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Warm Mix Asphalt (WMA) technologies: Benefits and drawbacks—a literature review

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ABSTRACT: Use of Warm Mix Asphalt (WMA) technologies is known as an effective method to reducing the energy consumption and emissions associated with conventional Hot Mix Asphalt (HMA) production. WMA technologies show significant benefits, such as extended window of paving season, attaining better compaction and providing longer haul distances. As a result, nowadays, WMA technologies are gaining more acceptance and popularity among asphalt industry compared to HMA. In a broad sense, WMA technologies are categorized as organic additives, chemical additives and those utilize foaming (i.e., water-bearing additives and water-based processes). The objective of this paper is to present an overview on different WMA technologies, and highlight the benefits and challenges associated with their application. The present literature review aims to indicate the areas where more research is needed to be used as a useful tool by pavement engineers who are interested in the implementation of WMA technologies.

1 OVERVIEW

Hot Mix Asphalt (HMA) has been used as the most common material for asphalt pavements construction, since 1900. For providing sufficient workability of HMA mixes, and proper coating of aggregates, both the asphalt binder and the aggregates are heated to high temperatures ranging between 140 and 180°C which results in high energy (fuel) costs and greenhouse gases emissions. As a result of the 1997 Kyoto treaty on climate change, European countries were confronted with greenhouse gas reduction requirements (Prowell et al. 2011). WMA technologies were developed to support the objective set by the Kyoto Protocol to reduce the emissions of carbon dioxide during the production and compaction of asphalt mixes. These technologies can either lowering the viscosity of the asphalt binder or improve the workability of the mix; thus, the production and compaction temperatures can be lower, as compared to those needed for conventional HMA. Generally, WMA mixes are produced at temperatures ranging from 20 to 60°C lower than conventional HMA (D'Angelo et al. 2008). However, the benefits of WMA technologies are not limited to the heart of potentially mitigating emissions and reducing fuel consumption; more benefits will be discussed later in detail.

Table 1. List of commonly used WMA technologies.

Technology or additive	Manufacturer	Description	Asphalt production Temperature (or reduction ranges), °C
Organic (wax) Additives			
Sasobit	Sasol Wax International (USA)	2.5–3.0% by mass of binder	(20–30)
Licomont BS 100	Clariant (Switzerland)	3.0% by mass of binder	
Asphaltan B	Romonta GmbH (Germany)	2.0–4.0% by mass of binder	
Chemical Additives			
Evotherm	MeadWestvaco (USA)	0.5% by mass of binder	115
Revix or Evotherm 3G	MeadWestvaco (USA)	0.5% by mass of binder	(30–40)
Rediset	Akzo Nobel (Netherlands)	2% by mass of binder	(30)
Cecabase RT	CECA (France)	0.3–0.5% by mass of binder	(30)
Iterlow T	Iterchimica (Italy)	0.3–0.5% by mass of binder	120
Foaming (Water-bearing Additives)			
Aspha-Min	Eurovia GmbH (Germany)	0.3% by mass of the mixture	(20–30)
Advera WMA Zeolite	PQ Corporation (USA)	0.25% by mass of the mixture	120
Foaming (Water-based Processes)			
WAM Foam	Shell (UK) and Kolo-Veidekke (Norway)	2–5% water by mass of hard binder	100–120
LEA—Low Energy Asphalt	LEA-CO (France)	3–4% water introduced with fine sand	100
Double—Barrel Green	Astec Industries (USA)	~2% water by mass of binder	116–135
Terex WMA system	Terex (USA)	~2% water by mass of binder	130
Gencor Ultrafoam GX	Gencor Industries Inc. (USA)	1.25–2% water by mass of binder	110–120
Accu-Shear	Stansteel (USA)	combination of water and/or additives (dependent on the additive/manufacturer)	122–158
Aquablack WMA	Maxam Equipment Inc. (USA)	1.5% –3.0% water by mass of binder	125–140
LT Asphalt (Nynas Low temperature asphalt)	Nynas (Netherlands)	Foam binder with hydrophilic additive the amount of which 0.5–1.0% by mass of binder	90
LEAB	Royal BAM Group (Netherlands)	Foam binder with a special additive (0.1% by mass of binder)	90

2 WMA TECHNOLOGIES

Examples of the available WMA products and processes are listed in Table 1. More information and summary of the recent related studies of the corresponding technologies are presented in the following sections.

2.1 *Organic additives*

Organic WMA additives, usually waxes or fatty amides, are added to asphalt binder to lower the viscosity at temperatures above about 90°C. These materials, typically, have melting points below HMA's production and laying temperatures. Organic additives are used to decrease asphalt binder's viscosity above its melting point, whereas below the melting point, they tend to increase the asphalt binder's stiffness (D'Angelo et al. 2008). The organic additives not only reduce the viscosity of asphalt binder at mixing and placing temperatures, but also increase viscosity at service temperatures, which is an added benefit specific to this type of technology (Perkins 2009). The organic additives can be either introduced to the asphalt mix or into the asphalt binder. The type of WMA additive must be selected carefully in order to keep melting point higher than that of expected pavement's in-service temperatures. Otherwise, permanent deformations may occur in the pavement, in the form of rutting. Also, use of the organic WMA additives may result in minimizing the embrittlement of the asphalt at low temperatures. Organic additives typically provide a temperature reduction between 20 and 30°C.

Sasobit®, produced by Sasol, is the most commonly used additive in this category. It is commonly used amongst the organic additives and has largely been associated to the discussion. The additive is a fine crystalline long chained aliphatic hydrocarbon, or simply wax (Sasol 2008). Sasobit® has a melting point range of 85–115°C. Therefore, it is completely soluble in asphalt binder at temperatures above 115°C. Sasobit® lowers the viscosity of the binder and also acts as a flow modifier in the mix which facilitates the aggregates free movement and coating by the asphalt binder. Sasobit® can be directly added to the mix during production stage or blended with the asphalt binder and then stored prior to mixing. Then the blend can be used to produce asphalt mixes. Licomont BS 100 is another fatty acid amide which acts as a viscosity enhancer. It is available in both powder and granular forms. The melting point of the Licomont BS 100 is significantly different from the wax additives; because it melts at a temperature range of 140–145°C. Another commercially available organic or wax-based additive is Asphaltan B with the mechanism to facilitate the production of WMA mixtures similar to that of Sasobit®. Based on a study by Rowe et al. (2009), use of Asphaltan B in asphalt binder provided a viscosity reduction similar to that of Sasobit®.

2.2 *Chemical additives*

Chemical additives, newly developed and emerging WMA technologies, are used to improve the ability of asphalt binder to coat the aggregate particles at lower temperatures rather than reducing the viscosity of asphalt binder. The chemical additives work at the microscopic interface of the aggregates and the asphalt binder by regulating and reducing the slip forces at that interface. This lets the asphalt mix particles to move over each other more easily, which in turn, results in a lower levels of mixing and compaction energy at lower temperatures (Anderson et al. 2008, Li et al. 2015). The additives may contain built-in anti-stripping agents to promote the adhesion between asphalt binder and aggregate, and to reduce the moisture-induced damage potential. The chemical additives package is used either in the form of an emulsion or may be added to the asphalt binder at the terminal and then mixed with hot aggregates. Minor modifications are needed to the asphalt plant or to the mix design process to apply this technology (Chowdhury and Button 2008).

Commonly used WMA additives in this category are Evotherm ET often referred to as just Evotherm, has eventually been replaced by Evotherm DAT and Evotherm 3G. Evotherm 3G is newly developed and falls in this category as a water-free version of Evotherm that can be introduced to the asphalt binder or at the asphalt mix production plant. The Evotherm ET is known as a binder-rich water-based emulsion with approximately 70% solids. It is capable of reducing the mixing temperatures by approximately 38°C. The water in emulsion turns into steam during mix production and facilitates the mixing and compaction processes. The emulsifiers in the Evotherm are adsorbed onto the aggregate surface with a long hydrocarbon tail extending beyond the aggregate surface which in-turn promotes the interfacial adhesion between the binder and aggregate surfaces (Chowdhury and Button 2008). The Rediset is a surfactant-based chemical additive produced by Akzo Nobel with the same objective of reducing the interfacial friction between thin films of the asphalt binder and coated aggregates, improving the workability and allowing for mixing and compaction at reduced temperatures. The additive includes built-in anti-strip agents to promote the interfacial adhesion between aggregate and asphalt binder. The third example in this category is Cecabase RT produced by CECA (France). The additive has the same hypothesized mechanism to produce WMA as that of surfactants such as Rediset. Iterlow T is a liquid chemical additive, when added to asphalt binder, allows for the production of WMAs at temperature around 120°C.

2.3 *Foaming technologies*

The foaming technologies are classified as water-bearing additives and water-based processes. In water-bearing additives, moisture is contained in the solid media and is released when it comes in contact with hot asphalt binder in production plant. Then, released water steam generates small bubbles and causes foaming of the asphalt binder. The concept behind the foaming technologies is that water expands by a factor of approximately 1,700 when it turns into steam (James 1965). This expansion of water inside the asphalt results in a reduction of the overall viscosity by increasing the volume and surface area of the asphalt binder due to the latent steam. Consequently, this mechanism facilitates the aggregate coating and asphalt mix compaction, at lower temperatures (Masson et al. 2001). Foaming techniques are widely used to produce WMA in many countries (Kristjanssdottir et al. 2007). A number of current WMA water-bearing additives use hydrophilic materials (synthetic zeolites), such as Aspha-min® and Advera®, to produce foamed asphalt binder. The water-based foaming process is another technology to produce the foamed WMA which adds benefits by eliminating the need for expensive additives and special asphalt cement by mixing a small amount of water (usually with a mass ratio of 1% to 5% to the asphalt binder) into the hot asphalt to create microscopic bubbles in the continuous phase.

2.3.1 *Water-bearing additives*

Currently, Aspha-min® and Advera® are two most commonly used foaming WMA additives. Advera® WMA, manufactured by the PQ Corporation, is a new generation of Aspha-min®. Both technologies consist of a synthetic zeolite (sodium aluminum silicate hydrate) that has been hydro-thermally crystallized. The amount of water held internally by the zeolite is between 18% and 21% by its mass which releases at elevated temperatures. When the additive is added to the asphalt mix, water is released as a fine mist, which creates micropores in asphalt binder. The generated micropores in asphalt binder help increase the workability of the mix (Barthel et al. 2004). To ensure consistent workability for longer times, the step-wise release of moisture is the critical point to be considered when using zeolite to produce WMA. Barthel et al. (2004) reported a step-wise release of moisture can be achieved until the temperature reaches 99°C to maintain a compactable mix. The release of water creates a controlled foaming effect, which can provide an improved workability for 6 to 7 h period, or until the temperature drops below 100°C. In this instance, the foaming results in an improved workability of the mix which can subsequently allow a decrease in the mix temperature by approximately 30°C with equivalent compaction performance.

2.3.2 *Water-based processes*

The concept of water foaming was used long time ago by Csanyi (1957) for soil stabilization. Since then, multiple techniques for producing foamed asphalt binder have been developed by industries including the Mobil Oil of Australia and Conoco. Water-based processes rely upon a foaming action of steam when water is introduced in hot asphalt. In essence, the direct foaming does not modify the chemical composition of the asphalt binder phase while causes the binder to foam. This foaming effect makes the coating of aggregate easier. When small amount of water is added to the hot asphalt, the water vaporizes and is encapsulated in the asphalt binder as a latent energy. This produces a foaming action in the asphalt binder and temporarily increases the volume of the asphalt binder and decreases the overall viscosity, which improves coating and workability of the mix. The foam then collapses and the asphalt binder behaves as a normal binder. Water-based processes must add enough water to cause foaming without adding so much to cause stripping problems. Therefore, some of the producers advise to use anti-stripping agents to minimize the moisture susceptibility of asphalt mix by promoting the interfacial adhesion between the asphalt binder and aggregate. This technology enables a temperature reduction of the asphalt mix about 20 to 30°C. Various foaming techniques are employed nowadays to introduce small amount of water into the hot asphalt binder.

An example of water-based system is the WAM-foam, a patented process developed jointly by the Shell Global Solutions and Kolo Veidekke in Norway. The mechanism of this process is based upon combining two different binder grades, soft and hard binders, with the mineral aggregate. The softer binder (20 to 30% of the total binder content) is mixed with the coarse aggregates, and then the harder binder is foamed and mixed with the pre-coated aggregates. The blended soft and hard binder characterize the required final binder grade (Middleton and Forfylow 2009). Coating the coarse aggregate with the soft binder satisfies the demand of absorption by coarse aggregate that may not otherwise occur with a stiffer binder at low temperature (Moen 2007). Upon using this process, the asphalt mix can be produced at a temperature range of 100–120°C and compacted at 80–110°C. In the Low Energy Asphalt (LEA) process, the coarse aggregates and a portion of the fine aggregates are heated to normal HMA temperatures and then mixed with the asphalt binder. A coating and adhesion additive (normally 0.5% by the weight of asphalt binder) is added to the binder in the asphalt supply line of the plant. After the heated portion of the aggregate is coated, cold and moist fine aggregates are added. The wet portion has a moisture content of 3 to 4%. When heated, this moisture is liberated as steam and causes the asphalt coating to foam and encapsulate the uncoated fine aggregates. The final discharge temperature is around 99°C, which allows the steam to condense into water and acts as compaction aid and workability enhancer of the mix.

2.3.3 *Characteristics of foamed WMA*

The water-based foamed asphalt is produced by introducing pressurized cold water and air to the hot asphalt, using specially-designed nozzles. Upon the contact of cold water and hot asphalt, heat transfers from the hot asphalt to the cold water causing water to evaporate. This causes the asphalt to foam (i.e., expand). There are several laboratory-scale foaming machines to replicate the full-scale field foaming machines (e.g., WLB 10 S produced by the Wirtgen Inc.). The foamed asphalt has been characterized by two main properties: expansion ratio and half-life. The expansion ratio is defined as the ratio of the maximum volume of foamed asphalt binder and the original volume of the binder, whereas the half-life is defined as the time, in seconds, for foamed asphalt to subside from its maximum expanded volume to half of its maximum expanded volume (Jenkins et al. 1999, Goh and You 2011). The expansion ratio is a measure of the foaming viscosity and is an indicator of the degree of dispersion of binder in the mix. The half-life is a measure of the stability of the foaming and provides an indication of the rate of collapsing of the foam during mixing. It is believed that maximizing expansion ratio and half-life would result in the best performing foamed asphalt mixes (Ruckel et al. 1983). The expansion ratio and half-life are mainly dependent on the foaming water content as well as the foaming temperature and the type of the asphalt binder (Brennen et al. 1983). The expansion ratio increases with the increase in foaming water content, whereas the half-life is inversely proportional to the foaming water content. It is expected that as the foaming temperature increases, the expansion ratio increases, and the half-life decreases (Saleh 2004).

3 BENEFITS OF WMA TECHNOLOGY

The WMA technologies have been developed to lower the production and placement temperatures of asphalt mixes, which offer several benefits over the conventional HMA. The most important benefit of WMA is the possibility to reduce the greenhouse emissions. This is achieved by the reduced production temperature of WMA. Figure 1 shows the reported emission reduction results from WMA European practice conducted by WMA technical working group for selected EU nations. In addition, the reduction of production temperatures provides energy savings as compared to HMA. However, this mostly depends on the production temperature and the kind of fuel used. Hassan (2009) reported that WMA provides a reduction of 24% in air pollution and a reduction of 18% on fossil fuel consumption as compared to HMA. In a study performed by Barthel et al. (2004), a reduction in energy consumption by 30% was reported, only 5.6 ltrs was sufficient as compared to 8 ltrs of oil per ton of mix, by using a synthetic zeolite. A mixing plant operator reported the difference between the fuel consumption of HMA and WMA in a low volume pavement construction project in Alaska (Saboundjian et al. 2011). Interestingly, a consumption of 0.5 gallons of fuel per ton of WMA produced as opposed to 1.5 gallon of fuel per ton needed for HMA production. The reduction of emissions is also beneficial to the working crew health and to the people in the surrounding areas of production and paving sites. This adds other benefits to mitigate the emission problems resulting from a plant site in urban areas. On the other hand, the production of WMA mixes at lower temperatures reduces the aging of the asphalt binder and tends to improve the pavement structural flexibility, which reduces susceptibility to fatigue and temperature cracking at early stages. This helps further improvement of the pavement longevity and reducing the potential costs for restoring the asphalt overlay (Perkins 2009). Use of higher amounts of RAP is reported to be feasible in WMA mixes (Guo et al. 2014). This is because of a higher workability of WMA mixes during production and compaction. Asphalt mixes containing up to 90% RAP was reported to be produced using WMA technology with a reasonable workability and less efforts needed for compaction, which translates to additional energy saving (Drüschner 2009). This helps utilizing the RAP materials and saving landfill space, reduction of virgin aggregate consumption and the energy used for mining (Dini-Almeida et al. 2016).

Less compaction effort is needed for WMA because of the higher workability of the resulted mix. The impact of this benefit becomes more dominant when working in cold weather

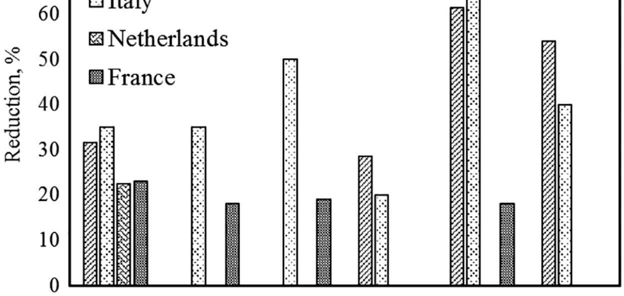

Figure 1. Reduction in plant emissions with the use of WMA for selected EU nations (Andersen 2007, Brosseaud 2007, Moen 2007).

because of the smaller difference between the mix and ambient temperature as compared to HMA. Therefore, a wider field construction window can be achieved by using WMA. This permits an extended paving season and/or paving during nights, ensuring a significant economic benefit for paving contractors. D'Angelo et al. (2008) reported better road density of WMA produced using Sasobit® at ambient temperatures ranging from +1 to + 3°C for field trial sections, compared with those of HMA mixes in Germany. Longer hauling distances are promised for WMA mixes because of the possibility to compact the mix at lower temperatures without compromising the workability. The WMA technology provides another benefit for urban or high maintenance roads that need early traffic opening because less time is necessary for cooling the mixture since the initial temperature is lower as compared to HMA. The WMA technology provides indirect economic effects such as the reduction of the mobilization costs and longer paving season. Additional indirect benefit is less wear of the asphalt plant due to the reduced mixing temperature (Hughes et al. 2009, Ball 2010). Finally, laboratory testing methods can be directly applied to WMAs to assess the potential benefits of these mixtures with both traditional and advanced procedures (Dondi et al. 2013).

4 DRAWBACKS OF WMA TECHNOLOGY

It is necessary to ensure that the WMA has the same or better mechanical characteristics and long-term performance as HMA in order to reach a widespread implementation. The technology has been applied to produce many types of asphalt mixes, including dense graded, stone mastic, porous, and mastic asphalt. Also, it has been used with modified binders as well as different types of aggregates and RAP amounts for a variety of layer thicknesses and traffic levels. Notwithstanding the benefits of WMA, there are concerns about the application of this technology. This is mainly because the technology is relatively new and insufficient in-situ performance data are available. Although several research studies have been conducted on different WMA mixes both in the laboratory as well as in the field, comparing WMA performance with reference HMA mixes, concerns still exist, particularly with respect to rutting and moisture susceptibility of WMA.

The rutting concern of WMA comes from the fact that decreased mixing temperature of WMA may lead to incomplete drying of aggregates, insufficient coating with asphalt binder and decreased oxidative hardening of asphalt binder (Goh and You 2008). This might be mitigated by adding adhesion promoting agents, or by initially choosing a harder binder grade. Potential rutting problems require careful evaluation of asphalt in laboratory, since the rheological properties of asphalt binder is the main contributing factor to rutting performance (Roque et al. 1987). However, WMA that is produced by adding waxes generally showed better resistance to rutting than the reference HMA. This can be attributed to formation of the lattice structure in asphalt binder below the crystallization point of wax, which stiffens the asphalt at in-service temperatures (Zaumanis and Haritonovs 2010). Ruckel et al. (1983) studied the rutting behavior of foamed WMA mixes and concluded that the rutting failure occurs usually weeks after the construction not years. This is possible due to insufficient curing (water dissipation) of the foamed WMA mix. Copeland et al. (2010) reported the rutting performance of control HMA and WMA mixes based on the Flow Number. The WMA was produced by foaming the asphalt binder by adding 2% water based on the weight of the binder and all mixes contained 45% RAP. It was reported that even with the addition of 45% RAP, the WMA was still more susceptible to rutting than HMA with RAP.

Moisture damage results in failures of adhesive bonding at the binder-aggregate interface and/or cohesive bonding within the asphalt binder (Hicks 1991). The loss of adhesion (i.e., stripping) is caused by the breakage of the interfacial adhesive bond between aggregate surface and asphalt binder, primarily due to the action of water and water vapor (Jo et al. 1997). The loss of cohesion is primarily caused by the action of moisture within the asphalt binder, which causes softening, and hence loss of stability of the mix. The moisture susceptibility of WMA pavements becomes a greater problem than HMA because the WMA binders may be softer and some technologies depend on utilizing water (i.e., water-bearing additives or water-based foaming processes) as a workability aid (Abbas and Ali 2011). The presence of water after foaming and even the incomplete drying of aggregates due to reduced production temperatures can impair the binder-to-aggregate bonding and may lead to an increased susceptibility to moisture damage. This problem may be successfully mitigated with addition of active adhesion agents. Diab et al. (2014a, 2014b) concluded a decrease of the moisture damage of the asphalt-aggregate in terms of the cohesive and adhesive bonding, with the use of the nano-sized hydrated lime as an additive to foamed WMA. However, it is extremely important to test the compatibility of the chemical additives used in producing WMA asphalt mix with aggregates and asphalt binders (Lamperti et al. 2015).

5 SUMMARY AND RECOMMENDATIONS

Increasing awareness over the human impacts on the environment such as global warming, carbon footprint, conservation of the natural resources and focus on energy consumption, are likely to stimulate interest in a wider use of WMA technologies, in the near future. Despite the decade-long history of the use of WMA in the early sites in Germany and Norway, this technology has not been applied to its full potential in the U.S. and other countries, so far. This is mainly due to the lack of information over the advantages and disadvantages of different types of WMA technologies and concerns over the long-term performance of the pavements constructed using WMA. Although wealth of knowledge available in the pertinent literature on the properties and laboratory performance of WMA, still many of the laboratory studies draw contradictory conclusions. Also, lack of long-term field performance data for this type of pavement material as it can be found for HMA, may lead to hesitations using this technology. Therefore, there is a need for a comprehensive literature search and summarizing the outcomes of different studies on WMA in a systematical way. In view of this objective, a selection of the available literature on WMA based on the recent publications and findings in this area was reviewed in order to identify the areas in which each of these technologies may be used with success. The current review was undertaken with a focus on the various categories of the WMA technology, benefits and drawbacks of their use. Based on the review of the previous studies and the discussions presented in this paper, the following aspects may be highlighted as follows:

1. Generally, the production and placement temperatures of an asphalt mix can be reduced from 20 to 60°C, depending on the WMA technology used. According to an increasing number of laboratory and field experiences, this temperature reduction leads to savings in energy cost, cutting emissions, providing a healthier work environment for the construction crew, early traffic opening, and a wider field construction window and radius.
2. Use of higher amounts of RAP is reported to be feasible in WMA mixes. Along with new plant mixing solutions a wide part of the ongoing research deals with new additives and rejuvenators to improve binders blending and effectiveness.
3. The concerns over the rutting of WMA mixes may be addressed by using an adhesion promoting agent and/or by choosing a harder binder type (bumping the PG grade up). In this case rheological properties of the asphalt binder should be studied.
4. Among WMA mixes, those produced by adding waxes generally showed a better rutting performance, even compared to their reference HMA mixes.
5. The moisture-induced damage potential is the most important concern associated with the WMA mixes. More specifically, WMA technologies involving water-bearing additives and those produced using water injection techniques are more prone to moisture damage. However, this issue can be mitigated by using an effective anti-stripping agents (e.g., hydrated lime).
6. Construction of test section(s) using different WMA technologies and performance monitoring of these test sections side by side with laboratory tests are key elements to understanding the long-term performance of the WMA mixes.

7. The economic benefits of WMA should be evaluated together with environmental benefits, especially if stricter emission standards are implemented. Therefore, the complete estimation of the potential economic benefits of using WMA technologies may not be feasible if it is not jointly evaluated with the environmental regulations and additional costs and offsets of WMA production.

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