalt binder, soft binder coating followed by foamed hard binder	Water addition 2.0%-5.0% w/b	100-120 ˚C
Water-based	Ultrafoam GX	Gencor Industries	Water-based foaming process that uses the energy supplied by head/pump to achieve foaming	Water addition 1.0%-2.0% w/b	-
Water-based	LT Asphalt	Nynas	Foam-bitumen with hydrophilic Additive	0.5%-1.0% w/b	90 ˚C

Water-based	Aquablack WMA	Maxam Equipment Inc.	Stainless steel foaming gun with nozzle	1.5%-3.0% w/b	125-140 ˚C
Water-based	Low Energy Asphalt (LEA)	LEACO	Binder coated hot coarse aggregate mixed with wet sand	3.0%-4.0% water with fine sand	<100 ˚C

Note: w/b and w/m specify by weight of binder and by weight of mix, respectively.

Organic/wax based additives has melting point less than the production temperature of conventional bituminous mix. On melting, the WMA additive, premixed with asphalt binder reduces its viscosity [4]. Sasobit is one of the most common additives which falls under this category. Table 2-2 illustrates the description about some of the commercially available organic or wax based additives [1,2,4,10,42].

Table 2-2. Organic additives used for temperature reduction

Technology	**Product/ Additive**	**Company**	**Description**	**Dosage of Additive**	**Reduction Range**
FT Wax	Sasobit wax	Sasol	Synthetic paraffin wax produced from the Fischer-Tropsch method	1.0%-3.0% w/b	(20-30 ˚C)
FT Wax	Sasobit Redux	Sasol	Synthetic paraffin wax produced from the Fischer-Tropsch method	0.75%-2.0% w/b	(20-40 ˚C)
Fatty Acid	Licomont BS	Clariant	Fatty acid amide	3.0% w/b	(20-30 ˚C)
Montan Wax	Asphaltan B	Romonta GmbH	Refined montan wax with Fatty acid amide for rolled asphalt	2.0%-3.0% w/b	(20-30 ˚C)
Polyethylene Wax-based	RH	China patent product	Polyethylene Wax-based additive produced from the cross-linked polyethylene	4.0% w/b	(30 ˚C)
Wax-based	SonneWarmix	Sonneborn, Inc.	Paraffinic hydrocarbon wax with high melting point	0.5%-1.5% w/b	(28 ˚C)

Wax-based	LEADCAP	Kumho Petrochemical co.	Low energy and low carbon dioxide asphalt pavement technology	1.5%-4% w/b	(30 ˚C)

Note: w/b and w/m specify by weight of binder and by weight of mix, respectively.

Table 2-3. Chemical additives used for temperature reduction

Technology	**Product/ Additive**	**Company**	**Description**	**Dosage of Additive**	**Reduction Range**
Chemical	Evotherm	Mead Westvaco	Chemical packages, with or without water	0.5% w/b	(30-50 ˚C)
Chemical	Rediset	Akzo Nobel	Cationic surface-active agents	1.5%-2% w/b	(30 ˚C)
Chemical	HyperTherm/QualiTherm	Coco Asphalt Engineering /QPR	Non-aqueous fatty acid-based chemical additive	0.2%-0.3% w/b	120 ˚C
Chemical	InterFlow T	IterChemica	Preferably used for RAPM inclusive asphalt concrete	0.3-0.5% w/b	(30-40 ˚C)
Chemical	Cecabase RT	CECA	Chemical package	0.2%-0.4% w/m	(30 ˚C)
Chemical	Zycotherm	Zydex industries	Chemical package	0.1% w/b	(30 ˚C)
Chemical	REVIX	Mathy-Ergon	Surface-active agents, waxes, processing aids and polymers	Not specified	(15-25 ˚C)
Molten liquid	Shell Thiopave	Shell Global	Sulfur-based and complementary non-sulfur based additive pellets	20%-25% w/b	(20-40 ˚C)

Note: w/b and w/m specify by weight of binder and by weight of mix, respectively.

In general, the reduction in the production temperatures using warm additives can be achieved based on the three mechanisms [58]:

- First mechanism: foaming the asphalt binder by using injected water or hydrophilic (zeolite) in the vaporisation process.

- Second mechanism: the organic additives reduce the viscosity of the asphalt binder; therefore, the aggregate can be fully coated at lower production temperatures
- Third mechanism: surfactants decrease the internal frictional forces between the interfaces of the aggregate and the binder and decrease the surface tension of the asphalt binder which leads to improve wettability of aggregate by asphalt binder.

This section of literature review mainly emphasizes on the well-known warm mix technologies, which have been extensively studied by researchers. In this section, the study more focus on the performance of Sasobit, Asphaltan A, Iterlow, and Rediset rather than foaming technology.

2.3.1 Foaming Technology

Using foaming technology, a small quantity of water may be injected straight into the asphalt mixing chamber or into the hot asphalt binder. During this, the water will evaporate and the released steam will be trapped in the binder, which can have ability to generate a lot of foam. This action will quickly and significantly reduce the viscosity of the binder by expanding its surface area. This will improve coating and workability by improving the distribution of asphalt binder over the aggregate in mixture [57]. But, extreme care should be taken during this procedure, only required quantity of water must be supplied to create foam otherwise the stripping issues may arise [59]. To overcome issues of moisture susceptibility, the anti-stripping additives can be used to form strong bond between asphalt binder and aggregate surface [51]. Foaming technology is further sub-divided into two groups: water based techniques and water bearing techniques.

2.3.1.1 Water Based WMA Technologies

In the studies conducted by Wielinski et al. and Middleton et al. the foaming process was thoroughly explained [60,61]. This process entails the addition of a specified volume of water to a binder heated to high temperatures. Upon contact with the hot binder, the water rapidly undergoes a phase change, transforming into steam due to the elevated temperature and atmospheric pressure conditions. As the steam is generated within the binder, it instigates the expansion of the binder material. This expansion creates a foam-like structure within the binder matrix[57]. The incorporation of steam into the binder matrix causes a notable reduction in viscosity, rendering the foamed binder more fluid and less viscous compared to its non-foamed counterpart. This reduction in viscosity exhibits improved workability and coating properties, facilitating better adhesion to aggregates and enhancing overall mixture performance [2,4]. This foaming action is generally achieved by various process like WMA-foam process, low energy asphalt process, and double barrel green technology [56]. In Europe, the WMA-Foam process stands out as the most widely adopted method, followed closely by LEA, which stands for Low Energy Asphalt process. Meanwhile, in the United States, the predominant technology is the Double Barrel Green, developed by Astec. This technology has gained significant attraction in the industry due to its innovative approach and demonstrated effectiveness in asphalt production.

A) **Warm asphalt mix foam**

The introduction of warm asphalt mix foam as a water-based foaming technology marked significant ground-breaking at the Eurasphalt and Eurobitumen Congress in 2000 [50]. WMA Foam is a two staged process developed in 1995 through a joint venture between Shell International and Kolo-Veidekke of Norway [46,57]. Unlike conventional water-based technologies, warm asphalt mix foam presents a distinct approach. It involves a two-stage mixing cycle, where soft and hard binders are introduced separately. Initially, aggregates are heated to approximately 130°C and coated with the soft binder, constituting 20% to 30% of the total binder. Subsequently, the hard binder is foamed by introducing water at 2–5% of its mass, at a temperature of roughly 180°C. This method ensures optimal bitumen absorption by the coarse aggregate, facilitating uniform binder distribution and enhancing workability for paving.

Despite 30% reduction in plant fuel consumption and emissions [62], there some challenges need to be addressed. Notably, the potential issues arising from incomplete water evaporation leading to stripping of asphalt binder [63]. Nevertheless, research indicates the viability of warm asphalt mix foam for both base and wearing courses, demonstrating comparable volumetric properties to traditional HMA. Consequently, its mechanical performance was found to be comparable with HMA. Field studies validate these findings, with paved sections utilizing warm asphalt mix foam showing equivalent resistance to permanent deformation and surface texture as HMA [57,59]. Further study also validate the process's efficacy in terms of fatigue life and resistance to permanent deformation [64].

B) **Low Energy Asphalt**

The Low Energy Asphalt WMA technology was developed by Advanced Concepts Engineering and distributed in the USA by McConnaughay Technologies, presents a distinct process for creating the foaming effect in asphalt binder [10]. In this method, hot bitumen (140-180°C) is mixed with hot coarse aggregate at a temperature of approximately 290°F/145°C, followed by the addition of wet fine aggregates at ambient temperature. This sequence induces a foaming action as the moisture in the fine aggregates evaporates as steam, facilitating fine aggregate coating [2,42,65]. Notably, this technology can lower the production mixing temperature to about 90°C, leading to substantial reductions in energy costs and gas emissions[66]. However, the various authors/researchers suggest incorporating coating and adhesion promoters into this technology to improve asphalt mixture performance and mitigate potential stripping issues [4,57,67,68].

Despite the reduction in the production temperature, implementing this technology necessitates significant plant modifications. In 2006, Romier et al. developed a tools adaptable to batch plants, enabling control over cold sand levels through a specialized hopper and integrating a mechanism for water addition to fine aggregate [29]. Additionally, the introduction of RAP directly into the mixer was emphasized [69].

From 2005 to 2010, over 400,000 tonnes of low-energy asphalt were produced globally (LEA-CO, 2014), with multifunctional systems predominantly employed to enhance foam ability and binder coating [70]. Despite limited published studies, further research is strongly advised to deepen understanding of asphalt mixture properties and validate the process across different materials, climates, and mix design methods, distinguishing it from other warm technologies. Gaudefroy et al. (2007) assess it as a WMA process with significant potential [71]. Figure 2-2 illustrates the LEA process for asphalt foaming [72].

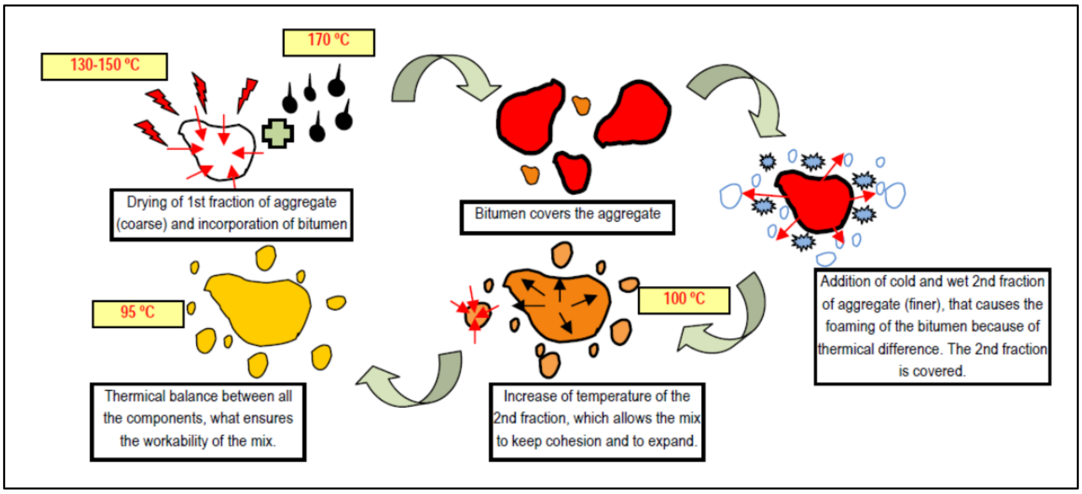


Figure 2-2. Low energy asphalt process for asphalt foaming

C) **Double Barrel Green**

This technology involves the precise injection of water into an asphalt binder stream through a specialized nozzle [9][66] . Automation of the nozzle allows for controlled regulation of water volume and foaming rate [73]. By introducing a small amount of water using a positive displacement piston pump, the binder undergoes microscopic foaming, resulting in the encapsulation of steam within the binder. This process leads to a significant expansion in binder volume and a reduction in viscosity. This technology was developed by Astec Industries in the USA since 2007 [10]. There are two generations of the technology: G1 and G2, differing mainly in their nozzle systems [56]. It usually doesn't require changes to the mixing process, but a foaming device is recommended for lab tests. Middleton and Forfylow (2009) observed that the properties of asphalt binder and mixtures treated with this technology resembled those of Hot Mix Asphalt (HMA) [74]. Additionally, mixtures produced using the Double Barrel Green process exhibited satisfactory resistance to rutting and did not display increased susceptibility to moisture. Environmentally, significant reductions of 10% in nitrogen oxide, carbon monoxide, and carbon dioxide emissions, as well as a 24% decrease in energy consumption, have been reported [74]. There is a belief that this technology could reduce the need for expensive additives, as it only requires a small amount of water injection. However, precise injection is crucial to avoid problems. Despite its popularity in the USA, there is less research available on it compared to other foaming technologies. Figure 2-3 illustrates the Double barrel green nozzles used in this technology [75].

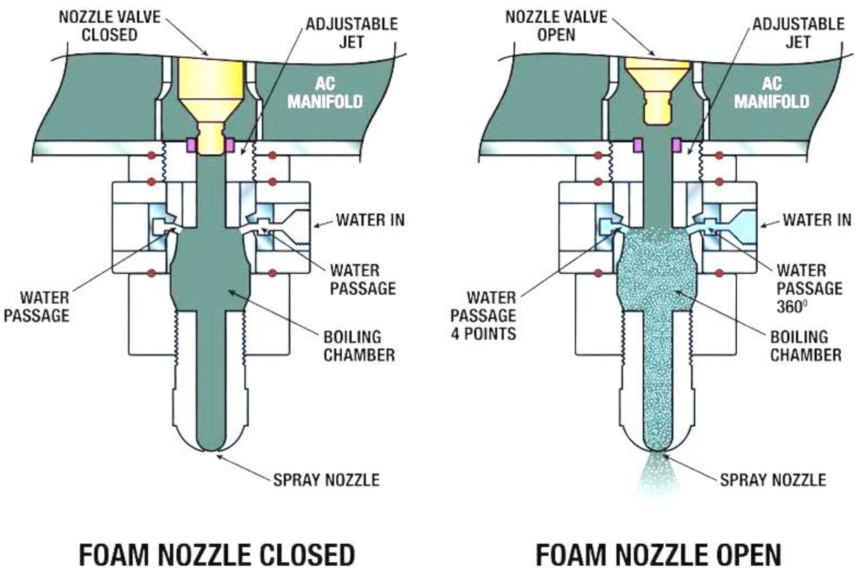


Figure 2-3. Double barrel green nozzle for asphalt foaming

2.3.1.2 Water Bearing Additive

It is another type of Warm Mix Asphalt (WMA) technologies that focuses on foaming achieved through the use of water-bearing additives [1,76]. The most common water bearing additives available are: Aspha-min and Advera which are available in the form of a finely powdered substance. Aspha-min is produced in Germany by Eurovia, while Advera is manufactured in the United States by PQ Corporation [4,77]. Both are synthetic zeolites composed of alumina-silicates and alkali metals, containing approximately one fifth of their weight as crystalline water [9]. When introduced into the asphalt binder mixture, these additives release water as the temperature surpasses 100°C. This water release initiates a foaming reaction by expanding the volume of the asphalt binder and decreasing its viscosity [57]. The gradual release of water from zeolite provides an extended period of workability for the asphalt mixture and facilitating the efficient coating of aggregates at lower temperatures compared to traditional HMA production methods [78]. The details about the water bearing additives can be found elsewhere [2,10,57]. Figure 2-4 (a) and (b) presents the physical appearance of Asphamin and Advera, respectively.

(a) (b)

Figure 2-4. Water bearing additives a) Asphamin b) Advera

2.3.2 Organic Additives

This technology utilizes waxes with high molecular weight hydrocarbon chains within asphalt mixtures. These additives lower the production temperature by decreasing the viscosity of the binder [2]. This method involves a viscosity reduction above the wax's melting point, facilitating the production of asphalt mixes at lower temperatures. As temperatures rise to the melting point of these waxes, they liquefy, reducing the viscosity of the asphalt binder. During cooling of asphalt binder below melting point, these additives solidify into microscopically small particles dispersed evenly throughout the bitumen [10]. Consequently, this phenomenon leads to a stiffening of the binder, resembling the behaviour of fibre-reinforced materials [79,80]. Several researchers have found that the lower melting point of the wax than the in-service temperature can lead to difficulties in the performance of asphalt binders [81,82]. Therefore, the selection of wax type must be done with precision to ensure that its melting point exceeds the expected service temperatures, thus minimizing asphalt embrittlement in colder conditions. To ensure this, the waxes should be resilient and solid at the intended service temperature. Indeed, the performance of synthetic waxes included in asphalt binder is influenced not only by the type of wax but also by the type of binder [83]. This is because the internal crystallizing fraction is dependent on the type of binder and its source [83,84]. The waxes employed in this technology consist of high molecular hydrocarbon chains with a melting point ranging from 80 to 120°C, capable of modifying the properties of the base binder [10,85]. The melting temperature of the wax is directly correlated with the length of the carbon chain (C45 or more) [2]. Typically, the amount of wax added ranges from 2% to 4% by weight of binder, resulting in a temperature reduction of 20 to 30°C [52,86]. Generally, the incorporation of synthetic waxes enhances the resistance to permanent deformation by enhancing the stiffness properties of the mixture. Conversely, there might be a detrimental impact on fatigue response due to the reduced ductile behaviour associated with stiffer materials. Therefore, the selection of type of wax and base binder is important to ensure the better fatigue performance of asphalt binder [87,88].

This process was developed in the late 1980s and has been practice regularly to the date by using three technologies employing different wax types for viscosity reduction: Fischer-Tropsch wax, fatty acid amide, and Montan wax [1]. The various organic additives used for the construction of flexible pavement are summarized in Table 2-2.

2.3.2.1 Fischer-Tropsch Wax

The Fischer-Tropsch (FT) wax process involves creating hydrocarbons and aliphatic compounds from synthesis gas (CO/H_2) [89,90]. This additive comprises pure hydrocarbons lacking functional groups, known for their strong chemical stability and resistance to aging. These waxes typically melt at around 100°C in its pure form, blending it with bitumen lowers its melting point to 80-85°C, allowing for asphalt compaction below 100°C [2]. During cooling, crystallization begins at 105°C and finishes at 65°C, resulting in evenly distributed, microscopic, stick-shaped particles. The difference between naturally occurring bituminous waxes and F-T waxes lies in their structure and physical properties, particularly longer chain lengths and a fine crystalline structure. Research indicates that these waxes demonstrate robust oxidation and aging stability, making them suitable for indefinite storage [91]. The Sasobit and Sasobit Redux are the example of this kind of wax.

A) Sasobit

Sasobit, categorized as a Fischer-Tropsch (FT) wax commonly appears as either a white powder or granules produced by Sasol Wax GmbH in Germany [10]. In Germany, it is also known as "ready-to-use" bitumen. Sasobit is a finely crystalline, long-chain aliphatic poly-methylene hydrocarbon produced from natural gas utilizing the Fischer–Tropsch (FT) process [49]. This involves synthesizing hydrocarbons and aliphatic compounds from synthesis gas (CO/H_2). In the synthesis process, coal or natural gas (methane) undergoes partial oxidation to carbon monoxide, which then reacts with hydrogen (H_2) under catalytic conditions, yielding a mixture of hydrocarbons with molecular chain lengths ranging from C5 to C100 carbon atoms

[92]. Initially, the gas reacts with an iron or cobalt catalyst to produce products like synthetic naphtha, kerosene, gasoil, and waxes. Liquid products are separated, and FT waxes are extracted for use in transportation fuels or chemical feedstock. Recovered Sasobit (FT wax) typically falls within the carbon chain length range of C45 to C100. In contrast, the macro-crystalline paraffin waxes have carbon chain lengths ranging from C25 to C50 [10]. Research indicates that the longer carbon chains in FT wax result in a higher melting point when blended with base binder. Additionally, studies suggest that the smaller crystalline structure of FT wax can decrease brittleness at lower temperatures compared to binders containing paraffin waxes. Sasobit is a long-chain aliphatic hydrocarbon wax generally characterized by a melting range spanning from 85°C to 115°C [53]. It exhibits high viscosity at lower temperatures and low viscosity at higher temperatures. The Sasobit contain wax in its structure which has melting point around 100^{o}C. It has been observed that when temperature is higher than 120^{o}C, the Sasobit completely miscible in asphalt binder. When temperature of binder reaches to melting point, the wax present in the binder liquefies and reduces the viscosity of asphalt binder. In short, Sasobit acts as viscosity reducer. This viscosity reducing behavior of Sasobit was responsible for lower mixing and compaction temperature of the asphalt binder [49]. In Sasobit modified asphalt binder, the crystallization initiates at 105°C and completes at 65°C, resulting in the formation of regularly distributed, microscopic, stick-shaped particles. Due to this behaviour, Sasobit forms a lattice structure at operational temperatures within the asphalt binder providing better stability to the asphalt binder. The formation of lattice crystalline structure wax within the binder ensures the better performance against rutting. Sasobit generally supplied in the form of greyish-white to yellowish pastilles and granules, offers the convenience of easy blending without requiring high-shear mixing apparatus. Whether blended manually or mechanically, Sasobit-modified asphalt binder properties remain unaffected [49,93]. Incorporating Sasobit into asphalt plants typically doesn't demand significant

modifications. It can be mixed with hot bitumen or directly added to the aggregate. The recommended Sasobit dosage ranges from 0.8% to 3% of the binder mass[49]. However, exceeding 3% can have adverse effects on bitumen's low-temperature properties, emphasizing the importance of adhering to dosage recommendations for optimal performance [94,95]. The performance of the Sasobit modified asphalt binder has been discussed in depth in section 4.

B) Sasobit Redux

The Sasobit Redux is also Fischer-Tropsch (FT) produced by Sasol Wax GmbH in Germany. Like Sasobit, it also reduces the production temperature by reducing the viscosity of base binder. This product is similar to Sasobit, only difference is lies in their length of carbon atoms. Sasobit Redux has lower carbon atoms than Sasobit which has impact on its crystallization temperature [10]. Crystallization of the additive initiates at 60°C. Its impact lies in the viscosity and aging susceptibility of the asphalt mixture rather than affecting the binder grade or adhesion between bitumen and aggregate. Notably, it only alters the properties of the asphalt mixture within desired parameters, even at lower temperatures. In addition, the past literatures showed the lower crystallization might be beneficial for higher reduction in production temperatures. The recommended Sasobit Redux dosage ranges from 0.75% to 2% by weight of asphalt binder [96].

2.3.2.2 Montan Wax

Montan wax comprises nonglyceride long-chain carboxylic acid esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons, and resins [2]. It is derived through solvent extraction of specific types of lignite or brown coal, also known as lignite wax or OP wax. Traditionally utilized in automobile construction, shoe polishes, paints, and as a lubricant for moulding papers and plastics, about one-third of its global production is allocated to car polishes. Unrefined Montan wax contains asphalt and resins, which can be eliminated through refining. As the pure form of this wax typically melts at around 75°C, therefore, it is frequently combined with substances having a higher melting point, like amide waxes [97]. Like Fischer-Tropsch (FT) wax, these waxes crystallises on cooling and solidifies on heating. Asphaltan A, and Asphaltan-B supplied by Romonta is a refined Montan wax blended with fatty acid amide is implemented as warm asphalt additives in Germany.

A) Asphaltan A

Asphaltan A is type of Montan wax with congealing points (temperature at which wax ceases to flow) at 78°C [10]. This hard wax generally extracted through solvent extraction of specific lignite or brown coal types. Similar to FT-waxes, it reduces the viscosity of base binder to reduce their production temperatures. During cooling of asphalt binder, they enhance stiffness, similar to fatty acid amide [98]. In Germany, it has been utilized as additive for mastic asphalt due to their capacity to adjust binder consistency and enhance adhesion between binder and minerals. The presence of fatty acid amide in this additive can promote better bonding between aggregate and asphalt binder. The recommended dosages for Asphaltan A falls between 0.8% and 3% by weight of binder [4]. However, dosage above the 3% threshold may negatively impact the low-temperature properties of asphalt binder.

B) Asphaltan B

Asphaltan-B, is also a refined Montan wax blended with a fatty acid amide, has a melting point just below 100°C. This product is similar to Asphaltan A, only difference is lies in their melting point [10]. It exhibits similar characteristics as that of Fischer-Tropsch waxes in improving asphalt flow at lower temperatures even though to a lesser extent. Manufacturer's has reported that this additive leads to increased compactibility, improved resistance to rutting, and enhanced moisture resistance in asphalt mixes. The recommended dosage for Asphaltan B ranges from 2% to 3% by weight of asphalt binder [10].

2.3.2.3 Fatty Acid Amide

The fatty acid amide known by various trade names are synthesized by reacting amines with fatty acids. Typically, they melt at temperatures between 140-145°C and solidify between 135-145°C [2]. They have been act as a viscosity modifier in asphalt binder. The viscosity modification in asphalt binder lead to reduction in production temperature. Like FT waxes, the fatty acid amide also enhances the stability and resistance to deformation by forming lattice crystalline structure as they cool within the asphalt binder. Licomont BS 100, developed by Clariant, is type of fatty acid amide. It is generally derived from fatty acid amide and created through the reaction of amines with fatty acids.

A) Licomont BS 100

Licomont BS 100 is a fatty acid amide produced synthetically by reacting amines with fatty acids. It typically melts between 140°C and 145°C and solidifies between 135°C and 145°C [10]. The reduction in viscosity due to this additive is responsible for the better workability of asphalt mixture at lower temperatures. Licomont BS 100 increases the stiffness of asphalt binder due to the formation of crystals of fatty acid amides within the binder matrix. The dose of 3% by weight of binder has been recommended for Licomont BS 100 to ensure better performance against the various distresses.

In the summary, it has been found that the organic additives reduced the production temperature by reducing the viscosity of base binders. In short, they are act as a viscosity reducer in asphalt binder. The wax present in their structure liquefies and lowers the viscosity of asphalt binder above their melting point. The additives form a lattice structure in the asphalt binder at temperatures below their melting point, which improves binder stability. In other words, asphalt binder modified using organic additive acts as a non-Newtonian fluid below their melting point and as a Newtonian fluid above the melting point. There are lot of organic additives available in market for reducing the production temperature of asphalt binder. Table

2-2 illustrates the description about some of the commercially available organic or wax based additives.

2.3.3 Chemical Additives

Another technology employed to lower manufacturing and compaction temperatures is chemical additives. These additives function differently to create WMA when incorporated into the mixture. These products achieve lower mixing and compaction temperatures without foaming and viscosity reducing mechanism. Instead of these mechanism, this technology involves use surfactants, emulsification agents, aggregate coating enhancers, and anti-stripping additives for temperature reduction [1,4].

- Surfactants: Surfactants are compounds that reduces the surface tension between asphalt binder and aggregate. By lowering the surface tension, surfactants improve the friction between asphalt binder and aggregate particles, resulting in production of asphalt mixture at lower temperatures [58]. In addition, surfactants also improve the adhesion and dispersion due to reduction in surface tension. This facilitates the formation of a stable asphalt mixture at lower temperatures.
- Emulsification Agents: Emulsification agents are materials that promote the formation of stable emulsions between asphalt binder and water. These agents encapsulate asphalt binder droplets, allowing them to disperse uniformly in the mixture. As a result, emulsification agents facilitate the mixing process at reduced temperatures by reducing the friction between asphalt binder and aggregate [76] .
- Aggregate Coating Enhancers: Aggregate coating enhancers are additives designed to enhance the coating of asphalt binder on aggregate particles. They improve the adhesion and coverage of asphalt binder on the surface of aggregates, ensuring better integration

of asphalt binder throughout the mixture [2]. This results in improved workability and performance of the asphalt mix at lower temperatures.

- Anti-Stripping Additives: Anti-stripping additives are compounds that mitigate the risk of moisture-induced damage by enhancing the adhesion between asphalt binder and aggregate [99]. These additives chemically modify the asphalt binder or aggregate surface to promote better bonding, thereby reducing the susceptibility of the mixture to moisture-related issues such as stripping and rutting.

Overall, chemical additives improve the properties at the interface of asphalt binder and aggregate either by reducing the surface tension of binder or by improving the wettability of aggregate by binder or improving the friction between asphalt binder and aggregate[10][76]. The improvement in the interface properties due to chemical additives can lead to the improved workability, durability, and performance of asphalt mixtures at lower temperatures. The reduction in production and placement temperature significantly depends upon the type of chemical additive used for construction of flexible pavement. Table 2-3 shows the details of various chemical additives available in the market.

A) Rediset

Rediset is a chemical additive consists of a blend of fatty polyamines, polymers, and non-ionic compounds. It contains long chain aliphatic hydrocarbon structure having amine (NH_3) in their structure [100,101]. Rediset is formulated using alkylamines and hydrocarbon waxes as its base components. According to literatures, Rediset is also referred as a poly functional additive based on fatty amine surfactants. It is water-free chemical additive used for the preparation of WMA mixture developed by AkzoNobel, Netherlands, Sweden, and United states. Rediset was introduced in the United States in 2007, as documented by Bonaquist in 2011 [58]. Its purpose was to address certain shortcomings observed in existing warm-mix asphalt (WMA) additives. It is available in two form i.e. solid and liquid. In its solid state, it is labelled as Rediset WMX, while in liquid form, it is known as Rediset LQ, as indicated by AkzoNobel documentation from 2011. These two form do not exhibit significant differences from one another. According to manufacturer, it is recommended to use 1–3% (by weight of binder) of Rediset WMX for the modification of base binder to achieve temperature reduction ranging from 17 to 35°C [58]. On the other hand, Rediset LQ is typically added at a rate of 0.5–1% (by weight of binder) into the asphalt binder [58]. These dosages of Rediset LQ can offered the reduction in the mixing and compaction temperature of base binder by 15–30°C. Rediset WMX is a solid, palletized additive developed in such a way that it does not adversely affect the high-temperature or low-temperature properties of asphalt binder, even at broader dosage levels. This additive showed both behaviour of surfactant and viscosity reducer as it contains long chain aliphatic hydrocarbon and amine group in their chemical structure. On the other hand, Rediset LQ is a new development by AkzoNobel which has functions of a surfactant and adhesion promotor. According to literatures, it can act like an anti-stripping agent and can improve the moisture susceptibility of the asphalt mixtures allowing by forming a strong chemical bond between the aggregate and asphalt binder [102]. According to the manufacturer, Rediset LQ does not alter the properties of base binder within the recommended dosage range. As stated earlier, Rediset LQ acts as an adhesion promoter, so its use can potentially eliminate the necessity for additional anti-strip agents, which can add benefits to the construction cost.

According to past studies [58], Rediset readily dissolves in hot asphalt binder without the necessity of a high-shear mixer device. According to research by Arega and Bhasin in 2012, this additive has a melting point of approximately 85°C and effortlessly mixes with the asphalt binder [103]. Suppliers typically recommend conventional mixing temperatures for blending Rediset with the asphalt binder. However, laboratory study done by Arega et al. have experimented with various mixing temperatures, methods, and durations to prepare Rediset-modified asphalt binder [104]. Rediset offers flexibility in its application, as it can be incorporated into the asphalt binder directly or during the mixing process, as indicated by Chowdhury and Button [44] . If blended directly with the asphalt binder at the refinery, existing asphalt plants require no modifications which can save extra cost of production of WMA mixture, as highlighted by Chowdhury and Button [44]. Previous studies also suggests that Rediset can be added to the asphalt binder in the supply tank at the asphalt plant or directly into the mixture in the asphalt plant drum [58].

In summary, Rediset is a multifunctional WMA additive (combination of surfactant and organic additive) that reduces the mixing and compaction temperature by reducing the surface tension of asphalt binder thereby improving the friction between asphalt binder and aggregate. There has been limited research on the effects of Rediset LQ on asphalt binder properties. In addition, it has not been extensively studied regarding its impact on the performance of asphalt binder and mixtures, as reported by Hamzah et al [58].

B) Iterlow

Iterlow is comprised of derivatives of amino substances developed by Iterchemica group in France. It enhances the workability of mixtures and enables the production and paving of mixtures at lower temperatures, typically ranging between 90 to 120°C, depending on the binder type [105]. Manufacturer typically recommend conventional mixing temperatures for blending Iterlow with the asphalt binder. It can be blended at a rate of 0.3–0.5% (by weight of binder) into the asphalt binder directly as recommended by manufacturer [4]. Similar to Rediset, it does not affect the rheological properties and performance of base binder. Limited research has been conducted on the effects of Iterlow on properties of asphalt binder. Moreover, its impact on the performance and workability of asphalt mixtures has not been extensively studied in literatures.

C) Evotherm

Evotherm is a specialized chemical package consisting of emulsification agents and antistripping agent additives manufactured by MeadWestvaco Asphalt Innovations, USA, and introduced to the market in 2005 [56]. These additives are designed to enhance various aspects of asphalt mixture performance, including aggregate coating, workability, and compaction. MeadWestvaco has developed and released three varieties of Evotherm into the market: Evotherm DAT, Evotherm ET, and Evotherm 3G. The dose of 0.5% by weight of binder has been recommended for the Evotherm [10].

D) Evotherm ET

Evotherm ET (Emulsion Technology) employs a specialized chemical blend of emulsification agents and antistripping additives to enhance aggregate coating, facilitate mixture workability, and promote compaction [42]. It is delivered in the form of bitumen emulsion comprises of 30 percent of the binder mass. Due to emulsification of asphalt binder, Evotherm effectively reduces the viscosity of the binder at lower mixing temperatures, ensuring better coating of aggregates at lower temperatures. The manufacturer's report suggests that pumping Evotherm to the asphalt plant doesn't require any special modifications or requirements. According to field paving experience, Evotherm has been pumped directly from a tanker truck and mixed with the hot aggregate. Due to this, the water in the emulsion evaporates and produces the steam which improve the workability of the mixture and promotes better coating of the aggregate. So, this process allows the production of asphalt mixture 50°C to 70°C lower than those typically used for traditional HMA. According to literature [56], it was found that the Evotherm ET showed minor effect on the performance of asphalt binder. Evotherm showed improved rutting resistance in comparison to HMA. However, despite its rutting benefits, visual stripping issues have been reported in the literatures [106–108]. To address the susceptibility of WMA mixtures to moisture damage, the use of liquid anti-strip agents or hydrated lime has been suggested to use with Evotherm [10].

E) Evotherm DAT

Evotherm DAT (Dispersed Asphalt Technology) similar to Evotherm ET involves the use of a chemical package mixed with a small quantity of water [42]. This mixture is generally injected into the asphalt binder just before reaching the mixing chamber. This can lead to the effective reduction in viscosity of the binder at lower mixing temperatures, thereby improving the coating of aggregates. According to literatures, this additive can reduce the production temperatures by 30% [56]. The cationic emulsifiers contained in Evotherm cause them to adsorb to the aggregate surface owing to their positively charged nature [109]. This process enhances adhesion by forming strong bonding between aggregate and asphalt binder.

F) Evotherm 3G

Evotherm 3G is advanced water-free form of Evotherm. These additives are designed to address internal friction issues within asphalt mixtures during production and construction phases [78]. The primary function of Evotherm 3G is to reduce internal friction between the asphalt binder and aggregate, as well as between the coated aggregate particles. This additive improves the workability of warm mix asphalt during production and construction processes due to the reduction in friction between aggregate and asphalt binder. As this product is newly introduced, there is currently limited independent research data available regarding its properties.

G) REVIX

REVIX is a chemical additive developed by Mathy Technology in cooperation with several companies [56]. It doesn't rely on foaming or viscosity reduction mechanism to lower mixing and compaction temperatures. Instead, it utilizes surfactant action for reducing the mixing and compaction temperature of asphalt binder. According to manufacturer, REVIX improves the friction between aggregate and asphalt binder due to reduction in surface tension of asphalt binder [10,110]. This technology enables a temperature reduction of approximately 15-27°C compared to similar HMA mixtures.

H) Cecabase

Cecabase is chemical additive produced by Arkema Group in France. It is an organic additive designed for use in the production of WMA mixtures. It improves the lubricating behaviour of binder at the interface between mineral aggregate and asphalt within the mix by reducing surface tension of binder [105]. In addition, it also improves the adhesion between a binder and aggregates without significantly altering the rheological properties of the asphalt binder. Specifically, it enables a reduction in production temperature between 20 to 40°C compared to traditional HMA technology. Despite this temperature reduction, the mechanical properties of the asphalt mix remain consistent with those of conventional HMA. Cecabase also possesses anti-stripping properties as reported in literatures [110,111]. This characteristic can enhance the moisture susceptibility of asphalt mixtures by reducing the likelihood of moisture-induced damage, such as stripping. In practical terms, the anti-stripping properties of Cecabase suggest that it may eliminate the need for additional anti-stripping agents when used in asphalt mixtures [111]. During the production process, there is no requirement for supplementary treatments to mitigate moisture susceptibility. Like Rediset, it can be added at a rate of 0.2–0.4% (by weight of binder) into the asphalt binder directly as recommended by manufacturer.

2.4 Benefits and Limitations of WMA Technologies

The major driving force for the development of Warm Mix Asphalt (WMA) is the benefits acquired through its implementation. These benefits incorporate a range of crucial factors ranging from environmental sustainability and energy conservation to enhanced pavement performance and construction efficiency. By adopting WMA technology, the asphalt industry can achieve significant reductions in greenhouse gas emissions and energy consumption compared to traditional Hot Mix Asphalt (HMA) processes [4]. Moreover, the lowered production temperatures associated with WMA decreased the fuel usage, minimized emissions of harmful pollutants, and reduced worker exposure to potentially hazardous fumes, thereby contributing to a healthier work environment. Furthermore, WMA's ability to extend the paving season by enabling construction in cooler weather conditions facilitates increased project flexibility ultimately translating to cost savings and improved project outcomes. Additionally, the enhanced workability and compactibility of WMA mixtures lead to improved pavement durability and performance, resulting in longer service life and reduced maintenance requirements. Overall, the comprehensive range of benefits derived from WMA implementation highlights its fundamental role in advancing sustainability, efficiency, and performance standards within the asphalt industry [10]. Based on the literature and field performance, the advantages of WMAs can be categorised into four groups: environmental benefits, production benefits, paving benefits and economic benefits.

2.4.1 Environmental Benefits

Several environmental benefits are noted with the use of WMA technologies includes: reduced energy consumption, reduced harmful emissions, and improved working conditions.

a) Reduced energy consumption

Hossain et al. found that the energy consumption for Warm Mix Asphalt (WMA) techniques varies between 20% to 75% of that required for Hot Mix Asphalt (HMA), depending on the specific method and operating conditions [67]. D’ Angelo et al. reported burner fuel savings ranging from 20% to 35% [42]. In certain processes like low-energy asphalt binder (LEAB) and low energy asphalt (LEA), fuel savings may exceed 50%. Studies have demonstrated that WAM-Foam WMA plants can operate with 40% lower energy consumption compared to HMA

[69]. Additionally, Eurovia observed a 30% reduction in energy consumption using Aspha-Min, attributed to a significant decrease in mixture temperature by 54 to 63°F [69]. Mohammad et al. showed that energy costs can be reduced by about 12-14% when using warm mix technology [112]. In recent study conducted by Mayank et al. the significant reduction in energy consumption around 12-14% is observed with use of organic and chemical additives [113]. It was found that the amount of reduction in energy consumption is a function of warm mix type and type of fuel used for the production of asphalt mixture. With continual increases in energy prices particularly for non-renewable sources, the WMA may emerge as a more economically viable alternative to HMA in the future.

b) Reduced emission

Using WMA instead of HMA in road pavements offers a notable advantage in terms of reduced harmful emissions originating from asphalt-producing plants. According to previous studies, emissions from WMA plants were found to range from 30 to 98% of emissions from HMA plants, depending on processing conditions and production temperature [2][66]. According to previous literatures [1,8], the use of WMA resulted in the following reductions in emissions across the board 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 both have seen reductions between 30% and 50%. In recent study conducted by Mayank et al. reported 35% reduction in greenhouse gas (GHG) emissions with the use of organic and chemical additives [113]. It was found that the amount of reduction in GHG emission is function of warm mix type and type of fuel used for the production of asphalt mixture. Table 2-4 shows comparative reduction in GHG emission using WMA technology obtained from various studies [2,10,42]. The importance of this benefit depends on the environmental factors and the severity of environmental regulations in a particular area.

Table 2-4. Comparative reduction (in %) in gas emission using WMA technology

Gas	D'Angelo et al.	Vaitkus et al.	Evotherm Website
CO	10-30	10-30	63
CO_2	15-40	30-40	46
SO_2	20-35	35	81
NO_X	60-70	60-70	58
VOC	50	50	30
Dust	20-55	20-25	-

2.4.2 Production Benefits

a) Higher use of reclaimed asphalt pavement material

The utilization of recycled asphalt pavement (RAP) in hot mix asphalt pavements has gained popularity for several reasons, including the limited space in landfills, diminishing availability of high-quality virgin aggregate, and rising oil prices [114]. While more than half of state Departments of Transportation (DOTs) in USA permit the use of high RAP (over 25% RAP) in asphalt mixtures, the actual adoption of high RAP content remains relatively modest compared to the available supply of RAP. This can be due to the various concerns about the resistance to fatigue and cracking in RAP mixtures [115]. Typically, a lower grade binder is employed to counterbalance the increased stiffness of RAP mixtures. The incorporation of WMA technologies can prove advantageous, especially in mixtures containing high RAP proportions due to its lower viscosity, facilitating compaction, and reducing the aging of the binder, which can compensate the increased aging of the RAP binder. Few studies showed that utilization of more than 50% RAP material can be possible with use of WMA technology [4,115].

b) Reduced oxidative hardening

The oxidation hardening of asphalt binder generally occurs during its mixing with hot aggregates and continues throughout the lifespan of the pavement. Aging occurs as a consequence of oxidation causing the binder to stiffen and harden [21,116]. The temperature of the asphalt oxidation reaction playing a crucial role in determining the rate of formation and the nature of oxidized compounds. Consequently, the use of WMA technologies could potentially mitigate the susceptibility of an asphalt mixture to aging and cracking, as the mixture is not subjected to the high temperatures of conventional production and placement processes. This could result in an extended service life for the pavement [2].

c) Easy plant establishment

Acquiring the necessary legislative approvals to establish plant sites within urban areas becomes a more straightforward process due to the notable reductions in emissions, dust, and noise associated with the use of WMA technology [10]. This alignment of environmental benefits with urban development objectives can facilitate smoother legislative processes and short-term positive relationships between contractor and local authorities.

2.4.3 Paving Benefits

Typically, most WMA technologies have the capability to decrease the viscosity of the binder. Lowering viscosity brings several benefits, enhancing the workability of the asphalt mixture [2]. This improvement leads to better compaction, requiring fewer roller passes to achieve the desired density. Additionally, integrating WMA facilitates improved workability at reduced temperatures. Consequently, WMA usage can extend the paving season, enabling longer haul distances for the asphalt mix while maintaining sufficient workability for placement and compaction [42,117]. In 2005, researchers at NCAT investigated the effect of Sasobit on binder viscosity. Their study involved adding a 2.5% dosage of Sasobit to a PG 58-28 binder, resulting in a modified PG 64-22 binder. A comparison between the modified Sasobit PG 64-22 binder and the unmodified PG 64-22 binder revealed that the compaction temperature required for the WMA-modified binder was approximately 18°C lower than that of the corresponding unmodified binder. In a study by D'Angelo et al., it was observed that various Warm Mix Asphalt (WMA) technologies were successfully employed in multiple projects across Germany, even in cold ambient temperatures ranging from -3 to 4°C [42]. Aspha-min was utilized for placing both base and Stone Mastic Asphalt (SMA) surface layers. It showed improved density compared to HMA and requiring fewer roller passes when the mixing temperature behind the paver ranged from 102 to 139°C [51]. The researchers noted that the actual production temperatures for WMA mixes during cool weather are influenced by factors such as the specific WMA technology used, environmental conditions, and transportation distance. Furthermore, the slower cooling rate of WMA can allow the longer haul distances for asphalt mixture. Notably, Kolo Veidekke stored WAM-Foam in a silo for 2 days and still achieved successful placement and compaction of the mixture. Additionally, it was reported that a Sasobit mixture was transported for 9 hours in Australia and remained sufficiently workable for unloading [44]. Moreover, the reduced temperature due to WMA technology shortens road construction durations and speeds up road opening times. This is particularly advantageous in specific scenarios, such as airport rehabilitations and heavily traffic urban roads.

2.4.4 Economic Benefits

The economic advantages of WMA technology depend on factors such as the energy source used in production, its cost, and its environmental impact [118]. In many countries, energy costs are relatively high, making the reduction in costs highly desirable for asphalt producers. This reduction in cost can be achieved with the use of WMA technology. In general, WMA typically consumes 60% to 80% less energy compared to HMA [46,54]. In a recent study, Mayank et al. reported the lower cost of production (around 1.4 times lower as compared to HMA) of asphalt mixture with the use of organic and chemical WMA additives [113]. Along with this, the temperature reduction in WMA also offers another potential cost-saving opportunity as it could lead to decreased wearing of the asphalt plant.

2.4.5 Limitations of WMA technology

Despite the considerable economic and environmental benefits associated with WMA, it is essential to consider the limitations regarding its mechanical and physical properties. Limitations of WMA technology are discussed as follow:

- Rutting: Reduced aging (as result of lower production temperature) of the asphalt binder increases the rutting susceptibility in the mixture [21,119,120].
- Moisture Susceptibility: Lower production temperatures can result in inadequate drying of trapped moisture within the aggregate, eventually increased the moisture susceptibility of asphalt mixture [121,122]. Additionally, various studies have shown that the presence of moist aggregates could substantially decrease the resistance of asphalt mixtures to permanent deformation [21,22,38,123]. Alternatively, moisture susceptibility can be reduced through the incorporation of anti-stripping agents. But, this approach might increase construction cost, thereby discouraging the implementation of WMA technology.
- Long-term Performance: WMA being relatively recent technology, there is limited data available regarding its long-term effectiveness [2]. Due to the limited experience regarding the long-term performance of WMA, widespread implementation of the

technology may encounter challenges [124]. This could be mitigated through the implementation of firm environmental regulations by governments or by ensuring that WMA offers clear construction and performance benefits.

- Economics: The expenses associated with the additives and plant adjustments might outweigh the benefits offered by WMA technologies [10,66].
- Low-Temperature Properties: Organic additives may exhibit slightly different behaviour in low-temperature properties as compared to HMA due to higher stiffness as result of wax crystallization. The concern is more complex with the use of stiffer materials such as RAP in asphalt mixture. Therefore, careful selection of binder type and grade should be made to avoid low-temperature cracking [49,94,123].

WMA is comparatively new technology for production of asphalt mixture which has limited data regarding its long-term performance in actual field conditions. Therefore, despite its advantages, it's crucial to take these limitations into account when planning to implement WMA technology in any project.

2.5 Mixing and Compaction Temperature

Mixing and compaction temperatures of asphalt mixture play important role in the performance of the flexible pavements. The successful performance of asphalt mixture in field depends on the appropriate production and placement of the asphalt mixture [12,125]. Similarly, for successful implementation of WMA technology in field, determination of the mixing and compaction temperatures plays an important role [2]. WMA technology efficiently lowers the mixing and compaction temperatures, commonly known as production temperatures, of HMA, thereby improving performance and workability of asphalt mixtures. The extent of temperature reduction is function of type of WMA technology used for the production of asphalt mixture [1]. Figure 2-5 shows the various WMA technology and their corresponding temperature reduction. Past studies also showed that the amount of temperature reduction is also the function of base binder used for the WMA modification. Table 2-5 shows the effect of base binder on reduction of production temperature of asphalt mixture [3,40]. As can be observed that the average temperature reduction is in the range of 20-40˚C. However, there are concerns related to the use of lower mixing and compaction temperature. Numerous studies have investigated the impact of mixing and compaction temperatures on the performance of asphalt mixtures [12,126]. Lower mixing temperatures can result in insufficient coating of asphalt binder on aggregates, potentially leading to moisture-induced damage. Conversely, lower compaction temperatures may present challenges during field compaction and result in decreased field density [127]. Excessively high temperatures during production and placement of asphalt mixtures can have severe consequences [125,128]. Sarnowski et al. noted that overheating of asphalt mixtures accelerates binder aging [129]. Cheraghian and Wistuba [130] explained that aging causes oxidative hardening of the asphalt binder, leading to premature pavement cracking. Mo et al. [131] highlighted that inadequate compaction of asphalt mixtures often contributes to 80% of premature failures in asphalt pavements. Therefore, it is crucial to carefully select appropriate production temperatures for the preparation of WMA. Over the years, several methodologies have been suggested for determining the mixing and compaction temperatures of asphalt mixtures [11]. The standard methods are available for establishing the production temperatures of HMA. However, currently no standardized approaches are available for determination of mixing and compaction temperatures for WMA technology. The various methods available for the determination of mixing and compaction temperature are discussed in subsequent section.

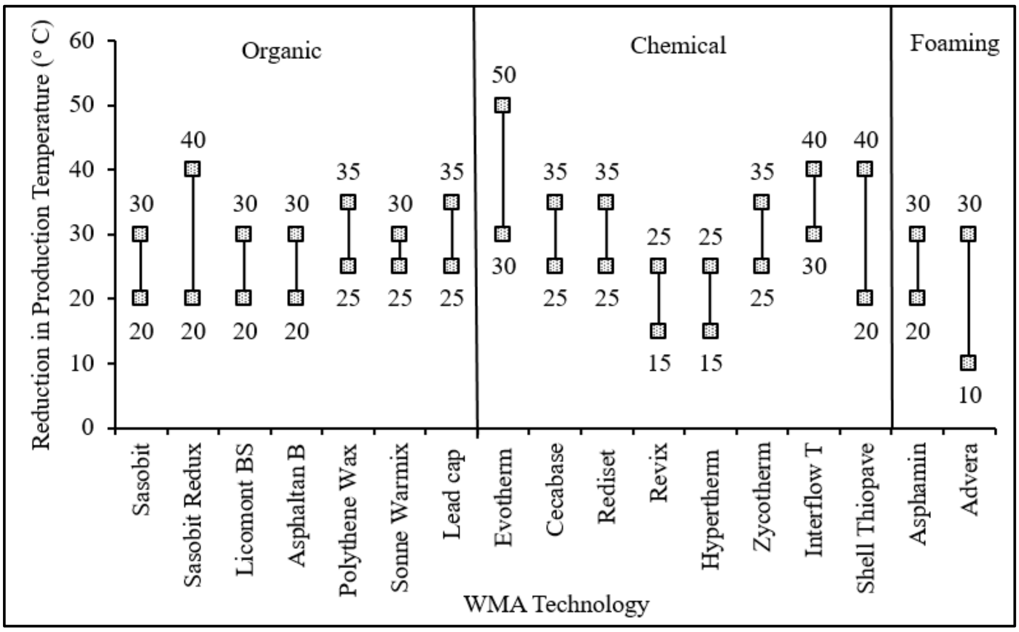


Figure 2-5. Range of production temperature reduction achieved using WMA technology

Table 2-5. Range of production temperature reduction achieved using WMA technology

Binder Type	**Production Temperature**		
	Mixing Temperature	**compaction Temperature**	**Rolling temperature**
VG10	125	115	85
VG20	130	120	85
VG30	135	125	90
VG40	145	130	100
Modified Binders	140	130	100

Note: In viscosity graded binder, VGXX, the number XX in VGXX indicates that the asphalt binder's dynamic viscosity (at 60°C) falls between the (XX × 100) ± 20% Poise range.

2.5.1 Various Approaches to Estimate Production Temperatures: A Critical Review

Based on the literature review, the viscosity of asphalt binder was found to be basic tool to determine the mixing and compaction temperature of convectional hot mix asphalt [132].

ASTM D2493 specify the guidelines for the measurement of mixing and compaction temperature and is purely based on the viscosity values obtained using Rotational Viscometer (RV) [133]. The temperature corresponding to 0.17±0.002 Pa.s and 0.28 ±0.003 Pa.s is taken as mixing and compaction temperature, respectively, for the production of asphalt mixtures. Previous literatures stated that ASTM D2493 concept popularly known as equi-viscous method is appropriate for determining the production temperatures for Newtonian fluids whose behaviour remain same with respect to shear rate [11,125,134]. However, addition of polymers and additives in the asphalt binder directly affects the viscosity which in-turn changes the production temperatures of asphalt mixture [135–137]. This can be attributed to the shear thinning behaviour of modified asphalt binders, indicating viscosity as a function of shear rate [138]. The viscosity of these asphalt binders, unlike conventional asphalt binder, has a dependency on shear rate, even at higher temperatures (>100°C) [132,139]. Few literatures stated that this principle is also valid and found practical for field conditions [132,138]. Also, the determination of production temperature without the incorporation of shear rate often yields higher values of temperatures. In general, high production temperatures not only degrade the binder performance but also increases the exposure to hazardous fumes during the production and placement of asphalt mixtures in the field [11]. To overcome this, Asphalt Institute suggested to contact the suppliers of additives or polymers for selecting the production temperatures of modified asphalt binders which is not a viable approach [125,140]. Therefore, there is a need of finding an alternative protocol for the estimation of mixing and compaction temperature irrespective of binder type.

To overcome such concerns, Yildrim et al. considered the effect of shear rate for the evaluation of production temperature in an appropriate manner [132]. The proposed method is based on the hypothesis predicting the development of higher shear rate (HSR ~ 500 1/s) during the compaction of asphalt mixture in Superpave gyratory compactor. The limit of the viscosities was different from the traditional equi-viscous approach and is presented in Table 2-6. This method extrapolates the value of viscosity to 500 1/s, however, extrapolation by using some trend line is still questionable due to the higher dependency of modified asphalt binders on the molecular structure [138]. Past literatures found that HSR method predicts lower mixing and compaction temperature by almost 14-38°C compared to equi-viscous method for modified asphalt binders. In 2006, Yildrim carried out a new investigation to validate the previous specified viscosities limits with few new modified asphalt binders [132]. After successful validation, the author revealed that the previously specified range often underestimate the production temperature and hence new limits were proposed. The procedure was kept same as HSR method but the name changed to the HSR evolution approach. Recently, Saboo et al. demonstrated that the principle of shear-thinning and reduction in viscosity is only applicable for the estimation of mixing temperature rather than compaction temperature [138]. It has to be noted that a higher shear rate indicates lower viscosity and so the mixing temperature. However, this concept provides unrealistic values of compaction temperature due to the little dependency on shear rate during compaction. The study stated that compaction temperature (for Marshall Compactor or field rolling condition) merely depends on the normal force of compaction and energy. Therefore, the prediction of compaction temperature using this phenomenon is again inappropriate. Considering the shear rate in the mixing plant, Saboo et al. recommended three different shear rates (1000, 10000, 100000 1/s) for the estimation of mixing temperatures using same viscosities limit as given in ASTM D2493[138].

Following several methods and protocols presented in previous literatures, Khatri et al. suggested the use of zero shear viscosity (ZSV) concept where the viscosity is measured at the shear rate approaching to zero [141]. The reason behind the evaluation of temperature at such low shear rate is the lower value of vertical compression rate while performing Superpave gyratory compaction process (NCHRP 459) [142]. To simply the ZSV approach, the researchers suggested the use of RV at 6.8 1/s with shifted viscosities limits for mixing and compaction temperature [142]. Notably, this method underestimates the mixing temperature as it is more dependable on shear rate whereas ZSV method recommended the quantification of mixing temperature at shear rate approaching to zero which is not accurate. Nevertheless, this method might stand true for the prediction of compaction temperatures. Table 2-6 present the summary of previously proposed methods, along with their salient features and proposed criteria.

Other than RV, several methods have been proposed to estimate the production temperature that employ dynamic shear rheometer. In the recent time, NCHRP recommended a test methodology for finding the production temperature based on the Newtonian behaviour of asphalt binders [142]. This method involves the testing of asphalt binder under an oscillatory based test procedure at 50°C, 60°C, 70°C and 80°C. The phase lag was selected as an important parameter to determine the mixing and compaction temperature and thus the method is popularly known as Phase angle method [134,143]. Master curve of phase angle was constructed at a reference temperature of 80°C and the frequency corresponding to the phase angle of 86° is taken for further evaluation of production temperatures. West et al. stated that the phase angle of 86° easily identifies the transition point of visco-elastic materials [144] . The equations involve in this methodology is given in Table 2-6. Phase angle method was undertaken to eliminate the effect of mixing stresses and shear rate which often creates complexity. Few literatures reported that the temperature obtained from DSR approach, in comparison to traditional equi-viscous method, limits the concerns related to binder degradation and emissions problems especially for modified binders.

A plethora of previous studies showed that viscosity being the common factor in all the proposed methodologies for the evaluation of mixing and compaction temperature. There has been a continuous debate on the reliability of viscosity based methods especially for WMA

[76,131]. Considering WMA, viscosity based methods are primarily applicable to the technologies that change binder's viscosity. However, WMA produced by foaming and chemical based methods does not alter the viscosity, even if it provides better workability and adequate compaction [131]. From this perspective, Mo et al. stated that viscosity of asphalt binder alone is not sufficient to directly compute the workability of asphalt mixtures [131,145]. Thus, the production temperature evaluated using conventional approaches was again unrealistic or inappropriate. To overcome the issues of convectional viscosity based approaches, various workability based approach has been used in past for assessment of production temperatures and workability of asphalt mixtures. The review on workability based method has been discussed in subsequent section.

Table 2-6. Representative list of proposed methods for the prediction of production temperatures

Method, Instrument, Reference	**Salient Features**	**Viscosity Criteria (Test Temperatures)**	**Remarks**
Zero Shear Viscosity (ZSV) Approach, RV, [141]	The viscosity is measured at the shear rate approaching zero. The production temperatures are determined by plotting the log-log viscosity as a function of log temperature (in degree Kelvin).	MT-3.0 Pa.s; CT-6.0 Pa.s (135˚C and 165˚C)	This method recommends quantifying the mixing temperature at a shear rate approaching zero, which may not be accurate. In an actual mixing plant, mixing of asphalt binder and aggregates generally occurs at a specified shear rate. Therefore, the shear rate dependency of asphalt binders is not considered in this method.
Simplified ZSV Approach, RV, [11]	To simplify the ZSV approach, the authors suggested operating RV at 6.8 s^{-1} with shifted viscosities limits for mixing and compaction temperatures. This method usually results in low	MT-0.75±0.05 Pa.s;	This method underestimates the mixing and compaction temperatures for some modified binders. This

	production temperatures for modified asphalt binders. The measured viscosity values are plotted on a log scale with respect to temperature.	CT-1.4±0.1 Pa.s (135˚C and 165˚C)	method does not provide any argument on the selection of shifted viscosity limits.
High Shear Rate Method (HSR-O), RV, [125]	The proposed method is based on the assumption that a higher shear rate (HSR ~ 500 s^{-1}) is developed during the compaction of asphalt mixture in a Superpave gyratory compactor. This method considers the shear rate dependency of asphalt binders. The viscosity values at 500 s^{-1} are extrapolated using a power-law model and plotted on a log scale with respect to temperature.	MT-0.17±0.02 Pa.s; CT-0.28±0.03 Pa.s (135˚C and 165˚C)	This method extrapolates the value of viscosity to 500 s^{-1}. Extrapolation using some trend lines may be questionable.
High Shear Rate Evolution Approach (HSR-E), RV, [132]	This method was developed with the view that HSR-O method often underestimates the production temperatures. Therefore, new limits of viscosity ranges were proposed. All the calculations and graphs are similar to HSR-O method.	MT-0.275±0.03 Pa.s; CT-0.55±0.06 Pa.s (135˚C and 165˚C)	Requires extrapolation of results similar to HSR-O approach. Hence questionable.
Flow Behavior Method RV, [138]	This method demonstrates that the principle of shear-thinning in asphalt binders is only applicable for estimating mixing temperature rather than the compaction temperature. The study states that compaction temperature (in Marshall compactor or during field rolling condition) merely depends on the normal force of compaction and energy. This approach suggests three different shear rates (1000, 10000, 100000 s^{-1}) for determining the production temperatures [138]. Cross model [146] is used to predict the viscosity value corresponding to high shear rates. Thereafter, the production temperatures are determined by plotting the viscosity values on a log scale with respect to temperature.	MT-0.17±0.02 Pa.s; CT-0.28±0.03 Pa.s (135˚C and 165˚C)	This method only provides the estimation of mixing temperature. At a high shear rate (100000 s-1), the mixing temperature, even for unmodified asphalt binder, is very low compared to the traditional EQ method. The criteria for the selection of various shear rates are not provided.

Steady Shear Flow (SSF), DSR, [14]	This method utilizes DSR with a 25 mm diameter spindle geometry and a 500-micron gap. As per this method, viscosity value approaches a steady-state at high shear stresses (around 500 Pa). This method yields lower mixing and compaction temperatures than the traditional method. Logarithmic of viscosity (determined at 500 Pa) versus logarithmic of temperature is plotted, and results are extrapolated to a temperature of 180° C.	MT-0.17±0.02 Pa.s; CT-0.35±0.03 Pa.s (76°C to 94°C)	This method requires extrapolation of viscosity corresponding to a higher temperature range (around 180˚C). Also, many modified asphalt binders may not reach a steady-state at 500 Pa.
Phase Angle Method (PAM), DSR, [11]	This method is based on the non-Newtonian behavior of the asphalt binders. The phase lag is selected as an essential parameter to determine the mixing and compaction temperatures. The phase angle master curve is constructed at a reference temperature of 80°C, and the frequency (ω) corresponding to the phase angle of 86° is taken for further evaluation of production temperatures.	MT- $325\,(\omega)^{-0.0135}$; CT- $300\,(\omega)^{-0.012}$ (50°C, 60°C, 70°C and 80°C)	This method indicates unrealistically low mixing and compaction temperatures for some polymer and warm mix modified asphalt binders.

Note: MT and CT indicate Mixing and compaction temperatures, respectively.

2.5.2 Review on the Suitability of Workability Approach for WMA Technology

In WMA technologies, the equi-viscous approach applies solely to additives that alter the viscosity of the binder for determination of MT and CT. However, when a WMA technology has minimal impact on viscosity, as is often the case with chemical and foaming-additives, determining the working temperature solely based on viscosity becomes impractical. Studies by Stimilli et al. and Wang et al. have pointed out that relying on binder viscosity alone is inadequate for determining production temperatures or overall workability, especially for modified asphalt binders and asphalt mixtures containing recycling material [145,147]. Past studies have 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 [15,16]. This reduction in friction leads to improved workability in the asphalt mixture. Therefore, it is advisable to directly assess production temperature based on workability for WMA applications. With this consideration, the quantification of workability, and its use for evaluating production temperatures, have gained a lot of research interest. However, lack of standardized workability index restricts the engineers and researchers to evaluate the workability of asphalt mixtures quantitatively. Various workability prototypes were developed and demonstrated in the previous literatures for the measurement of workability. However, the utilization of workability as a primitive tool for the prediction of production temperatures are scanty. First workability device was developed in 1979 by Marvillet and Bougault for assessing the workability of asphalt mixture [9]. This workability device used a spring and potentiometer to measure mixing resistance via torque values. This torque serves as a fundamental indicator of workability. This device measured the workability in terms of the torque required to rotate the spindle through a loose mix inside a cylindrical bowl. Torque value was found to be decreases with an increase in temperature and vice-versa. Workability was defined as the inverse of torque value. Higher torque values signify poor workability of the asphalt mixture, while lower values suggest better workability. Gudimettla et al. studied the workability of hot mix asphalt mixture through workability device [148]. From the study, it was concluded that workability was affected by the type of binder and aggregate, NMAS, and temperature. Subsequently, various workability measurement devices have been invented to differentiate between HMA and WMA. The detailed description of various workability device for assessment of workability of HMA and WMA can be found elsewhere [9]. Wang et al. carried out an investigation on the evaluation of mixing and compaction temperature using equi-torque temperature method employing workability device [147]. The study reported that the prediction of mixing and compaction temperature based on equi-torque technique is more realistic and the range of reduction is consistent with the actual reduction recommended by the manufacturer. The principle of equi-torque method is similar to the equi-viscous temperature method. The authors also stated that the proposed method is more convenient and effective for getting higher accuracy in the results. It is worth noting that Wang et al. defined the torque range based on the temperature limits recommended by Technical Standard of Highway Engineering (China), JTG E20, which can change with the change in country specifications [147]. However, this approach again arises various question of concerns regarding the temperature range of virgin binder. Hence, there is a need of investigation for finding a suitable temperature range for virgin binder based on experimental work rather than country specification. Considering workability as a vital tool, Zhao and Guo demonstrated that decrease in mixing and compaction temperature adversely affect the workability of asphalt mixtures [149]. Thus, the lower permissible temperature that ensure good workability must be chosen, else it would lead to poor construction and cause difficulty in compaction which is not desirable. Findings from the study revealed that the workability of WMA containing 2% Sasobit (by weight of binder) at 145°C is equivalent to HMA's workability at 175°C, indicating a reduction of 30°C in production temperature. Workability was assessed using a workability index derived from torque measurements during mixing. This 30°C reduction was further validated by comparing the air void contents in both asphalt mixtures, which showed comparable values. Apart from this, several studies supports/recommends the use of workability parameter for the performance evaluation of WMA technologies [12,147,150–155].

In brief, numerous attempts have been made to evaluate the workability of WMA technology, leading to the development of various workability devices with differing procedures and complexities. However, there is a necessity to assess workability of different WMA technologies and compare them with the conventional HMA. Furthermore, the limited data available for determining mixing and compaction temperatures using workability devices emphasizes the need for further research to establish absolute conclusions. Finally, the workability studies also revealed that the mechanism by which warm mix technologies improve the workability could be related to the reduction in friction at the contact zone of the mineral aggregates and asphalt binder [17]. The friction between mineral aggregate and asphalt binder can be studied using the science of tribology [18]. The in-depth review regarding the tribology as tool for WMA technology has been discussed in subsequent section.

2.5.3 Global Overview of WMA Production Temperature Guidelines

1. **United States**
    - In the U.S., methods for determining production temperatures for WMA are largely based on the guidelines provided by the National Asphalt Pavement Association (NAPA) and AASHTO [156].
    - The typical approach involves reducing mixing and compaction temperatures by 20–40°C compared to conventional hot mix asphalt (HMA).
    - The exact reduction depends on the type of WMA additive or technology used (e.g., chemical additives, foaming technologies), with each method having its own temperature optimization recommendations.
    - Testing methods, such as the Superpave mix design, are commonly used to verify mix performance at lower temperatures.
2. **Germany**
    - In Germany, WMA temperature selection often follows guidelines from the German Asphalt Pavement Association (DEGES), based on the type of binder and additives used [4,8].
    - Germany emphasizes a combination of laboratory testing and field trials to determine the optimal mixing and compaction temperatures.
    - Temperature reductions typically range from 10–40°C depending on the specific WMA technology used, with a strong focus on ensuring adequate binder coating at lower temperatures.

3. France

- France generally uses an empirical approach, where production temperatures for WMA are based on laboratory workability tests and performance assessments.
- Temperature reductions are typically 20–30°C, similar to Germany, but the country also relies heavily on manufacturer guidelines for specific WMA technologies [4,8].
- As part of their practice, the French ensure that WMA mixtures meet the necessary requirements for field compaction and long-term performance, even at lower temperatures.

4. United Kingdom

- In the UK, WMA temperature selection follows guidelines from the Department for Transport and is typically based on laboratory trials and performance testing.
- The UK focuses on reducing mixing and compaction temperatures by 20–30°C, but the specific reduction depends on the binder and WMA additive used. Guidelines are provided by the European Asphalt Pavement Association (EAPA) which advocates for performance-based testing to assess the effectiveness of WMA mixes [157].
- Testing methods include both the binder performance at lower temperatures and the mixture's workability, to ensure that the mix meets the necessary specifications.

5. Australia

- Australia follows similar practices to the UK, with a focus on reducing production temperatures by 15–30°C depending on the WMA additive used.
- The Australian approach emphasizes field performance trials and laboratory workability tests to determine the best temperatures for mixing and compaction.

- Guidelines are provided by the Australian Asphalt Pavement Association (AAPA) which advocates for performance-based testing to assess the effectiveness of WMA mixes [158].

6. **China**

- In China, WMA technology is widely used, and the country has developed its own approach to determining production temperatures based on both laboratory testing and field performance.
- The typical temperature reduction is around 20–40°C, with variations depending on the WMA technology and binder used.
- China's methods often incorporate testing such as the high-temperature viscosity and the workability of binder and mixtures at reduced temperatures.
- GB/T 23456-2009 - "Technical Specification for Asphalt Pavement Construction" This standard provides guidelines for the construction of asphalt pavements in China, including the use of WMA [4].
- It encourages the reduction of mixing temperatures for WMA by 20–40°C compared to conventional Hot Mix Asphalt (HMA).

7. **India**

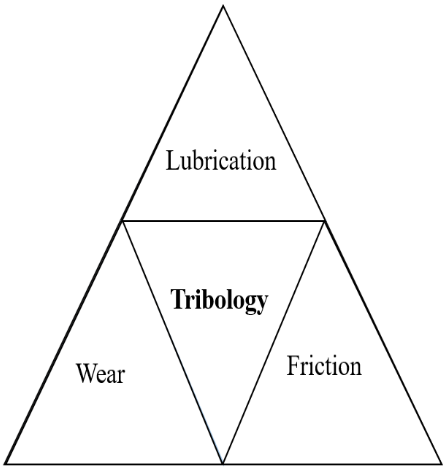
- In India, WMA technology is relatively new, and there is no standardized method for determining production temperatures yet. However, the adoption of WMA is increasing, particularly in projects focused on sustainability and cost reduction.
- Indian practices often follow IRC SP101:2019 guidelines with temperature reductions typically in the range of 15–30°C [40].

- Laboratory testing, including binder viscosity and mix performance tests, is conducted to ensure that mixes are workable and durable at the reduced temperatures.

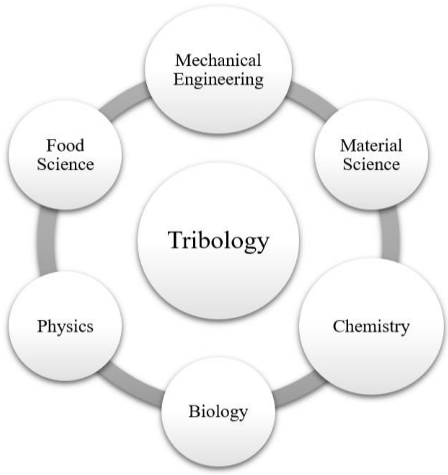
Despite these practices in various countries, there is no globally standardized method for selecting WMA production temperatures, emphasizing the need for research-based guidelines tailored to local materials and conditions.

2.6 Tribology as Emerging Science for Warm Mix Technology

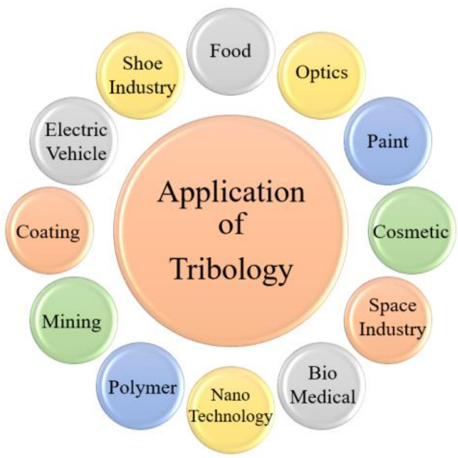
Concept of friction has been documented and used by mankind for hundreds of years. It is used for various applications starting from fire invention due to frictional heat [19]. Scientific ways to study the friction phenomena are an output of studies during the seventeenth and subsequent centuries [20]. The evolution (industrial) with time has motivated researchers to develop the science which addresses the issues related to energy loss due to friction and wear. This energy loss problem gives rise to the science of tribology [159]. The word 'tribology' is derived from the Greek word "tribo," meaning "to rub, " and the suffix "logia," meaning "study or learning"[20]. It was first used in England and was coined by Sir Peter Jost in 1966 [160]. The term was coined to integrate the historic independence of friction, wear, and lubrication in an interdisciplinary manner shown in Figure 2-6 [15,161–171]. Tribology is usually associated with 'tribo-system' that consists of interacting surfaces separated by a lubricant [19,160]. A wide variety of tribo-system exists in various domains of science and engineering [165,172–174]. Nowadays, investigations in the field of tribology have grown rapidly in terms of both scope and depth. Tribology is widely used for assessing the performance of lubricants, which reduce the wear of the machine components [18,175]. This is an interdisciplinary science comprises of various branches of science and technology, as shown in Figure 2-6 (b). Tribology has recently been used in advanced domains, including super lubricity, wear, surface engineering, bio-tribology, high-temperature tribology, and computational tribology [165]. Regarding environmental aspects, tribologists are focusing more on evaluating biodegradable lubricants and biofuels such as vegetable oil and biodiesel [18,165,176,177]. Also, nano-materials as performance improvers have been evaluated using tribology [178,179]. Currently, tribological applications are actively used in various industries as shown in Figure 2-6 (c).



(a)



(b)



(c)

Figure 2-6.(a) Tribology as interdisciplinary science, (b) tribology in various domains of science, (c) application of tribology in various industries

In the paving industry, tribology is comparatively a young science, recently adopted to investigate warm mix asphalt (WMA) technologies. Recently, tribology has been used as a tool for assessment of the WMA technology which promises several benefits compared to HMA. It is used to understand the mechanism by which WMA technology reduces the production temperature. Previous studies have shown that reducing the viscosity of asphalt binder using WMA technologies aids in reducing mixing and compaction temperature. However, in recent studies, it has been found that these viscosity criteria underestimate the workability and densification behaviour of asphalt mixes prepared using warm-mix (WM) modified binders. Therefore, the reduction in viscosity offered by WMA additives cannot be used for quantifying the improved workability and lower production temperatures offered by the technology. Hence, it is crucial to understand the difficulties related to WMA technology and to define the mechanisms related to its constructability. It has been hypothesized that mixing and compaction temperature reduction using WMA technology is probably associated with the friction mechanisms at the contact zone between the aggregates. Therefore, the lubricating behaviour of asphalt binder may be a possible mechanism involved in the densification of the asphalt mixture in addition or alternative to viscosity reduction. The frictional properties at a binder-aggregate interface can be studied using the science of tribology. The lubricating behaviour of asphalt binder within the mineral aggregates in relative motion during production has been successfully studied using the various aspect of tribology. The detailed description about the tribological aspect can be found elsewhere [18,160].

2.6.1 Basics of Tribology and Tribo-system

This section provides an overview of tribology and tribo-systems. Tribology has been used to investigate the friction and lubrication behaviour of various tribo-systems. Friction, in general, is a resistive force opposing the motion of interacting surfaces, either static or moving (sliding or rolling) [19]. The friction is quantified in terms of the coefficient of friction, which is the ratio of frictional force to normal load, as given in Equation 2-1. Figure 2-7 represents the tribo-system consisting of the contacting bodies and the lubricant.

$$F_F = \mu F_N \tag{2-1}$$

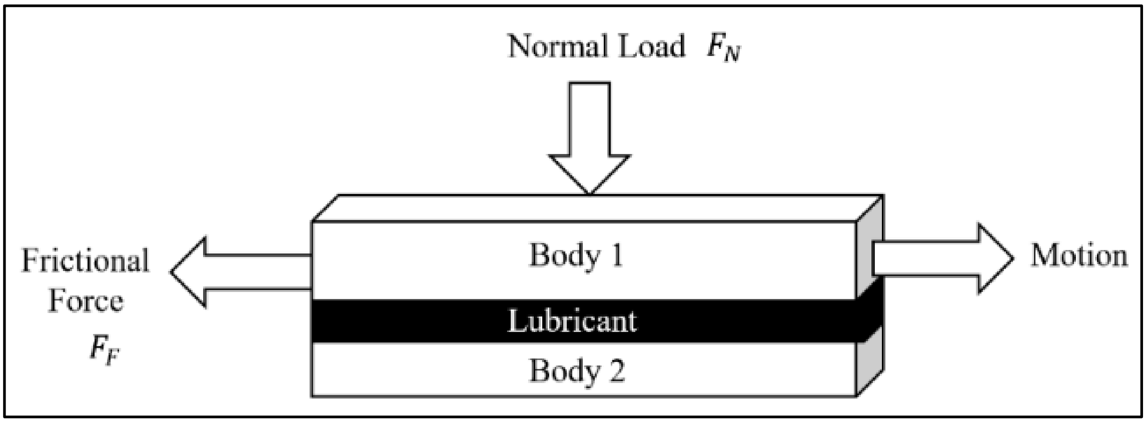


Figure 2-7. Tribo-system (Two Bodies separated by Lubricant)

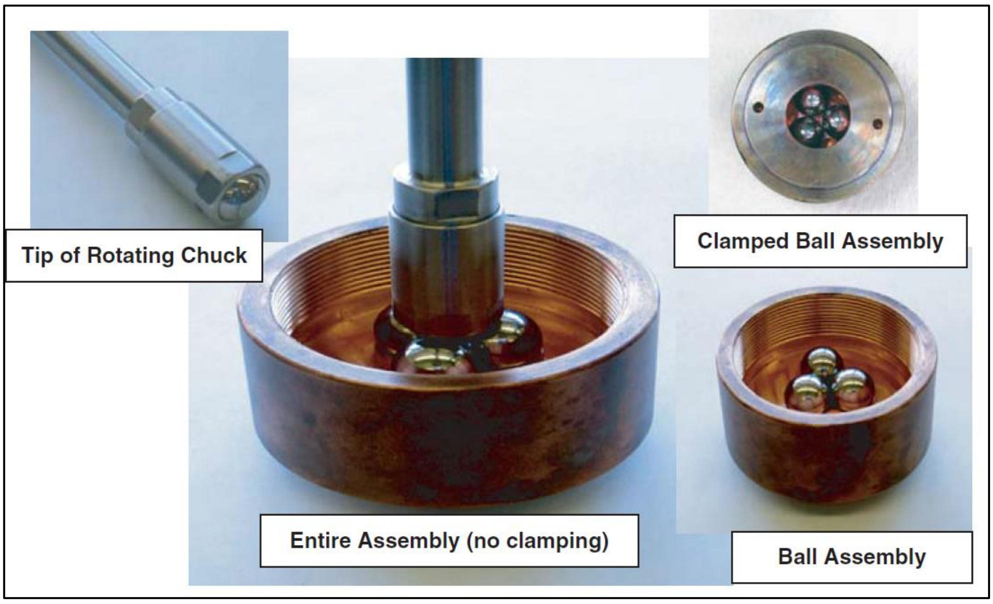
Where μ is the coefficient of friction, F_F and F_N are frictional force and normal force, respectively. The coefficient of friction usually lies between zero and one, but may be greater than one. The coefficient of friction is somewhat complicated as the surfaces moving one another may appear smooth (visually) but are always irregular at the microscopic level [19]. These irregularities at the microscopic level are usually termed as asperities. Generally, the load applied is carried by the plastic deformation of these asperities, forming the contact that results in friction due to adhesion at the microscopic level. From this, it can be realized that the value of the coefficient of friction depends upon the nature of the contacting surfaces, surface irregularities, and their distribution [19,180,181]. Therefore, friction is not a material intrinsic property, but it is a property of the tribo-system that comprises at least two bodies in contact, along with the surrounding environment and the interface referred to as lubricant [19,20]. Generally, tribo-systems are of two types: Dry tribo-systems and Lubricated tribo-systems [182]. Dry tribo-systems have no lubricant between the contacting surfaces, whereas lubricated tribo-systems consist of two contacting bodies with a lubricant in-between. The aggregate-binder interaction is an example of the lubricated tribo-system where aggregates are separated by lubricating asphalt binder film, while the tyre-pavement interaction is an example of a dry tribo-system. The performance of tribo-systems is controlled by many parameters such as temperature, humidity, roughness and hardness of contacting surface, surface chemistry, lubricant nature, relative velocity, type of motion, contact pressure, and contact geometry [183]. The behaviour of a tribo-system is usually assessed through tribometers and evaluated using the coefficient of friction [20,160]. The in-depth information regarding tribometers can be found elsewhere [184,185].

2.6.2 Tribological Characterization of Asphalt Binders

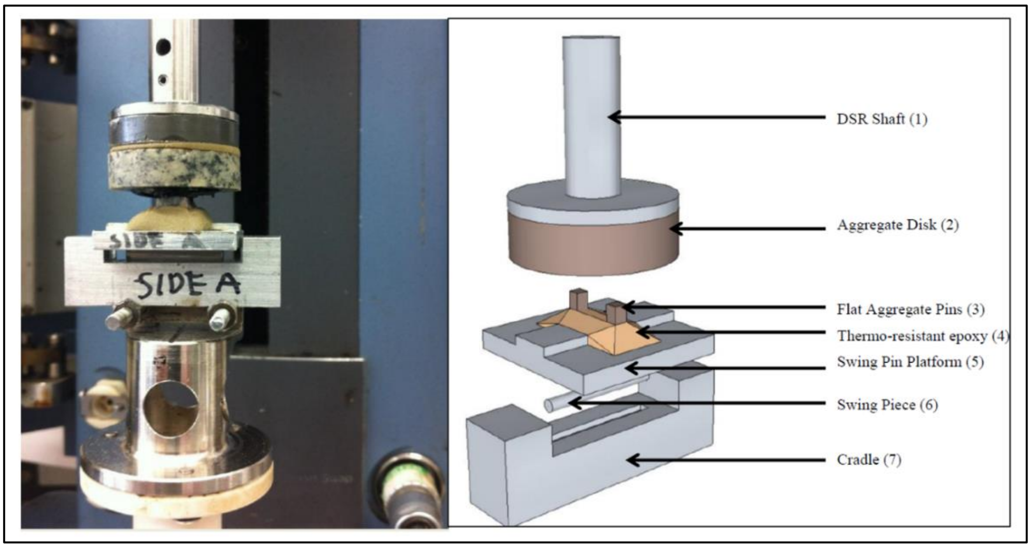
It is a general belief that the warm mix technology lowers the production temperature due to the reduction in viscosity. But all WMA additives do not reduce the viscosity of the base binder, so it cannot be used as a justification for the lower production temperatures offered by the additives. Therefore, it is important to understand the mechanism by which WMA technology reduces the production temperature [15,186,187]. In recent studies, it has been demonstrated that the mechanism involved in the compaction and densification of WMA Modified asphalt mixes can be related to two physical properties [15–17,160]. These include the lubrication properties of modified asphalt binder, and the change in frictional properties at the binder-aggregate interface [15–17,160]. This section deals with the evolution of different tribological equipment employed in previous studies The present section also identifies the difference in the testing conditions and adopted procedure for measuring tribological behaviour. The various methods have evolved with time for the characterization of the tribological behaviour of asphalt binders. The concept of lubricity was first introduced by Reinke [12,188]. The study was performed using a parallel plate setup in a dynamic shear rheometer to evaluate the effectiveness of WMA at a reduced temperature. This test is a modification of the tribo-rheometry test developed by Chasen, Kavehpour, and McKinley [189,190]. It mainly covered the tribo-rheological characterization of complex fluids and solid-liquid systems. The test was performed at various temperatures (105°C, 115°C, and 125ºC) depending on the type of binder. A sufficient amount of binder (1gm for 25 mm) was placed between the plates to form a sufficient film. Proper care is required to avoid spreading the binder on the Peltier enclosure or the inner surface of the oven [188]. The binder sample was brought to the initial gap thickness by loading the sample between the plates. Four gaps were used for testing purposes at a single temperature. The steady shear test was performed at rotational speeds varying from 0 to 1433 rpm (1 to 150 rad/sec) with the initial gap set to 500 μm and further repeated at 100 μm, 50 μm, and 25 μm gap settings. The test results comprised of rotational velocity (rad/sec), normal force (N)and viscosity (Pa.s) [188]. From this study, it was concluded that the performance of the warm-mix additive is affected by two parameters: the magnitude of rotational speed, and the magnitude of the normal force. The study further concluded that reduction in internal friction between binder-aggregate interface is possible if warm mix additive is capable of producing enough shearing under applied load.

After introducing the concept of lubricity in asphalt binder, the researchers performed various tribological tests using different fixtures/geometries such as four ball lubricity test, asphalt boundary lubrication test, and ball-on-three-plates test. Figure 2-8 shows the different tribological geometries used for the characterization of asphalt binders. These tests were performed on the asphalt binder to determine its lubricating behaviour and mechanism associated with warm mix technology. A detailed description of these studies is stated in Table 2-7. The key features, test conditions, procedure adopted, and determination of coefficient of friction in these studies have been highlighted in Table 2-8.

(a)


Tip of Rotating Chuck
Clamped Ball Assembly
Entire Assembly (no clamping)
Ball Assembly

(b)


SIDE A
DSR Shaft (1)
Aggregate Disk (2)
Flat Aggregate Pins (3)
Thermo-resistant epoxy (4)
Swing Pin Platform (5)
Swing Piece (6)
Cradle (7)

(c)

(d)

Figure 2-8. Different tribological geometries used for asphalt binder a) Tribo-Rheometry testing fixture and sample loading b) Asphalt lubricity tester (four ball test) and its assembly c) Asphalt boundary lubrication test apparatus proposed by Puchalski d) Ball-on-three-plates test mounted on dynamic shear rheometer.

Table 2-7. Detailed description of various tests used for tribological characterization of the asphalt binder.

Author	**WMA Process**	**Additive and dosage**	**Tribology Test**			
			Tribo-rheometry test	**Four ball lubricity test**	**Asphalt lubricity test**	**Ball-on-three plates test**
Hanz et al. [17]	Chemical and Foaming	• Revix as 0.5% by weight of the binder • Water concentration of 1.0% to 2.0%	-	Yes	-	-

Hanz et al. [191]	Chemical	• Oxidized polyethylene Lubricant: 1% to 4% by weight of the asphalt binder • Amine-based surfactant:1% to 2% by weight of the asphalt binder	-	Yes	-	-
Puchalski [160]	Chemical	• Rediset WMX: 1%, 2%, and 3% by weight of the asphalt binder • Functionalized Polyolefin Polymer (FPE): 3.5% by weight of the asphalt binder • Cecabase RT: 0.7% by weight of the asphalt binder	-	Yes	Yes	Yes
Baumgardner et al. [188]	Organic Chemical	• Sasobit: 0.5% by weight of asphalt binder • Evotherm with 3G: 0.5% by weight of asphalt binder	-	-	-	Yes
Mannan et al. [187]	Neat Binder	-	-	-	-	Yes
Ingrassia et al. [15]	Organic Chemical	• Wax additive: 0.5 % by weight of asphalt binder • Chemical additive: 0.4% and 0.8% by weight of asphalt binder	-	-	-	Yes
Bairgi et al. [186,192,193]	Foaming	• Foaming using six different FWCs (Foaming Water Content), 1.0% – 3.5% with an increment of 0.5% in PG 64-22	-	-	-	Yes
Bairgi et al. [194]	Chemical	• Evotherm (3-Generation): 0.25%, 0.50%, and 0.75% by weight of asphalt binder	-	-	-	Yes
Ingrassia et al. [195]	-	• Graphene Nano-platelets: 3% and 6% by weight of the asphalt binder.	-		-	Yes
Yan et al. [178]	-	• Graphene Nano-platelets: 3% and 6% by weight of the asphalt binder.	-	-		Yes

Table 2-8. Key features of various tests used for tribological characterization of the asphalt binder.

Author	Description	Test condition	Key Features
Reinke et al. [188]	• Test is a modification of tribo-rheometry test developed by Chasen, Kavehpour, and McKinley. • It mainly covers the tribo-rheological characterization of complex fluids and solid-liquid systems. • Performed on DSR based on concept of thin film rheology	T=105°C, 115°C and 125 ºC v= 0 to 1433 rpm gap= 500,100,50 and 25 µm	• The sufficient amount of binder (1gm for 25 mm) was placed in a cup to form sufficient film. • Proper care is required to avoid spreading of binder on peltier enclosure or on the inner surface of the oven[188]. • The binder sample was brought to the initial gap thickness by loading the sample into the cup. Four test gaps used for testing purposes at single temperature. • The steady shear test is performed at rotational speeds varying from 0 to 1433 rpm (1 to 150 rad/sec) with initial gap set to 500 µm and further repeated at 100 µm, 50 µm and 25 µm gap settings. • The test results comprised of rotational velocity (rad/sec), normal force (N)and viscosity (Pa. s).
Hanz et al. [17]	• This test is a modified version of Four-ball wear tests generally used to characterize lubricant and wear behavior according to ASTM D5183-05. • The asphalt lubricity equipment consists of four steel balls, out of which three balls claimed in a cup and fourth ball attached to the spindle of DSR • substrate: steel chromed balls (12.5 mm in diameter)	T= 80°C, 90°C and 100 ºC v = 50 rpm F_N= 20, 30N	• Revix reduces the coefficient of friction (by 5-10%) at both testing temperature which indicates potential of warm-mix additives to densify mix at a lower temperature. • Four ball lubricity insufficient to capture the effectiveness of foamed bitumen because of insufficient binder after increased volume.
Hanz and Bahia [191]	• The test features were very similar to previous study. • The purpose of test was to determine the effect of WMA on compactibility of the mixture.	T= 85°C, 115°C and 145 ºC v= 50 rpm F_N =10N substrate: steel	• For oxidized polyethylene lubricant, the coefficient of friction decreased as the testing temperature increased for both binder grades. Conversely, the amine-based surfactant caused significant reductions in the coefficient of friction only at 85°C, and the magnitude of reduction varied with binder grade.

			• A significant (~33%) decrease in the bituminous binder coefficient of friction is caused by amine-based surfactant whereas the small reduction (~10%) was observed in SBS modified binder (PG 76-22) at the high dosage level.
Puchalski [160]	• Test was performed based on study of Hanz and Bahia [191]	T= 85°C, 115°C and 145 °C v= 50 rpm FN =10N substrate: steel	• The test procedure was very analogous to study performed by Hanz et al. [17] • The resultant coefficient of friction is determined using the following equation $\mu = C \times \frac{T}{F * d}$...........2.2 where, C = 2.842 is a constant for the four-ball testing fixture geometry, T = torque (Nm), F = normal force (N) and d = diameter of the ball (m).
Puchalski [160]	• The primary purpose of the ball-on-three plates test was to understand the effect of substrates (steel ball-steel plates, steel Ball-Teflon plates, Teflon Ball-Teflon plates) on the lubricity of bituminous binder	T= 85°C, 115°C and 145ºC v= 0.01 to 3000rpm F_N =21N substrate: steel and Teflon	• The ball on three plates test was performed using 21N axial force with rotational speed ranging from 0.01 to 3000 rpm at same temperature. • To consider repeatability, the three replicates were considered for each binder for given ball and plates • The results were analyzed using Stribeck curve.
Puchalski [160]	• Asphalt Boundary Lubrication Test developed based on The shortcoming of four ball and ball-on-three-plates test conducted by Puchalski [160] • The test based on the concept of characterizing binder in boundary lubrication regime. • The purpose of the test is to determine effect of substrate on effectiveness of lubrication offered by warm mix technology.	T= 90°C, 115°C and 145ºC v= 0.05 rad/sec σ_N= 100 kPa, 500kPa and 1MPa substrate: Limestone and granite	• Sample of 0.1 g was prepared in an 8-mm DSR mold and placed between aggregate disk and flat aggregate pin. • The sample was preconditioned by keeping at 150ºC for 20 min. • Spindle was lower and stopped when bituminous binder just touched the aggregate pins. • Before performing the test, the sample was kept at 145°C for 20 min. • After 15 min, at each temperature (from 145°C to 90ºC), the pressure was consecutively increased, and the resulting coefficient of friction was measured. • Three replicates were prepared for each binder.

	• The test is version of pin-on-flat type of geometry assembled in DSR due to its compactibility and easy fabrication. • The rectangular shaped pin in this geometry provides easy fabrication and precision in the contact area. • To use different aggregates (granite and limestone), pin and disk were kept exchangeable, Substrate used: Limestone and granite.		• The coefficient of friction was calculated using equation [160]. $\mu = \frac{T}{F \times d`}$ ………………2.3  where, T = torque (Nm), F = normal force (N) and d` = distance between centroids of the top surfaces of the two pins (m).
Reinke and Baumgartner [188]	• The test was performed using MCR 301 DSR designed by Anton par • The apparatus was operated either in torque or speed controlled mode. • The test temperature was maintained by a Peltier controlled system at the bottom plate. • The ball on three plates tribology set-up consists of a ball attached to the shaft of DSR, three plates were held in the cup in an inclined manner. • The rotational speed applied to the shaft, produces sliding of the ball over the three plates at contact points along with the normal load perpendicular to plates. • The resultant torque was correlated with friction through simple geometric calculations. • Substrate: steel	T= 115°C, 130°C, 145°C and 160°C v= 0 to 1433rpm F_N =10N	• Test was performed using ball-on-three-plates fixtures assembled in DSR • The test was performed with 1g of bitumen sample placed in a cup where plates held the cup • Ball attached to spindle brought into contact with cup and plates. • An axial load of 10N was maintained, and the test temperature was stabilized through the Peltier system. • Then the test was started by varying rotational speed ranges from 0 to 150 rad/sec. • The resultant coefficient of friction was determined from the below mentioned parameters. $F_L = 2\ (cos\alpha) F_N$…………. 2.4 $T = (\sin\alpha)\ F_F * r_{ball}$……………2.5 Where F_L= Normal force F_F= Frictional force T= Torque F_N= Axial force r_{ball} = radius of the ball, and α = the angle of the plates. (With the geometrical dimensions r_{ball} =6.35 mm and α =45°), the tribological parameters can be calculated as follows: • Normal force: $F_L = \sqrt{2}\ F_N$……2.6 • Frictional force: $F_F = M \frac{\sqrt{2}}{r_{ball}}$…2.7

			• Sliding Distance: $S_S = 1/\sqrt{2} \times r_{ball} \times \varphi$ (φ =deflection angle, rad)…………………….2.8 • Sliding velocity: $V_S = 1/\sqrt{2} \times r_{ball} \times \omega$ (ω = Angular velocity, rad/sec)……………..2.9
Reinke and Baumgartner [18]	• This oscillatory test was performed to compare oscillatory tests with rotational tests. • Substrate: steel	T= 115°C, 130°C, 145°C and 160ºC v= 0 to 1433rpm F_N =10N f = 1 Hz (oscillatory test)	• The test procedure was very analogous to study performed by Reinke and Baumgartner [188]
Mannan and Tarefder [187]	• The test parameters were very similar to previous study conducted by Reinke and Baumgartner • Substrate: Steel	T= 25°C, 50°C and 135ºC v= 0.001 to 1000rpm F_N =10N substrate: Steel	• Approximate 1g sample was placed in the cup to form sufficient film. • The test temperature was maintained through Peltier closure. • Ball attached to spindle brought into contact with cups and plates. • Initial contact maintained through 0.1N for 10 min and assembly kept at testing temperature. • An axial load of 10N was applied and hold it for 1min • Finally, the test was started by varying rotational speed from 0.0001 to 1000 rpm in 1000 sec • Five runs were performed for each binder, and the mean of the last four trials was taken. • The coefficient of friction calculated in a similar manner as determined by Reinke and Baumgartner.
Lorenzo Paolo Ingrassia et al [15]	• The test was optimized based on previous literature regarding the tribological behavior of lubricant • Substrate: Steel (ball=6.35 mm radius and plates=3×6×16 mm)	T= 85°C &120ºC v= 0 to 1433rpm F_N =10N	• The optimized procedure was adopted for tribological testing based on previous literature • About 1 g of the binder was placed in a cup • Peltier system was used to stabilize the temperature for 10 min • The contact between ball and plates was maintained to stabilized axial force • The axial force of 10N was applied and kept constant during the test

			• Perform the test by increasing rotational speed logarithmically from 0.1 to 1433 rpm. • Give one minute to the specimen for rest, and then a new repetition starts by changing the rotational speed within the testing range. • Five runs were performed for each binder, and the mean of the last four runs were taken. • The coefficient of friction can be determined using the following equation [15]. $\mu = \frac{F_{F-TOT}}{F_{N,tribo-TOT}}$………...2.10 • $F_{F\text{-}TOT}$ and $F_{N,tribo\text{-}TOT}$ is the total friction force and the total normal force respectively experienced by the specimen that was calculated using following equation. $F_{F\text{-}TOT} = 3(\frac{T}{3.sin\alpha.r_{ball}}) = (\frac{T}{sin\alpha.r_{ball}})$……2.11 $F_{F\text{-}TOT} = 3(\frac{F_N}{3.cos\alpha}) = (\frac{F_N}{cos\alpha})$……………2.12 Where, F_N = axial force (N) T = Torque (Nm) r_{ball} = radius of the ball α = angle between the plates and the horizontal plane (α=45°)
Biswajit Kumar Bairgi et al [192][186][193][194]	• Tribological characterization was performed with a ball on three plates fixture assembled in DSR. • The test features were analogous to the above-mentioned study conducted by Mannan and Tarefder • Substrate: steel	T= 25°C, 60°C, 100°C, and 135°C v= 0.001 to 1000rpm F_N =10N	• Test procedure and determination of the coefficient of friction was analogous to the study conducted by Mannan and Tarefder [187].
Lorenzo Paolo Ingrassia et al [195]	• Test was conducted to study the effect of graphene Nano-platelets on lubrication	T= 110°C, 130°C and 150°C, v= 0.1 to 1433rpm F_N =10N	• The test procedure and the determination of the coefficient of friction followed the same methodology as a previous study by Ingrassia et al. [15]

	behaviour of bituminous binder • Substrate: steel		
Lorenzo Paolo Ingrassia et al [178]	• Test was performed using different surface texture (different surface roughness) of the testing fixtures (ball and plates) • substrate: steel with different roughness (smooth and rough)	T= 110°C, 130°C and 150°C, v= 0.1 to 1433rpm F_N =10N	• The test procedure and the methodology for determining the coefficient of friction adhered to the protocols established in a previous study by Ingrassia et al. [15]

2.6.3 Major Influencing Factors

The outcomes from various studies (mentioned in Table 2-9) suggested that the lubricating behaviour is a function of many variables other than sliding speed, including the fluid's viscosity, the nature of the interacting surfaces, and the vertical force applied. With the introduction of viscoelastic material, such as asphalt binder, an additional variable i.e., the temperature also has to be considered, which is the most impacting variable. The influence of various parameters on the lubricating behavior of the asphalt binder is stated in Table 2-9.

Table 2-9. Parameter influencing lubricating behaviour of asphalt binder

Influencing Parameter	Inferences	Reference
Binder Type	• Different grade of asphalt binder ensures the different lubricating behaviour. • Binder with higher PG grade has less coefficient of friction. • Binder from different sources with the same PG grade showed a different coefficient of friction due to chemical modification as a result of the refining process.	[17] [188] [187]
Viscosity	• The decrease in film thickness is observed due to a reduction in viscosity that leads to a lower coefficient of friction. • The viscosity of asphalt binder has a significant influence on the formation of lubrication regimes. • It has a significant influence on the minimum coefficient of friction in the elastohydrodynamic regime.	[18,186,192,193]
Temperature	• Temperature plays a vital role in the frictional behaviour of thermo-dependent materials such as asphalt binder. • High temperature reduces the coefficient of friction due to the reduction in film thickness.	[15,187,188,195]

	• Reduction in temperature shifts behaviour of asphalt binder from lubricating media to adhesive media. • Coefficient of friction is thermo-dependent as it decreases with an increase in temperature and vice-versa.	
Sliding Speed	• Sliding speed affects the appearance of lubrication regimes with a temperature variation. • High sliding velocities result in surface frictional heating and thus the formation of a thin molten layer at the asperity contacts reduces the shear strength at the contact resulting in a very low friction coefficient.	[186,192,193]
Normal Load	• The change in normal load significantly affects the test results. • The wear mark due to an increase in normal load may significantly affect the coefficient of friction.	[17,160]
Motion	• Performing test in rotational and oscillatory mode affects the tribological behavior of asphalt binder. • Oscillatory tests afford more precise measurement and less wear, but for a conclusion, more data is needed.	[188]
Substrate type	• Coefficient of friction depends upon the nature of the substrate used. • Substrates from the previous test have significant wear that may affect the repeatability of test.	[15,160]
Type of Geometry	• Different geometries resulted in a different way of tribological characterization. • Each geometry has resulted in particular contact area such as conformal and non-conformal which affects the determination of the coefficient of friction • Formation of lubrication regimes is significantly affected by the type of geometry.	[16,18,160]
Repeatability	• The value of the coefficient of friction from the first repetition is considerably different from subsequent repetitions because of the formation of insufficient lubricating film between the ball and plates.	[15]
Material Pairing	• Tribo-pairs such as Steel-Steel, Steel-Teflon, and Steel-Granite or steel-limestone have a significant impact on the coefficient of friction because of the different hardness of the material.	[160]
The surface roughness of the substrate	• The substrate with different surface roughness may affect the adsorption of asphalt binder which subsequently affects the friction behavior.	[178]

2.6.4 Effect of WMA Additives on CoF

To overcome the viscosity criteria, the researchers conducted various studies to understand the mechanisms involved in the improved workability of the asphalt mixes offered by warm mix technology. The researcher used various WMA additives to study the lubricating behavior of asphalt binders. The influence of these warm mix additives on the lubrication properties of the asphalt binder is summarized in Table 2-10. As can be seen, the application of warm mix additives improved the coefficient of friction, irrespective of warm mix technology.

Table 2-10. The Influence of warm mix additives on the lubrication properties

Warm Mix Additive	**Inferences**	**Reference**
REVIX	REVIX reduces the coefficient of friction which densify the mix at a lower temperature.	[17]
Oxidized polyethylene lubricant	It reduces the coefficient of friction with increasing in testing temperature. The reduction in coefficient of friction is significant to justify the densification of the mix at a lower temperature.	[191]
Amine based surfactant	It acts as a surfactant agent and reduces the surface tension of binder which subsequently reduces the coefficient of friction.	[191]
Rediset WMX	It reduces compacting effort justified by a reduction in coefficient of friction.	[160]
Functionalized Polyolefin Polymer (FPE)	This additive typically improves the boundary lubrication characteristics when compared to the control binder.	[160]
Cecabase RT	It showed promising improvement in the lubricating behaviour of asphalt binder.	[160]
Sasobit	Sasobit modified asphalt binder has a significant impact on the lubricating behaviour of binder as its lubricating behaviour remains in the elastohydrodynamic regime.	[188]
Evotherm	The Evotherm at 115°C showed the same lubricating behavior as a near binder at 160°C. Evotherm reduces the value of the coefficient of friction.	[188,194]
Wax additive	The wax additive showed an insignificant reduction in coefficient of friction. However, it caused an evident reduction in viscosity	[15]
Chemical Additive	Chemical additive showed a significant reduction in the coefficient of friction which is justified by changes in chemical composition due to chemical additive.	[15]
Foaming	The foaming shows improved coating and lubrication due to a reduction in the coefficient of friction. However, some studies showed insignificant results with foamed asphalt binders.	[17,186,192,193]

2.6.5 Relation of CoF with the Asphalt Binder and Mixture Properties

From the studies mentioned above, it has been revealed that the mechanism involved in the ease of compaction and densification of asphalt mixes prepared using WMA modified binders can be related to the lubrication properties of the modified asphalt binders at the binder-aggregate interface. In order to understand lubricating behaviour at the binder-aggregate interface, efforts have been made to correlate this behaviour with binder and mixture properties. Table 2-11 shows the relation of coefficient of friction with asphalt binder and mixture properties.

Table 2-11. The relation of coefficient of friction with asphalt binder and mixture properties.

Property	Index	Effect	Reference
Workability	N92 (gyrations required to reach 92% of G_{mm}) or Torque (N.m)	• The reduction in coefficient of friction showed significant improvement in the workability of mix. • Considering the effect of aggregate gradation and volumetric, the workability may result in a strong correlation with a coefficient of friction.	[17,191]
Coatability	Coatability Index (CI)	• The coating of asphalt binder with aggregate increases as the coefficient of friction decreases which shows better lubricity.	[17]
Compactibility	N92 (gyrations required to reach 92% of G_{mm})	• The lubricating behaviour at the binder-aggregate interface showed less compaction efforts due to reduced friction. • Many warm mix additives also showed promising behaviour with improved compactibility of mix.	[160,186,192,193]
Viscosity	η (Pa.s)	• The viscosity of asphalt binder has a good correlation with a minimum coefficient of friction in the elasto-hydrodynamic regime where the lubricating film is not excessively thin or excessively thick. • Some studies also showed that mastic viscosity is a more reliable parameter and it is a function of the coefficient of friction in boundary lubrication.	[15,160,186,192,193]
Stiffness	($G^*/\sin\delta$)	• At temperature (50-60°C), aggregate and binder are in	[186,187,192,193]

		relative motion, where binder has enough lubricity and acts as adhesive media. • The parameter G*/sin δ showed a promising correlation with the coefficient of friction measured at 60°C.	
Chemical Composition	C=C, C=O, S=O, $(CH)_n$ indices	• Change in chemical fractions of asphalt binder affects the frictional characteristics.	[15] [186,192,193]

From the above-mentioned studies, it is worth to consider the following aspects regarding the tribological characterization of asphalt binders.

- Specifying proper guidelines regarding the testing parameters such as sliding speed and normal load is necessary
- Proper attention to the overall test procedure, including the pre-run phase and cleaning should be given.
- Necessary use of new tribo-pair to avoid the influence of wear for each test.
- The repetitions on the same sample or the different samples should be properly distinguished as the first aspect provides information regarding the repeatability of the test while the latter aspect provides information regarding the reliability of the test.
- The possible influence of surface roughness of different aggregate substrates on frictional behavior of asphalt binder shall be considered.
- There is a necessity to specify the lubrication regime for analysis to evaluate the benefits of the WMA additive.

2.6.6 Future Opportunities in Tribology of Asphalt Binder

Based on the findings of previous literatures regarding tribology of asphalt binders, the following thoughts are suggested for future research direction:

- The coefficient of friction can be used for the determination of production temperatures of WMA technology. It might be possible to specify different ranges of the coefficient of friction for the determination of production temperatures of WMA technology and polymer modified binder.
- It can be suggested that tribological characterization may be used to determine the optimum dosage of warm mix additive.
- Relationship between the workability of mix and lubricating behavior of asphalt binder can be developed for a better understanding of the mechanism related to WMA technology.
- As long as the tribological characterization of the asphalt binder is concerned, the aggregate substrate of different surface roughness can be used to determine the effect of roughness on the frictional characteristics of asphalt binder. In the future, for the determination of surface roughness, a stylus profilometer or atomic force microscopic technique can be used to measure and quantify surface roughness parameters for the aggregate substrates. More efforts will be needed for identifying the best representative roughness parameter.
- Furthermore, friction between aggregate and asphalt binder at high service temperatures (40 ˚C-70 ˚C) might be related to the permanent deformation of pavement. Therefore, tribological characterization may be used to predict the pavement's rutting performance.
- Finally, if the tribological test fails to characterize the asphalt binder, it is better to perform the tribological test on mastic, as it is an actual binder in an asphalt mixture.

In summary, tribological characterization provides a better understanding of the mechanisms involved, which may encourage the pavement industries to use sustainable and green materials to achieve sustainable development. The ultimate goal of tribology is to understand and freely implement WMA technology to encourage innovation and competition.

2.7 Physical Properties of WMA Modified Binders

Many studies evaluate the physical properties of warm mix modified binders using various test such as penetration test, softening point, viscosity test, and true failure temperature using DSR. The studies showed that physical properties of warm mix modified binder is significantly affected by amount of additive, type of additive, and type of base binders used for the modification. From the previous studies, it has been found that the binder modified with wax additive (organic) showed the better improvement in the physical properties of base binders due to crystallization effect of wax present in the additives [54]. At elevated temperatures surpassing their respective melting points, organic waxes undergo a congealing phenomenon, wherein they undergo transition from a molten state to a solid state. This congealing process is attributable to the ability of the waxes to re-establish a lattice crystalline structure while cooling [196]. This lattice formation causes interlocking arrangements within the wax matrix, thereby increasing the stiffness of asphalt binders. On the other hand, the addition of chemical additives to asphalt binders resulted in either lower values or similar physical characteristics compared to base asphalt binders [197]. However, the literature review did not provide a complete conclusion on the influence of chemical additives, regardless of the source and grade of asphalt binder. This might be due to only physical interaction of chemical additives with the base binder. From the literatures, it has been found that the extent of improvement in physical properties is majorly depends on the base type of base binders, irrespective of type of warm mix additives. Table 2-12 shows the effect of WMA additives on the physical properties of different base asphalt binders [76,101,105,197–213].

Table 2-12. Effect of WMA additives on physical properties of asphalt binders

Physical properties	**WMA additives (WMA Technology)**				
	Viscosity Grade Binder				
	Sasobit (Organic)	**Asphaltant A (Organic)**	**Rediset (Chemical)**	**Iterflow (Chemical)**	**Evotherm (Chemical)**
Softening Point	Increase	Increase	Marginal Increase	Marginal Increase	Decrease
Penetration Value	Decrease	Decrease	Marginal Decrease	Marginal Decrease	Increase
Absolute Viscosity	Increase	Increase	Marginal Increase	Marginal Increase	Decrease
True Failure Temperature	Increase	Increase	Marginal Increase	Marginal Increase	Decrease
Modified Binders					
Softening Point	Increase	-	No change	No change	Decrease
Penetration Value	Decrease	-	No change	No change	Increase
Absolute Viscosity	Increase	-	No change	No change	Decrease
True Failure Temperature	Increase	-	No change	No change	Decrease

2.8 Performance of WMA Modified Binders

2.8.1 Rutting Performance

The lower production temperature associated with Warm Mix Asphalt (WMA) could potentially impact the asphalt mixture's susceptibility to rutting, as the binder undergoes less oxidation at lower temperatures compared to Hot Mix Asphalt (HMA) [21,22,201]. Although short term aging of asphalt binders generally assures stiffening, which may be advantageous in resistance to permanent deformation, the reduced aging in WMA modified asphalt binders could increase the rutting potential, depending on the type of WMA technology [214,215]. However, in the field of WMA, certain warm technologies like organic additives (Sasobit) have the capacity to counterbalance the reduced stiffness of the asphalt binder, thereby mitigating this concern [49]. Table 2-13 presents the inferences from past literatures on the rutting performance of WMA modified asphalt binders. These studies evaluated the rutting potential of warm mix modified binder using Superpave rutting parameter G*/sin δ and PG plus parameter non-recoverable creep compliance (J_{nr}) and % Recovery (%R) under unaged and short-termed aged condition. The studies showed that rutting potential of warm mix modified binder is significantly affected by amount of additive, type of additive, aging temperature and duration of aging. Previous study conducted by Bennert et al. [21] revealed that the use of WMA technology reduces the high-temperature performance grade by 3^{o}C when the aging temperature of the binder is lowered by 30^{o}C. Various other researchers have also reported inconsistent rutting performance of WMA modified asphalt binder, as shown in Table 2-13. The overall conclusion derived from the review of literatures is that the organic WMA modified asphalt binder showed better rutting performance with respect to the control asphalt binder. This can be attributed to crystallization effect of wax present in the organic additive which impart stiffness to the asphalt binder. On the other hand, binder modified with foaming and chemical additives showed the poor performance against rutting due to reduced stiffness as result of reduced aging. The use of Aspha-min, Rediset, Evotherm, and Advera showed lower or equal rutting resistance [67,119,135,197,216]. Past studies also found that the rutting performance of WMA modified binder is function of amount of additive and the type of WMA technology used for the modification.

Table 2-13. Results of previous studies on the effect of WMA additives on rutting

Author	Additive and its Dosage	Rutting Parameter	Aging	Inferences
Xiao et.al. [217]	(Cecabase-0.3–0.4%, Evotherm-0.5% , Rediset-1.5%, and Sasobit-1.5%)	G*/sin δ	RTFO	• Aging process increases the rutting resistance of binder. The effect is more in case of Sasobit modified binder due to crystallization while chemical additive shows significant improvement in rutting performance. • The improvement in rutting performance is also depends on the source of binder.
Ragni et al. [216]	Evotherm (0.4%)	J_{nr} and %R	RTFO (163 and 120^o C)	• Aging at lower temperature results into higher value of J_{nr} and lower value of %R. • The value of J_{nr} is decreases with increase in aging temperature. • The addition of chemical additives showed less resistance to rutting.
Abbas et al. [218]	Foaming (1.8%)	G*/sin δ	RTFO/ PAV	• Foaming reduces the aging of asphalt binder which turn in shows the lower value of G*/sin δ. • In short, foaming showed less resistance to rutting in comparison with HMA due to less aging. • Similar trends are observed for PAV aged binder. However, PAV aged binder showed more

				resistance to rutting than RTFO aged binder due to prolonged aging.
Kim et al. [219]	Organic additive (1.5%)	G*/sin δ	RTFO	• The wax additive has positive impact on rutting behaviour of binder. • The wax modified bitumen showed higher rutting resistance than neat binder regardless of aging
Singh et al. [220]	Zycotherm (0.1%)	J_{nr} and %R	RTFO	• The chemical additive does not have impact on value of J_{nr} and %R. However, WMA modified bitumen is highly temperature susceptible depending on the type of the base binder. • After aging WMA modified binder does not have any negative effect on rutting performance of binder.
Kheradmand et al. [221]	Sasobit (1.5 and 3.5%)	G*/sin δ	RTFO	• Aging increases the rutting resistance of Sasobit modified binder in comparison with neat binder due to partial oxidative hardening. • After RTFO aging Sasobit modified binders increases the elasticity of the binder results into better rutting performance.
Abdullah et al [222]	Chemical (1,2,and 3%)	J_{nr} and %R	RTFO	• The chemical additive does not have any effect on rutting performance

				of binder. However, higher dosage of additive may have positive impact on rutting behaviour.
Abbas et al. [223]	Foaming (1.8%)	G*/sin δ	RTFO/PAV	• The value of rutting parameter of PAV aged sample is higher than RTFO aged sample. • The WMA modified bitumen showed less resistance to rutting in comparison with HMA due to reduced aging.
Sadeq et al. [224]	Advera ((4.8–5.0 %by weight of the binder)	G*/sin δ	RTFO (163ºC for 45 min and 85 min)	• Advera does not showed any significant change in rutting performance of binder. However, some change is observed with higher aging duration. • After complete short-term aging, Advera showed roughly similar percentage of recovery to the unaged binder. • After RTFO Aging, Advera has little impact on reduction of J_{nr} value.
Sadeq et al. [224]	Sasobit (2%)	G*/sin δ	RTFO (163ºC for 45 min and 85 min)	• After RTFO aging, Sasobit modified binder shows increase in rutting resistance of binder. • G*/sinδ value increases with increases in aging duration. • Sasobit significantly lowered the unrecovered creep compliance and increase %R in

				comparison with neat binder. • Sasobit modified binder showed better rutting performance as compared to base binder.
Ragni et al. [225]	Chemical (PMB+0.4%)	J_{nr} and %R	RTFO (120 °C and 163 °C)	• The reduction of the RTFO aging temperature from 163 to 120 °C reduces the value of non-recoverable creep compliance and increase %R for all the binders. • Without additives, there is no effect on J_{nr} value after aging at 120°C whereas reduction in J_{nr} is significant after aging at 163 °C. • Addition of additives to the binder increase the value of J_{nr} and reduces %R after aging in comparison with neat binder. • The additives showed less resistance to permanent deformation because of reduced aging. • The study revealed that the type of chemical additive and aging temperature has significant impact on recoverable behaviour of binder.
Iwański et al. [226]	PMB+synthetic wax (1.5%, 2.5% and 3.5%) PMB+fatty amine	G*/sin δ	RTFO (135°C)	• Binder containing synthetic wax is more resistance to rutting than binder modified with fatty amine. However,

	(0.3% and 0.6%)			both additives cause reduction in value of G */sin δ after aging.
Banerjee et al. [102]	Sasobit (VG30+3%, PMB+3%)	G*/sin δ	RTFO (115 and 163°C)	• Sasobit-modified binders show significantly higher values of G*/sin δ at both the aging temperatures in comparison to control binders. • This increase in rutting resistance of binders containing Sasobit is attributed to the presence of wax crystals in the binders.
Banerjee et al. [102]	Rediset (VG30+3%, PMB+3%)	G*/sin δ	RTFO (115 and 163 °C)	• Rediset modified binder is more susceptible to rutting due to reduced aging. This is clearly observed in reduction of G*/sin δ values.
Banerjee et al. [102]	Evotherm (VG30+0.5%, PMB+0.5%)	G*/sin δ	RTFO (115 and 163 °C)	• Evotherm based warm binders aged at 163°C and at a lower temperature showed comparable values of G*/sin δ to that of the control binder aged at 163°C.
Arega et al. [227]	Sasobit (1.5%)	G*/sin δ	RTFO (143°C)	• Sasobit-modified binders show similar or higher values of G*/sin δ after aging in comparison to control binders.
Arega et al. [227]	Evotherm 3G (0.5%), Evotherm DAT (5%), Cecabase RT (0.4), Rediset WMX (2%)	G*/sin δ	RTFO (143°C)	• Chemical- or surfactant-based additives shows similar or reduced value of G*/sin δ after aging in comparison to control binders. This indicates higher

				rutting susceptible of chemical- or surfactant modified bitumen.
Arega et al. [227]	Sasobit (1.5%)	J_{nr} and %R	RTFO (143°C)	• Sasobit-modified binders show similar or lower values of J_{nr} after aging in comparison to control binders. • Sasobit modified binder improved the recovery behaviour of base binder. • Sasobit modified binder shows higher resistance to rutting.
Arega et al. [227]	Evotherm 3G (0.5%), Evotherm DAT (5%), Cecabase RT (0.4), Rediset WMX (2%)	J_{nr} and %R	RTFO (143°C)	• Chemical- or surfactant-based additives shows similar or higher value of J_{nr} after aging in comparison to control binders. • The addition of chemical additives showed reduced recovery of base binder. • This indicates higher rutting susceptibility of chemical- or surfactant modified bitumen. • The reduced stiffness (or increased susceptibility to permanent deformation) in case of chemical additive is attributed to chemical interactions between the additive and the binder and this could not be explained solely by the reduced short-term aging.

Note: RTFO and PAV are the abbreviation for the rolling thin film oven and pressure aging vessel, respectively.

2.8.2 Fatigue Performance

The current school of thought within the asphalt industry is that the lower mixing and compaction temperatures in WMA technology leads to reduced aging in the asphalt binder, thus providing more flexibility to base binder which may improve the fatigue performance of the binder [34,228]. However, it is crucial to focus on the fatigue resistance of asphalt binder, especially with organic additives which can impart more brittleness the base binder. To date, limited data are available to draw a firm conclusion regarding the fatigue performance of WMA modified asphalt binder. Some studies discussed in Table 2-14 have reported the better fatigue performance of WMA modified asphalt binder due to reduced oxidative aging of an asphalt binder [10,201,225]. Previous studies have shown that the use of surfactant-based WMA additives in the base asphalt binder did not demonstrate any noticeable effect on fatigue resistance of the asphalt binder. Conversely, previous literature has documented both favourable and adverse effects associated with organic as illustrated in Table 2-14. Based on the studies mentioned in Table 2-14, it can be concluded that even though adding organic additives might make asphalt more prone to fatigue cracking, the choice of using WMA is still up for debate. We need more studies to understand how well WMA performs against fatigue by considering factors like dosage of warm additives and the temperature during production.

Table 2-14. Results of previous studies on the effect of WMA additives on fatigue cracking.

Reference	**Additives (Technology)**	**Performance parameter**	**Inferences**
Mo et al. [131]	(Organic and Chemical)	Critical strain energy release rate (J_c)	• WMA mixture shows better fracture resistance
Leng et al. [229]	Evotherm and Rediset (Chemical)	Critical strain energy release rate (J_c) and ITS	• WMA mixture shows better or equal fatigue resistance as compared to HMA

Shivani Rani et al. [230]	(Chemical)	G*×sinδ	• Due to reduced oxidative aging, the fatigue resistance of WMA is higher than HMA
Aniket et al. [34]	Sasobit (Organic) Rediset (Chemical) Advera (Water based)	N_f (LAS Test)	• WMA shows higher or equal fatigue life compared to HMA
Hamzah et al. [58]	Rediset (Chemical)	G*×sinδ	• Improvement in fatigue life
Singh et al. [231]	Sasobit (Organic) Evotherm (Chemical) Advera (Water based)	N_f (LAS Test)	• Chemical additives improved the fatigue life of binder due to reduced aging. • Sasobit modified binder showed slightly lower fatigue life due to higher stiffness imparted by crystallization effect of wax present in it.
Behl et al. [232]	Sasobit (Organic) Evotherm (Chemical) Rediset (Chemical)	N_f (LAS Test)	• Addition of chemical warm mix additives decreased stiffness, resulting in greater improvement in fatigue life, as measured by Nf values. • Sasobit modified binder showed no impact on fatigue life of base binder due to reduced aging. • The fatigue life of WMA modified binder was found to be function of base binders. • The effect of WMA additives was found to be more prominent with polymer modified binders.
Wang et al. [233]	Wax type WMA (Organic) Chemical WMA	Stiffness (G*)	• Both wax-based and chemical-based additives used in Warm Mix Asphalt (WMA) slightly improved the fatigue life of the original asphalt. • The inclusion of a wax-based additive made the

			base asphalt stiffer, resulting in higher stiffness and slower relaxation. This is likely because the wax crystallizes in the binders at lower temperatures, leading to increased stiffness. Conversely, the addition of a chemical Warm Mix Asphalt (WMA) additive softened the base asphalt by reducing its stiffness.
Kumar et al. [234]	Organic Additive Chemical Additive	N_f (LAS Test)	• The fatigue life increases with the addition of Warm Mix Asphalt (WMA) additives compared to the control binders.
Abdullah et al. [235]	Chemical Additive	G*.sinδ	• The chemical additives improved the fatigue resistance of binder • The improvement in fatigue performance can be due to the softening of asphalt binder due to chemical additives.
Zaumanis et al. [236]	Rediset	G*.sinδ	• The evaluation of G*. sinδ for Rediset showed that this chemical additive has almost no effect on this property.

2.8.3 Moisture Sensitivity of WMA Modified Binders

The primary challenge associated with WMA technology is their moisture sensitivity. This arises due to the lower production temperature, which results in inadequate drying of water trapped within the aggregate. Consequently, this weakens the interface and adhesive properties between the aggregate and the asphalt binder. As per the previous literature [21,237,238], WMA mixtures perform well against rutting and fatigue failures; however, adding WMA additives increased the sensitivity of asphalt mixtures toward moisture damage. This is attributed to the improper drying of aggregates at lower production temperatures. Moisture damage is considered one of the primary modes of failure in asphalt pavements, irrespective of the technology type (HMA and WMA). The moisture intrusion causes adhesion loss (between asphalt binder and mineral aggregates) or cohesion loss (within asphalt mixture components). These losses (adhesion/cohesion) are associated with the bond strength (BS) of asphalt binder and mineral aggregates. Past studies [239,240] reported that moisture penetration affects the bond strength and accelerates other distresses, such as rutting, fatigue, raveling, and potholes. Thus, it is imperative to understand the complex phenomenon of moisture damage and its associated factors. Although various factors lead to moisture-induced damage, the properties of asphalt mix components, such as aggregate source and asphalt binder grade, are the most critical ones [241]. Variability in aggregate sources and their interaction with different asphalt binder grades may significantly affect their bonding behaviour in the presence of moisture. Such an effect becomes more critical when combined with WMA additives as the corresponding reduction in production temperatures depends on the combination of aggregate and asphalt binder [242,243]. Table 2-15 briefly reviews the response of WMA modified binder against moisture damage evaluated using bond strength test. The effect of WMA technology on different moisture sensitivity parameters are shown in Table 2-16. The overall results indicated that moisture sensitivity of WMA mixtures is more critical for foaming-based technologies, followed by organic and chemical-based agents. This is because foaming-based additives such as Aspha-min and Advera consist of residual moisture, which is difficult to evaporate after mixing. Considering aggregate type, siliceous aggregates were more prone to moisture damage. In contrast, the aggregate with high iron oxide and calcium oxide was suitable for moisture-resistant asphalt mix, irrespective of WMA technology. Past studies [244,245] have also shown that the base binders used for WMA modification impact the moisture resistance of the WMA modified asphalt binders. In addition, it has been shown that the extent of moisture damage is dependent on the type of WMA technology, type of aggregates, regional climatic conditions and loading conditions[239,246,247].

Table 2-15. Inferences from past studies on the bonding behaviour of WMA mixtures

References	WMA Additive	Aggregate Type	Asphalt Binder	Inferences
Mogawer et al. 2011 [248]	Advera, Evotherm, Sasobit, and Sonnewarmix	Limestone	PG 64-22	• Sasobit significantly improved the BS value, particularly in the dry state. • The difference in BS value with other additives was negligible. • The addition of WMA additives did not negatively affect the moisture resistance of asphalt mixtures.
Alavi et al. 2012 [122]	Foaming, Surfactant, and Chemical based viscosity reducer	Granite and Rhyolite	PG 64-22 and PG76-22 (SBS)	• Effect of modification is a function of aggregate mineralogy. • Viscosity reducer showed higher BS in comparison to other WMA additives. • Chemical and surfactant additives improved the moisture resistance.
Zhang et al. [249]	Rediset	Limestone and Granite	40/60 PEN	• Aggregate type has no significant effect on the BS. • The addition of Rediset improved the bond between the aggregate and asphalt binder at all the test temperatures (-10, 10, and 40°C). • Rediset acts as an antistripping agent, resulting in improved moisture resistance.
Liu et al. [250]	Foam	Granite	SBS	• Higher foaming content is unfavorable for BS. • Foaming water tends to be entrapped at the interface of asphalt and aggregate, hence reducing the BS. • Residual foaming water in asphalt mixtures leads to reduced moisture stability. • The change in moisture sensitivity may be due to a chemical reaction between foaming water and asphalt binder.
Habal and Singh [251]	Sasobit, Advera, and Rediset	Basalt	VG30	• The addition of any WMA additive lowered the bond strength ratio (BSR) value.

				• Sasobit showed higher BSR among the WMA additives, followed by Advera and Rediset.
Habal and Singh [243]	Sasobit, Advera, and Rediset	Limestone and Granite	VG30	• BS increased with the addition of Sasobit. • The addition of Rediset and Advera reduced the BS, irrespective of aggregate type and conditioning process. • Advera displayed the highest BSR with granite, whereas it showed the worst performance with limestone. • Similarly, Sasobit showed higher moisture resistance with limestone but failed to resist moisture damage with granite. • Limestone showed higher BS and BSR in comparison to granite.
Ahmed et al. [252]	Sonnewarmix	Not mentioned	60/70 PEN and CRMB	• The incorporation of WMA increased the moisture resistance, as indicated by higher BSR. • The extent of improvement was found to be higher in CRMB.
Bo Li at al. [253]	Fischer-Tropsch (FT) wax and Chemical WMA additive	Not mentioned	SBS modified binder	• The addition of wax-based warm additive reduces the adhesion of warm mix recycled SBS modified asphalt due to the reduction in polar component.

Note: SBS and CRMB refer to styrene butadiene styrene and crumb rubber modified binder, respectively. PEN and PG indicate penetration grade and performance grade, respectively.

Table 2-16. Effect of WMA technologies on various moisture sensitivity parameters.

Author	**Additives (Technology)**	**Performance parameter**	**Inferences**
Thomas Bennert et al. [21]	Sasobit (Organic) Rediset (Chemical)	TSR	• WMA mixture indicates poor performance against moisture damage
Feipeng Xiao et al. [254]	Sasobit (Organic) Asphamin (Water based)	TSR	• WMA mixtures show lower TSR value, indicating higher moisture susceptibility
Haritha Malladi et al. [238]	Sasobit (Organic) Advera (Water based)	TSR	• WMA technologies are more susceptible to moisture damage
Alavi et al. [247]	Water-bearing mineral (foaming)	Bond Strength	• Due to reduced temperatures, WMA showed increased moisture susceptibility

	solid pelletized surfactant additive (Chemical) Viscosity Reducer (Organic)		because of poor bonding between the aggregate and asphalt binder.
Shivani Rani et al. [230]	Chemical	Surface Free Energy ratio (SFE)	• WMA Shows better moisture damage resistance. However, improvement is depends on aggregate type.
Mogawer et al. [248]	Advera (Water based) Sasobi and Sonne warmix (Organic) Evotherm (Chemical)	Stripping Inflection Point and Bond Strength	• All WMA additives showed a reduction in bond strength after wet conditioning indicating lower resistance against moisture damage. However, this reduction depends on the type of WMA additive.
Ayyanna Habal et al [243]	Sasobit (Organic) Rediset (Chemical)	Surface Free Energy ratio (SFE) and Bond strength ratio (BSR)	• Indicating negative impact of additives on the bond strength in wet condition. However, the performance is majorly depends on type of aggregates and additives. • Rediset improved the bonding behaviour due to its antistripping properties.
Habal et al [251]	Sasobit (Organic) Rediset (Chemical)	TSR, Energy ratio (SFE) and Bond strength ratio (BSR)	• All these parameters showed that the resistance to moisture damage is deteriorated with addition of Sasobit. However, Rediset showed better performance due to its antistripping properties.
Oliveira et al. [120]	Zycotherm (Chemical)	TSR	• WMA additives showed better performance against moisture damage.
Ziari et al. [255]	Sasobit (Organic)	TSR	• TSR values showed poor performance of Sasobit against moisture damage.
Fakhri et al. 2013 [204]	Sasobit (Organic)	TSR	• Sasobit modified binder showed slightly lower value of TSR as compared to control mixture indicating higher moisture sensitivity.

Note: TSR and SFE indicate tensile strength ratio and surface free energy, respectively.

2.8.4 Aging Potential of WMA Technology

During the construction and in-service life of asphalt pavement, the asphalt binder is subjected to high heating temperatures, environmental oxygen and atmospheric moisture, leading to the oxidation of molecules and loss of volatile components [137,256,257]. This oxidation of asphalt binder is called as aging. Consequently, it affects the chemical composition and the rheological characteristics of the asphalt binder and may contribute to the premature deterioration of asphalt pavements [216,258]. Aging, in general, is a very complex phenomenon [259], and the complexities become more critical when WMA technologies are involved [260–262]. Aging generally occurs in two stages. The primary stage initializes at a very rapid rate during the production of the asphalt mixture and is referred to as short term aging (STA), whereas the second stage occurs after a certain service life of the pavement and is designated as long term aging (LTA) [259,263]. Although WMA 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 [37,223,261,264]. While offering reduced production temperatures, WMA technology minimizes the oxidative aging of the asphalt binder, which may possibly affect the structural performance of the binders. The aging performance of the WMA technology is generally studied through by observing the changes in chemical composition of asphalt binder. Fourier transform infrared spectroscopy (FTIR) is often used to assess the variations in the chemical composition of asphalt binders after STA and LTA [35,215]. It is well known that the most significant functional groups affected by aging are the carbonyl group (C=O), and the sulfoxide group (S=O) [41,256]. After aging, the carbonyl group (C=O), and the sulfoxide group (S=O) peaks increases with increase in aging of binder. This can be due to the conversion of potentially active molecular compounds (such as benzyl hydrogen and aliphatic sulphide) into polar groups (carbonyls and sulfoxides respectively) when they react with oxygen [256,263]. The previous studies have shown that the use of WMA technology reduced the aging of the asphalt binder due to lower production temperatures offered by this technology [256,260].

Table 2-17 presents the inferences from past literatures on the aging of WMA technology. Figure 2-9 shows the improvement in aging indices with incorporation of WMA technology from past studies [216,218,225,260,265]. These studies also shown that the aging mechanism of WMA technology is a function of type of WMA technology, amount of temperature reduction, and type of base binder used for the modification. In summary, the findings of these studies indicate that the inclusion of Warm Mix Asphalt (WMA) additives did not negatively affect the characteristics of the asphalt binder as they aged.

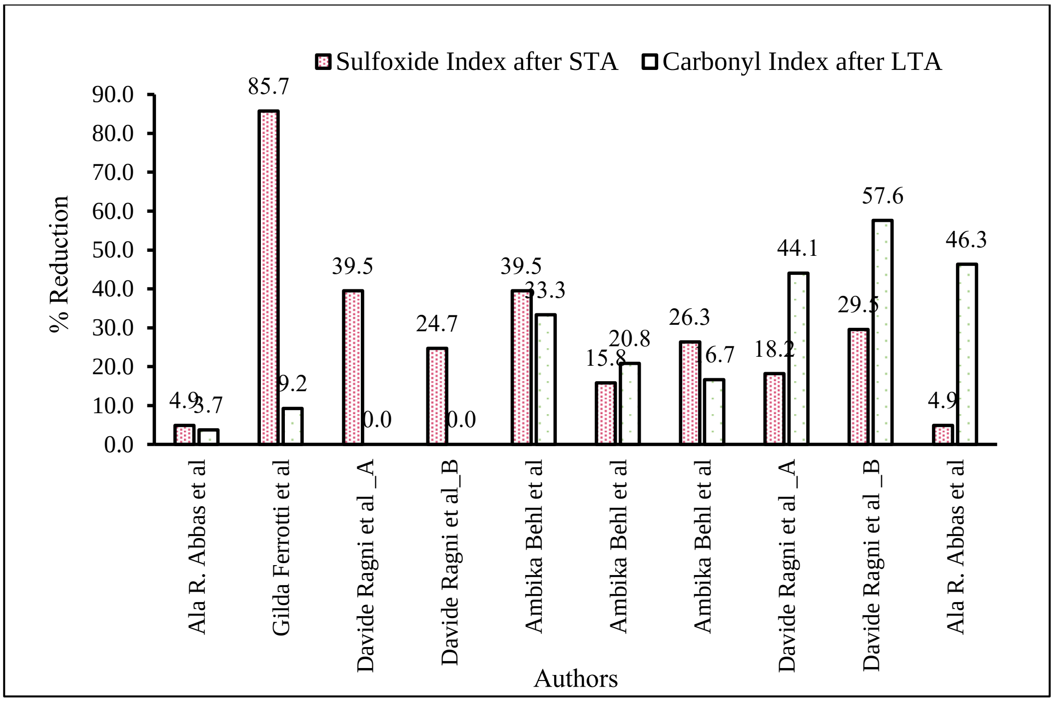
Table 2-17. Effect of WMA technology on aging of asphalt binder

Author	Technology	Short term aging simulation	Long term aging simulation	Key Findings
Abbas et al. [218]	Foaming (foaming water content of 1.8% by weight of the asphalt binder)	RTFO	PAV	• The carbonyl and sulfoxide indices offer improved quantification of aging effects. • In both RTFO and PAV aging processes, the carbonyl and sulfoxide indices indicate that foamed bitumen experiences less aging compared to HMA.
Ferrotti et al. [265]	The foaming process	RTFOT (123 and 163 °C)	PAV	• The variance observed between the RTFOT aging conducted at 123°C and 163°C could be linked to the extra duration between the RTFOT conditioning at 123°C and the subsequent FTIR measurement. • Carbonyl index showed a lower oxidation of WMA in comparison with HMA.
Ragni et al. [225]	Chemical additive (adding 0.4% (by	RTFO (120 °C and 163 °C)	-	• The study revealed that the Carbonyl index reaches zero after RTFO aging, whereas the Sulfoxide index rises with increased oxidation as the

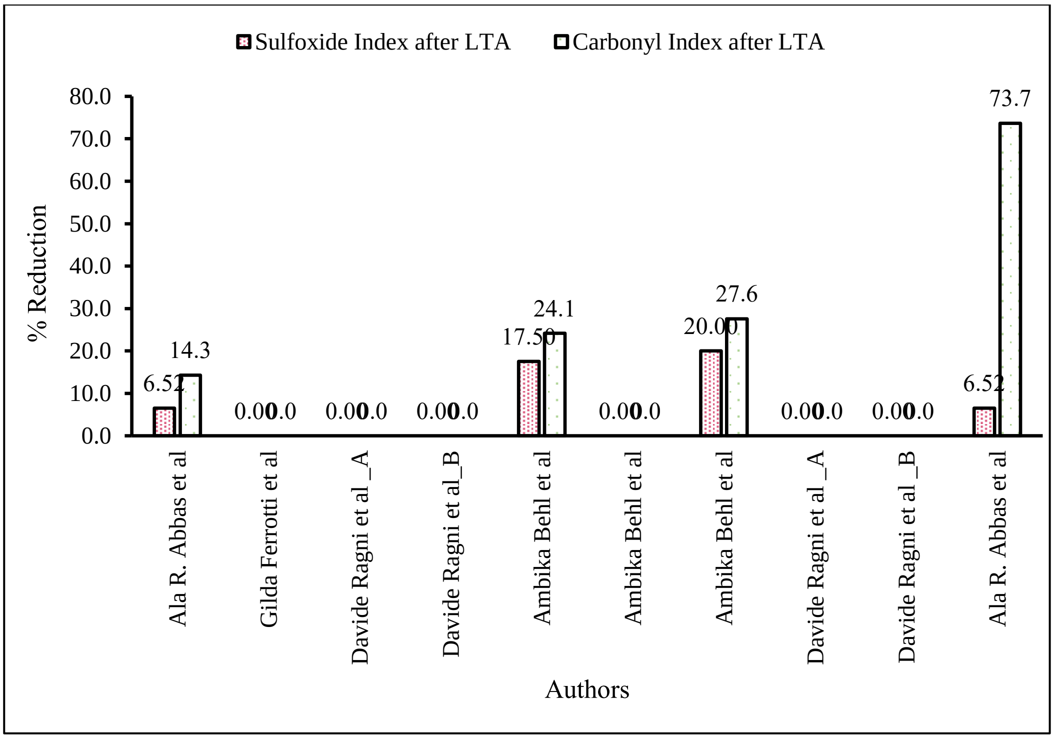
	binder weight)			RTFOT temperature escalates from 120°C to 163°C. • The WMA chemical additive exhibited a lower Sulfoxide index, indicating a reduced propensity for aging.
Banerjee et al. [102]	Organic (Sasobit: 3% by weight of Bitumen)	RTFO (115 °C and 163 °C)	PAV	• In both RTFO and PAV aging processes, Sasobit-modified bitumen demonstrates a decrease in Carbonyl and Sulfoxide indices, confirming the lower aging potential of the WMA-modified binder compared to the control binder.
Banerjee et al. [102]	Chemical (Rediset: 3% by weight of Bitumen)	RTFO (115 °C and 163 °C)	PAV	• Rediset exhibits a reduced aging propensity, as evidenced by lower Carbonyl and Sulfoxide indices after both the RTFO and PAV aging processes.
Banerjee et al. [102]	Chemical (Evothermt: 0.5% by weight of Bitumen)	RTFO (115 °C and 163 °C)	PAV	• The Carbonyl and Sulfoxide indices that Evotherm undergoes less oxidation compared to the neat binder during both RTFO and PAV aging processes.
Ragni et al. [216]	Chemical (0.4% by bitumen weight)	RTFO (120 °C and 163 °C)	-	• Higher Carbonyl and Sulfoxide index values indicate a more noticeable oxidation process. • The Carbonyl and Sulfoxide indices demonstrate that the RTFOT temperature notably affects bitumen oxidation, with greater aging observed at 163°C compared to 120°C. • Carbonyl and Sulfoxide indices verify that the incorporation of chemical additives generally alleviates the aging process compared to the base bitumen.
Xiao et al. [95]	Chemical: (0.3% Cecabase, 0.5% Evotherm, 1.5% Rediset (by bitumen weight)	RTFO	PAV	• The study revealed that Cecabase binder exhibits the lowest absorbance of the Carbonly (C-O) stretch, whereas the control binder demonstrates the highest absorbance.

				• Evotherm and Rediset also showed promising results of reduced aging. • The absorbance of the C=C stretch at spectral bands generated for various RTFO aged binders remained consistent irrespective of the type of WMA additive used. • The study also revealed that the absorbance values of the C=C remained similar after long-term aging for both WMA-modified and neat binder.
Xiao et al. [95]	Organic (Sasobit: 1.5 % by bitumen weight)	RTFO	PAV	• A slight variation in absorbance was noted in the C-O stretch and C-H bend regions for the Sasobit modified binder compared to the neat binder. • Sasobit modified binder was less prone to oxidation than neat binders as indicated by lower value of Carbonyl index.
Abdullah et al. [222]	Chemical (at 1%, 2%, and 3% (by weight of asphalt binder)	RTFO	PAV	• Research indicated that adding WMA modifiers to binders could reduce or delay the oxidative reaction of the binders, thereby enhancing the aging process. • After prolonged aging, warm mix modified asphalt displayed a slower aging rate than the control binder.
Kheradmand et al. [221]	Organic (Sasobit:1.5 and 3 % by bitumen weight)	RTFO	-	• Sasobit-modified bitumen exhibited a lower aging potential, as evidenced by the lower Carbonyl and Sulfoxide indices

Note: RTFO and PAV are the abbreviation for the rolling thin film oven and pressure aging vessel, respectively.



(a)



(b)

Figure 2-9. Percent reduction in Carbonyl and Sulfoxide index due to WMA technologies a) After short term aging b) After long term aging

2.9 Interaction of Polymer Modified Binder with WMA technology

The use of polymers in asphalt binders has been helpful in improving various engineering properties of asphalt pavements. These properties include enhanced resistance to rutting and thermal cracking, as well as reduced fatigue and stripping. Although the use of polymer modified binder provides several benefits but it demands a higher production temperature for the construction of an asphalt pavement [266–268]. This higher production temperature requires more energy in the production and placement of an asphalt mixture [269]. Besides the more energy consumption, it also increases harmful emissions and asphalt binder aging [270]. Also, the exposure of polymer modified binder to such higher temperature may lead to the degradation of polymeric network present in it [271,272]. Thus, asphalt paving industries are looking for a sustainable technology that can overcome the issues associated with polymer modified binders and thereby promote their use for constructing environment friendly asphalt pavements. Few studies showed that this problem of higher production temperature can be overcome with the implementation of WMA technology. WMA technologies offer a solution by reducing the viscosity or improving the lubricating behaviour of asphalt binders at lower temperatures, thereby allowing lower mixing and compaction temperatures [201,273,274]. The past studies also aim to explore whether WMA techniques can be effectively utilized to lower the construction temperatures required for polymer-modified asphalt pavements. The past studies also revealed that the use of WMA technology with polymer modified binder could potentially offer benefits such as energy savings, reduced emissions, and improved workability during construction.

Numerous studies have consistently found that the utilization of WMA technologies in Polymer Modified Bitumen (PMB) asphalt mixtures yields comparable or superior performance in terms of resistance to various types of distress [120,275,276]. Moreover, aside from enhancing mechanical properties, WMA concurrently reduces energy consumption and greenhouse gas

(GHG) emissions [10,118,277]. Some studies indicate that the overall reduction in energy consumption and harmful emissions is estimated to be around 16.7% and 33.3%, respectively, compared to conventional HMA. In various studies, Sasobit was incorporated into Polymer-Modified Asphalt (PMA). The findings revealed that PMA containing Sasobit exhibited higher values of G*, G*sin δ, and stiffness compared to control samples containing only polymers [278–280]. A total of 12 mixtures were prepared using Aspha-Min and Sasobit, among which four served as control samples without any WMA additives [278]. Multiple tests, including TSR, APA, resilient modulus, and indirect tensile strength after long-term oven aging, were conducted on these mixtures. The results showed that all PMB containing Sasobit and Aspha-Min met the Superpave mixture requirements regarding rutting and moisture susceptibility. In conclusion, it was found that the addition of WMA additives did not adversely affect the engineering properties of the mixtures. Moreover, the inclusion of Sasobit improved the storage stability of the PMB mixtures [281], and no molecular separation was observed [282,283]. The summary of effect of WMA additives on performance of PMB are shown in Table 2-18. Despite extensive research on understanding the interaction of WMA additives with polymer modified binders, there is limited literature available on quantifying the impact of WMA technologies on the mechanical performance of polymer modified binders. Consequently, a comprehensive experimental investigation on the interaction between PMB and WMA is recommended to encourage the adoption of warm mix inclusive polymer modified asphalt mixtures.

Table 2-18. Performance summary of PMB-WMA interaction.

Performance	**Key Findings**	**Reference**
Rutting performance	• Even though warm mix modified polymer-modified bitumen (PMB) mixtures are	[25,278,284–286]

	produced at lower temperatures compared to traditional hot mix asphalt (HMA), they demonstrate comparable or even superior resistance to rutting. • The findings also emphasizes the potential of warm mix technologies with PMB to improve the sustainability and effectiveness of asphalt pavement systems against rutting.	
Fatigue cracking	• The WMA additives facilitate easier mixing and compaction at lower temperatures, while the PMB enhances the cohesive properties and structural integrity of the asphalt binder through polymeric network present in it. As a result, the asphalt mixture exhibits improved resistance to fatigue-induced cracking, making it more suitable for high-traffic pavements subjected to repetitive loading and thermal cycling. • Overall, the combination of WMA additives and PMB represents a promising strategy for enhancing the performance and durability of asphalt pavements, contributing to sustainable and resilient construction of flexible pavement.	[21,43,93,287]
Moisture sensitivity	• The addition of WMA to PMB increased the resistance to moisture damage.	[26,43,278,288–290]

	• This interaction between WMA and PMB reinforces the asphalt mix, rendering it more resistant to detrimental effects caused by water ingress and subsequent deterioration. • Polymeric network present in the polymer modified binder enhance bond strength at interface of aggregate and asphalt binder which subsequently improved the resistance against moisture damage.	

2.10 Field Project on WMA Technology

NCAT (National Centre for Asphalt Technology), USA

Two section N1 and E9 has been constructed in October 2005 using Warm Mix Asphalt (WMA) incorporating Evotherm on the NCAT (National Center for Asphalt Technology) test track [291]. The WMA mixtures incorporating Evotherm consisted of two base courses, each with a thickness of 2 inches, mixed and placed at a temperature around 110^{o}C. It was reported that the average rutting observed in sections constructed with Evotherm did not exceed 6 mm after subjecting to the 5.6 million Equivalent Single Axle Loads (ESALs) [291,292]. The study reported that the Evotherm did not affect the voulmetrics of asphalt mixture even at lower temperature.

Ohio Department of Transportation (DOT), USA

The Ohio DOT conducted demonstration project and built the test sections SR 541 using two WMA technologies: Asphamin and Sasobit [293,294]. Asphamin was added at 0.3% and Sasobit at 1.5% of the total binder. Environmental tests showed lower emissions (SO_2, NOx, VOCs, CO) for Asphamin and Sasobit compared to the control mix, indicating environmental benefits of WMA technologies. The test section showed similar field performance of WMA technology as compared to HMA.

Federal Highway Administration (FHWA), USA

Three sections were constructed at Wyoming under the supervision of FHWA division. Three sections covering approximately 7 miles were constructed using a control HMA mix, along with 8,750 tons of Advera warm mix and 7,450 tons of Sasobit warm mix in the field project [295,296]. Advera was added at 0.3% and Sasobit at 1.5% of the total binder. Results from this field trial have revealed that workers did not encounter any difficulties in handling the warm mix asphalt, and there were no indications of moisture susceptibility in the warm mixtures.

Missouri Department of Transportation, USA

In 2006, Missouri Department of Transportation used three warm mix technologies (Asphamin, Evotherm, and Sasobit) for construction of test section in Missouri to check the impact of lower production temperature on performance of asphalt mixture. A total of 7,000 tons of warm mix were placed with the field compaction temperature ranging between 100 and 120°C. The Sasobit showed lower rut depth as compared to the control mixture. The test section made of Evotherm and Asphamin showed satisfactory rutting performance compared to the control mixture [57,297,298]. The field section constructed using WMA technology showed smooth road surface and no bump were observed in trial section.

Texas, USA

In September 2007, Warm Mix Asphalt (WMA) was showcased at the American Public Works Association. A total of 3,000 tons of Evotherm warm mix were used to construct the final surface of the pavement [44,293,299]. The warm mix was prepared at temperatures ranging from 110 to 115°C and placed at 95°C. It was reported that the asphalt mixture was easily compacted in field at these lower temperatures without any difficulties. Measured densities were found to be comparable for both WMA and HMA sections. Additionally, no difference in performance was observed between the two types of asphalt sections.

Germany

Two runways has been constructed in Germany using stone matrix asphalt containing 3% Sasobit. It has been reported that the SMA mixture containing Sasobit showed superior compaction at temperature 30°C lower than HMA [292,300]. The rutting performance of runways were found to be superior as compared to the HMA.

Canada

Three trial sections of WMA utilizing Aspha-min zeolite has been constructed in Montreal, Canada. The Hot Mix Asphalt (HMA) control section was blended at 160°C, whereas the Aspha-min sections were mixed and laid at temperatures ranging from 130-135°C [301]. There were no reported difficulties encountered during the mixing, laydown, or compaction processes. After 2-3 years following construction, the performance of the Aspha-min section was found to be comparable to that of the HMA section [301].

United Kingdom

The M6 motorway near Birmingham, UK was getting worse quickly, but fixing it during busy times wasn't possible. So, repairs had to be done at night. They used a Sasobit to repair about 1 km of road over eight nights. This method let them compact the asphalt at lower temperatures [42,46]. As a result, the repaired section cooled down faster and could handle traffic sooner than usual. All three layers of the pavement has been laid at temperatures 20-30°C lower than HMA. The performance of repaired section was reported be satisfactory after several years of construction [46].

Norway

The initial field trial of the WAM-Foam process took place on a major road in Norway in 2000. Studies conducted on this trial between 2000 and 2003 revealed that the rut depths in WMA and HMA sections were equally similar [46,302]. However, air voids were found to be slightly higher for WMA.

China

In August 2007, Southeast University collaborated with Changzhou Traffic Engineering Co. to carry out a successful trial paving of Warm Mix Asphalt (WMA) mixtures on provincial road 340. By September 2007, Henan Yiyang Expressway Co., Ltd. utilized Evotherm DAT for paving middle and top layers in the test road on the Henan Zhubi expressway [4,303]. Throughout scientific research and engineering applications, relevant technical standards for WMA technology have been developed and continuously improved. From the research on field trials it has been reported that the performance of WMA pavement was similar to HMA even after several years of construction [4].

Brazil

A WMA mixture (using a surfactant technology) with asphalt rubber was evaluated in a field project in Sao Paulo, Brazil in 2010, together with a control section [304]. No issues were reported during the mixing and laying process of the WMA section. The WMA pavement was laid at reduced temperatures, resulting in fewer harmful fumes. Field compaction and performance for the WMA section was found to be similar to that of HMA section.

South Africa

The initial trial of WMA technology in South Africa was constructed in Durban in November 2008 [305]. The 2% Sasobit has been used in surface mixture for this trial section. A broad range of parameters, including ambient temperature, bitumen temperature, mix temperature, and burner fuel consumption, were closely monitored during the evaluation of trial section. Around 15-20% reduction in fuel consumption was observed during the evaluation. Moreover, comparable density to HMA was achieved at a compaction temperature 20-30°C lower than HMA [305,306].

India

Central Road Research Institute (CRRI) is one of the initial institutes to have started working on WMA technology in India [32]. Many wax and chemical based WMA additives have been tried and implemented in different roadway projects. It has been found that the fatigue and rutting behaviour of WMA additives resulted in positive rutting and fatigue performance even at lower temperature. A brief review of use of WMA in various projects in India have been presented by Kumar and Chandra [39]. The performance of these WMA mixes were found to be inconsistent with different type of WMA additives. 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. Literature review from India on 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 technology.

In summary, based on both field and laboratory performance evaluations, trial section of WMA technology demonstrates comparable or even superior performance in terms of resistance to rutting, and fatigue-related distress, workability, compaction, and density when compared to HMA sections. Numerous trials have showcased various advantages such as, reduced mixing and compaction temperatures, enhanced workability, and improved compaction efficiency. Countries like Germany, India, USA, China, Canada, and South Africa have reported that no significant difference in strength gain was observed over time between WMA and HMA. Moreover, it is anticipated that warm mix modified asphalt mixtures would exhibit increased durability depending on the type of WMA technology used for the construction. Field trials have shown positive results concerning construction and short-term performance of WMA technology. However, comprehensive data on the long-term performance of WMA field sections remains limited. Although many trials have been in service for 12-15 years or more, detailed published data is necessary to draw concrete conclusions about WMA long-term performance. The same has been reported in past literatures. Several agencies are actively engaged in assessing the short and long-term performance of constructed field sections through methods such as field cores and ongoing performance monitoring.

2.11 Summary

Based on the comprehensive literature review on WMA technologies, several conclusions can be drawn:

- **Temperature Reduction:** WMA processes allow for mixing and compaction of asphalt mixtures at temperatures 10-40°C lower than those required for Hot Mix Asphalt (HMA) production. This reduction in temperature is attributed to innovative processes and technologies implemented in WMA. The degree of temperature reduction achievable with WMA is influenced by the specific technology implemented, as well as factors such as mixture type and climatic conditions. Different WMA techniques may result in varying temperature reductions.
- **Compatibility with Other Technologies:** WMA can be effectively used in conjunction with other asphalt technologies such as Polymer Modified Bitumen. This compatibility enhances the sustainability and performance of asphalt mixtures.
- **Determination of Production temperatures:** A plethora of previous studies showed that viscosity being the common factor in all the proposed methodologies for the evaluation of mixing and compaction temperature. There has been a continuous debate on the reliability of viscosity based methods for determination of MT and CT for WMA. Past studies have 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. This reduction in friction leads to improved workability in the asphalt mixture. Therefore, it is advisable to directly assess production temperature based on workability for WMA applications. With this consideration, the quantification of workability, and its use for evaluating production temperatures, have gained a lot of research interest. However, lack of standardized workability index restricts the engineers and researchers to evaluate the workability of asphalt mixtures quantitatively.

- **Tribology for WMA Technology:** Recently, tribology has been used as a tool for assessment of the WMA technology which promises several benefits compared to HMA. It is used to understand the mechanism by which WMA technology reduces the production temperature. Previous studies have shown that reducing the viscosity of asphalt binder using WMA technology aids in reducing mixing and compaction temperature. However, in recent studies, it has been found the reduction in viscosity offered by WMA additives cannot be used for quantifying the improved workability and lower production temperatures offered by the technology. It has been hypothesized that mixing and compaction temperature reduction using WMA technology is probably associated with the friction mechanisms at the contact zone between the aggregates and can be studied using the science of tribology.
- **Factors Influencing Tribology:** The main purpose of the tribology test is to determine the coefficient of friction for understanding the lubricating behavior of the material like WMA technology. The coefficient of friction (CoF) is not a material intrinsic property, but it is a property of a tribo-system that comprises at least two bodies in contact, along with the surrounding environment and the interface referred to as lubricant. In the pavement industry, asphalt binder acts as the interface (lubricant) between mineral

aggregates. The frictional behavior of asphalt binders during the test is influenced by various parameters such as normal load, sliding speed, surface roughness, temperature, etc. These factors should be taken into consideration while measuring the CoF.

- **Use of Tribology for Determination of MT and CT:** The production temperatures for WMA technology can be evaluated using the coefficient of friction measured from various tests available in literatures.
- **Performance of WMA Technology:** Previous laboratory studies conducted by researchers have shown that Warm Mix Asphalt (WMA) can achieve equal or superior rutting and fatigue resistance compared to conventional Hot Mix Asphalt (HMA), irrespective of the testing methods and analyses employed. Foaming technology is susceptible to moisture damage due to incomplete aggregate drying during production. Research indicates that incorporating anti-stripping agent can enhance the resistance of foam technology against moisture damage. On the other hand, chemical technology improve resistance to moisture damage by containing anti-strip properties. Organic technology showed similar or lower performance against moisture as compared to HMA. The mechanical performance of asphalt mixtures is significantly influenced by factors such as binder type, temperature reduction, additive type and its dosage, type of aggregate gradation, aging conditions, and prevailing climatic conditions. These investigations may be helpful to understand the consequence while implementation of WMA technology.
- **Field Performance:** Available field data indicate that there is no significant difference in performance between WMA and HMA. However, further investigation is required to fully understand the long-term behaviour of WMA.

Overall, the literature review emphasizes the potential of Warm Mix Asphalt as an innovative and sustainable alternative to traditional Hot Mix Asphalt, offering benefits such as energy savings, reduced emissions, and improved workability without compromising performance. Further research and implementation efforts are necessary to standardize the process to fully utilize the advantages of WMA technology in asphalt pavement construction.

2.12 Research Gaps

- Various methods are available for determination of mixing and compaction temperatures of viscosity grade binder and modified binders. However, no standard method has been reported in literature for the determination of mixing and compaction temperatures of WMA technology.
- Workability study has been carried out for the assessment of WMA technology. However, comprehensive data on the workability of WMA technology remains limited in the literature, primarily due to the lack of standardized testing protocols, variation in materials and additives used across studies and the regional focus of most investigations. Most existing studies focus on region-specific materials and technologies, resulting in limited generalizability of findings across different geographical and climatic contexts.
- Although tribology has been emerged as tool for assessment of workability of WMA technology. But the limited literature has been available regarding the use of tribology for WMA technology.
- The past literatures used Stribeck curve for the assessment of workability of WMA technology. However, the use of Stribeck curve to understand mechanism involved in reduction in production temperature of WMA technology is still a big question.
- The workability of WMA technology could be effectively studied using coefficient of friction but the information regarding this has been missing in literatures. In addition,

no method has been available in literatures based on coefficient of friction for determination of mixing and compaction temperatures of WMA technology.

- The effect of WMA technology on performance of asphalt mixture has been studied in past. However, the consequences of lower production temperature due to WMA technology on performance of asphalt mixture have not been studied with much rigor.
- Despite numerous studies investigating the performance disparities between WMA and HMA, an absolute conclusion regarding the fatigue life of WMA remains intangible. Specifically, it is uncertain whether the improved fatigue life of WMA results from the lower production temperature or the influence of warm additives.
- Till date, research on the adhesive bond strength between aggregate and binder has primarily been conducted indirectly, focusing on the mixture as a whole. In the realm of asphalt mixtures, bond strength test has been developed to assess the bond strength between aggregate and binder within the mixture. However, the use of bond strength test to assess the moisture sensitivity of WMA technology has been explored with limited experience.
- Field trials have demonstrated encouraging outcomes regarding the construction and short-term performance of WMA technology. Nevertheless, there remains a lack of comprehensive data concerning the long-term performance of WMA field sections. Despite numerous trials being in operation for longer period of time, the detailed published data is required to formulate definitive conclusions regarding the long-term performance of WMA.
- The various new WMA additive has been available in markets, but the laboratory and field performance of various new WMA additives like Asphaltan A, Asphaltan B, Licomont BS-100, and Iterflow etc. has been limited in literature.

- Past literatures have reported successful use of WMA technology for the lowering the production temperature of polymer modified binders. However, the comprehensive study the interaction between polymer modified binder and WMA technology has been limited in literature. In addition, the guidelines regarding the determination of mixing and compaction temperature of polymer modified binder containing WMA technology has been missing in literatures. Moreover, there is a need to investigate the impact of incorporating WMA additives on polymer-modified binders. This exploration is crucial because employing WMA additives has the potential to enable the heating of polymer-modified mixtures at reduced temperatures, thereby potentially resulting in energy savings.