CHAPTER 2

LITERATURE REVIEW

2.1 Preface

This chapter extensively reviews the laboratory and field performance of WMA binders and mixtures. The state-of-the-art review is to assimilate information on available WMA technologies, mix design of WMA, mixing and compaction temperatures, and the importance of workability analysis for WMA technologies. Details on the change in morphological, chemical, and physical characteristics of asphalt binder, with the addition of WMA additives, are gathered and compiled to understand the effect of WMA technologies more holistically. Additionally, the influence of WMA technologies on the rheological and mechanical properties of base asphalt binders and mixtures, respectively, are comprehensively reviewed and summarized. Interaction of WMA additives were different materials such as polymer modified binder (PMB), crumb rubber modified binder (CRMB), and reclaimed asphalt pavement material (RAPM) is also presented. Subsequently, previous works on life cycle cost assessment, greenhouse gas emissions, and economic benefits related to various WMA technologies are surveyed and analysed.

A systematic literature review (SLR) approach was adopted to quantify the number of published documents in the domain of WMA. SLR is an integral part of any research project that allows mapping and assessing the relevant intellectual work. It is generally used to specify the research questions, challenges, and further aid in defining the objectives of any study. As shown in Figure 2.1, different steps were followed to complete the SLR in the present study.

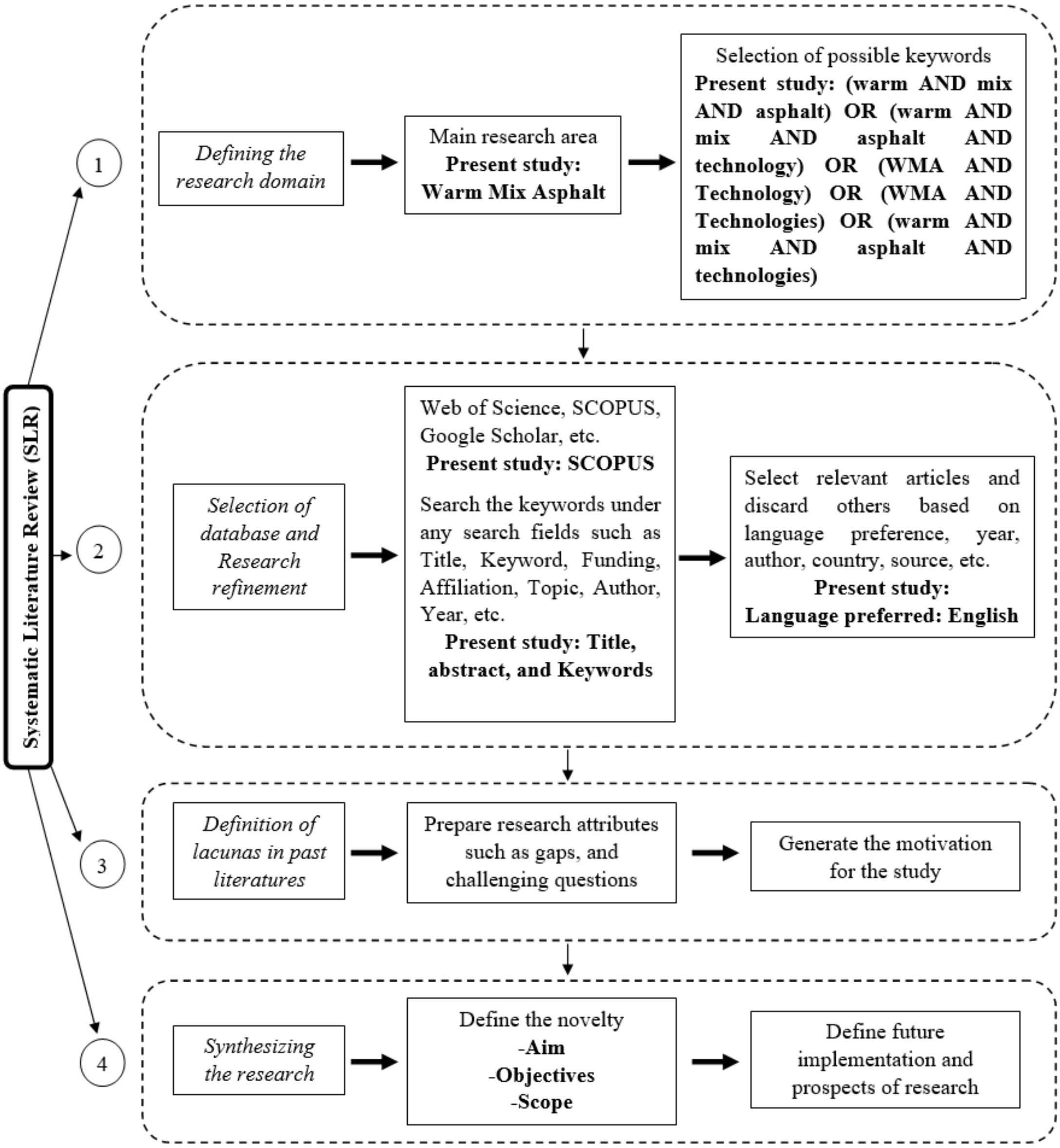


Figure 2.1 Four pillars (steps) of systematic literature review (SLR)

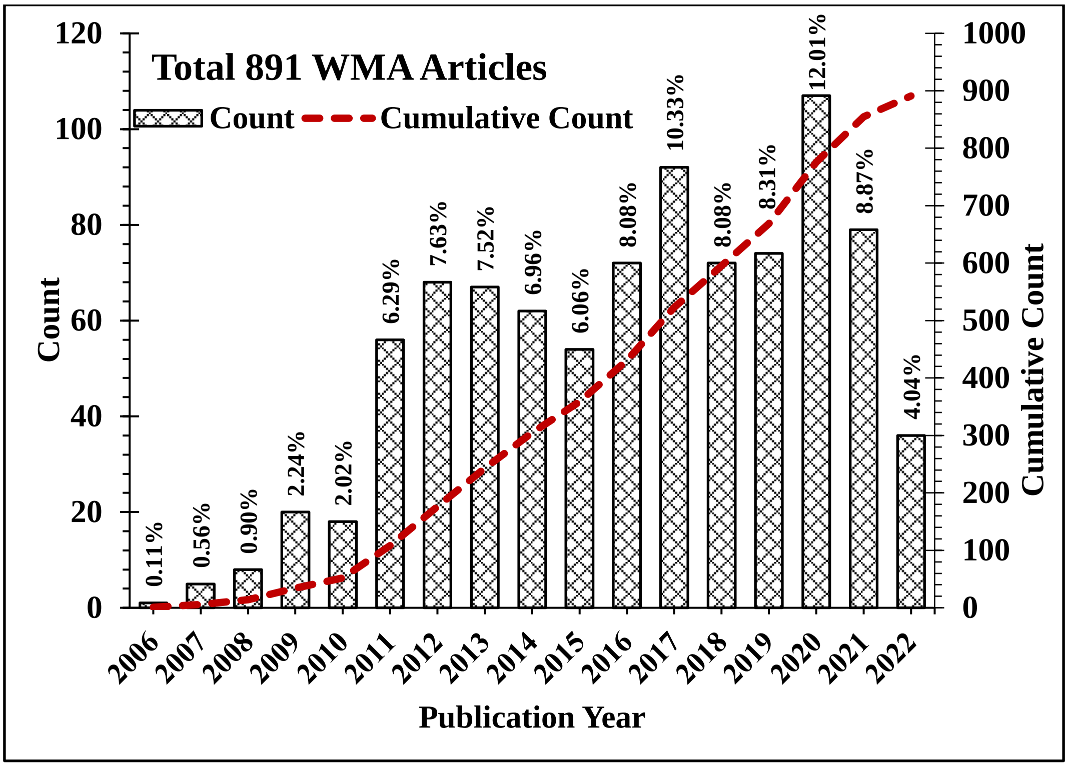
SLR, particularly in the present study, intends to fulfil the following key points/ideas on the application of WMA:

- To draw a complete picture of WMA technology for pavement construction based on different aspects such as mix design, performance, field investigations, and economic and environmental characteristics.
- To explore different techniques used to find the mixing and compaction temperatures of WMA mixtures.

- To understand the interaction of WMA technology with different alternative materials.
- To identify the benefits/limitations of WMA technology over the conventional HMA.
- To point out the research gaps and subsequently define the objectives for future expansion of the research work.

The first step is to define the research domain. The present study aims to explore the information about warm-mix asphalt technologies for pavement construction. From this perspective, several key terms were defined and subsequently searched using the Boolean operators under a bibliometric database platform. The searched key terms are listed in step 1. The second step is to select a bibliometric platform. In this study, SCOPUS was used for the SLR of WMA technologies. SCOPUS includes the information/data of a wide range of technical articles, review articles, conference proceedings, book chapters, and many others. Next, the predefined key terms were searched under a particular search field (such as article title, reference, funding, affiliation, country, language, source, etc.). In this study, the key terms were surveyed under article title, abstract, and keywords. Initially, all the documents were searched without any limitations or constraints, such as publishing year range, specific source title, particular language or country, etc. A total of 981 documents were retrieved after a comprehensive search based on the defined search criteria. Out of these documents, the irrelevant articles were omitted using excluding option. The excluding criteria include language (only articles in the English language were selected). Moreover, the abstract of the articles was reviewed to further eliminate/filter the irrelevant documents, which resulted in 891 relevant documents. These articles were thoroughly read and various key ideas and concepts were studied. The research questions and possible gaps relevant to the research domain were also identified. This comes under the third step of the SLR. The last step covers the descriptive analysis of contents in the form of research aim, objective, scope, summary, future prospects, and implementation of the proposed research work.

Figure 2.2 shows the count of documents based on the publication year, article type, publication titles, and country. Since there are over 100 publication titles and 70 countries with papers on the selected topic, it is very challenging to show all the captured data in a single graph. Therefore, one constraint was applied to further filter the documents for the purpose of graphical presentation. Figure 2.2 (c-d) only shows the data of publication titles and countries, where the count of documents is greater than 1% of the total count (891), for example: the countries and publication titles with a count greater than 9 are shown in respective figures. As shown in Figure 2.2a, there is a rapid increase in the count of documents after the year 2010. This sudden increase may be attributed to the popularity of WMA after the availability of long-term in-field performance of several WMA pavements [16,84]. After seeing/understanding the benefits of WMA, researchers started to explore different WMA technologies for pavement construction. However, till now, very less individual research work characterizes the overall performance starting from micro to macro scale at different stress/strain, temperature, and time/frequency conditions. Thus, there is a need for such rigorous studies on WMA in the coming future. Out of the total documents, there are 598 technical articles, 255 conferences, and 16 book chapters, whereas only 20 review papers are available in the database, as shown in Figure 2.2b. Few other articles, such as technical notes and short surveys (0.11%), were also published. Around 67% and 29% of the documents were identified as technical articles and conference proceedings, which provide information not limited to the characterization of WMA, their performance based on different test methods, and corresponding environmental life cycle assessment. Most of the articles were published in the journal of Construction and Building Materials (around 149 articles account for 17% of total documents), as indicated by a sudden hike in the bar corresponding to Construction and Building Materials (Figure 2.2c). The second top publisher title accounts for only 7%, which is around 10% lower than the top scorer (17%). Based on the country data, as shown in Figure 2.2d, it was analyzed that 36% of the articles, irrespective of their type, year, and publication titles, were from the United States (321 articles, highest among all the countries). It was identified that only 6% of the total research work on WMA was carried out in India, which is too less to comment/support their implementation on road infrastructure as per Indian conditions. These conditions include the climate and environmental condition, construction material and their corresponding price, testing protocol and their respective specifications, and many others. Hence, comprehensive research work is required to facilitate the application of WMA, produced at reduced temperatures based on Indian conditions. Some of the articles, randomly selected from different countries, years, publication titles, and article types have been summarized in the subsequent sections.


Total 891 WMA Articles
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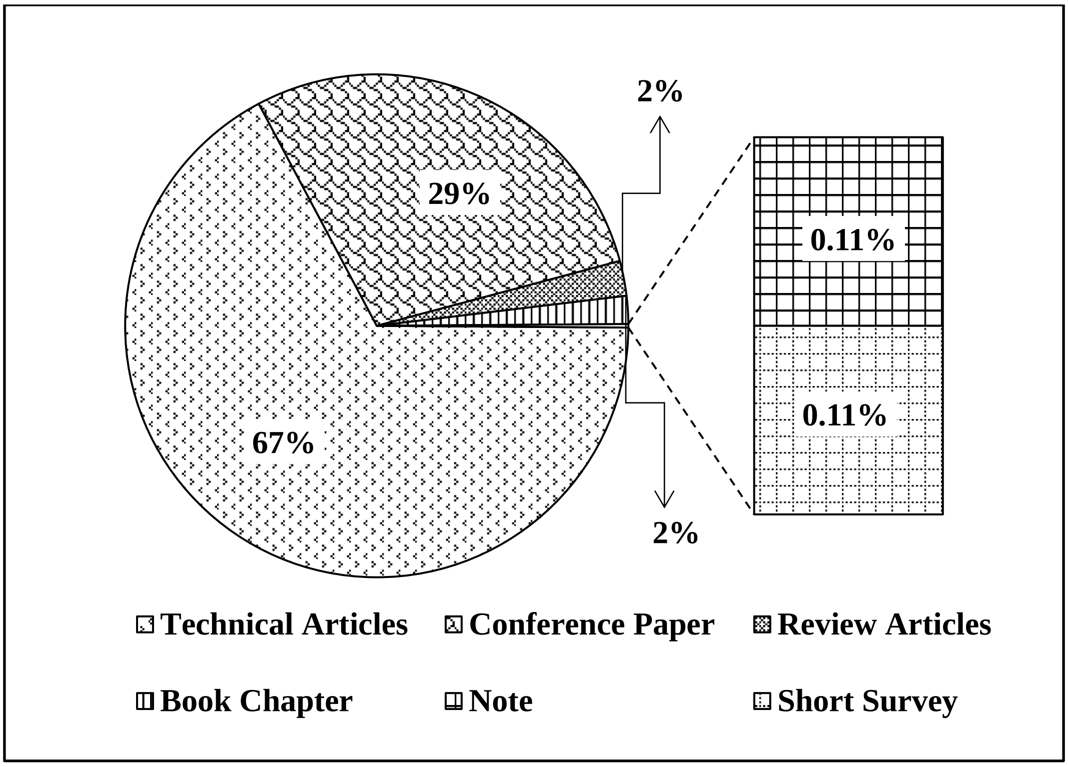
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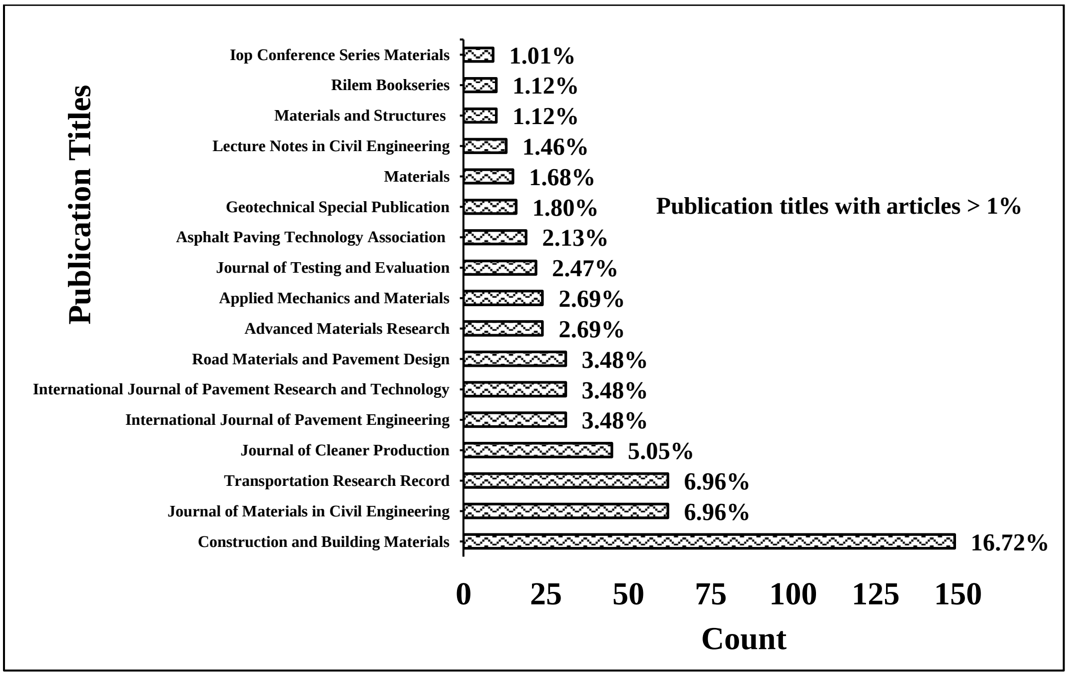
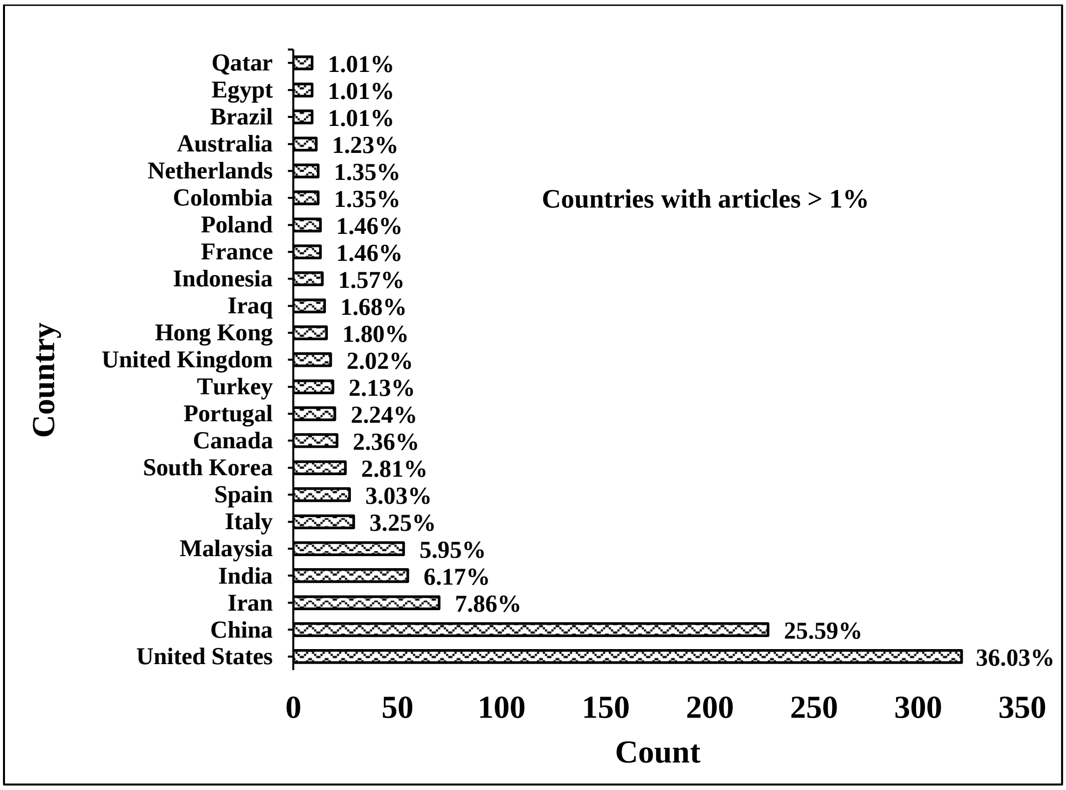


(c)



(d)

Figure 2.2 Systematic literature review based on different aspects (a) Publication year, (b) Article type, (c) Publication title, and (d) Country data

This chapter is divided into ten sections, of which this is the first one. The second section presented a brief introduction, evolution, and definition of WMA technologies. Mix design practices followed for WMA are placed in the third section. The third section also outlined the methodologies used to estimate production temperatures. Discussion on the mix design parameters and corresponding workability requirements are comprehensively detailed in the fourth section. The fifth section shows the influence of WMA additives on the morphological, chemical, and physical behavior of base asphalt binders. Comparisons between WMA and conventional materials based on rutting, fatigue, and moisture resistance characteristics are described in the sixth section. The performance of WMA obtained in different field studies is discussed in the seventh section. The eighth section covers the interaction between WMA additives and alternative materials, including PMB, CRMB, and RAPM. The ninth section provides a brief on the environmental and economic investigations carried out on WMA technologies. A summary of the overall review and the key conclusions derived from this chapter are provided in the last section.

2.2 Introduction to WMA

Conventional construction of hot mix asphalt (HMA) with higher production temperatures (>150˚C) results in increased fuel cost, hazardous fumes, and increased gaseous emissions [85–87]. Over the decades, there have been constant efforts in the HMA industry to conserve non-renewable resources and reduce environmental pollution [7,8]. This has led to a search for technologies that can reduce energy and fuel consumption to produce asphalt mixtures. The reduction in production temperatures is a step towards achieving this goal. Depending on the production temperature, the asphalt mixtures are broadly differentiated as cold mix asphalt (CMA), half warm mix asphalt (HWMA), warm mix asphalt (WMA), and conventional HMA, as shown in Figure 2.3.

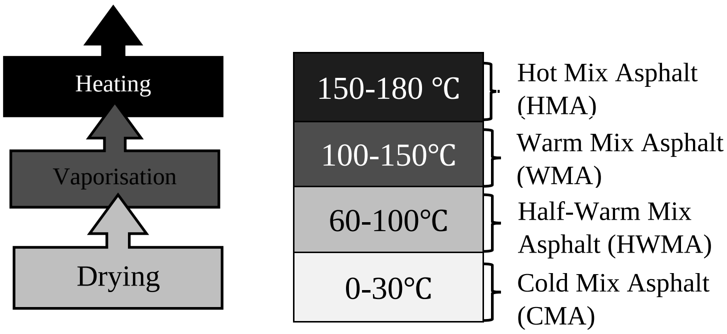


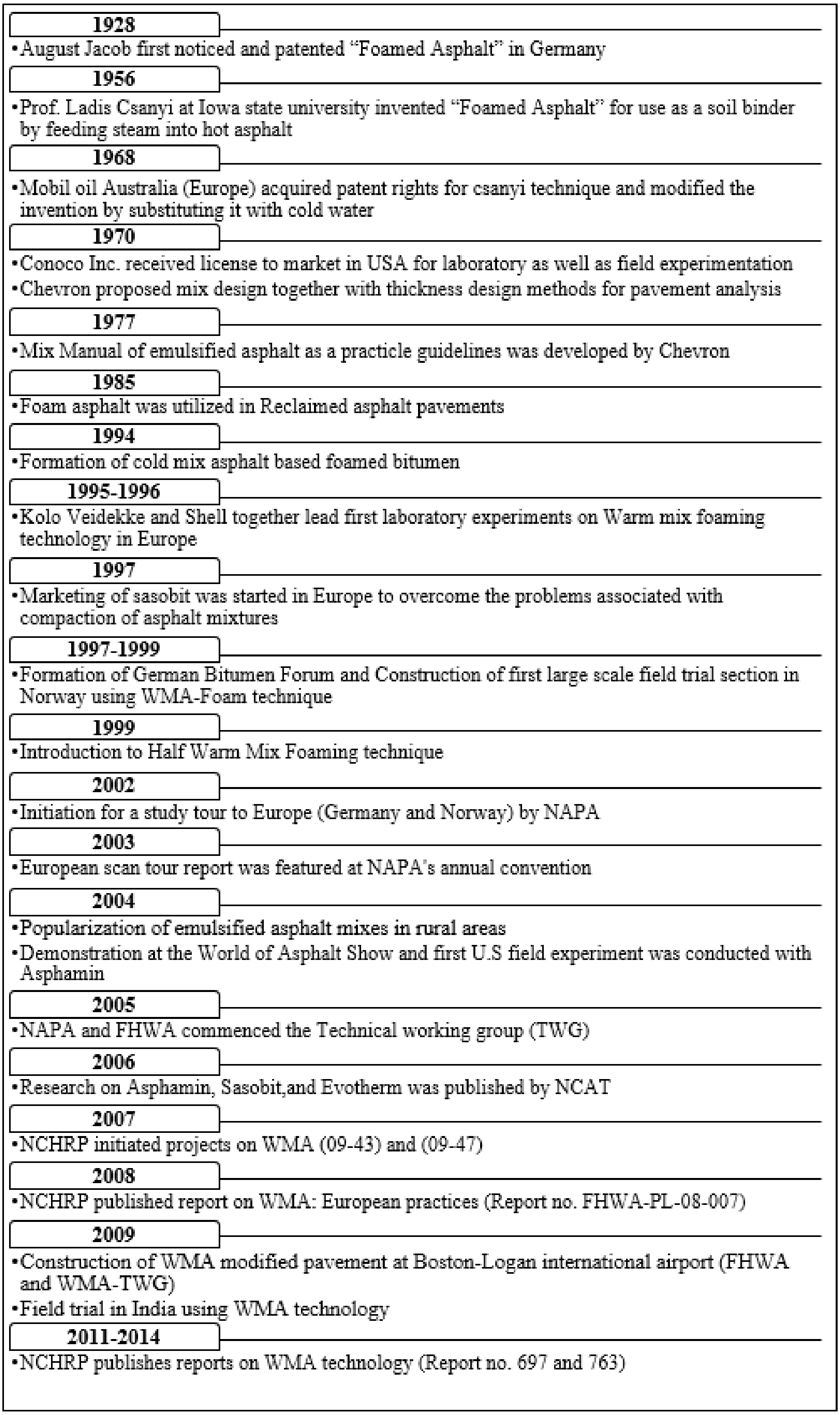
Figure 2.3 Classification of asphalt mixtures

Amongst the above-stated advanced technologies, WMA has been widely used to construct asphalt pavements with a wide range of production temperatures [88,89]. WMA technology lowers the production temperatures (about 10-40 °C) without compromising the engineering performance [14–21]. WMA technologies lessens harmful emissions and hazardous fumes from asphalt production plants, thereby improving the working condition for plant operators and workers [90,91]. Besides the benefits of reduced temperature, WMA's use also results in improved workability and increased hauling distance. Additionally, lower production temperatures lead to a reduction in energy consumption, thus reducing production cost [19,42]. Table 2.1 illustrates a brief history of the evolvement of WMA technologies.

Following the evolvement of WMA technologies, different WMA additives have been developed and are being used for pavement construction. These products (WMA additives) are patented that come in different forms such as solid, liquid, and powder, and uses a different process for mixing and blending the additives. The performance of these additives may or may not be similar as it depends on various factors including the chemical composition of the additive, production process, etc. These WMA additives can be divided in three broad categories depending on their working mechanism. These are organic, chemical, and foaming-based technologies [77]. Organic and chemical based additives are usually added to the virgin bitumen, while foaming additives can be added to the bitumen or directly to the bituminous mixture [92]. These technologies finally improve the workability of the mixture, and are able to provide bitumen coating, consistency, and compaction characteristics similar to the hot bituminous mixture, but at reduced temperatures. Organic based additives generally reduce the viscosity of the base binder, which leads to improvement in workability. They are waxes or fatty amides, which melts in the temperature range of 80-120 °C [77]. Below the melting point they crystallize and form lattice structure which helps in improving the stiffness of the base bitumen [15]. Chemical additives are mostly surfactants, emulsifiers, polymers, or hybrid products, which reduces the frictional forces between the bitumen and mineral aggregates, thereby facilitating appropriate coating at reduced production temperatures [14]. In foaming technologies, water is added either to the hot bitumen using artificial nozzles, or to the bituminous mixture in the form of zeolite. They temporarily increase the volume of bitumen, which helps in coating the aggregate particles and improves the workability of the mixture [42,93]. The in-depth details on all the above-stated technologies can be found in chapter 1.

Previous review works [13,58,94] have summarized WMA additives with respect to their concerned technologies. With further development, an effort has been made to review and incorporate additional technologies to the list for a better understanding of WMA. Table 2.2 demonstrates the overview of different WMA additives generally used for the construction works.

Table 2.1 Brief history of WMA technologies [12,16,97,21,24,26,28,29,73,95,96]



1928
- August Jacob first noticed and patented "Foamed Asphalt" in Germany

1956
- Prof. Ladis Csanyi at Iowa state university invented "Foamed Asphalt" for use as a soil binder by feeding steam into hot asphalt

1968
- Mobil oil Australia (Europe) acquired patent rights for csanyi technique and modified the invention by substituting it with cold water

1970
- Conoco Inc. received license to market in USA for laboratory as well as field experimentation
- Chevron proposed mix design together with thickness design methods for pavement analysis

1977
- Mix Manual of emulsified asphalt as a practicle guidelines was developed by Chevron

1985
- Foam asphalt was utilized in Reclaimed asphalt pavements

1994
- Formation of cold mix asphalt based foamed bitumen

1995-1996
- Kolo Veidekke and Shell together lead first laboratory experiments on Warm mix foaming technology in Europe

1997
- Marketing of sasobit was started in Europe to overcome the problems associated with compaction of asphalt mixtures

1997-1999
- Formation of German Bitumen Forum and Construction of first large scale field trial section in Norway using WMA-Foam technique

1999
- Introduction to Half Warm Mix Foaming technique

2002
- Initiation for a study tour to Europe (Germany and Norway) by NAPA

2003
- European scan tour report was featured at NAPA's annual convention

2004
- Popularization of emulsified asphalt mixes in rural areas
- Demonstration at the World of Asphalt Show and first U.S field experiment was conducted with Asphamin

2005
- NAPA and FHWA commenced the Technical working group (TWG)

2006
- Research on Asphamin, Sasobit,and Evotherm was published by NCAT

2007
- NCHRP initiated projects on WMA (09-43) and (09-47)

2008
- NCHRP published report on WMA: European practices (Report no. FHWA-PL-08-007)

2009
- Construction of WMA modified pavement at Boston-Logan international airport (FHWA and WMA-TWG)
- Field trial in India using WMA technology

2011-2014
- NCHRP publishes reports on WMA technology (Report no. 697 and 763)

Table 2.2. Overview of WMA technologies

Technology	**Product/ Additive**	**Company**	**Description**	**Dosage of Additive**	**Production Temperature or (Reduction Range)**
Organic Based Technology					
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%-4.0% 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)
Chemical Based Technology					
Chemical	Evotherm	Mead Westvaco	Chemical packages, with or without water	0.5% w/b	(30-50 ˚C)
Chemical	Rediset	Nouryon (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	IterChimica	Preferably used for RAPM inclusive asphalt concrete	0.3-0.5% w/b	(30-40 ˚C)
Chemical	Cecabase RT	CECA (Arkema)	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)

Foaming Based Technology					
Water-containing	Advera	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	1.0%-2.0% w/b	-

			turbulence to enhance foaming		
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.

2.3 Concept of Mix Design

Best practices for mix design methodologies, production, and field placement of warm mix modified asphalt mixtures are not very different from HMA. These practices include minimizing stockpile moisture, maintaining asphalt plants, and tuning burners [16]. Implementing these protocols would generate economic benefits and improved productivity for both HMA and WMA production. The typical mix design methods adopted globally follow Marshall, Superpave, and Hveem mix design procedures [98,99]. Review work by Wang et al. [100] indicates that almost all the WMA studies have adopted mix design protocols similar to conventional HMA. However, little modifications in the HMA plant might be required for WMA. Asphalt mix design methods for WMA involves five significant selections: a) material selection (binder grade and aggregate type), b) aggregate gradation, c) additional additives, d) curing and conditioning of WMA, and e) mixing and compaction temperature. This is followed by the workability assessment, volumetric analysis, and determination of optimum binder content (OBC).

2.3.1 Material Selection

Material properties, including asphalt binder and aggregate type, can profoundly influence the performance of compacted WMA.

The asphalt binder is selected following local environmental conditions and traffic loading with or without consideration of WMA technologies [101,102]. Chowdhury and Button [21] suggested the use of one grade stiffer asphalt binder for WMA to compensate for the tendency of rutting failure and reduced stiffness. This is attributed to the reduced ageing of WMA in comparison to conventional HMA. However, it was suggested that no change in grade is required for PMB, CRMB, and RAPM mixtures. In contrast, Wang et al. [100] recommended using similar asphalt binder as used in conventional HMA. It is suggested that there should not be an arbitrary grade bumping for WMA.

As far as the aggregate type is concerned, similar aggregates are used in both HMA and WMA [97,103,104]. One concern in executing WMA technology is the incomplete drying of aggregates at lower production temperatures [105,106]. This results in high water absorption, which can cause moisture-related damage. Thus, it is recommended to adopt specific limits for water absorption while using WMA technology [73].

2.3.2 Aggregate Gradation

Most of the available studies have used dense-graded mixtures for laboratory and field studies of WMA technologies [107–109]. However, various literature has also encouraged to use WMA technology for the production of gap graded mixtures, stone mastic asphalt, open-graded asphalt mixes, and RAPM inclusive asphalt mixtures [110–114]. In a study done by Kristjansdottir [79], the use of Sasobit in stone mastic asphalt and guss asphalt gave satisfactory performance. Furthermore, Zettler [115] pointed out that WMA technology offers excellent potential for any type of aggregate gradation from interstate highways to parking lots. Evidently, no noticeable changes can be observed from the available literature in the aggregate gradation for WMA and HMA [38,80,116]. However, depending on the WMA technology and asphalt gradation, the mechanical performance varies widely [14,117].

2.3.3 Additional Additives

There is evidence on the use of additional additives, such as antistripping agent (ASA) with WMA technology [35,118–120]. Usually, for organic and chemical-based technologies, ASA’s are not required. However, in case of extreme exposure of WMA to moisture, the use of ASA’s have been recommended [121,122]. In WMA technology, involving foaming processes, ASA’s can help counteract the problem associated with the loss of adhesion and coating at the binder aggregate interface [77,87,123].

2.3.4 Curing and Conditioning Process

Chowdhury and Button [21] reported that, although WMA testing follows standard guidelines as that of HMA, it is necessary to define appropriate curing and conditioning period for technologies involving the use of moisture. The presence of water in foaming technologies may harm the long-term performance of asphalt mixes. However, there are no standard guidelines to choose these conditioning periods. Short term ageing for 2 hours on compacted samples is suggested for foaming based technologies to replicate field conditions and remove the entrapped moisture [124]. For chemical and organic-based WMA technologies, there are no requirements of curing and conditioning compacted samples [21].

Control HMA specimens are often reheated for the evaluation of volumetric and performance-related parameters [125]. Unlike HMA, Bonaquist [32] found that reheating of WMA does not alter its mechanical performance. However, reheated specimens induce a negative impact on volumetric parameters attributed to the existence of irreversible constituents in WMA technologies [100,126].

2.3.5 Mixing and Compaction Temperature

WMA technology effectively reduces the mixing and compaction temperature (generally referred as production temperatures) of HMA and subsequently enhances the performance and workability. The reduction in temperature depends upon the technology adopted for paving operation [127,128]. Figure 2.4 indicates the decrease of production temperature corresponding to different WMA technologies. The reduction of production temperature as a function of base asphalt binder (viscosity graded (VG) binders and modified binders) is also presented in Figure 2.5. As can be observed, the average percent reduction is in the range of 20-40˚C. However, there are concerns related to the use of lower mixing and compaction temperature. Reduced mixing temperature can result in poor aggregate coating efficiency, thus initiating moisture-induced damages [43,129]. The reduction in compaction temperature can cause difficulty during field compaction, resulting in lower field density [75]. Mo et al. [130] stated that over 80% of premature failures, such as permanent deformation, moisture damage, and raveling, are attributable to inadequate compaction. Kristjansdottir [79] concluded that lower mixing and compaction temperature up to a permissible limit is not detrimental for the workability and performance of warm mix modified asphalt mixes. Nevertheless, the selection of appropriate production temperatures for the preparation of WMA is critical.

2.3.5.1 Review of Methodologies used for the Estimation of Production Temperatures

ASTM D2493 [131] provide guidelines on evaluating the production temperatures for HMA. The method is based on the viscosity of asphalt binder, determined using a Rotational Viscometer (RV). This method is popularly known as the equi-viscous (EQ) method [132]. As per the procedure, the temperature ranges, corresponding to the viscosity values of 0.17±0.02 Pa.s and 0.28±0.03 Pa.s, are taken as mixing and compaction temperatures, respectively. It is debated that the EQ method is not suitable for asphalt mixtures produced using modified binders, such as polymer and warm mix modified asphalt binders [61,133,134]. The viscosity of these asphalt binders, unlike the conventional asphalt binder, has a dependency on shear rate, even at higher temperatures (>100 °C). Yildirim et al. [135] observed that the determination of production temperatures without incorporating the effect of shear rate often yields higher values. Asphalt Institute [136] suggests contacting the suppliers of WMA additives for selecting the production temperatures. Researchers [137,138] have opined that selecting temperatures based on supplier recommendation may not be a viable approach. Therefore, various alternative methods have been proposed and adopted for estimating the mixing and compaction temperatures of WMA mixtures. These methods, which are hypothesized to eliminate the limitations of EQ method, require testing of asphalt binders using RV and/or DSR [132,139]. Table 2.3 present the summary of previously proposed methods, along with their salient features and proposed criteria. As shown in Table 2.3, all the methods, except PAM, uses viscosity criteria to establish the production temperatures. There have been a continuous debate on the reliability of viscosity-based methods. For WMA, viscosity-based methods may be applicable for the technologies that changes the binder's viscosity [140]. However, WMA mixtures produced by foaming and chemical-based technologies have less influence on the viscosity of asphalt binder [92,130]. From this perspective, Stimilli et al. [141] stated that criteria(s) based on the viscosity of asphalt binder are not sufficient to describe the workability of asphalt mixtures. Thus, the production temperatures evaluated using conventional approaches may be unrealistic or inappropriate.

A state-of-the-art review on WMA inferred that optimum mixing and compaction temperatures can be assessed by equalizing the bulk density of WMA and conventional HMA [77]. In one study, WMA were fabricated at three different temperatures lower than the working temperatures of HMA. The temperature at which the densities of WMA and HMA became the same was chosen as the compaction temperature [21]. A similar methodology is used in Europe for the mixing and compaction temperature of warm mix modified asphalt mixtures [142]. Wu et al. [143] developed an equi-volumetric technique for asphalt mixtures to determine the production temperature for WMA technology. This was achieved by carrying out binder viscosity tests and evaluating the compaction ability of WMA. Studies by Celik and Atis [144] and Sanchez-Alonso et al. [145] support the use of compaction tests to determine mixing and compaction temperature of warm mix modified asphalt mixes. During the compaction process at different temperatures, the comparison in the thickness of compacted HMA and WMA specimens is used as a potential indicator for determining production temperature.

Table 2.3**.** 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, [146]	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, [139]	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 production temperatures for modified asphalt binders. The measured viscosity values are plotted on a log scale with respect to temperature.	MT-0.75±0.05 Pa.s; CT-1.4±0.1 Pa.s (135˚C and 165˚C)	This method underestimates the mixing and compaction temperatures for some modified binders. This method does not provide any argument on the selection of shifted viscosity limits.
High Shear Rate Method (HSR-O), RV, [147]	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, [135]	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.
Flow Behavior Method RV, [148]	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 [148]. Cross model [149] is used to predict the viscosity value corresponding to high shear rates. Thereafter, the	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.

	production temperatures are determined by plotting the viscosity values on a log scale with respect to temperature.		
Steady Shear Flow (SSF), DSR, [150]	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, [139]	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	MT- 325 $(\omega)^{-0.0135}$; CT- 300 $(\omega)^{-0.012}$	This method indicates unrealistically low mixing and compaction temperatures for some polymer and warm mix modified asphalt binders.

	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.	(50°C, 60°C, 70°C and 80°C)	

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

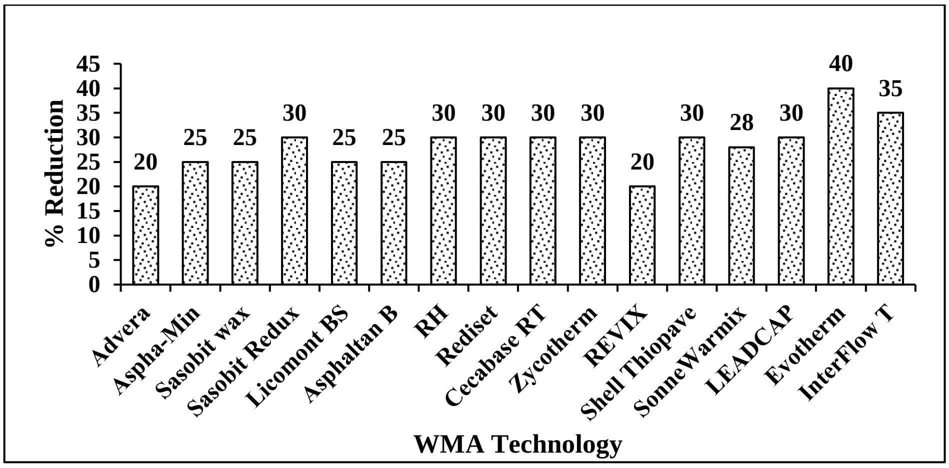


Figure 2.4. % Reduction in production temperature in comparison to HMA [13,16,94]

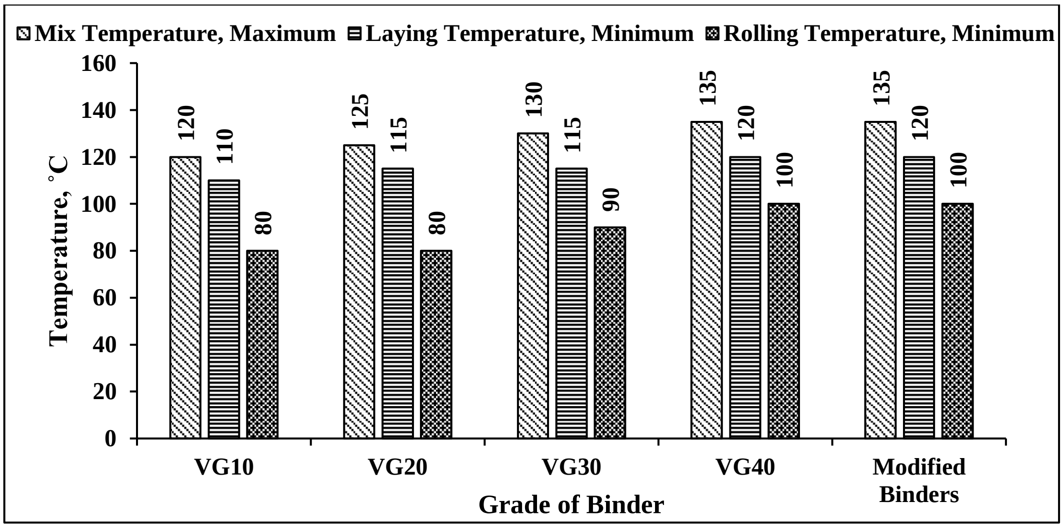


Figure 2.5. Reduction in production temperature corresponding to base binder [27]

2.4 Discussion on Mix Parameters

2.4.1 Workability

Conventionally, the viscosity of the asphalt binder is used to compute the production temperature of asphalt mixtures. There have been several arguments on this concept's applicability for modified asphalt binders such as warm mix-modified asphalt binders [151,152]. In WMA based technologies, the equi-viscous principle is only applicable to the additives that change the binder’s viscosity. However, if any WMA technology has less impact on the viscosity, as it usually happens with chemical and foaming based methods, the working temperature cannot be determined based on viscosity [140,153]. Stimilli et al. [141] and Wang et al. [75] indicated that the use of binder’s viscosity is not sufficient to quantify the production temperatures or the overall workability, specifically for modified asphalt binders and RAPM inclusive asphalt mixtures. Eventually, direct evaluation of production temperature based on workability should be used for WMA. Quantification of workability, and its use for evaluating production temperatures, have gained a lot of research interest in the recent years [75,152,154–161]. However, there is no standard index to quantify the workability of asphalt mixture objectively. In 1979, Marvillet and Bougault [155] developed a workability device, using a spring and potentiometer, that determines the mixing resistance based on torque values. As an intrinsic indicator of workability, the torque value increases with the decrease in temperature. Higher the torque more inferior will be the workability of asphalt mixture and vice-versa [159,162]. Following this approach, several workability devices have been developed to ascertain the variation between HMA and WMA. Table 2.4 displays a brief description of developed workability measurement devices from 1979 to 2018.

Wang et al. [75] examined the mixing and compaction temperatures for WMA mixtures through a workability device, using an 'equi-torque temperature method'. The principle of equi-torque method is similar to the EQ temperature method. The study reported that the proposed method is more convenient and realistic for getting higher accuracy in the prediction of production temperatures for WMA mixtures. Also, the range of reduction is consistent with the actual reduction recommended by the manufacturers. It should be noted that Wang et al. [75] defined the torque range based on the temperature limits recommended by the Technical Standard of Highway Engineering (China), JTG E20 [163]. The temperature limits may change based on the specification adopted. Hence, there is a need to investigate this further. Zhao and Guo [158] assessed the workability of WMA mixtures and recommended using lower production temperatures. Findings from the study divulged that workability of WMA mixtures at 145˚C is equivalent to HMA's workability at 175˚C, indicating a reduction of 30˚C in production temperatures. This reduction of 30˚C was also validated and confirmed with the determination of air voids of compacted asphalt mixtures. On the other hand, Tao and Mallick [74] carried out an investigation on warm mix modified RAPM asphalt mixture. Based on torque tester results, the authors concluded that HMA with 100% RAPM could be produced with the aid of WMA technologies (Sasobit and Advera) at lower temperatures.

In summary, various efforts have been made to compute the workability of WMA. These efforts lead to the development of different workability devices with different operating procedures and complexities. Nevertheless, there is still a need to examine the workability for different WMA technologies and compare them to the corresponding HMA. Moreover, insufficient data for the computation of mixing and compaction temperature with the utilization of workability devices entails rigorous research to firm a concrete conclusion.

Table 2.4. A brief history of workability devices

Year	**Developers**	**Description**	**Workability Measurement**	**Mix Type**
1979	Marvillet and Bougault [155]	Their equipment included a mixing chamber, a motor-driven paddle, and a temperature controller. The speed was adjusted using a variable resistor, i.e., potentiometer, and the resistance of the mix was measured by both potentiometer and a set of springs.	An electric signal was expressed in terms of torque	HMA
2004	Gudimettla et al. [152]	The device was developed to evaluate the variation in workability with the change in mix characteristics. The study concluded that workability was affected by the type of binder and aggregate, NMAS, and temperature. The workability of mixes was measured by evaluating the force required for paddle movement inside the mixture at a given rate of revolution.	Force was converted to torque	HMA

2009	Tao and Mallick [74]	Their device consisted of a fixed metal container and a torque wrench attached to an axle stabilizer. The torque required to rotate the paddle through the mixture within the container was measured. In this study, the workability values were observed just after the mixing and after 60 minutes of mixing to clarify the temperature dependency of WMA.	Torque values were transformed into workability number by multiplying the reciprocal of obtained torque values by 1000	HMA, WMA, and RAP M
2010	Bennert et al. [160]	The asphalt workability equipment was fabricated at the University of Massachusetts, Dartmouth. The asphalt mixture was rotated at a constant rate of 15 rpm, and the torque exerted on the fixed blade was measured. The testing was carried out at different temperatures for comparing control HMA and WMA.	Torque measurement	HMA and WMA
2010	Mongawer et al. [164]	They presented a workability device that can only determine the testing temperature but cannot maintain the temperature throughout the test. Their device is different from the previous development in the same area.	Torque value	HMA, WMA, and RAP M

		In this device, the mixing bucket, rather than the blade, was rotated to measure workability in units of torque.		
2011	Khalil et al. [157]	The device was attached with a motor, transducer, bowl with preinstalled heater, and temperature controller. The apparatus also included a computer with installed software for the measurement of torque. This study measured the workability using a transducer and developed a new protocol to determine the effect of mixing temperature on compatibility and workability. Additionally, the study examined the impact of different paddle shapes.	Torque value using software	HMA
2012	Khalil et al. [162]	They developed a prototype mixture for measuring asphalt concrete workability using a transducer and heat regulator. This is followed by the evaluation of mixing temperatures. The work also focused on selecting the optimum rate of paddles revolution and types of configuration. The temperature controller in this	Transducer fitted in the device transmits digital data and provides clean and definite data transmission to end-users in torque.	HMA

		device is not only used to measure mixing temperature but also aids in maintaining the temperature throughout the testing.		
2012	Zhao and Guo [158]	In this study, a torque sensor was installed on the mixing pot's stirring teeth, which indirectly measures the degree of difficulty in mixing asphalt mixture. The rate of rotation can be changed with the use of a frequency conversion device.	Data acquisition was made with the help of a software which displays the value of torque	WMA, HMA, and PMB
2013	Dongre and Morari [165]	Dongre workability device was used to evaluate asphalt mixtures' workability at a predefined control rate and stress level. Also, this device was developed to predict the field compaction temperatures. Variations in workability due to the change in aggregate gradation and type of binder could be resolved by conducting Dongre workability test.	The slope of nonlinear stress (kPa) versus volumetric strain (%) at 600 kPa stress level is taken as workability value.	HMA, WMA, and PMB
2013	Wang et al. [75]	They developed a prototype workability device that comprises a metal bowl, a paddle, and a torque wrench for torque measurement. This device was created with the	Resistance of the mix was expressed in terms of torque on the	WMA and HMA

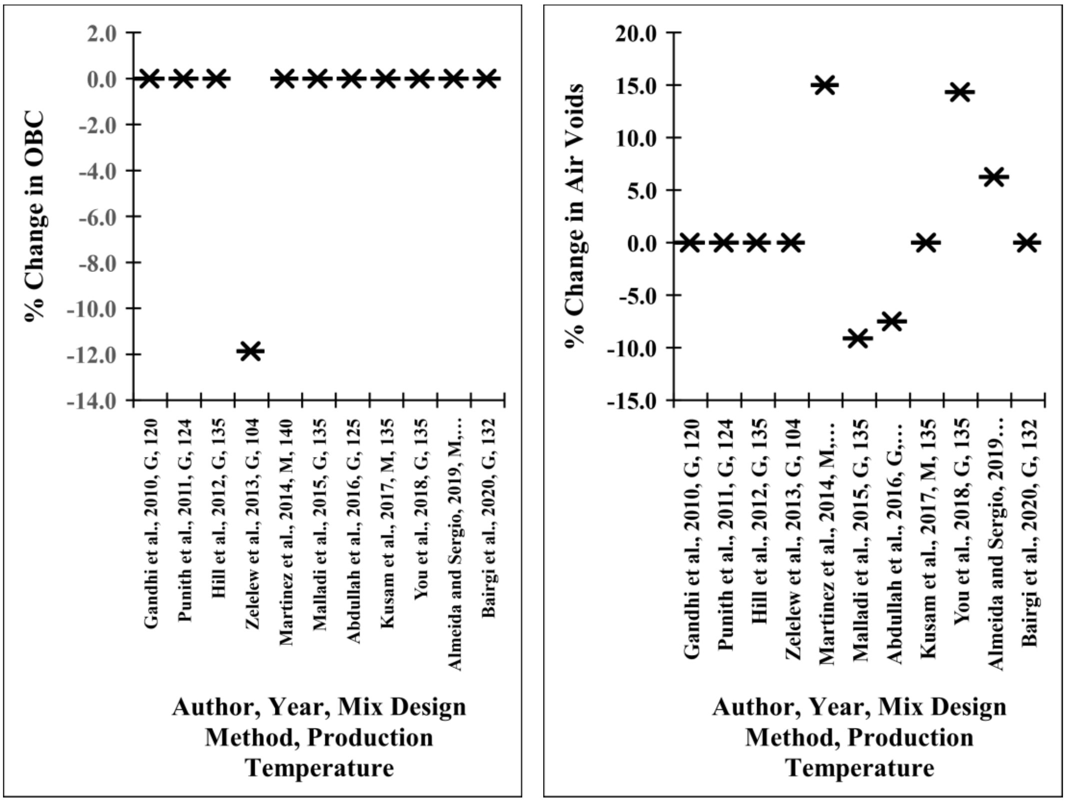
		objective of identifying the production temperature of WMA through workability.	screen of torque wrench	
2014	Ali et al. [159]	The University of Akron's workability device was installed to rotate the material contained bucket while the paddle was fixed to the upper shaft. In this device, the gear reduction unit and speed control unit were attached, which allows the apparatus to operate at variable speed and handle the force generated while performing the test.	Software-based torque measurement	WMA and HMA
2016	Poeran and Sluer [154]	This workability meter prototype consisted of a mixing bowl that does not rotate, but the height can be adjusted automatically even when the paddle is in motion. Three temperature sensors were used to monitor the working temperature accurately. This investigation concluded that rotational speed and shape of paddle greatly influence the mix performance.	In this prototype, torque measurement was done by using a shaft-to-shaft rotary torque sensor attached to an encoder.	HMA, and PMB

2018	Diab and You [156]	Their device utilized a commercially available motorized vane shear instrument, which is used to determine the shear strength of the soil. A specially designed spindle was attached to the mixing pot to replicate aggregate influence during the mixing procedure. This prototype estimated the mixing temperatures of the asphalt mixtures based on the principle of the Workability Index.	Torque meter was used to measure the torque at constant revolution	HMA, WMA, and PMB

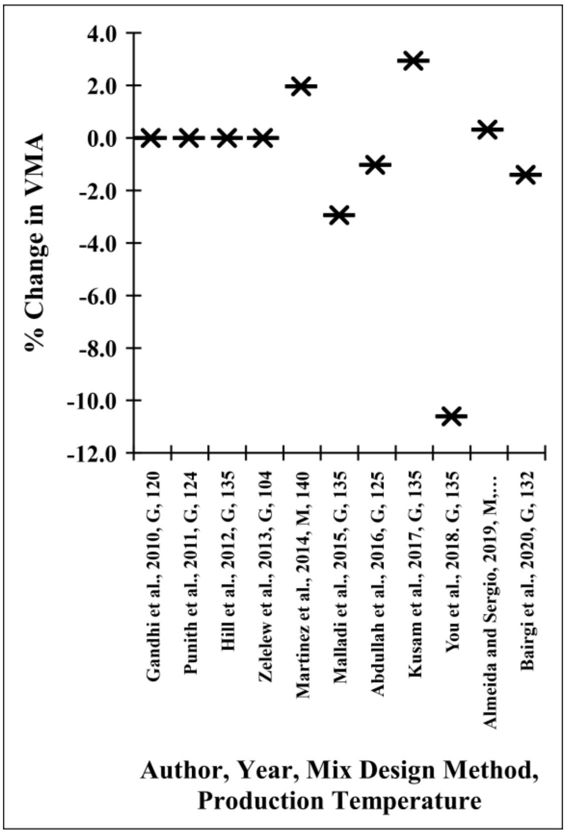
2.4.2 Optimum Binder Content and Volumetric Analysis

Many research works have evaluated and compared the volumetric parameters of WMA with conventional HMA [104,166,167]. As stated previously, similar mix design steps are involved in WMA and HMA based technologies. The difference in mix parameters is attributable to the change in production temperature in WMA [168]. A detailed review has been carried out in this study to understand the effect of WMA additives on the change in volumetric parameters of asphalt mixtures. These parameters include optimum binder content (OBC), voids in mineral aggregate (VMA), voids filled with bitumen (VFB), and air voids (AV). A representative of the review work, to incorporate different additives under each category of WMA technologies, is presented in Figure 2.6. Notably, the OBC in WMA is determined before adding the WMA additives [77]. OBC in WMA is usually kept the same as that of the control HMA [119,169–171].

As shown in Figure 2.6c , in most studies, no change in VMA was found in WMA and HMA [172,173]. Few studies have also attempted to evaluate the OBC and volumetric parameters separately to assess the change in the amount of asphalt binder required for WMA [166,174]. Higher VFB (calculated using VMA and AV) obtained for WMA in comparison to the HMA sample indicates an enhancement in durability. This is attributed to the increased film thickness of asphalt binder over the aggregate. Regardless of the mix design method used (Marshall, Superpave or Hveem), the OBC for WMA is usually determined corresponding to 4% AV. The AV in WMA samples is found to be comparable to or lower than HMA. This indicates better compactability for WMA.



(a) (b)



(c)

Figure 2.6**.** [38,66,181,172,174–180] Variation in Mix Parameters: (a) % Change in OBC,

(b) % Change in Air Voids, and (c) % Change in VMA

Note: In Figure 2.6 (a), (b), and (c): G and M indicate Superpave Gyratory Method and Marshall Method of mix design, respectively; and production temperature is in °C.

2.5 Morphological, Chemical, and Physical Characteristics

2.5.1 Morphology of WMA Binders

Morphological study is usually done to examine and visualize the homogeneity/ compatibility between asphalt binder and any additive/modifier in terms of their distribution, surface texture, and nano and micro-structure [182,183]. Different techniques such as scanning electron microscopy (SEM) [184], atomic force microscopy (AFM) [185], fluorescence microscopy (FM) [186], and optical microscopy (OM) [187], can be used to assess the morphological observations. All these techniques have a different working principles as well as different visual output characteristics. Previous literatures [184,188–193] reported that the change in physical, rheological, and mechanical performance can be predicted by understanding the microstructure of the asphalt binder. This forms the motivation for performing morphological studies in the field of pavement engineering.

Since WMA additives are added to the asphalt binder, it is desirable to ascertain the dispersibility of these additives within the asphalt blend. It has been reviewed that the change in surface morphology is dependent on the type of WMA additives and their respective dosages [189,194–196]. The particles of WMA additives were found to be uniformly distributed within the asphalt matrix, irrespective of their dosages [197]. However, the change in the surface morphology was more pronounced at the higher dosages of WMA additives [196]. On the other hand, Nazzal et al. [198] identified similar morphological characteristics as base asphalt binders, indicating no significant change in the binder properties with the incorporation of chemical and foaming-based WMA additives (Evotherm and Advera, respectively).

The addition of WMA additives resulted in the macroscopic degradation of asphalt binder surface [195]. A study conducted by Menapace et al. [199] reported the presence of ripples over the surface wherein the ripple density was dependent on the type of WMA additive. Nazzal et al. [198] studied the nano-structure of asphalt binder with and without WMA additives using AFM technique. Findings of the study indicate the presence of a bee-like structure in the control asphalt binder. While the addition of WMA additives, such as Evotherm and Advera, maintains the homogeneity/consistency of asphalt binder by showing a similar dimension of bee structure, the blending of Sasobit, on the other hand, reduces the width from 0.582 to

0.385 µm. The authors attributed the crystallization of waxy molecules as the main reason behind the contraction in bee structure. Similarly, the changes were observed in the form of a smoother and saturated surface of asphalt binder with the addition of a chemical-based WMA agent such as Evotherm [200]. Zheng et al. [184] indicated a uniform and embedded phase of WMA in asphalt binder with a crystal-clear boundary. The reason being the effective and efficient mixing/blending protocol adopted for the preparation of WMA binders [196]. An interlocking and dendrite network was observed over the surface of Sasobit modified asphalt binder [194]. This may be attributed to the interaction of Sasobit crystals with the components of asphalt binder. The same microstructure was detected with the change in asphalt binder source and grade [189]. However, the morphology changes progressively with the state of ageing (STA and LTA). After STA, few changes were observed in the micro-surface texture of asphalt binder, which further progressed after LTA [184,194,196].

In general, higher ageing temperature leads to a reduction in the dimensions of bee structure. A study done by Veeraiah and Nagabhushnarao [201] showed that WMA additives are distributed uniformly and found to be compatible with base asphalt binder and CRMB, but at optimum ageing temperatures. The authors also stated that the morphological changes after ageing are dependent on the type of WMA additives. Menapace et al. [194] observed no significant difference in the morphology of unaged and aged WMA binder prepared using Advera, whereas substantial changes in the microstructure were reported after ageing of Sasobit-based WMA binder. A plausible clarification for such change is the presence of wax in Sasobit modified asphalt binder, which alters the ageing process and generates dissimilar microstructure and chemical composition compared to unaged asphalt binder.

The application of WMA technologies improved the micromorphology of PMB, CRMB, and RAPM inclusive asphalt binder [184,200–203]. The visual observations directly deliver information about their synergistic effect on engineering performance. Based on the literature review, it can be inferred that the asphalt binders' micro-morphology significantly affects the macro-scale performance. However, very few studies are available, and that too on a very few WMA additives (mostly the studies are on Sasobit). In addition, the effect of WMA additive dosages on the morphology of asphalt binders has not been studied with enough rigor. Thus, extensive work is required to observe the influence of different base asphalt binders, WMA technologies, and their respective dosages on the surface morphology.

2.5.2 Chemical Characteristics of WMA Binders

In addition to surface morphology, asphalt modifiers/additives influences the chemical characteristics of asphalt binders at the molecular level [204–207]. Previous studies [208–210] stated that the change in chemical characteristics significantly affects the performance of asphalt binders and mixtures. Various techniques, such as Gel permeation chromatography (GPC) [89], Fourier transform infrared spectroscopy (FTIR) [211], and Corbett chromatography [212,213], could be used to analyze the chemical nature of asphalt binders. However, FTIR is the most widely used tool to identify the chemical structure of asphalt binder, owing to its convenience and reliable results [214]. It identifies the difference between the absorption spectrum and provides information on the functional group of asphalt binder. This technique is also used to analyze the qualitative and quantitative characteristics of organic compounds present in the asphalt binder. Table 2.5 shows some of the commonly detected functional groups of asphalt binders, along with their respective peak range and vibration modes.

Table 2.5. Common functional group detected in asphalt binder [214–218]

Absorbance Peak, cm^{-1}	**Functional Group**	**Vibration Modes**
600-1200	-	Fingerprint region
720-725	CH_n	Long chain methyl rocking, n>4
729	CH_n	Rocking, n<4
700-900	=C-H	In-plane bending vibration in aromatics
910 and 990	$-CH=CH_2$	Wagging
1030	S=O	Stretching, Sulfoxide group
1000-1300	C-O	Stretching, Ester
1350-1370	C-H	Methyl rock
1380	C-H	Symmetric bending of CH_3
1376-1452	C-H	Symmetric deformation in CH_2 and CH_3 vibration
1450-1460	C-H	Bend or scissoring in CH_2
1464	C-H	Asymmetric bending in CH_3
1597	C=C	Stretching vibration in aromatics
1637	C=C	Benzene ring
1700-1725	C=O	Stretching, Carbonyl group
2754-3100	C-H	Stretching vibration in CH_2 and CH_3
3000-3600	N-H or O-H	Stretching Vibration

Several studies [203,215,219,220] have carried out FTIR analysis to identify the change in chemical characteristics of asphalt binder with the addition of WMA additives. The formation/appearance of a new peak (functional group) in the absorption spectra indicates that the blend between the binder and modifier/additive is due to their chemical interaction [221]. On the contrary, if no new peak was detected, the interaction process is termed a physical process, indicating no change in the chemical composition of base asphalt binder [210]. A large number of studies [209,216,222–224] showed that the interaction between WMA additives and asphalt binder is purely physical, however, few literatures [54,225,226] contradict the physical interaction, rather observed the occurrence of a chemical reaction between them. The difference in their interaction is a function of WMA technology. Liu et al. [216] investigated the effect of foaming water on the chemical composition of asphalt binder using the FTIR method. Although the authors found the variation in the Cole-Cole plot between foamed and unfoamed binder, but indicated physical interaction, as no new peak appears after the addition of WMA. The absorption peaks corresponding to any wavenumber for base binder appear exactly at the same position for WMA binder. However, the study [216] reported the discrepancies in the intensity of the absorption peaks, which may be a probable reason for the change in rheological performance of WMA binders [227]. While examining the interaction between base asphalt binder and WMA additive (Evotherm DAT), Yu et al. [209] also observed that the addition of WMA additive reduced the peak intensity, despite having a similar absorption spectra as base asphalt binder. The authors stated that this behaviour is due to the synergistic effect of water and surfactant present within Evotherm DAT (a chemical-based WMA agent). Reduction in strength of peaks offer improved rheological performance, increased ductility, and reduction in viscosity values [209]. A study conducted by Hossain et al. [215] revealed that FTIR absorbance values of two different WMA binders and the corresponding data obtained from rheological testing follow a similar trend. Findings of the study showed that an increase in the absorption value of any organic compound of alkane (Table 2.6) leads to an increase in rutting resistance. However, the extent of increment is dependent on the working mechanism of WMA technology. Sasobit delivered improved rheological performance, whereas a slight improvement was observed with the use of Aspha-Min in base asphalt binder. It was found that the variation caused by Aspha-Min was not statistically significant [215].

Table 2.6. Form of alkanes that influences the rheological performance [215]

Form of alkanes	**Wavenumbers, cm^{-1}**
C-H stretch	2850-3000
C-H bend	1450-1470
C-H methyl rock	1350-1370
C-H long chain methyl rock	720-725

Overall, it was investigated that the application of WMA additives does not variate the chemical structure of the base asphalt binders but may alter the intensity of absorbance peak, depending on the WMA technology, additive dosage, and base asphalt binder. However, more emphasis on the chemical characteristics of WMA is required to ascertain their effect on the engineering performance of asphalt binders and mixtures.

2.5.3 Physical Properties of WMA Binders

The physical properties of WMA binders are a function of chemical characteristics, base binder source, WMA technology, and their respective dosages. Table 2.7 shows the influence of WMA additives on the physical characteristics of base asphalt binders. As can be seen, the effect of WMA additives may be the same or different in both unmodified and modified asphalt binder, for example: the addition of Cecabase indicates no significant change in the viscosity values when blended in unmodified asphalt binder, while lower viscosity values were observed in modified asphalt binders. Here modified asphalt binder refers to binder modified with different modification materials, such as polymers, crumb rubber, nanoclay, PPA, etc. Similar variations were perceived, depending on the type of WMA technologies. On average, organic-based

WMA additives resulted in lower penetration and rotational viscosity values, whereas their addition led to a higher softening point, irrespective of the base binder. This consistent behaviour of organic additives is attributed to the difference in their physical structure above and below the melting point [15]. At a temperature higher than their melting point, organic wax congeals, whereas it forms a lattice crystalline interlocking structure (as stated in the previous section), which increases the stiffness of base asphalt binder. In line with the same context, Zhang et al. [228] experimentally investigated the effect of Sasobit, an organic-based WMA technology, by performing a viscosity test at 60°C and 110°C. The authors observed lower viscosity at 110°C, while the results were completely opposite at 60°C. It was found that the addition of chemical agents either led to lower values or indicated similar physical characteristics as base asphalt binders. Based on the literature review, no concrete conclusion can be made on the influence of chemical agents, irrespective of asphalt binder source and grade. Similarly, few literatures [229–232] observed a change in physical characteristics with the addition of foaming-based WMA technologies, such as Aspha-Min and Advera.

Table 2.7. Physical characteristics of WMA binders

WMA	**Binder Type**	**Basic Properties**				**Reference(s)**
		PV	**SP**	**V**	**FT**	
Sasobit	Unmodified	↓	↑	↓	↑	[54,215,231,233–238]
	Modified	↓	↑	↓	↑↔	[184,206,233,235,238–242]
Evotherm	Unmodified	↓	↓	↓	↔	[233,236,243]
	Modified	↓	↓	↓	↕	[233,243,244]
Rediset	Unmodified	↓↔	↑↔	↓	↓↔	[207,234,236,237,245]
	Modified	↓	↑	↓	↓	[245,246]

Cecabase	Unmodified	↕	↕	↔	↓	[39,236,245,247,248]
	Modified	↓	↑	↓	-	[245,249]
Zycotherm	Unmodified	↕	↕	↓↔	↔	[250–254]
	Modified	↕	↕	↓↔	↔	[251,252,254]
Aspha-Min	Unmodified	↓	↑	↑↔	↑	[120,215,231,232,255]
	Modified	↓	↑	↑	↑	[230,232]
Advera	Unmodified	↓	-	↕	↕	[45,207,229]
	Modified	↓	↑	↑	↓	[246,256]

Note: PV, SP, V, and FT denote penetration value, softening point, viscosity at 135°C, and failure temperature, respectively. Symbols such as ↑*,* ↓*,* ↕*,* ↔*,* ↑↔*, and* ↓↔ *indicate increase, decrease, inconclusive result (may increase or decrease), no significant change, increase or no change, and decrease or no change, in the basic properties of base asphalt binder, respectively.*

2.6 Performance of WMA Binders and Mixtures

Ensuring satisfactory laboratory performance of asphalt binders and mixtures has a direct relation to infield performance. This section reviews the laboratory performance in terms of resistance to rutting, fatigue, and moisture damage of WMA and compares it with the performance of HMA.

2.6.1 Resistance to Rutting Potential

Rutting is one of the primary causes of failure associated with WMA pavements. Lower production temperatures prevent the stiffening of the asphalt binder and make it susceptible to permanent deformation [257]. Several studies [227,240,242,258–263] have been carried out to understand the behaviour of WMA binders against rutting resistance. Many studies [227,240,243,258,262–266] showed a positive effect, while few [90,258,267–269] indicated adverse/indefinite trends with the addition of WMA additives in base asphalt binders, depending on WMA technology. Table 2.8 presents the inferences of some of the past studies, which showed the behaviour of WMA binders against rutting distress. It was found that chemical agents did not affect the rutting behaviour whereas organic-based WMA additives showed a positive impact on the high-temperature rutting resistance of base asphalt binders. As far as foaming technologies are considered, they showed inconclusive results. It should be noted that several factors, including additive type and dosage, the grade of asphalt binder, and ageing condition affect the rutting characteristics [257,270].

Table 2.8**.** Inferences of past literatures on rutting behaviour of WMA binders

Authors	**WMA Technology**	**Inferences**	**Influential Parameter**
Kim et al. [271]	Aspha-Min and Sasobit	• Asphalt binders containing WMA additives indicated higher rutting resistance, irrespective of the ageing condition. • The authors revealed that the ranking of WMA additives is dependent on the properties of base asphalt binder.	Base binder source and WMA type
Wang and Zhang [272]	Sasobit wax	• Experimental results revealed that rutting resistance improved with the inclusion of WMA additives in both unmodified and modified asphalt binder. • Results indicated that an increase in dosage of WMA	Base binder type and additive dosages

		additive considerable ameliorate the rutting performance.	
Morea et al. [273]	Chemical agents	• No significant variation in the non-recoverable creep compliance of unmodified asphalt binder was observed with the addition of WMA additives. • The authors found a drastic reduction in non-recoverable creep compliance with WMA inclusive polymer modified asphalt binder. • Findings of the study revealed that the addition of WMA additives improves the elastic response and thereby imparts better rutting performance.	Type of base binder and WMA additive
Zelelew et al. [38]	Sasobit, Low emission asphalt, Advera, and Gencor	• Sasobit modified asphalt binder showed higher rutting performance followed by Advera, Gencor, and LEA. • The adoption of LEA showed lower G*/Sinδ in comparison to base asphalt binder at 54.4°C, representing lower rut resistant. • MSCR test results indicated that all the WMA additives, except LEA, impart superior rutting performance as	WMA technology

		compared to base asphalt binder.	
Kok et al. [274]	Sasobit	• WMA binder prepared with 4% Sasobit resulted in around 1.6 times higher rutting performance as compared to base asphalt binder. • The authors recommended to use Sasobit with SBS modified asphalt binder for superior rutting resistance.	WMA additive dosage
Zhang et al. [275]	Sasobit	• WMA binder showed superior rutting performance, irrespective of the base asphalt binder, as indicated by higher value of rutting factor (G*/Sinδ). • Increase in dosage significantly increased the G*/Sinδ parameter and the extent of improvement was more pronounced for 70# asphalt binder. • The authors reported 3% and 5% Sasobit as the optimum dosage for 70# and 90# asphalt binder, respectively.	Base binder source and WMA additive dosage
Singh and Kataware [260]	Sasobit, Advera, and Rediset	• Sasobit was found to be more effective in improving the rutting resistance flowed by Advera and Rediset.	WMA type and additive dosages

		• Rediset showed the worst performance at all the dosages. • The rutting resistance of Rediset was even lower than the base asphalt binder, as analyzed by the values of non-recoverable creep compliance and G*/Sinδ.	
Kataware and Singh [246]	Sasobit, Rediset, and Advera	• Addition of chemical and foaming agents either indicated similar or lower rutting resistance than control asphalt binder. • Organic based WMA technology such as Sasobit showed improved rutting performance, owing to the formation of crystalline network of wax molecules.	WMA technology and their respective dosages
Ali et al. [276]	Sasobit and LEADCAP	• Wax additives lead to higher G*/Sinδ value, indicating better rutting resistance. • The effect of wax additives was more pronounced in PG 64-22 than PMB. • MSCR test method was unable to assess the effect of WMA additives.	Base asphalt binder and type of WMA additive
Syed et al. [277]	Foaming, Evotherm, Cecabase,	• WMA binders, irrespective of WMA type, yield higher rutting resistance.	WMA type

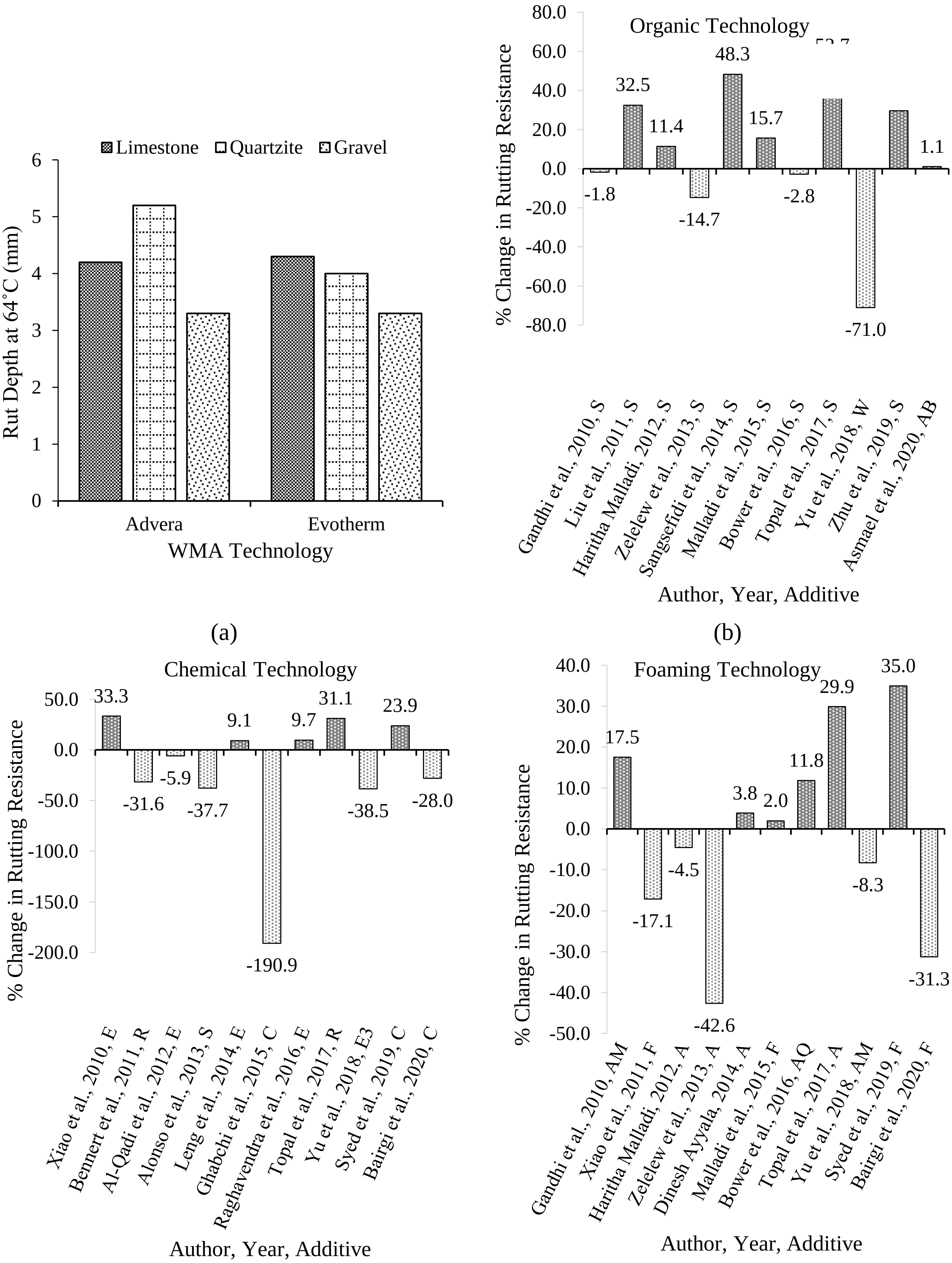
	and Cecabase +	- Cecabase+ indicated higher improvement followed by Foaming, Cecabase, Evotherm, and base asphalt binder.	
Ameli et al. [278]	Sasobit, Rheofalt, and Zycotherm	- All the WMA binders indicated higher G*/Sinδ at both the ageing condition (unaged and STA). - Addition of WMA additives increases the recovery value and lowers the non-recoverable creep compliance, irrespective of the WMA type.	WMA type, additive dosages, and ageing condition

Along with the above influential parameters at binder level, aggregate gradation and the source of aggregate play a vital role in characterizing the rutting behaviour of WMA mixtures. Sebaaly et al. [20] carried out laboratory work using chemical and foaming-based technologies to ascertain the effect of different sources of aggregate and WMA technology on the rutting behavior of WMA. Results (as shown in Figure 2.7a) indicated that type of aggregate and technology adopted significantly alters WMA's rutting behavior. Gandhi et al. [279] investigated WMA's rutting performance using two aggregate types, two binder sources, and two warm mix additives. Findings from the study demonstrated that the use of WMA additive significantly changes WMA's rut depth. Moreover, the study concluded that the binder source does not influence the rutting resistance considerably. As far as the aggregate source is considered, marble schist indicated improved performance compared to micaceous granite. The increased resistance could be attributed to the higher toughness and more fractured faces in marble schist, showing better interlocking of aggregates and reduced rutting [279]. In another study, when the rutting potential of the coarse graded mixture and fine graded mixture are compared for granite and slag type aggregates, it was found that the coarse graded mixture performed better than fine graded mix for granite aggregates [104]. This increased resistance is associated with the stone-on-stone contact between coarse aggregate, which increases the load-bearing capacity, thereby minimizing the potential for rutting. However, the results are opposite for the mixtures containing slag aggregates. The opposite trend could be attributed to the higher abrasion value of slag aggregates. Therefore, the slag mixtures seem to rely on mastic and mixes with finer gradation rather than coarse gradation.

In WMA, mixing and compaction temperatures influence the rutting resistance, as well. Xiao et al. [170] found that the temperature range between 102℃ to 118℃ can be appreciably chosen for improving the field performance concerning rut depth. Zhao et al. [80] and Bennert et al. [280] examined the effect of production temperature and mentioned that WMA is anticipated to have lower resistance to rutting in comparison to HMA. This is ascribed to the lower aging of WMA at reduced mixing and compaction temperature. Hamzah et al. [281] stated that Aspha-Min exhibits lower rutting resistance, followed by Evotherm, Advera, Cecabase, and Rediset modified asphalt mixtures. Among the various WMA technologies, Sasobit has been widely used to counteract WMA's rutting related concerns [175].

Similarly, Xiao et al. [282] researched the rutting characteristics with moist aggregates. They found that Sasobit exhibits better performance compared to the mixture containing Aspha-Min and Evotherm. This could be associated with the crystallization of Sasobit pellets in the asphalt binder, which increases the stiffness and improves resistance against permanent deformation [59]. Few studies [174,263,283–285] concluded that WMA improves rutting resistance despite being produced at a significantly lower temperature.

Figure 2.7 (b-d) illustrates some examples from previous literature published within the year 2010-2020, showing percent change in rutting resistance for WMA relative to traditional HMA. Sample air voids of 4% - 7% were adopted in all the previous literature based on the testing methodology and in-situ compaction density. As already stated, irrespective of the literature, boundary variables such as asphalt binder grade, mix type, testing temperature, testing instrument, and wheel load are kept constant to compare HMA and WMA. However, it has to be noted that the boundary conditions change in different studies. It can be elucidated from Figure 2.7 (b-d) that no specific conclusion can be made on WMA's rutting behavior. However, among different WMA technologies, organic-based additives' rutting resistance is relatively better than chemical and foaming-based technologies. Mixture with chemical-based additive generally depicts the lowest rutting resistance. This might be attributed to the binder softening and lubricating effect due to chemical agents [181]. Moreover, there is no clear trend regarding the effect of foaming techniques on rutting behavior. Therefore, rutting performance is still a big challenge, which entails further research on WMA's improvement and assessments. Additionally, it is recommended to specify minimum mixing and compaction temperature to achieve WMA's adequate rutting performance.



(a) (b)

(c) (d)

Figure 2.7. Review on rutting behavior of WMA mixtures

(a) Variation of rut depth with different aggregate type [20],

(b) % Change in Rutting Resistance for Organic Technology [174,239,291,270,279,284,286–290],
(c) % Change in Rutting Resistance for Chemical Technology [122,126,292,168,173,181,277,280,282,284,289], and
(d) % Change in Rutting Resistance for Foaming Technology [38,119,293,174,181,277,279,284,286,288,289].
Note: In figure 2.7 (b): S, W, and AB in Additive indicate Sasobit, Wax, and Asphaltan B, respectively.
In figure 2.7 (c): E, R, S, C, and E3 in Additive indicate Evotherm, Rediset, Surfactant, Cecabase, and Evotherm 3G, respectively.
In figure 2.7 (d): AM, F, A, and AQ, in Additive, indicate Aspha-Min, Foam, Advera, and Aquablack, respectively.

2.6.2 Fatigue Resistance

Fatigue cracking is one of the critical distresses in asphalt pavements associated with repetitive traffic loading. These cracks predominantly occur at intermediate temperature conditions [294]. Understanding the capability of asphalt binders and mixtures to resist fatigue cracking from repetitive loading conditions continues to challenge researchers and practitioners. These challenges become more critical when the asphalt binder is modified with WMA additives. Similar to rutting potential, various factors affect the fatigue resistance of WMA binder. Table 2.9 indicates the inferences of previous studies, which shows the effect of WMA additives on the fatigue resistance of base asphalt binders. No conclusive remarks can be given on the influence of WMA additives on the fatigue behaviour of asphalt binders. On average, no influence on fatigue resistance was observed with the application of surfactant-based WMA additive in base asphalt binder. On the other hand, both positive and negative impacts of organic and foaming technologies were reported in previous literatures, as shown in Table 2.9.

Table 2.9. Observations of previous studies on fatigue potential of WMA binders

Authors	**WMA Technology**	**Inferences**	**Influential Parameter**
Gandhi et al. [295]	Aspha-Min and Sasobit	• The authors found that effect of WMA additive on the fatigue resistance is dependent on the ageing temperature. • WMA binders prepared at lower ageing temperature (130-140°C) do not indicate any adverse effect on fatigue life compared to WMA binders aged at 163°C. • The effect of Aspha-Min on the fatigue cracking resistance was found to be more appreciable than Sasobit.	Ageing temperature and WMA additive type
Arega et al. [296]	Sasobit, Cecabase, Evotherm, Evotherm 3G, and Rediset	• On an average, chemical-based WMA binders indicated improved fatigue resistance in comparison to the binders prepared with organic-based WMA additive. • The effect of reduced STA on the fatigue resistance of base asphalt binder is a function of binder source and WMA technology.	WMA technology, ageing condition, and base asphalt binder
Hossain et al. [45]	Advera	• The asphalt binders prepared using 4% and 6% Advera satisfied the Superpave	WMA additive dosage

		fatigue criterion (≤5000 kPa) at 25°C. • It was found that the critical intermediate temperatures of WMA binders were higher than the base asphalt binder, irrespective of their dosages. • The authors concluded that Advera-based WMA binders could exhibit higher fatigue cracking than base asphalt binder.	
Yu et al. [297]	Foaming	• The authors found that the change in fatigue performance is dependent on the amount of water added for the creation of foam. • Fatigue temperature in unmodified binder decreased with the application of 1% water content, while it shows an increasing trend at higher water content, which is not desirable from fatigue point of view. • The optimum foaming water content, which improved the fatigue resistance, was found to be 2-3% for polymer modified asphalt binders.	Base binder source and variation in foaming water content
Safaei et al. [298]	Foaming and Evotherm	• Experimental results indicated that after LTA, the difference in the fatigue resistance of	WMA type and ageing condition

		WMA and base binders become insignificant. • The authors stated that the effect of reduced STA in WMA binders diminishes progressively with the increase in LTA, and hence the fatigue performance of WMA binders, measured on LTA samples, was similar to the base asphalt binder.	
Babagoli and Razi [299]	Rheofalt	• WMA binders showed higher fatigue life at all the strain levels in comparison to control asphalt binder. • The addition of 4% Rheofalt in base asphalt binder imparts stiffening effect and thus a slight reduction in fatigue life was observed.	WMA additive dosage
Abdullah et al. [300]	Rediset	• G*.Sinδ value of asphalt binder decreased significantly after the addition of chemical-based WMA agent, indicating improved fatigue resistance. • The authors revealed that the increase in dosage of WMA additive considerably reduces the stiffness of asphalt binder and imparts the elasticity, which results in higher resistance to fatigue cracking.	WMA additive dosage

Singh et al. [268]	Sasobit, Evotherm, and Advera	• The authors reported adverse effect of Evotherm and Advera on the fatigue life of base asphalt binder. • It was found that the performance of Sasobit-based WMA binder is a function of strain values. At lower strain (<2.5%), its fatigue life is approximately similar to the base asphalt binder, whereas it showed detrimental effects at higher strain values (>2.5%).	WMA technology
Kataware and Singh [207]	Sasobit, Rediset, and Advera	• All the WMA binders showed improvement in the fatigue life of base asphalt binder, depending on their dosages. • Addition of lower dosage of WMA additive resulted in excellent fatigue resistance. • The fatigue life of Sasobit (1-2%), Rediset (1%), and Advera (4%) modified asphalt binder was around 3.4, 2.32, and 1.88 times higher than the base asphalt binder.	WMA type, and their respective dosages
Sun et al. [301]	Wax and Surfactant	• Both wax and surfactant-based WMA binders indicated higher resistance to fatigue cracking, especially at higher strain levels.	RAPM content and WMA technology

		• The blending of wax-based WMA additive in base asphalt binder was more effective/beneficial, in terms of fatigue resistance, as compared to surfactant-based WMA additive. • The authors reported that wax additive imparts softening, whereas no influence on stiffness was observed with the application of surfactant-based WMA additive.	
Zhang et al. [235]	ZYF, Sasobit, and Aspha-Min	• Addition of WMA additives in unmodified and SBS modified asphalt binder significantly affects the fatigue factor. • Around 7.2% and 5.5% reduction in fatigue factor was observed with the addition of Sasobit in unmodified and SBS modified asphalt binder, respectively. • The influence of foaming based additive and chemical agents on the fatigue life of asphalt binders was found to be insignificant.	Base binder source and WMA technology

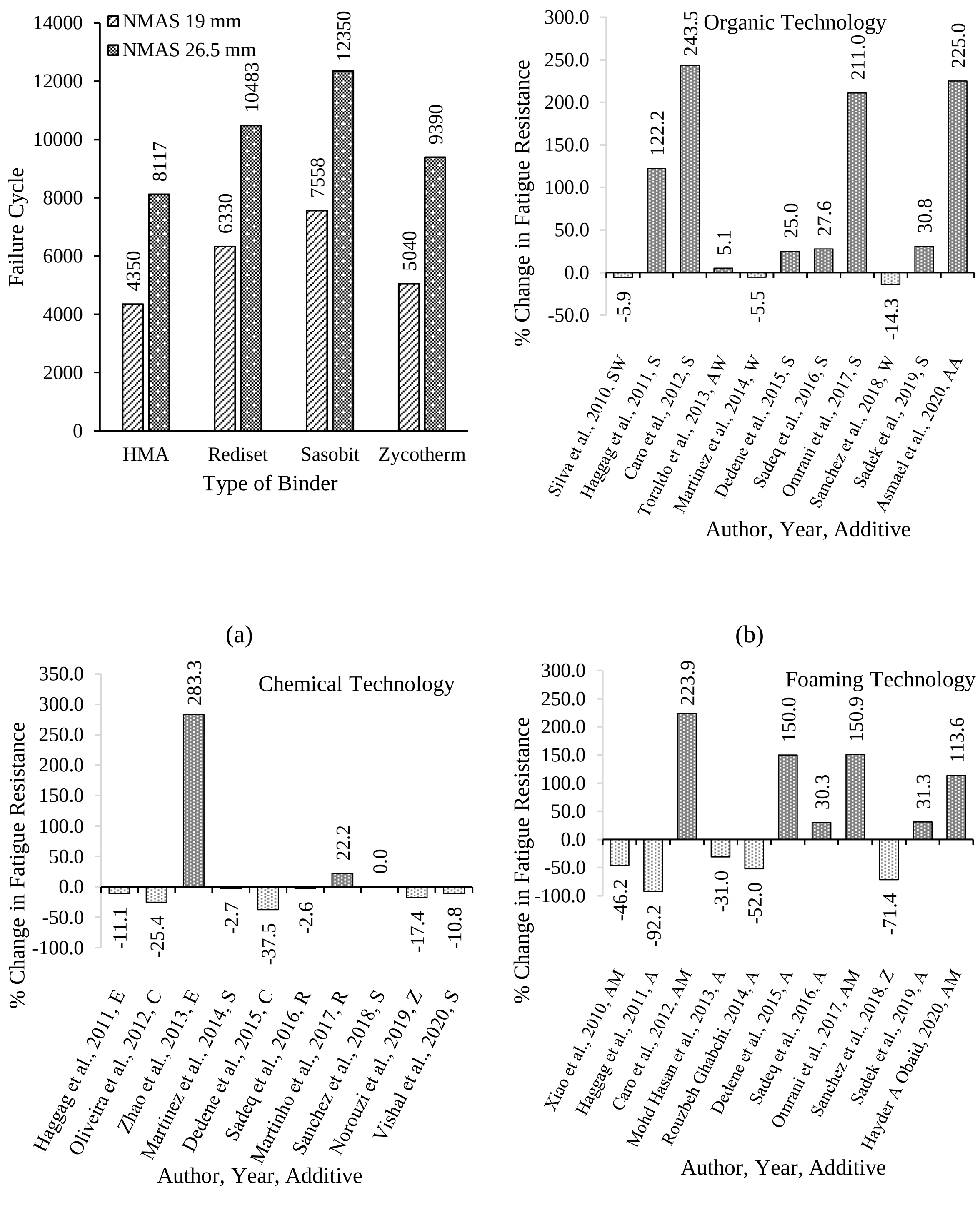
As per the previous literatures [13,302,303], WMA technology, testing method, and stress-strain levels, greatly affect the fatigue life. The fatigue life of WMA produced by organic and chemical additives was evaluated at three different strain levels, i.e., 600, 800, and 1000 microstrain by Norouzi et al. [304]. Findings from the study indicated that irrespective of technology, fatigue life is higher at the lower strain level. The study also concluded that the addition of Sasobit and Rheofalt in virgin binder improves the fatigue resistance at each strain level, whereas mixtures with zycotherm indicated the worst performance. Similar behavior of WMA indicating higher fatigue resistance at lower strain level was observed by Vishal et al. [305] and Fakhri et al. [306].

Along with the aspects mentioned above, WMA's compaction temperature greatly influences fatigue characteristics [51,307]. Similar or even better fatigue life, in comparison to HMA, can be attained by selecting the appropriate compaction temperature of WMA. This can be attributed to the lower aging of WMA during production and paving applications, which tends to enhance pavement flexibility and reduces the concerns related to fatigue cracking [308]. Goh and You [309] found that WMA compacted at 100˚C indicates the same fatigue life as HMA. On the other hand, adopting a compaction temperature of 115˚C enhanced fatigue performance in comparison to traditional HMA. These discrepancies need to be addressed for justifying the efficacy of WMA technology in pavement engineering.

There are no well-established provisions specified in pavement specifications for the design of fatigue resistant WMA. It is considered that NMAS significantly affects the fatigue life of WMA [310,311]. Figure 2.8a compares the effect of NMAS on different WMA. It can be perceived that with the increase in NMAS, the number of cycles to failure increases. The fatigue resistance of WMA with NMAS 26.5 mm is significantly higher than the WMA with NMAS 19 mm, irrespective of the WMA technology. Hence, an appropriate selection of NMAS should be made to improve fatigue resistance.

Based on the field pavement performance in various countries (France, Germany, and Norway), D’Angelo et al. [73] found that both wax-based (Sasobit) and foaming-based (Aspha-Min) WMA pavements exhibited fatigue cracking similar to HMA. Mohd Hasan et al. [307] stated that water containing technologies perform relatively well compared to water-based technologies. Figure 2.8a shows that irrespective of NMAS, Sasobit indicates higher fatigue resistance, followed by Rediset, Zycotherm, and conventional HMA. In short, it can be elucidated that the type of WMA additive influences the fatigue performance of WMA.

Figure 2.8 (b-d) demonstrates some of the examples from previous literature published within the year 2010-2020, showing the percent change in the fatigue resistance at their respective stress/strain levels for WMA relative to control HMA. Similar to the rutting potential, the variables for comparing HMA and WMA are kept the same for each considered literature. It can be stated that the influence of WMA over the fatigue behavior of asphalt mixtures is not conclusive. A few literature [56,312] reported improved fatigue resistance with the incorporation of WMA additives, whereas many researchers obtained negative results [55,65,306,313]. This review indicates that the fatigue performance of WMA is complicated and often difficult to predict. From this perspective, it is suggested to perform further experimental studies to draw a more justifiable conclusion on WMA's fatigue resistance.



(a) (b)

(c) (d)

Figure 2.8. Review on fatigue behavior of WMA mixtures

(a) Effect of NMAS on the Fatigue cycle of WMA [109],

(b) % Change in Fatigue Resistance for Organic Technology [55,56,318,66,85,303,308,314–317],
(c) % Change in Fatigue Resistance for Chemical Technology [65,66,304,305,308,314,315,318–320], and
(d) % Change in Fatigue Resistance for Foaming Technology [85,303,323,307,308,314–316,318,321,322].
Note: In figure 2.8 (b): SW, S, AW, W, and AA in Additive indicate Synthetic Wax, Sasobit, Artificial Wax, Wax, and Asphaltan A, respectively.
In figure 2.8 (c): E, C, S, R, and Z in Additive indicate Evotherm, Cecabase, Surfactant, Rediset, and Zycotherm, respectively.
In figure 2.8 (d): AM, A, and Z in Additive indicate Aspha-Min, Advera, and Zeolite, respectively.

2.6.3 Resistance to Moisture Damage

One of the complex yet common concern for WMA is its propensity to moisture damage, especially after 4-5 years of construction. Reduced adhesion between the aggregate and asphalt binder and/or cohesion in the binder-filler mastic may lead to moisture-induced damage in asphalt mixtures [87,111]. Several factors, such as extra moisture associated with foaming additives, use of moist aggregates, and lower binder absorption by aggregates at reduced processing temperature, can contribute to moisture damage [170,174]. Lower production temperature leads to incomplete drying of entrapped water within the aggregates, which further results in moisture damage [119,289].

Several test protocols have been developed and adopted to characterize the moisture damage phenomenon [324–327]. The commonly used methods for evaluating moisture damage are bifurcated into two categories. One is to test loose mixtures to quantify stripping while another involves compacting specimens to evaluate moisture-induced damage in asphalt mixtures. The loose mixture can be tested by assessing boiling water test and static immersion test, while the compacted mixture can be evaluated using Modified Lottman test and Retained Marshall Stability test. Recently, a pull off test is being used to assess the bond strength (BS) at the interface of asphalt binder and aggregate matrix [328,329]. Pneumatic adhesion tensile testing instrument (PATTI) is required to perform the test. The test can be performed on dry as well as wet conditioned specimens, irrespective of the aggregate substrate and asphalt binder combination [330]. The general guidelines and methodology for measuring the BS are given in AASHTO T361 [331]. Since the test can be conducted under dry and wet conditioned state, few literatures [327,332] have applied the BS approach to ascertain the moisture potential of asphalt mixtures. The loss of BS due to the conditioning of specimens can be measured as the ratio of BS under wet and dry condition and is defined as bond strength ratio (BSR) [327]. In general, higher BSR is desirable for high moisture resistant asphalt mixture and vice-versa.

Mirzababaei [333] carried out boiling water test to understand the stripping characteristics of WMA mixtures prepared with different aggregate sources and gradations. The author stated that both the variables, such as aggregate source and gradations, significantly affect the stripping resistance of HMA and WMA mixtures. However, WMA mixtures exhibit lower stripping than asphalt mixtures prepared without WMA additive, irrespective of any variable undertaken in the study. On the other hand, Ai et al. [334] reported unsatisfactory performance of WMA mixtures against stripping resistance, as around 20% of the total aggregate area was exposed after the boiling test. Since both the studies [334] and [333] analysed different WMA additives, it can be inferred that the stripping resistance of WMA mixtures is a function of WMA technology. In the same context, Habal and Singh [332] evaluated the moisture sensitivity using the BS mechanism incorporating three different WMA additives and two aggregate substrates. It was identified that Sasobit improve moisture resistance when bonded with limestone aggregates, whereas the asphalt binders prepared with Rediset and Advera perform relatively similar to the base asphalt binder. In case of granite aggregates, Advera modified asphalt binder indicated superior performance against moisture damage followed by Rediset and Sasobit. Overall, it can be stated that the moisture potential of asphalt mixtures is dependent on the combined effect of WMA additives and aggregate source. In general, the foaming-based WMA technologies indicates higher chances of moisture damage. Liu et al. [335] carried out various experimental investigations, including boiling water and BS test. Findings of the study revealed that foaming water restrains the adhesive characteristics of asphalt binder and hence no stripping was observed on the aggregate surface. However, the authors observed unfavourable effect of foaming water on the BS value of foamed WMA mixtures. This is due to the presence of residual foaming water at the interface of asphalt binder and aggregate matrix, which erodes the asphalt binder and thereby weakens the BS [336]. Various studies [327,337–339] have performed boiling water and BS test to assess the moisture sensitivity due to its simplicity, despite of their weak correlation with asphalt mixtures.

A number of studies [340–343] employed Modified Lottman test to directly evaluate the moisture performance of asphalt mixtures. This test is conducted in accordance with AASHTO T283 [344] and indicates the moisture susceptibility in terms of Tensile Strength Ratio (TSR), which is the ratio of the indirect tensile strength of conditioned and unconditioned specimens. Table 2.10 compares the variation in TSR values for different WMA technologies in comparison to HMA. As can be seen, WMA technology, aggregate type, and asphalt binder grade have varying effects on asphalt mixtures moisture sensitivity. Similar behavior has also been reported in other literature

[87,340,345]. Table 2.10 illustrates that foaming-based techniques are highly susceptible to moisture, followed by organic and chemical-based methods respectively. At times, the WMA, in the foaming category, even fails to meet the minimum TSR values. This could be associated with the presence of entrapped moisture in foaming-based WMA. In addition, the failure in organic and chemical-based technologies could be attributed to the lower mixing and compaction temperature, resulting in lower aging and incomplete drying of aggregates. On the other hand, few researchers stated that chemical agents are considered to be effective among all the WMA technologies [208,346]. This is attributed to the adhesion-promoting effect of chemical-based technologies, which acts as a bridge between aggregate surface and asphalt binder [77]. However, chemical agents entail careful consideration because a reduction in binder's surface tension occurs without influencing the physical properties.

Considering binder type, no particular trend is observed with the change in asphalt binder grade. Factors such as aggregate type and WMA technologies have a more dominant effect than binder type to cause variation in WMA moisture sensitivity. As far as aggregate type is considered, on an average, the asphalt mixtures prepared with granite and basalt aggregate showed improved resistance to moisture damage relative to other aggregates. The asphalt mixtures incorporating limestone aggregate indicated both positive and negative results based on the technology used. However, it is still very difficult to ascertain the impact of aggregate on the moisture sensitivity of asphalt mixtures due to the availability of different aggregate types and sources. Besides, it causes difficulty in determining the effect of aggregate gradation due to the variability of aggregates. Thus, comprehensive research work is required to draw a conclusive statement concerning different aggregate types.

A few literatures [43,340,343] reported that the condition of aggregates (moist or dried) also affects the moisture sensitivity. Ji et al. [347] found that moist aggregates in WMA may have the potential of moisture-induced damages. The study also indicated that the increase of moisture content in aggregates from 0% to 3% reduces the TSR value by 21.29%. This reduction in TSR value may be attributed to the inadequate coating of asphalt binder over the moist aggregates, resulting in moisture-induced damage. It is considered that adopting different protocols in WMA production could mitigate concerns related to moisture damage. In general, moisture sensitivity enhances with an increase in compaction temperature, irrespective of WMA additive. The increase in compaction temperature directly simulates the ageing effect [87]. A similar phenomenon is attained when WMA's curing/conditioning is executed for at least 2 hours, permitting a higher absorption and aging of the asphalt binder [14,348]. Xiao et al. [171] reported that aging removes the entrapped moisture from the moist aggregates, which indirectly leads to improved TSR values irrespective of WMA technology.

Field investigations reported that warm mix inclusive asphalt pavements are more prone to moisture damage as compared to traditional HMA pavements [173,349]. Therefore, it is recommended to incorporate ASA’s in WMA to improve the resistance to moisture damage [167,350]. As per the data reported by Bonaquist [32], 67% of WMA pavements, together with an ASA, offer similar or even higher TSR as compared to HMA. Conversely, 79% of WMA pavements exhibit lower TSR in the absence of ASA’s. Kavussi and Hashemian [123] divulged that using 2% hydrated lime as an ASA in WMA improves the moisture sensitivity in terms of TSR. However, WMA typically indicates lower wet and dry ITS values than the corresponding HMA. These observations are in line with the findings by other researchers [43,351]. Few researchers have recommended PMB and CRMB in WMA to increase the adhesion between the aggregate and asphalt binder and thus reduce its moisture sensitivity [161,306,312,352–355]. In brief, it is suggested to select appropriate WMA technology, type of binder, and type of ASA wherever necessary based on the climatic condition, traffic loading, and overall pavement integrity to overcome the moisture damage concerns.

Table 2.10**.** Variation in TSR of WMA corresponding to HMA

Reference, Year	**WMA Agents**	**Aggregate**	**Base Binder**	**% Change in TSR**
Organic Technology				
Gandhi et al. [279], 2010	Sasobit	Granite	PG 64-22	20.4
Liu et al. [239], 2011	Sasobit	NA	PG 58-28	9.5
Sangsefidi et al. [270], 2012	Sasobit	Limestone	PEN 60/70	-9.4
Xie et al. [356], 2013	Sasobit	Basalt	PMB	2.6
Malladi et al. [174], 2014	Sasobit	Granite	PG 64-22	11.6
Mohdhasan et al. [357], 2015	Sasobit	NA	PG 58-34	-7.0
Nakhaei et al. [17], 2016	Wax	Limestone	PEN 60/70	16.9
Ranieri et al. [19], 2017	Sasobit	NA	PMB	-23.7
Martinho et al. [358], 2018	Sasobit	NA	PEN 35/70	6.5

Zhu et al. [290], 2019	Sasobit	Basalt	PEN 60/80	11.4
Yang et al. [343], 2020	Wax	Basalt	PEN 80/100	0.1
Chemical Technology				
Jones et al.[346], 2010	Rediset	Granite	PG 64-16	180.0
Punith et al. [176], 2011	Rediset	Schist	PG 64-22	-2.03
Punith et al. [340], 2012	Evotherm	Schist	PG 64-22	-12.35
Sengoz et al. [359], 2013	Chemical	Basalt and Limestone	PEN 50/70	7.9
Leng et al. [168], 2014	Evotherm	NA	PG 64-22	-16.7
Mohdhasan et al. [357], 2015	Cecabase	NA	PG 58-34	-11.8
Mirzababaei et al. [333], 2016	Zycotherm	Limestone	PEN 60/70	5.3
Mohd Hasan et al. [360], 2017	Zycotherm	Granite	PEN 80/100	6.6
Singh et al. [169], 2018	Evotherm	Basalt	VG 30	-5.2
Sanij et al. [208], 2019	Zycotherm	NA	PEN 60/70	15.1
Yang et al. [343], 2020	Chemical	Basalt	PEN 80/100	0.9
Foaming Technology				

Gandhi et al. [279], 2010	Aspha-Min	Granite	PG 64-22	12.2
Goh and You [361], 2011	water foam	NA	PG 58-34	20.7
Punith et al. [340], 2012	Aspha-Min	Granite	PG 64-22	8.43
Sengoz et al. [359], 2013	Synthetic Zeolite	Basalt and Limestone	PEN 50/70	-75.2
Malladi et al. [174], 2014	Advera	Granite	PG 64-22	-33.3
Sebaaly et al. [20], 2015	Advera	Quartzite	PG 64-28	-5.9
Wosjuk and Franus [362], 2016	Synthetic Zeolite	Limestone, Grandodiorite, Dolomite	PEN 35/50	6.5
Wu and Li [49], 2017	Advera	Basalt	PG 58-28	-26.3
Sanchez-Alonso et al. [363], 2018	Zeolite	Ophite and Limestone	PEN 50/70	-8.2
El-Hakim et al. [364], 2019	WMA Foam	Limestone and Dolomite	PG 70-22	-27.8
Zhang et al. [235], 2020	Aspha-Min	Limestone	PEN 80/100	-14.7

2.7 Field Survey

In the past decades, WMA's performance was apparently based on laboratory investigations [365]. In recent times, the construction of the road with WMA technology is progressively running at a rapid rate. WMA technology has been used for the construction of pavements at airfields, bus stops, parking lots, expressways, highways, and port facilities [73]. However, the lack of awareness and experience restrains the contractors and engineers from employing this technique on a larger scale. There are two major concerns for this reluctancy. First, the implementation of WMA technology in the paving operation demands proper quality control [102]. Additionally, the inadequacy of available data on the long-term behavior of WMA pavements [21]. This could be associated with the fact that field demonstration projects are still at the initial stages.

Different levels of traffic exist along with a wide variety of vehicles throughout the in-service life of the pavement. Hence, loading modes could be significantly different based on pavement utility [366]. This could be allied with varying configurations of axle and the respective number of repetitions. The required guidelines for mix design methods, aggregate and binder type, and climatic conditions can be substantially different based on the specifications of different countries. Therefore, an attempt has been made to compile the data gained from the field performance of different countries. This data will help the concerned field engineers ascertain the effects of WMA technology under various loading and environmental conditions. Field implementation with WMA has been done for a variety of aggregate gradations, such as dense-graded asphalt mixture, SMA, and porous asphalt [16]. Several field demonstration projects have been successfully constructed in India, South Africa, Germany, USA, Norway, Canada, China, France, and Brazil [367]. Some of the field survey findings to quantify the performance of WMA are presented in Table 2.11.

Table 2.11. Summary of field survey

Year	Location	Binder Type	WMA	Performance Observed	References
Organic Based Technology					
2006	Virginia	PG 64-22	S	• Sasobit did not cause any significant change as far as volumetric is considered. • Field permeability and density were the same as that of HMA. • Rutting resistance of WMA and HMA was not statistically different.	Diefenderfer et al. [368]
2007	United States	PG 64-22	S	• Without an increase in compactive effort, the WMA section's average in situ density was approximately 93.5%, whereas the HMA section reported 92% field density. • Rutting resistance was reduced with the use of WMA. • Reduction in air emission and fuel	Anderson et al. [101]

				consumption were identified.	
2008	South Africa	PEN 40/50	S	• 15-20% reduction in fuel consumption was observed. • Similar density as that of HMA was achieved at 20°C lower production temperature.	Naidoo and Lewis [369]
2008	Alaska	PG 58-28 (PMB)	S	• Extended paving season and improved compaction were achieved. • No adverse low-temperature cracking was found after one year of construction. • WMA was found to be more rut resistant than HMA. • 30% reduction in fuel consumption was detected. • The surface appearance was the same as that of newly constructed pavement.	Saboundjian et al. [370]

2010	Korea	PG 64-16	L and S	• HMA section met the target degree of compaction (96%), while the degree of compaction in the WMA section was approximately 95%. • Higher rutting resistance than HMA.	Baek et al. [371]
Chemical Based Technology					
2005	Alabama	PG 67-22	E	• The rut depth for both HMA and WMA test sections were reported to be 1mm after 500,000 ESAL.	Button et al. [95]
2006	Texas	PG 76-22	E	• Measured densities are comparable for both WMA and HMA sections. • No difference in performance was observed.	Button et al. [95]
2007	China	AH-70	E	• The performance of WMA pavement was similar to control HMA even after several years of construction. • WMA can be easily compacted at low air	Tao et al. [372]

				temperatures due to the wider compaction window. • After one year, the maximum rut depth was reported as 3.5 mm, indicating a rut resistant mix.	
2009	India	VG 30	ST	• Mixing time in pug mill was reduced from 26 sec to 23 sec, indicating an increase of 12% in production rate. • According to the deflection results, the differences in WMA stretch and HMA stretch are not significant. • Outcomes of Marshall stability, rutting resistance, and resilient modulus test, TSR and RMS indicate WMA's benefits in terms of compactability and constructability.	Behl et al. [373]

2010	Brazil	CRMB	ST	• No difficulties were stated during the mixing and laying operation of the WMA section. • WMA pavement was constructed at lower temperatures with less hazardous fumes. • Field compaction in WMA was the same as that of the HMA section. • Overall, the performance of WMA road segment was comparable to HMA sections.	Motta et al. [374]
Foaming Based Technology					
2000	Norway	PEN 50/70	WF	• Air voids are slightly higher for WMA. • Lower rutting resistance was observed after some years of evaluation.	Larsen et al. [375]
2001	Norway	PEN 50/70	WF	• Rutting is marginally lower for WMA sections as compared to HMA.	Larsen et al. [375]

				• Saving in fuel consumption and reduction in overall emissions were reported.	
2005	Canada	PG 64-28	Am	• The mixing temperature for WMA and HMA pavements are 132.5°C and 160°C, respectively, indicating a reduction in production temperature by approximately 30°C. • No difficulties in mixing, laydown, compaction were reported. • After 2-3 years of construction, the WMA section performs similar to that of the HMA section.	Davidson [376]
2007	United States	PG 64-22	A	• Rutting resistance was reduced with the use of WMA. • Reduction in air emission and fuel consumption were identified.	Anderson et al. [101]

2008	South Carolina	PG 64-22	DBG	- No significant difference in rut depth for WMA and HMA has been noted.	Anderson et al. [101]

Note: S, L, E, ST, Z, WF, Am, A, and DBG in WMA refers to Sasobit, LEADCAP, Evotherm, Surfactant, Zycotherm, WAM Foam, Aspha-Min, Advera, and Double Barrel Green, respectively.

2.7.1 Summary of Field Survey

Based on the field and lab performance, WMA appears to provide similar or even better performance in compaction, density, rutting, and fatigue-related distress compared to HMA. Few trails exhibit various benefits such as longer hauling distance, lower mixing, and compaction temperature, enhanced workability, and improved compaction. Some countries such as Germany, India, USA, and South Africa have also reported that WMA helps enhance the haul distance and provide extended paving season. Most of the countries reported no evidence of difference in strength gain with an increase in time for WMA while contrasting to similar HMA. Finally, it is presumed that warm mix modified asphalt mixtures would last longer.

Experience on the field trials have been positive based on construction and short-term performance. Sufficient details on the long-term performance of WMA field sections are not available. Many trials have serviced more than 12-15 years, but no detailed published data is available for justifying any concrete conclusion on WMA's long-term performance. Several agencies are still making progress in quantifying the short and long-term performance of constructed field sections through field cores and performance monitoring.

2.8 Interaction of WMA with Different Materials

This section summarizes the effect of WMA technology with PMB, CRMB and RAPM at the mixture level. This effect is reviewed using performance indicators such as rutting resistance, fatigue resistance and moisture sensitivity. Table 2.12 presents the effect of this interaction on the rutting, fatigue and moisture resistance properties of modified asphalt mixtures. The parameters influencing this performance is also highlighted.

WMA technologies have been primarily used for PMB and CRMB mixtures to reduce the production temperatures [90,345,377–379]. Most of the studies have concluded that the use of WMA technologies in PMB and CRMB asphalt mixtures give either similar or better performance in terms of resistance to different distresses [306,353,380,381]. In addition to improving mechanical performances, WMA reduces energy consumption and GHG emissions [382,383]. The addition of warm mix additive in the CRMB mixture reduces energy consumption by about 13% in comparison to the control CRMB asphalt mixture [384]. Few studies have reported that WMA lowers the energy consumption and emissions for the production of 20% CRMB inclusive asphalt mixture. The overall reduction in energy consumption and harmful emissions is estimated to be 16.7% and 33.3% as compared to control HMA [382]. Though much investigation have been done on understanding the interaction of WMA additives with PMB/CRMB modified binders, little works can be found on the quantification of the impact of WMA technologies on the mechanical performance of PMB/CRMB modified mixtures. From this perspective, a detailed experimental study on PMB-WMA interaction is recommended to support the implementation of warm mix inclusive polymer modified asphalt mixtures.

The RAPM proportion present in conventional HMA poses unique challenges both in design and construction [74]. These challenges stem from the undesired intrinsic property, such as stiffened asphalt layer over the aggregates, which often leads to workability and compactability issues [161,385]. The primary concern associated with RAPM is high production temperature. Various researchers have attempted to combine WMA technologies and RAPM to overcome the drawbacks of high RAPM in asphalt pavements [386–389]. The WMA-RAPM interaction may be favorable in two aspects, i.e., the viscosity reduction will aid in improving compactability followed by the lower aging of asphalt binder [73]. Table 2.12 illustrates the summary of findings from the previous literature based on the mechanical performance of RAPM-WMA mixtures. Several experimental works on the efficiency of WMA-high RAPM mixtures have shown that the addition of WMA additive could be executed with RAPM >50% without compromising the mechanical performance [65,386,390–393]. With their capability of lowering the viscosity at low processing temperature, WMA technologies may provide a feasible solution to produce asphalt mixtures with 100% RAPM [74,394]. In addition, the interaction of WMA-RAPM might assist in reimbursing the aged RAPM asphalt binder. Mallick et al. [395] conducted a laboratory investigation and commented that WMA technology could rejuvenate the RAPM binder to a level at which the performance is comparable to that of conventional asphalt mixture. Similar behavior of WMA-RAPM has been observed by the other researchers [112,396]. In light of the above-stated findings, it is apparent that higher RAPM content can be utilized with the application of WMA technology. The synergistic use of WMA-RAPM supports the consideration of implementing sustainable technologies and balancing the drawbacks of both the materials. For example, applying WMA technology in RAPM inclusive asphalt mixtures may ameliorate their durability due to improved coating ability and compactability. On the other side, RAPM-WMA improves the rutting resistance and moisture sensitivity because of the stiffening effect of RAPM asphalt binder [15,397]. Shu et al. [398] performed an experiment for evaluating the moisture susceptibility of foaming based WMA comprising 0-50% RAPM. They found that the addition of RAPM in foamed WMA exhibited similar performance as that of HMA as far as moisture susceptibility is considered. The study also highlighted that high RAPM dosages are beneficial to improve the moisture sensitivity of both WMA and HMA. Overall, it can be adjudged that the WMA-RAPM combination demonstrates positive results and could be regarded as a promising approach for future construction. It also provides a way towards sustainability and cleaner development.

Table 2.12**.** Summary of WMA interaction

Interaction	**Performance**	**Description**	**Parameters influencing performance**	**References**
WMA-PMB	Rutting Resistance	Despite being produced at a significantly lower temperature, warm mix modified PMB mixtures indicate similar or even better rutting resistance than that of HMA.	Type of polymer Blending Temperature WMA technology Dosage of additives Rate and time of mixing	[345,371,399,400]
	Fatigue Cracking	A combination of WMA additive and PMB effectively improves the fatigue resistance of asphalt mixtures.		[20,280,306,315]

	Moisture Susceptibility	WMA-PMB interaction eradicates the moisture-induced damage and improves durability.		[20,345,354,401,402]
WMA-CRMB	Rutting Resistance	WMA and CRMB possess a positive effect on the rutting resistance of control asphalt mixtures.	• CR type and dosage • WMA's and dosage • Blending temperature • Rate of mixing • Mixing time	[68,352,378,380,384]
	Fatigue Cracking	Even though the warm mix inclusive CRMB mixtures are produced at a temperature lower than HMA, the fatigue resistance is equivalent to or better than that of HMA.		[68,312,378,380,384]
	Moisture Susceptibility	Implementation of WMA additive in CRMB mixtures ameliorates the moisture susceptibility even at lower processing temperatures.		[379,380,384]
WMA-RAPM	Rutting Resistance	RAPM inclusive WMA exhibit superior rutting performance than the control asphalt mixtures.	• Type and amount of RAP aggregates • Type of virgin binder	[403–408]

	Fatigue Cracking	In comparison with control asphalt mixtures, incorporation of RAPM resulted in similar or even better fatigue resistance.	• Selection of WMA technology • Dosage of WMA’s	[319,386,394,407]
	Moisture Susceptibility	The synergistic impact of RAPM-WMA significantly enhances moisture susceptibility.		[172,398,403,407–410]

2.9 Environmental and Economic Survey

To ascertain the positive impact of WMA technologies on the environment, the present section compiles the information’s published on the life cycle assessment (LCA), green-house gas (GHG) emissions, energy consumption and economical benefits of WMA.

2.10 Life Cycle Assessment

Asphalt pavements have substantial environmental burdens through its life cycle. The comparison between WMA and HMA production at equal boundary variables (such as type of aggregate and binder; the difference in plant location and construction site; and climatic condition) can provide a significant approximation of WMA's efficacy solely due to the distinction in production temperatures. However, the application of WMA based on the difference in production temperatures does not provide a strong justification [81]. In addition, this approach may overlook the critical environmental effects that should be considered to comprehend the cradle to grave performance of WMA. Hence, a complete LCA, which is yet to be adopted, would more comprehensively address the environmental and economic benefits [411,412]. Generally, LCA consists of six steps: a) extraction and processing of raw material, b) transportation, c) construction, d) utilization, e) maintenance and repair, and f) final disposal at the end of life [413,414].

Cheng et al. [415] executed an LCA on WMA and stated that the introduction of WMA could reduce the photochemical ozone formation (POF) and fuel utilization by almost 65-75% and 20-25%, respectively as compared to HMA. Blankendaal et al. [416] performed a cradle to grave analysis and reported that Wm modified asphalt mixtures reduce the negative environmental impact by approximately 33%. Likewise, Hassan [417] concluded that the overall environmental influence of warm mix inclusive asphalt mixture is 15% lower than that of conventional HMA. Moreover, incorporation of WMa could reduce environmental exposure as compared to HMA considering air pollutants, fossil fuel reduction, smog formation, and global warming [418]. Figure 2.9 shows the percent improvement in each of the aforementioned categories with the addition of WMA technology. Consequently, some evidences support the implementation of WMA over HMA, considering positive environmental and sustainable development [23,26,93,419].

While working with different types of WMA additives, Tatari et al. [420] proposed a hybrid LCA model for the comparison of environmental benefits. The study revealed that Sasobit and Evotherm modified asphalt mixtures emit the least pollutants, among others considered warm mix additives. Conversely, few literatures state that Rediset improves the environmental impacts of health, safety, and sustainability [281,421]. It has to be noted that the studies on the selection of appropriate WMA additive based on life cycle assessment are scanty. Thus, a more systematic and complete comparative study between different WMA technologies is further recommended for better understanding.

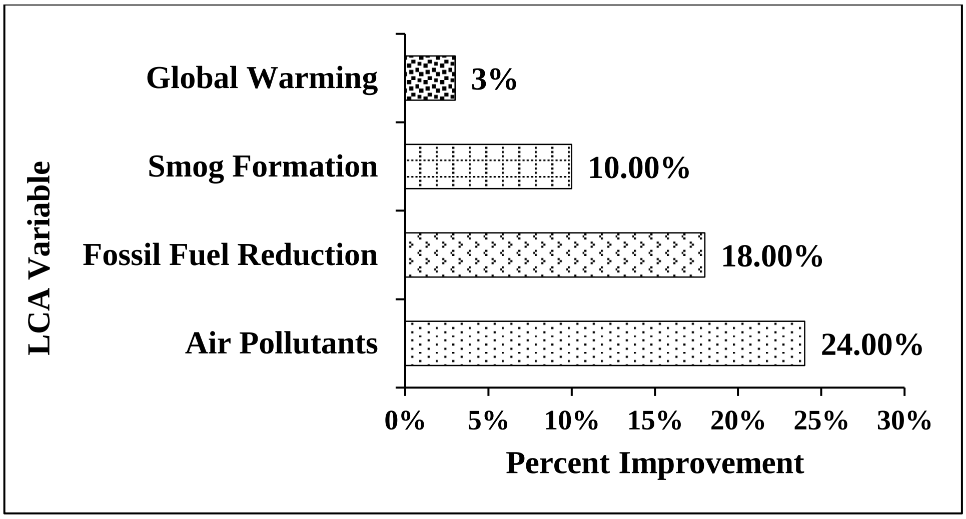


Figure 2.9. Percent improvement in different environmental exposures

2.10.1 Greenhouse Gas Emissions

Optimizing greenhouse gas (GHG) emission shifts the asphalt production plants towards the environmentally efficient zone [72,366]. In general, the change in production temperature is responsible for the variation in GHG emissions. Results based on the study conducted by Stimilli et al. [141] stated that the manufacturing and transportation of WMA is also a significant phase for the increase/decrease in GHG emission. However, few other studies [422,423] opined that the contribution of transportation and manufacturing of WMA is minimal as compared to the variation caused by the change in production temperature.

Reduction in GHG emissions with the incorporation of WMA is a two-stage process [424]. The first stage comprises the reduction in GHG emission owing to the reduced fuel consumption, while the second stage includes the reduced GHG initiated from a heated asphalt binder. As per the investigation led by Croteau and Tessier [425], 4.1 to 5.5 kg of GHG emission could be decreased per ton of WMA. They also concluded that GHG emissions could be reduced by 20-35% with the inclusion of WMA additives. Supporting WMA's application, few investigations reported that there is virtually no emission at a temperature below 80 ˚C; even at 150 ˚C, emissions recorded were only about 1 mgh^{-1} [73]. On the contrary, a considerable amount of emissions were generated at a temperature range of 170-180 ˚C (HMA) [5,426]. In this regard, a reduction in temperature resulted in a drastic drop in fumes and various air contaminants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), volatile organic compound (VOC), carbon monoxide (CO), nitric oxide (NO_x), and dust [46,58,71,81,117,427]. Figure 2.10 shows the percent reduction in harmful fumes and GHG emissions with the use of WMA technologies over HMA. The average reduction in corresponding to different emissions has also been calculated and illustrated. The environmental benefits gained by the incorporation of WMA can be appreciated from Figure 2.10.

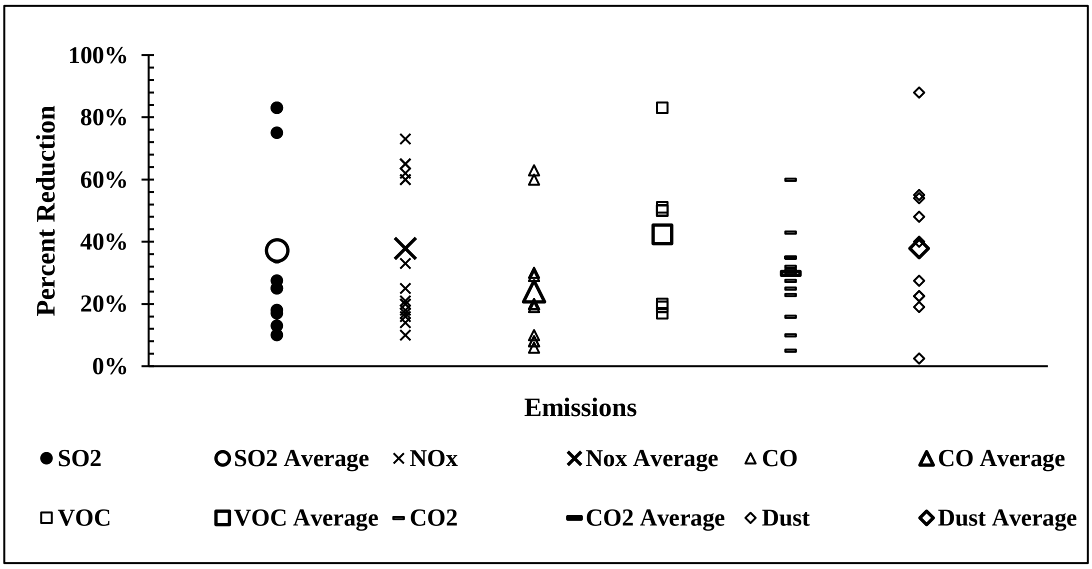


Figure 2.10. Percent reduction in fumes and air contaminants [21,51,422,428–435,71,73,84,141,366,375,418,419]

Various studies used total particulate matter (TPM) and benzene soluble matter (BSM) to investigate the variation in GHG emissions [91,436]. TPM comprises of dust and other particulates that do not produce asphalt fumes. On the other hand, BSM indicates the percent of TPM that could be generated by the exposure of hazardous asphalt fumes [437]. As per the reports of Ministry of Transportation of Ontario (MTO) [438], there is a dramatic drop in BSM values considering the amount of BSM behind the paver and at the location of the paver operator. It was reduced by 63% in the former case and 72% for the latter case. A field survey conducted by Hurley et al. [439] reported that the inclusion of warm mix additive reduces both TPM and BSM by an average of 75% as compared to HMA. Table 2.13 shows the results of industrial hygiene tests executed at four different WMA pavement sections [436]. Replacement of HMA with WMA leads to the reduction in TPM and BSM values, as illustrated in Table 2.13. In this way, WMA would reduce the health risk of plant operators and provide a better working environment.

Table 2.13**.** Results of industrial hygiene tests [436]

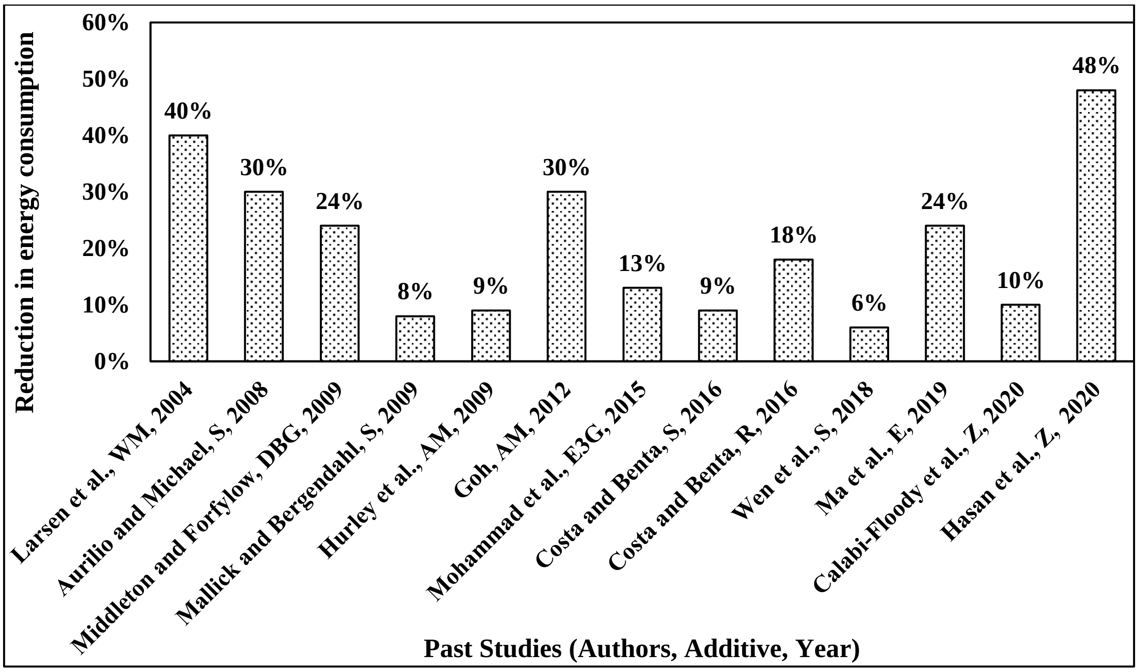
Mixture	**TPM (mg/m^3)**	**BSM (mg/m^3)**	**% Change relative to HMA**	
			TPM	**BSM**
HMA	1.25	1.05	-	-
Evotherm	0.29	0.29	76.80	72.50
Aspha-Min	0.41	0.20	67.20	81.00
Sasobit	0.33	0.21	73.60	80.00

2.11 Energy Consumption and Economic Benefits

The significant economic benefit of WMA is associated with the reduction in energy consumption during the production of WMA. This reduction in energy consumption is directly dependent upon the decrement in production temperature [83,248,440]. A comparison between WMA and HMA indicated that the incorporation of WMA technology could reduce energy consumption by about 20-75% based on the different temperature reduction range [441]. Figure 2.11 demonstrates the details of the reduction in energy consumption indicated by previous researchers. As can be seen in the figure, the range of percent reduction in energy consumption is estimated to be 6-48% depending on the fuel type, energy source, and production temperature.

Theoretically, positive savings are raised because fewer roller passes were required to achieve the desired compaction value. According to Croteau and Tessier [425], 25% of energy can be saved with a reduction in asphalt mixtures' production temperature by 20˚C. Prowell and Hurley [16] stated that WMA could reduce fuel consumption by approximately 10-35%. It is estimated that for every 6 ˚C drops in production temperature, there is a 3% reduction in fuel usage [16]. Likewise, Hassan [81] reported that WMA reduces fossil fuel consumption by 18% as compared to HMA. However, the cost of WMA additives, transportation cost, installation cost for the application of machines in asphalt plant, and licensing fee increases the cost of WMA production. Larsen et al. [375] indicated that WMA could increase the costing of asphalt mixtures between $2 to $4 per tonne of the mix. Table 2.14 illustrates the comprehensive data on the supplementary costs per ton of mix [435]. The purpose of Table 2.14 is not for the comparison between WMA technologies but rather to depict that these innovative technologies have an additional cost that must be at least matched by their apparent benefits. Kristjánsdottir et al. [83] opined that WMA is potentially beneficial for places where the fuel charges are relatively higher. In line with the context, Rubio et al. [77] reported that financial benefits attained through energy savings could offset the associated costs incurred on WMA chemicals and machine installation/modifications. In this regard, the increased likelihood of success for WMA justifies the supplementary expenses.

Briefly, it is noteworthy that the reviewed potential outputs illustrated WMA's efficacy for reducing energy consumption, providing a significant reduction in GHG emissions. The overall positive effects in terms of sustainability directly correspond to economic feasibility and thereby support WMA's application in comparison to HMA for paving operation.



Note: WM, S, AM, E3G, R, E, and Z denote WAM Foam, Sasobit, Evotherm 3G, Aspha-Min, Rediset, Evotherm DAT, and Zeolite, respectively.

Figure 2.11**.** Reduction in energy consumption based on past studies [10,51,444,445,71,375,418,426,435,439,442,443]

Table 2.14. Supplementary cost for WMA technologies [435]

Economic Parameter		Machine Modification/Installation Costs ($)	Additive Cost ($)	Additive Dosage	Royalties ($)	Estimated Increased Cost of Mix ($) (per ton of mix)
WMA Technology	**Evotherm**	Minimal	35-50 Premium on asphalt binder	30% water/ 70% asphalt concrete	NA	3.5-4
	Sasobit	0-40000	1.75/kg	1.5-3% w/b	NA	2-3
	Zeolite	0-40000	1.35/kg	0.3% w/m	NA	3.6-4
	LEA	75000-100000	undefined	0.5% w/b	NA	0.5-1
	WAM Foam	60000-85000	75 Premium on soft binder	3% w/b	15000 first year/ 5000 per plant per year/ 0.35/ton	0.27+0.35 royalty
	Double Barrel Green	100000-120000	undefined	2% addition of water to the asphalt binder	NA	NA

2.12 Summary

WMA is a rapidly growing innovative process wherein mixing and compaction of asphalt mixtures could be achieved at 10-40 °C lower production temperatures compared to HMA. This reduction depends on the technology implemented along with other aspects such as mixture type and climatic conditions. Considerable laboratory investigations have been done on WMA technologies such as organic additives, chemical agents, and foaming processes. Literature review indicated that WMA techniques could be employed for all the types of mixtures, including dense, gap graded and open graded mixtures. Additionally, WMA can be used with other technologies such as CRMB, PMB and RAPM. The conclusions drawn from the comprehensive literature review are as follows:

- Mix design methods for WMA are similar to HMA. However, the selection of production temperature and conditioning of asphalt mixtures needs to be judged based on different laboratory and field trails. Amongst the mix design parameters, quantification of workability is a function of the type of WMA additive used. Use of torque meters are suggested to evaluate the workability and the production temperatures for WMA. In terms of mechanical performance, the selection of binder type, additive dosage, and aging conditions plays a viable role. Laboratory investigations done by previous researchers indicate that equal or even better rutting and fatigue resistance can be achieved in WMA in comparison to conventional HMA, regardless of the test method and analysis. Foaming based technologies are susceptible to moisture related damage. Use of ASA’s and adopting appropriate curing conditions can help to improve the resistance to moisture damage.

- Field surveys have reported that WMA aids in enhancing the haul distance and provide extended paving season. No significant change in performance is observed between WMA and HMA from available field data. Accordingly, more effort is needed to ascertain the long-term behavior of WMA.
- The incorporation of WMA additives manifests to be a useful measure for reducing the mixing and compaction temperatures of PMB and CRMB mixtures. Insignificant differences in performance were observed while comparing the control mixtures (PMB and CRMB) and warm mix inclusive PMB and CRMB mixtures. On the other hand, WMA's application provides a feasible solution to produce asphalt mixtures with high RAPM content without affecting the mechanical performance and durability.
- Incorporating WMA reduces environmental exposure considering air pollutants, fossil fuel reduction, smog formation, and global warming. The findings also assist that utilizing WMA technologies provides better working conditions for workers at the time of paving operation.
- Although accepting this technology includes several limitations, WMA technologies advantages as a whole elucidated to surpass their barriers. Table 2.15 shows the overall impact of WMA on various performance parameters. It is noteworthy that the difference in the results might be influenced by various factors such as type of binder and aggregate, aggregate gradation, NMAS, WMA technology, blending time, rate of mixing, and climatic conditions.

Table 2.15. Overall impact of WMA technology

Technology		Rutting	Fatigue	Moisture	Production Temperature	Workability	Emissions
WMA	**Organic**	P	N	P/N	P	P	P
	Chemical	P/N	N	P	P	P	P
	Foaming	P/N	N	N	P	P	P
WMA-PMB		P	P	P	P	P	P
WMA-CRMB		P	P	P/N	P	P	P
WMA-RAPM		P	P/N	P	P	P	P

Note: P and N indicate positive and negative impacts, respectively.

Based on the literature review, it was anticipated that a comprehensive study is required for justifying the use of WMA technologies for road infrastructure. From this perspective, an attempt has been made to broadly investigate the micro and macro scale performance of WMA over a wider range of test conditions. Different performance-based parameters at binders and mixtures phase have been evaluated and proposed in order to ascertain the efficacy of WMA technologies. The present study proposed and validated a novel method for the evaluation of mixing and compaction temperatures of WMA mixtures. A theoretical analysis has also been done to quantitatively evaluate the economic and environmental burdens associated with the production of asphalt mixtures. It is envisaged that the data presented and the research carried out in this study will be helpful for asphalt industries, policymakers, and environmental authorities or decision-makers for implementation of WMA in pavement construction.