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Advancements and Challenges in the Use of Cold Mix Asphalt for Sustainable and Cost-Effective Pavement Solutions

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Abstract. Even with the high advancement of the pavement industry, the use of traditional hot mix asphalt (HMA) for pavement construction and maintenance is associated with high energy consumption, greenhouse gas emissions, and production costs. As a result, researchers and industrial practitioners aspire to use cold mix asphalt (CMA) as an alternative that offers environmental and economic benefits. This paper provides an overview of the advancements and challenges in using CMA for sustainable and cost-effective pavement solutions. The paper reviews portrays, and discloses CMA's recent benefits, such as reduced energy consumption, lower emissions, and enhanced durability. Additionally, the paper addresses the challenges associated with using CMA, including its limited application areas and potential performance issues. It discusses the strategies being developed to overcome these challenges. Furthermore, the paper concludes with recommendations for the future of research and industry development of CMA to further promotion. Meanwhile, it is finalizing the current sight for using CMA as a sustainable, cost-effective pavement solution.

Keywords: Asphalt; Bitumen material; Challenges and Economic benefits; Cold mix asphalt; Cost-effective pavement solutions; Sustainable pavement solutions.

1. INTRODUCTION

No doubt, pavement construction, and maintenance are significant contributors to greenhouse gas emissions and climate change, with traditional hot mix asphalt (HMA) production and transportation being major sources of energy consumption and carbon emissions. According to the U.S. Environmental Protection Agency, the transportation sector is responsible for nearly 27% of the total U.S. greenhouse gas emissions, with road transportation being the largest contributor[1]. Cold mix asphalt (CMA) has emerged as a promising alternative to HMA for sustainable and cost-effective pavement solutions, potentially reducing energy consumption and greenhouse gas emissions while improving pavement performance and durability. Where CMA is produced and applied at ambient temperatures, eliminating the need for high-temperature production and reducing energy consumption and greenhouse gas emissions[2, 3]. In addition, CMA can be produced using a variety of materials, including recycled asphalt pavement, which further reduces environmental impact and project costs[4-6]. Recent research has demonstrated CMA's environmental and economic benefits, including reduced carbon footprint, lower construction and maintenance costs, and improved sustainability [7-9].

Nevertheless, challenges remain significant in implementing CMA, including performance issues such as rutting, cracking, and stripping, as well as quality control and testing issues, such as lack of standardization and limited testing protocols[10]. Technological barriers, such as limited availability of equipment and materials, limited expertise and training, and limited research and development, also pose challenges to wider adoption and acceptance of CMA technology. This paper aims to review and analyze the recent advancements and challenges in using CMA for sustainable and cost-effective pavement solutions. The paper discusses the properties and benefits of CMA, such as its ability to be used in cold weather conditions, reduced energy consumption during production, and its potential for use in low-volume roads. The authors also examine the challenges associated with using CMA, such as its potential for lower strength and durability compared to HMA, and the need for improved quality control during production.

Overall, the paper aims to provide insights into the use of CMA as a sustainable and cost-effective alternative to HMA in pavement construction and to highlight areas where further research and development are needed to enhance the performance and durability of CMA. Case studies of real-world projects using cold-mix asphalt as a sustainable and cost-effective pavement solution will also be presented.

2. THE GLOBAL ADOPTION OF COLD-MIX ASPHALT

CMA technology has been in use by the pavement industry in multiple countries since the 1960s, Grave emulsion, a cold reprofiling asphalt, was developed in France in the 1970s; this type of CMA was standardized by Leech [11]. In France alone in the last decade, for example, annual manufacturing levels of 1.5 million tons were achieved for these mixtures, which has contributed to the development of a comprehensive understanding of their performance [12]. The warm and dry climate in France nominated location facilitates the curing process of the emulsion. As a result, this technology has also gained recognition in Spain [13], Ireland [14,15], USA [16], and Chania [17].

Interestingly, the favorable climate, in combination with the large distances between hot-mix plants and job sites, has led to wider adoption of CMA in the USA. During the 1970s, Chevron's research on stabilized paving mixtures with emulsified bitumen in the USA led to the development of a practical guideline for producing such mixes [18]. Accordingly, the Asphalt Institute has suggested Hveem and Marshall design methods for both in-situ and plant mixed materials in his designated publication MS-14 [19] in the 1980's, while three editions of this design manual have been published.

Despite several efforts, the UK has been slow to adopt CMA on a large scale. The Highway Authorities and Utilities Committee (HAUC) attempted to encourage the use of storable cold mixes with in-situ performance equivalent to HMA after installation through the publication of the "New Roads and Street Works Act" document in 1991, which included an appendix A10 specifying the requirements for reinstatement of openings in highways[20].In addition, CMA has gained interest in several other countries, including various European nations, South Africa, Australia, and New Zealand [21]. In Sweden, for example, cold recycled asphalt materials are commonly utilized for flexible pavements due to the large amount of old pavements that are recycled each year, estimated to be around 1 million tons [22]. Spain, another example, has been utilizing emulsion mixtures since the late 1950s. As stated by Needham in 1996, these mixtures consist of either gravel or open-graded materials [7]. High viscosity, medium setting, cationic, or anionic emulsions were used in open-graded mixtures to ensure a thick bitumen coating on the aggregate. In South Africa, the implementation of bitumen emulsion for base construction is spearheaded by the South African Bitumen Association (SABITA). Recognizing the advantages of this method, SABITA released various design guidelines and standards in 1993 and 1999[7]. In China, cold patch asphalt plays an important role in maintaining China's vast network of roads and highways[17].

In the past few years, there has been a rise in the number of research studies dedicated to exploring (CMA) as a viable pavement solution. Several countries and regions have acknowledged the potential advantages of employing CMA. According to Scopus, a widely recognized database [23, 24, 25], to date, approximately 980 documents were published on CMA between 1970 and 2023. Figure 1 illustrates the trend in the number of publications and documents per year (from 2000 to 2020) and the number of documents by country related to CMA, as shown in Figure 2. Many conclusions can be disclosed from these figures, mainly the steady increment in the number of research continually. Also, as expected, there is a variety of interest in both developed and developing countries, where the developed countries are predominated this research sector. The last is a vital indicator of the significance of this branch of knowledge.

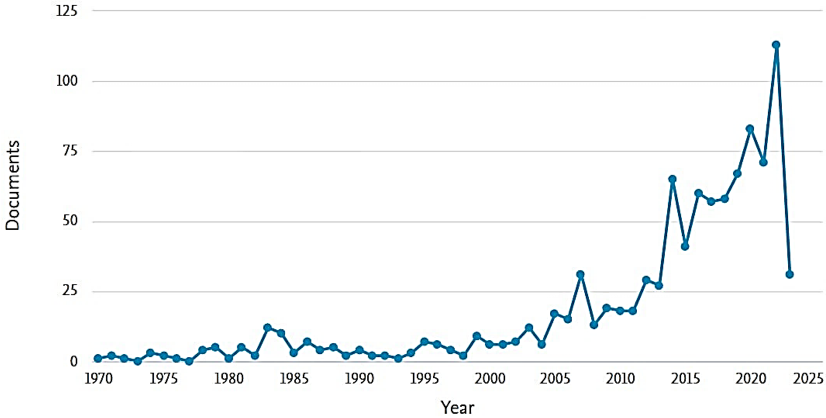

Figure 1: Number of research documents on cold mix asphalt by year (graph sourced from Scopus)[26].

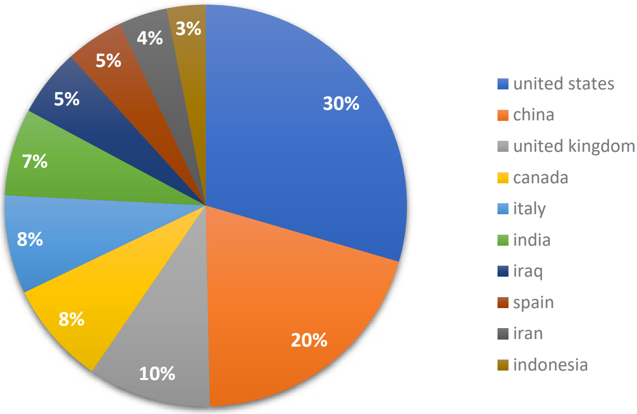

Figure 2: Number of research documents on cold mix asphalt by country (graph sourced from Scopus) [26].

3. SUSTAINABILITY BENEFITS OF COLD MIX ASPHALT

CMA offers a range of sustainability benefits, making it an attractive pavement solution for environmentally conscious projects. The use of cold-mixed asphalt reduces the amount of energy needed during production and placement compared to HMA, as it does not require heating. When considering energy consumption per ton of laid material, both CMA and cold in-situ recycling methods utilize less energy compared to HMA and hot in-situ recycling methods. Specifically, the cold in-situ recycling method has the lowest energy consumption due to its lower requirement for binder and the fact that reclaimed aggregates are used. To manufacture one ton of laid material, HMA consumes 680 MJ of energy, while CMA and cold in-situ recycling consume 2/3 and 1/5 of this amount, respectively. Therefore, it can be concluded that CMA is more energy-efficient than HMA[27]. Figure 3 presents information on the total energy utilized in constructing various asphalt mixes, including the energy consumption associated with each component. This data is based on a study conducted by Chappat and Bilaj [28]. Since CMA is produced at ambient temperature, using a hydraulic mixture for concrete mix or manual mixing is preferable. Using a cold recycled mix can reduce 52% of Greenhouse Gas (GHG) emissions and 54% of nitrogen oxide emissions. Furthermore, aggregate consumption can be reduced by up to 62%.[28]. Figure 4 displays the data on the total gas emissions produced during the construction of various asphalt mixes and the gas emissions associated with individual components[28].

On the other side, CMA is often produced using recycled materials, such as reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS), which reduce waste and conserve natural resources[6]. Using recycled materials in the cold mix as CMA asphalt production can also reduce the need for virgin aggregates and asphalt binders, reducing environmental impact[29]. Overall, the sustainability benefits of CMA make it a promising pavement solution for sustainable infrastructure development.

Several recent studies have demonstrated the sustainability benefits of cold-mixed asphalt. The National Cooperative Highway Research Program (NCHRP) published a synthesis in 2018 highlighting the reduced environmental impact of CMA through recycled materials[30]. According to Lu et al. in 2013, CMA is significantly superior to HMA and WMA. It is now widely used to minimize potholes, eliminating the need for an aggregate dryer and heating mix or aggregates, resulting in considerable energy savings[31]. Table 1, summarizing these recent studies, shows that using CMA can offer several sustainability benefits, making it an attractive pavement solution for environmentally conscious projects.

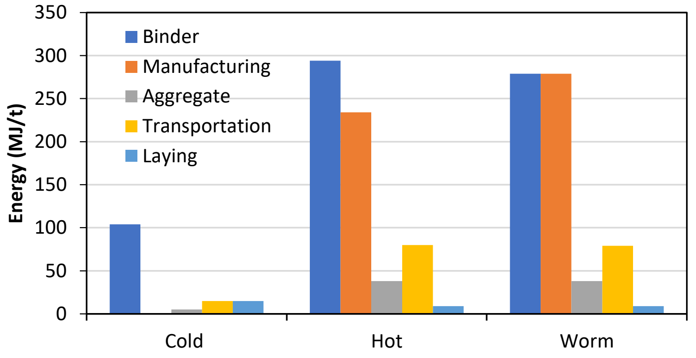

Figure 3: The energy required for producing various asphalt mixes type [28].

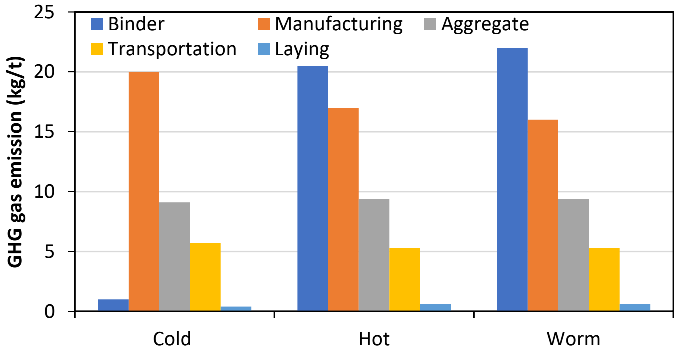

Figure 4: The GHG emission required for producing various asphalt mixes type [28].

Table 1: Recent studies on sustainability benefits of cold mix asphalt.

Author(s)	Date	Materials	Benefits
Kari [32]	1973	Use of emulsified asphalt instead of cutback asphalt	Reduced energy consumption
Jenkins [33]	2000	Use of emulsified asphalt and foamed bitumen	Cost savings and Reduced energy consumption
Chehovits and Galehouse [34]	2010	Use CMA construction technologies	Construction of CMA is 95% less energy consumption compared to HMA and WMA
Al-Busaltan et al. [35]	2012	Use of emulsified asphalt with cement and fly ash	Cost savings and environmentally friendly
Hussain and Yanjun [36]	2013	Use of reclaimed asphalt pavement (RAP)	cost-effective and eco-friendly material.
Dondi et al. [37]	2014	Use of crumb rubber	Cost savings and environmentally friendly for CMA than HMA
Xiao et al. [38]	2018	use of a cold recycled mix	This technology can decrease GHG, nitrogen oxide, and sulfur dioxide emissions by 52% and 54%, respectively. Additionally, it can reduce aggregate consumption by up to 62%.
Pasetto et al. [39]	2019	Use of recycled asphalt shingles (RAS)	Reduced energy consumption and carbon dioxide emissions
Offenbacker et al. [40]	2021	use of a recycled mix of CMA or cold in-place recycling (CIR) technology	Implementing this technology led to a reduction in energy consumption by 57% to 63%, resulting in significant cost savings of up to $10,000 to $12,000.
Singh and Jain [41]	2022	Use of emulsified asphalt with cement and hydrated lime	Cost savings

4. CHALLENGES IN IMPLEMENTING COLD MIX ASPHALT PROJECTS

CMA has several advantages as a pavement solution, but it also presents a range of challenges. The use of CMA in some countries can pose several administrative, logistical, and technical challenges. Here are some of these challenges in more detail:

4.1 Administrative and Logistical Challenges

The implementation of novel technologies like CMA pavement could create several administrative and logistical hurdles for nations, according to findings conducted by authors' survey on local experts' interviews and global governmental reports and publications. The challenges can be identified as:

1. Lack of awareness: The lack of awareness about the benefits of CMA may make it difficult for some countries to accept and adopt this new technology.
2. Resistance to change: Normally, highway authorities value their current practice, i.e., some authorities may resist changing their existing practices and adopting new technologies, especially if they have invested heavily in traditional pavement construction methods.
3. Regulatory compliance: Countries may have different regulatory frameworks for using new technologies. Therefore, obtaining the necessary permits and approvals for the use of CMA may be challenging.
4. Training and capacity building: CMA requires specialized equipment and expertise. Highway authorities may need to invest in training and capacity-building programs to equip their workforce with the necessary skills and knowledge to handle this technology.
5. Supply chain issues: The supply chain for CMA materials may not be well-developed in some countries, leading to delays and higher costs for acquiring the required materials.

4.2 Technical Challenges

In addition to administrative and logistical challenges, the use of CMA pavement can also pose several technical challenges. Some of these challenges include:

1. Mix design: Cold mix asphalt requires a specific mix design that can vary depending on the application and climate conditions. Developing a mix design that meets the performance requirements can be challenging, especially if there is a lack of experience or expertise in the country [42].
2. Shorter lifespan: One of the main challenges of CMA is its relatively shorter lifespan compared to HMA, whereas studies have shown that the CMA pavements last for shorter periods [43].
3. Curing time: CMA requires more time to cure than HMA. In some cases, the curing time may take several days, leading to longer road closures and disruptions [35].
4. Performance: CMA may not perform as well as HMA in terms of strength, durability, and resistance to deformation. Its lower strength and stiffness, compared to HMA, can affect its durability and resistance to deformation. Several studies have shown that CMA pavements have lower stiffness and elastic modulus compared to HMA pavements [44-46]. This reduced strength can lead to premature failure and increased maintenance costs.
5. CMA can vary significantly in composition, quality, and performance, leading to inconsistent performance and reduced pavement life [47,48].
6. Maintenance and repair: Maintenance and repair of CMA pavements can also be challenging, leading to increased costs and disruption of traffic flow [49].
7. Climate conditions: Cold-mixed asphalt may not perform well in extreme climate conditions, such as very cold or very hot weather. Therefore, it may not be suitable for some countries with such climates.
8. Testing and evaluation: CMA requires specialized testing and evaluation procedures to ensure that it meets the required performance standards. Highway authorities may need to invest in testing equipment and establish testing protocols to evaluate the performance of CMA.

Addressing the challenges associated with CMA and improving its adoption as a pavement solution requires a coordinated effort between the public and private sectors, including policymakers, industry stakeholders, and academia. Further research is needed to develop improved CMA formulations and manufacturing processes and identify the most effective applications for CMA as a pavement solution.

Additionally, maintenance and repair strategies are needed to improve the durability and lifespan of CMA pavements.

5. ADVANCEMENTS IN COLD MIX ASPHALT TECHNOLOGY

In recent years, significant advancements in CMA technology have been aimed at improving its performance and durability. These advancements have focused on using bio-based additives, recycled materials, new binders, and production methods. One promising advancement in CMA technology is the use of additives derived from natural or by-product sources such as lime, cement, fly ash, etc. These additives show improvements in performance and durability, as well as reduce their environmental impact [35,50,51]. CMA technology is advanced by using recycled materials, such as recycled asphalt pavement, as a substitute for virgin materials. This reduces waste and environmental impact and lowers the cost of CMA production[52, 53]. Additionally, researchers have explored the use of new binders, such as bio-oil, as a substitute for petroleum-based binders. Bio-oil is a renewable and sustainable alternative that improves CMA's performance and durability. Table 2 summarizes previous studies that were carried out on improving CMA characteristics using various methods.

Table 2: Recent studies on improving cold mix asphalt characteristics.

Year	Authors	Materials Used	Enhancement in Performance	Remarks
2005	Asi and Assaad[54]	Use Jordan oil shale ash	improved the mix resistance to moisture damage	Jordan oil shale ash is Fly ash that can be generated through the direct combustion of Jordanian oil shale.
2007	Chavez et al.[55]	Use 1% dose of polyvinyl acetate additives with Cationic (Quick setting) emulsion	increases 31% compressive strength	Polyvinyl acetate should be added in dry form
2009	Borhan et al.[56]	Use cylinder oil (CO)	CO improved the properties of CMA	/
2011	Bocci et al. [57]	Use CMA with 3% cationic emulsion, 2% cement, and 50% recycled aggregate	In comparison to HMA mixture, the fatigue life is typically reduced in CMA due to the higher cement content and lower residual bitumen content present in the mixture.	/
2012	Al-Busaltan et al. [46]	Use CMA with 50% fly ash (LJMU- FA1) as a replacement filler.	Use 50% LJMU- FA1 Increases the stiffness modulus by 9 times and Increases 26 times permanent deformation resistance	/
2014	Al-Hdabi et al. [58]	Use 3% waste fly ash and 1% silica fume with Cationic setting emulsion	The use of waste fly ash and silica fume in CMA can achieve similar stiffness as 125-pen hot-rolled asphalt.	/
2016	Babagoli et al. [59]	Use polymer-modified emulsion with lime and cement	Incorporating cement, lime, or polymer-modified emulsion led to a decrease in permanent deformation.	The emulsion used is a slow-curing emulsion.
2016	Gomez-Meijide and Perez [60]	Use 100% recycled aggregate	Replacing natural aggregates with recycled aggregates in CMA resulted in an increase in ITS by 12.8%	/
2016	Ojum and Thom [61]	Use RAP (20 mm pen, 5mm pen) with Cationic emulsion (Slow setting)	Using RAP in a cold mix produces superior results compared to using only virgin aggregate, and it is even more cost-effective.	/

Table 2: Continued.

Year	Authors	Materials Used	Enhancement in Performance	Remarks
2017	Rezaei et al. [49]	Use CMA with different materials as a dense-graded (DG) or open-graded (OG) aggregate mixture.	▪ DG Mixes with DG, which contain different bitumen contents, consistently showed lower rutting values compared to mixes with an OG one. DG mixtures exhibit higher stiffness and lower workability compared to OG mixtures.	Use Cutback bitumen
2017	Juntao Lin et al. [62]	Use CMA with 3.5% cationic slow setting emulsion, 2% cement, and 100%recycled aggregate.	Extending the curing time can improve the fatigue life of a material by augmenting the effective asphalt content and decreasing the amount of air voids present.	Use different curing protocol.
2017	Dulaimi et al. [63]	Use alkali-activated (NaOH solution) with cementitious filler-containing high-calcium FA	increment in mechanical properties and moisture resistance of CMA	/
2018	Xiao et al. [38]	Use 1 to 2% cement	The overall effectiveness and strength of the cold mix were improved, as evidenced by enhanced stiffness (ITSM), greater resistance to creep, and increased early strength.	/
2018	Shanbara et al. [3]	Use jute and coir fibers	The mechanical properties of cold mix asphalt were enhanced, resulting in improved overall performance.	/
2018	Lian et al. [64]	Use Dense-graded CMA with Modified emulsion or addition of cement	Improve the moisture resistance of CMA	Use CSS-1 h (Cationic emulsion)
2019	Kadhim et al. [65]	use crushed waste glass has a comparable gradation to virgin fine aggregate, with a Nominal Maximum Aggregate Size (NMAZ) of 2.36mm.	adding crushed glass (up to 100%) as a fine aggregate led to the development of a new CBEM with mechanical and durability properties that exceed those of traditional HMA.	/
2021	Lu et al. [66]	Use CMA containing 2% OPC, 1% FA, and 1% GGBS	The use of blended cementitious fillers in CMA exhibits superior stiffness, reducing the amount of air voids, and improving the bonding interface between the aggregate and asphalt matrix.	/
2021	Al-Kafaji et al. [67]	Use CMEA containing both ordinary Portland cement (OPC) and an acrylic (AR) polymer.	the addition of OPC and AR improves water damage resistance. The CBEM using a blend of OPC and 1.25% AR displayed the most favorable results with a 12% increase in resistance compared to HMA.	/
2022	Dulaimi et al. [68]	Use CMA with paper sludge ash (PSA) and cement kiln dust (CKD)	The stiffness of a mixture that includes high-calcium fly ash is 27 times greater than that of the reference mixture.	/
2023	Al Nageim et al. [69]	Incorporating wastewater sludge fly ash (UFA) and bottom ash (UBA) CMA mixture.	▪ At 3 days of age, using CMA with 2.1% OPC and 3.9% UFA resulted in ITSM values that were 11 times higher than traditional CMA. ▪ At 28 days of age, the use of CMA with the same percentage of OPC and a lower percentage of UFA (3.3%) and an additional 0.6% UBA resulted in ITSM values that were 5 times higher than traditional CMA.	/

6. CASE STUDIES: SUCCESSFUL APPLICATIONS OF COLD MIX ASPHALT

CMA has been successfully used in various applications, including pothole repairs, patching, and overlaying worn-out pavements. One case study published in the International Journal of Emerging Technologies and Innovative Research described the successful application of CMA for repairing potholes in rural roads in India. The study found that cold mix asphalt was a cost-effective and environmentally friendly solution that could be easily applied using manual labor and minimal equipment [40]. In another case study, cold mix asphalt was used to repair Alaska airport runways. The study found that CMA provided a durable and long-lasting solution for repairing the runways in harsh weather conditions[70]. These case studies demonstrate the versatility and effectiveness of CMA in various applications, highlighting its potential as a cost-effective and sustainable pavement maintenance and rehabilitation solution.

In the United Kingdom, a park-and-ride construction scheme was supplied with material during the spring of 2008. The project had two objectives: to showcase the speed of laying and the ability of the CMAs to withstand sideways forces from buses in a turning circle. The material's stability under site traffic conditions allowed for the construction of a second layer much sooner than what could be achieved with HMA. This was seen as a significant advantage. Figures 5a and 5b depict the turning circle during construction and after three years [71].

(a)

(b)

Figure 5: a: Construction of the bus turning circle, b: Bus turning circle 3 years after construction[71].

Transport Scotland granted permission to trial the CMA material on the A90, making it the first known use of this material on a UK trunk road. The traffic counts on this road indicated 19,500 vehicles per day, of which 15% were multi-axle HGV vehicles. The targeted section for reconstruction was 800 meters long and had previously been designed with 260 mm of HMA base course. This was substituted with 300 mm of CMA, as depicted in Figure 6 [71].

Figure 6: Application of cold mix asphalt on A90 trunk road site before compaction [71].

7. FUTURE TRENDS AND POTENTIAL DEVELOPMENTS IN COLD MIX ASPHALT TECHNOLOGY

CMA technology has been gaining popularity as a sustainable and cost-effective pavement solution. However, this field still has much room for improvement and development. This section displays relatively deep discussions of some of the future trends and potential developments in CMA technology.

1. Improved Durability and Performance: One of the main challenges of CMA is its relatively lower durability and performance compared to HMA. Researchers and engineers continuously work to improve CMA's durability and performance by developing new mix designs, incorporating additives and modifiers, and using advanced testing methods. The aim is to develop a CMA that can provide a similar level of performance and durability as HMA.
2. Increased Use of Recycled Materials: CMA technology is already considered a sustainable solution due to its lower energy consumption and lower emissions compared to HMA. However, there is still a lot of potential for increasing the sustainability of CMA by incorporating more recycled materials, such as reclaimed asphalt pavement (RAP), recycled concrete aggregate (RCA), and other waste materials. Using recycled materials can reduce the need for virgin aggregates and the environmental impact of CMA production [72].
3. Development of New Binders: The binder is one of the key components of asphalt mixtures, and its properties can significantly affect the performance and durability of the pavement. Traditional binders, such as asphalt cement, have limitations in terms of their low-temperature performance, aging, and susceptibility to moisture damage. Researchers are exploring new binder technologies such as bio-based binders, polymer-modified binders, and recycled binders to improve the performance and sustainability of CMA.
4. Advancements in Production and Placement: The production and placement of cold mix asphalt can be challenging due to its low-temperature properties and lack of workability. Advancements in production and placement techniques, such as foamed asphalt technology and additives, can improve the workability and performance of cold-mixed asphalt. These advancements can also lead to faster construction times, lower construction costs, and reduced environmental impact.
5. Integration with Intelligent Transportation Systems: Intelligent Transportation Systems (ITS) are advanced technologies that can improve transportation systems' safety, efficiency, and sustainability [73]. Integrating CMA with ITS can enable real-time monitoring of pavement conditions, predict maintenance needs, and optimize pavement management strategies. This integration can also lead to more sustainable pavement solutions by reducing the need for frequent maintenance and rehabilitation.

8. CONCLUSIONS

The current CMA technology is still under development according to research and industrial practice,; surveying the updated publications refer to the following as a main conclusion:

- CMA is a promising solution for sustainable and cost-effective pavement construction and maintenance.
- CMA offers many benefits, including reduced energy consumption, lower emissions, and improved working conditions for workers.
- CMA technology faces challenges and limitations in terms of its performance and durability.
- The future of CMA technology looks promising, with ongoing research and development focused on improving production and placement techniques, developing new binders and additives, and integrating CMA with intelligent transportation systems.
- Further research and development will be essential to address these challenges and ensure that CMA continues to meet the evolving needs of the transportation industry and society.
- Overall, the potential benefits of CMA for sustainable and cost-effective pavement solutions are clear, and its future is bright.

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