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The Use of Geopolymers in Warm Mix Asphalt Technology – A Review

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Abstract – The utilization of geopolymers as additives in warm mix asphalt has recently gained significant attention in the field of asphalt technology. This paper provides an in-depth review of the current literature on using geopolymers in warm-mix asphalt. Warm mix asphalt has captured the attention of many researchers due to its production temperature being lower than Hot Mix Asphalt, which can result in a reduced number of gases released during production, allow for better handling of the binder on-site during the application, reduced energy consumption, and allow for quick opening to traffic. The review focuses on the effects of geopolymers on the physical and mechanical properties, moisture susceptibility, and rutting resistance of warm mix asphalt. This review's findings show that adding geopolymers can improve the mechanical properties of warm mix asphalt, such as stiffness and fatigue resistance. Moreover, including geopolymers in warm mix asphalt can improve their resistance to moisture damage and rutting. Additionally, the review highlights the need for further research on optimizing the geopolymer's dosage and their interaction with the other constituents of warm mix asphalt. Overall, this review provides valuable insights into the potential benefits and challenges of using geopolymers as additives in warm mix asphalt and highlights the need for further research in this area.

Keywords: Warm mix asphalt, geopolymers, additives, sustainability, pavement performance

1. Introduction

Warm mix asphalt (WMA) technology was introduced to produce asphalt at temperatures slightly above 100 °C, with performance and characteristics similar to or better than traditional Hot mix asphalt (HMA) [1]. The production of WMA focuses mainly on the binder by adding various additives to improve its qualities by providing adequate aggregate coating, enhancing workability and compatibility while lowering production and compaction temperatures by 20 - 40 ° C [2], [3]. Compared to HMA, the coating of the aggregates is massively increased and can be achieved at lower temperatures (less than 30 °C) [4]. WMA being produced at low temperatures significantly reduces environmental burdens and lowers greenhouse gas emissions [5], [6], [7]. WMA also has lower production costs as it is produced at lower temperatures resulting in low energy consumption [8].

1.1 Warm Mix Asphalt Techniques, benefits, and drawbacks

Different techniques are used to reduce the binder's viscosity and are classified differently. WMA technologies are classified into three types according to the technology used to reduce temperature: Foaming techniques, both water-based and water-bearing; organic or Wax additives; and chemical additives [9]. Table 1 summarizes WMA technologies and their usage, as highlighted by [10]. WMA has a lot of environmental, economic, and technical advantages to bituminous mixtures [4]. The benefits are determined mainly by the type and dose of WMA additives used and the properties of other elements in the bituminous mixture, including the binder, aggregate, and recycled materials. The main advantage of WMA is the decreased viscosity of the asphalt mix [11]. WMA lower production temperatures lead to lower emissions and improve working conditions, benefiting construction workers by minimizing harm from direct exposure to fumes [4]. Using WMA as an alternative to HMA has drawbacks: increased production costs from extra equipment and additives, but lower energy consumption may help balance the expenses. Additionally, some WMAs exhibit reduced resistance to moisture damage and bonding/coating challenges compared to HMA [12]. This makes WMA mixtures more prone to moisture damage leading to cracking and rutting. WMA's lower optimal binder content than HMA could be the source of the long-term durability problems of WMA. Unlike HMA, WMA lacks design standards, making comparing and evaluating different WMA technologies and their overall performance difficult.

Table 1: Summary of Warm Mix Asphalt Additives and their Mixing Temperature

Type Technology	WMA Additive	Company	Recommended Additive Usage	Mixing Temperature (°C)
Foaming	Aspha-min	Eurovia and MHI	0.3% by total mass of the mix	130-170 based on stiffness of binder
	ADVERA WMA	PQ Corporation	0.25% by total mass of the mix	130-170 based on stiffness of binder
	LEA	LEA-CO	0.2-0.5% by weight of the binder	<100
	LEAB	BAM	0.1% by weight of the binder	90
	LT Asphalt	Nyanas	0.5 - 1.0 % of hygroscopic filler	90
Organic Additives	Sasobit	Sasol	0.8-3.0% by weight of asphalt	130 - 170 based on stiffness of binder
	Asphaltan-B	Romonta	2.5% by weight of asphalt	130 - 170 based on stiffness of binder
	Licomont BS 100	Clariant	3% by weight of asphalt mix	130 - 170 based on stiffness of binder
Chemical Additives	CECABASE RT	Arkema Group	0.2-0.4% by weight of asphalt	90 - 100
	HyperTherm/QualiTherm	Coco Asphalt Engineering	0.2-0.3% by weight of the binder	120
	Rediset WMX	Akzo Nobel	2% by weight of the mix	120 - 130

1.2 Mix design methods for Warm Mix Asphalt

The Marshall and Super- pave mix design procedures are used globally to prepare bituminous mixes [13], [14]. The design method to determine the parameters of a hot mix vary depending in the geographic location. The Marshall method, which is widely used in South Africa, requires light and inexpensive equipment. The stability, flow value, density, and air void content findings are studied when choosing the best asphalt concrete. The procedures used to produce WMA are not dissimilar to those used to produce HMA; previous research has demonstrated that all WMA investigations use HMA mix design approaches with a few modifications in the bitumen mixing plant. WMA mix design is influenced by material parameters (binder and aggregate), aggregate gradation, mixing and compaction temperature, and curing technique.

1.3 Mix design Properties

The optimum binder content (OBC) and volumetric parameters are critical properties of the overall performance of bituminous mixtures. The bituminous mixture's volumetric properties include air voids, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB). The OBC of the bituminous mix is determined before adding WMA additives, and the same content is used for WMA and HMA. Most studies adopt an air void content of 4% for WMA and HMA mixtures, the same percentage suggested by Sabita Manual 35. WMA mixtures usually have lower air voids, ensuring better compactibility of the samples [15]. Tang [16] controlled the air voids content for their investigation at 4.5% and the optimum binder content at 5,07%. The study results showed that WMA samples have an average reduction in air void content of 0.32%. WMA samples exhibit greater VFB values than HMA samples, indicating that they may be more durable, though this needs to be confirmed by field investigations.

2 ASPHALT BINDER ADDITIVES

Different mechanisms and additives can be used to modify asphalt binders, such as polymers, crumb rubber, styrene butadiene styrene (SBS), natural rubber (NR), nano clay, geopolymers, etc. [17]. As a result of the development of modified asphalt binders, transportation agencies now have the tools necessary to create balanced asphalt mixtures that can withstand these conflicting stresses while retaining good long-term durability [18]. The ones that are often investigated are discussed in the following sections.

2.1 Polymers

One of the first modifiers utilized in asphalt modification was polymer additives. Polymers were first used to modify asphalt in 1843, as suggested by the study of [19]. Abbas [20] reported that 1% fly ash and 4% SBS rubber recorded the highest asphalt stiffness and great resistance to deformation. The presence of SBS reduced the binder's temperature susceptibility and increased its penetration index (PI). Adding 5% fly ash and 5% SBS increased the binders softening point.

2.2 Geopolymers

Different geopolymer materials have been used in pavement technology to modify the properties of bitumen and reduce various kinds of pavement distress. Geopolymers offer a solution to solid waste disposal and being used on paved roads. They were first developed by [21] more alike materials have evolved. Geopolymers are formed when alumino-silicate materials and alkaline solutions undergo chemical reactions called the geopolymerization process at high curing temperatures [22]. Alumino-silicate materials are mostly a by-product of industrial waste the likes of fly ash (FA), ground granulated blast furnace slag (GGBS), bottom ash, silica fume, red mud, and other materials [23]; they can also be natural minerals like kaolinite, clays, etc [24]. The most used alkaline activator is a combination of sodium hydroxide (NaOH) and (sodium silicate) $NaSiO_3$ [25]. According to Vijaya Rangan [24], additional water in the geopolymer mix has no impact on the chemical reaction but improves the workability of the mixture during handling. In recent years more geopolymers have been developed due to their excellent mechanical properties, which can be very beneficial in pavement construction.

The choice of geopolymer material depends on cost, availability, application technique, and the end user's demand [24]. Generally, concrete-based materials have a high repair cost as they require special rapid setting materials to be used to shorten the repair time and quickly open the road to traffic. However, the deflection of any repaired patch under traffic load needs to be the same as of the surrounding pavement, therefore repairs using cement-based materials are not recommended. Over the years researchers have investigated the use of geopolymers in road construction as a pavement repair material [26], [27], [28], some have used geopolymers to modify asphalt mixes [29], [30], [31], stabilize the base, and even make aggregates using geopolymers [32], [33], [34] and have resulted in significant findings.

3 GEOPOLYMER MODIFIED ASPHALT BINDER

3.1 Manufacturing of geopolymer additive

The geopolymer microstructure has many pores and channels, producing a large specific surface area that adsorbs free water and hydrated metallic ions [35]. The water will then be gradually released and evaporated into steam at 90 - 140 °C. When geopolymer is introduced to bitumen, bubbles will likely form in the bitumen, resulting in the viscosity of bitumen being reduced by steam pressure, reducing the mixing temperature [12]. The innovative usage of geopolymer as WMA additives is intended to not only pave the route for the reuse of industrial waste, but also to lower the asphalt mixing temperature. Figure 1 below highlights the process of making a geopolymer additive.

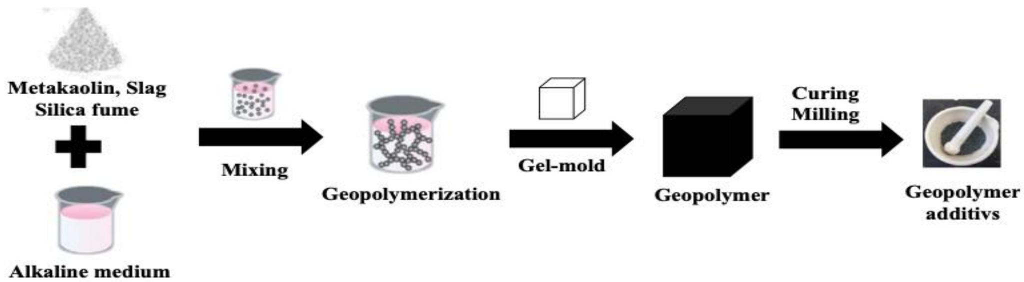

Figure 1. Manufacturing of geopolymer additives [12]

3.2 GMAB physical properties

Geopolymer modification of asphalt mixtures in warmer regions increases elasticity and stiffness while improving elastic and engineering qualities [36]. To produce a balanced and outstanding modified asphalt, factors such as temperature, mixing time, and the properties of the asphalt and geopolymer are constantly considered. These factors all significantly impact how well the asphalt mixtures [36]. function. Geopolymers can improve mechanical properties, withstand damage during operation, and lower greenhouse gas emissions and energy consumption. Geopolymers can also reduce the bitumen required in the asphalt mix, leading to a more sustainable and environmentally friendly pavement [12]. Using geopolymer in asphalt mixtures helps improve the physical properties of the asphalt binder, like viscosity, penetration, ductility, and softening point. Several studies have investigated using geopolymers to modify asphalt, Table 2 below highlights some of the studies and their key findings.

Table 2. Type of Asphalt, Ratio, and Activator for geopolymer to modify asphalt

Reference	Asphalt Type	Geopolymer		Key Findings
		Activator	Pozzolanic & Ratio	
[37]	60/80	NaOH + $NaSiO_3$	MK+S+SP 3, 5, 7, and 9%	Enhanced the binder's resistance to permanent deformation and resilience.
[16]	AH-90	NaOH + $NaSiO_3$	MK+GGBS+SF 0, 0.3, and 3 wt%	Decreased the rutting resistance, and improved crack resistance at low temperatures with a higher dosage.
[38]	60/70	NaOH + $NaSiO_3$	Palm Oil clinker powder 2,4,6, and 8%	Improved softening point, temperature susceptibility, and lower penetration value
[39]	PG 58-28	NaOH + $NaSiO_3$	Class F, FA 3, 6, and 9%	Increased temperature susceptibility and shear modulus, improved rutting resistance, and failure temperature
[12]	AH-90	NaOH + $NaSiO_3$	MK+SF 2, 6, and 10%	Optimized dosage of the geopolymer additive was 6%.
[30]	60/70	NaOH + $NaSiO_3$	Class F, FA 3, 5, and 7%	Improved rutting resistance at high temperatures, optimum results obtained with 5% geopolymer
[29]	80/100	NaOH + $NaSiO_3$	Class F, FA 0, 3, 5, 7, and 9%	Addition of 5% geopolymer resulted in optimal results

NaOH+NaSiO3= sodium hydroxide & sodium silicate; MK= Metakaolin; S95 slag; SP = Silicon powder
GGBS = ground granulated blast-furnace slag; SF = silica fume; FA = fly ash

3.2.1 Viscosity

Asphalt binder must be adequately fluid at high temperatures for better handling during mixing and compaction. Ibrahim [29] reported that GMAB with 5% fly ash geopolymer dosage had the highest viscosity value of 0.460 mPa.s and 0.169 mPa.s at 135 °C and 165 °C, respectively. Bujang [40] also reported that an increase in the geopolymer dosage increased the viscosity of the asphalt binder, where up to 3% fly ash geopolymer dose at 120 °C and 180 °C for bitumen grade 60/70 recorded viscosities of 1668 and 132 Pa.s, respectively. Asphalt binder grade 80/100 recorded viscosities 1044 and 72 Pa.s with the same geopolymer dosage and same temperature. The study also noted that the binder's viscosity decreases as the testing temperature increases.

3.2.2 Penetration and Softening Point

The penetration test helps to grade the binder, in turn helping to assess its suitability in different climatic conditions and the type of construction it can be used in. Bujang [40] studied the penetration of 60/70 and 80/100 bitumen grade when modified with fly ash geopolymer. the results of the study indicated a drop in the penetration value from 86.6 d.mm to 77 d.mm and 68 d.mm to 55.6 d.mm, respectively, with 9% geopolymer dosage. The study also noted that the penetration value was lower for both binder grades regardless of the geopolymer dosage. The softening point test determines the temperature at which the binder should be heated i.e., shows the temperature at which the binder attains a certain viscosity. Bujang [40] reported that 9% fly ash geopolymer dosage for 80/100 and 60/70 bitumen grade resulted in a 13% and 11% increase in the softening point, respectively, compared to the base binder, which recorded 51.1 °C. The same trend was noted in [29] study, where 3% and 5% fly ash geopolymer increased the softening point of the binder from 47 °C to 49 °C and 56.5 °C, respectively. A high softening point for asphalt binders decreases their rate of rutting.

3.2.3 Ductility

A ductility test is conducted to measure the adhesive properties of the bitumen and its ability to stretch under a standard testing condition below its softening point [40]. Bujang [40] reported that adding 9% fly ash geopolymer reduced the ductility value for asphalt binder grades 80/100 and 60/70 from 150 mm to 103 mm and 150 mm to 89 mm, respectively, compared to the base binder. Tang [12] recorded a reduction in ductility with the increase in geopolymer dosage, 10% geopolymer dosage reduced ductility from 137.4 mm to 127.8 mm.

4 GMAB RHEOLOGICAL PROPERTIES

Geopolymers can improve the strength and stiffness of the asphalt binder, reducing its susceptibility to rutting and fatigue [39]. Geopolymers can also reduce the bitumen required in the asphalt mix, leading to a more sustainable and environmentally friendly pavement [12].

4.1 Effect of geopolymer on rutting factor

Rutting is one of the most common pavement defects caused by repetitive deformation due to traffic loading. It shortens the lifespan of the pavement and demands repeated repairs. Hamid [39] reported an increase in the rutting factor at 58 °C by 22%, 58.2%, and 86.6% by adding 3%, 6%, and 9% FA geopolymer by mass, respectively, compared to the neat binder. Ali [30] reported that 5% GPMB inclusion improved the binders' resistance against rutting at high temperatures. The study recorded a 1.12 KPa at 70 °C compared to the neat binder, which recorded 0.31 KPa. According to the Superpave specification, the rutting factor must be a minimum 1.0 KPa for the unaged binder at 10rad/sec. With 15% replacement using class F, FA, a 1.066 kPa rutting factor was also recorded by [41] which is enough to qualify for a grade increase, and with up to 60% replacement with both class F and C fly ash, the rutting factor reached 1.819 kPa and 1.548 kPa respectively.

4.2 Effect of geopolymer on performance grading

Several studies have shown that geopolymer can be used to improve the high temperature properties of bitumen. According to the study done by [30], the neat binder had a failure temperature of 59 °C, while the geopolymer-modified binders had improved failure temperatures, with increases in failure temperature of 39.22%, 35.19%, and 31.37%, respectively, for dosages of 5%, 7%, and 3% of geopolymer. In another study, [39] reported that the neat binder recorded a failure temperature of 60.6 °C while adding 3%, 6%, and 9% of geopolymer resulted in an increase in the failure temperature by 1.98%, 5.78%, and 8.58%, respectively.

5 CONCLUSION AND RECOMMENDATIONS

This paper reviewed different studies carried out in the literature on WMA technology and the different materials and techniques used. Using byproducts and wastes such as GGBS, FA, silica fume, and MK is a sustainable approach because waste disposal has become a serious concern. WMA technology has been proven to enable binder softening for mixing and compaction benefits regardless of the additives or foaming methods used. Adding geopolymer to asphalt binder improved storage stability, fatigue resistance, rutting resistance, low-temperature cracking, and increased asphalt mixture flow. The above literature showed that geopolymers can be effectively used as an additive in WMA technology to improve their properties and provide a more sustainable approach than HMA. The long-term performance of WMA is still being debated, and the technology lacks design guidelines compared to HMA. There is also a shortage of literature on their use in WMA mixtures.

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