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Using Cement as Filler to Enhance Asphalt Mixes Performance in Hot Climate Regions

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ABSTRACT

This paper investigates the addition of different percentages of ordinary Portland cement as a filler in conventional asphalt concrete for a range of heavy traffic. Road pavement agencies in hot areas face the daunting challenge of preserving their pavements in a fair to good condition to increase their lifespan. This challenge is due to the high occurrence of permanent pavement deformation via rutting, which is one of the major distress factors influencing pavements. This is a particularly serious issue in hot and arid countries which are closely associated with various aggravating factors. These aggravating factors include the choice of bitumen binder viscosity, the type of bitumen, the available low-quality materials, and the high environmental temperatures. Ultimately, poor performance will show within the first few years of service as permanent deformations such as rutting, shoving, and depressions. The examined properties include the resilient modulus and the resistance to rutting. Findings indicate that the resistance to rutting and the rigidity of the asphalt concrete are both substantially increased as the cement content is increased. Moreover, to meet the heavy traffic spectrum requirements, increasing the embedded cement content in the asphalt concrete improves pavement structural capacity. Finally, based on the rigidity expected for different cement levels, design curves are provided for pavement design in hot climates using low quality aggregate materials.

Keywords: Portland cement; filler; Hot Mix Asphalt; rutting; B60/70

INTRODUCTION

Pavement rutting is often observed in countries where good construction material is not always available to build pavements that can withstand heavy traffic. Rutting is even more severe when the in-service is high. This is because Marshall formulated conventional Hot Mix Asphalt (HMA) mix designs still employs conventional filler materials. They also do not use the temperature equivalent modulus of the HMA to withstand the expected traffic loads resulting in substantial rutting and shoving (Almadwi and Assaf 2017). The temperatures of pavement surfaces in the Sahara's and other hot geographical areas can rise up to 70°(Salem, Uzelac, and Matic 2014). Unfortunately, the HMA design relies on traditional materials like bitumen penetration grade asphalt binders (e.g., B60/70) and others. This combination of mix design and hot environment results in considerable shoving and rutting. Moreover, Libya's present road construction testing uses the conventional "Marshall Method" (MM) from 1939 (Zumrawi and Sheikh Edrees 2016). This test was once widely used but it is unsuitable for roads in hot countries, such as Libya. Nonetheless, it is presently almost exclusively used for pavement in high climates.

Due to its increasing popularity in recent years, the current work applies the "Superpave Method" (SPM) that the Strategic Highway Research Program (SHRP) created between 1987-1993 (Swami, Mehta, and Bose 2004). One benefit of SPM is that it uses various pavement additives, such as cement, polymers, or fibers, to improve asphalt-concrete mix performance (Guha and Assaf 2020b). However, the present study investigates the employment of OPC using B60/70 bitumen to increase asphalt mixture performance. This new mix is achieved by offsetting the B60/70 bitumen's soft performance. Performance is graded based on deformation resistance at 25°C and using ingredients that are of low-cost and are easily accessible. OPC fillers improve the anti-rutting performance and moisture stability of the asphalt mixture compared to single limestone powder fillers. This is mainly because the content of calcium oxide in cement is higher than that of mineral powder; therefore, its alkalinity is higher than that of mineral powder. In the preparation of an asphalt mixture, the alkaline component of cement reacts with the acidic component of asphalt to produce a substance with strong adhesion. This results in strong binding of the aggregate and asphalt, thereby improving the water stability of the mixture (Fan et al. 2019).

Asphalt pavement rapidly deteriorates, resulting in much shorter lifespans than originally projected. It is especially evident in hot countries that asphalt pavements fail to perform as required, particularly in terms of permanent deformation (e.g., rutting and shoving). The primary sources of deformation are heavy traffic and high temperatures (Guha and Assaf 2020). Pavement constructed using MM regulations with the B60/70 bitumen demonstrate high occurrences of perpetual deformation that require greater maintenance costs. The substantial deformation of road surfaces in desert regions is due to; a) the use of widely obtainable rounded Saharan sand, and b) poor bitumen deformation resistance in hot temperatures (Almadwi & Assaf 2018). Therefore, the challenge, particularly in hot developing countries, is to both use better quality materials and minimize the project's total cost.

These challenges been widely investigated {e.g., (Willway et al. 2008; Montanelli & Srl 2013)}. For instance, (Li, Zhao & Pang 1998) found that composites of OPC-asphalt emulsion maintain the asphalt binders' flexibility and the OPC's strength. Flexible pavement presents rutting when there is a higher total axle-load stress than is acceptable for HMA. These outcomes mainly rely on the bitumen viscosity at the established service temperature, the angularity of the aggregates, and the asphalt mix's design. Moreover, various studies explore how to increase HMA stability with OPC as an alternative filler. Using recycled, wet aggregates in asphalt mix, OPC is commonly employed to both prevent binder stripping and enhance the bitumen coating (James & Reid 1969). Also, to improve resistance to wet and dry resilient modulus, lime and OPC are added to the asphalt mix (Schmidt & Graf, 1976; Oruc et al. 2006). (Head, 1974) and 85 percent of the material retained in the No. 4 sieve was fractured. Stability and flow analyses were performed on each cured specimen (cured at 40F, 50F, and 120F found that OPC additives not only improve the stability of cold-mix asphalt, but also its resilience. Likewise, (Uemura and Nakamori 1993) demonstrate that adding a mere one-percent more of OPC enhances MM stability from 250% to 300%.

Furthermore, (Al-khateeb & Al-akhras 2011) show that mixing cement with asphalt binders enhances both the speed of rotation and the viscosity of the asphalt binder (up to 135^{o}C). They also discovered that a cement-to-asphalt ratio of 0.15 is needed for a stable rise of the rotational viscosity. These changes improve the mix's successful functioning and overall stiffness in hot temperatures. Additionally, (Brown & Needham 2000) report that parameters such as curing time, void content, additives (e.g., OPC), and binder grades affect the mechanical properties of OPC in both asphalt-emulsion mixes and cold-mix. They also report that adding OPC changes the emulsion droplet characteristics, in which its electronic charge converts from negative to positive. Other qualities this addition influences are temperature, pressure, emulsifier level, and bitumen type. Conversely, (Pouliot, Marchand, and Pigeon 2003) analyzed the hydration process of mortars, microstructures, and their mechanical properties with a binder made of a small portion of asphalt emulsion (SS-1 and CSS-1) and a cement slurry. Their findings indicate that an asphalt emulsion added to the mix in small amounts had a slight yet significant influence on the OPC's hydration process. Furthermore, mortars that use cationic emulsions (CSS-1) have an elevated elastic modulus than those using anionic emulsions (SS-1), and, therefore, have increased strength. In a study on the practical use of polymeric admixtures' in pavement emulsions, (Song, Do, and Soh 2006) found significant pavement quality improvements by rising the polymer-cement ratios. These improvements affect waterproofness, chloride-ion penetration, and carbonation resistance. Increasing polymer-cement ratios was also found to reduce the mix's compressive strength and its propensity to cling to the mortar substrate.

Wang & Sha (2010) demonstrate that the interactions from the aggregate and the OPC-asphalt emulsion differ from the interactions of mixes with either the bitumen or OPC and the aggregate. This study also uses an apparatus that measures micro hardness (MH-5) to estimate the impacts of OPC varieties, aggregate lithology, and fineness on differences in pavement rigidity due to binder and aggregate interactions. Finally, the study shows that additional OPC and fine mineral filler improves pavement rigidity. However, when the mineral filler was too fine, this advantage was lost. Oruc et al. (2013) investigated various asphalt additives' influence on creep-strain in heavily used roads, such as highways. The authors added various percentages of salvaged factory waste asphalt as a mineral filler in their HMA mixtures. Moreover, they used the MM to prepare a series of cold-mix asphalt emulsion mixtures. The literature shows that asphalt works as a subordinate binder for emulsion mixtures. Both creep-resistance and pavement deformation were enhanced in mixtures with more OPC. Another work by (Amhadi & Assaf 2019) studied how by mixtures of manufactured aggregates, OPC, and natural sand were impacted by base course layer stabilization in low-volume roads. Traditionally, a mixture of cement and sand are used for base-course stabilization, as both of OPC's physical and chemical properties enhance the characteristics of natural sand. Previous studies demonstrate that when base materials are of low-grade, mixtures using 30% (by weight) crushed sand (i.e., manufactured) and 70% natural sand are successfully stabilized. Stabilization also depends on the amount of added OPC (e.g., 3%, 5%, and 7%). Ultimately, the economic advantages of this approach are clear since the transportation of manufactured sand results in higher costs compared to those combining OPC with local materials.

The penetration grade of the chosen aggregate's bitumen is determined by the final asphalt mixture's quality. This mixture quality includes characteristics such as flexibility, stability, durability, as well as moisture and fatigue resistance. Bitumen excess causes wheel pathway bleeding and a reduced pavement lifecycle operation. Therefore, the bitumen's properties directly affect those of the HMA. Standard B60/70 penetration grade bitumen is customarily chosen for pavement works in high temperature locations (Almadwi & Assaf 2018). To evaluate bitumen hardness, there is a standard test requiring a specific needle gauge that, during a period of five seconds, repeatedly penetrates a sample vertically at 25°C. During the day, pavement surface temperatures in Libya often reach 70°C. This temperature is well above 49-54°C, which is bitumen B60/70's softening point. (Amhadi & Assaf 2019) tested two approaches to this problem, which consist of a polymer-modified pavement and a harder grade of bitumen mix (e.g., PG70-10).

The current study's primary purpose is to examine whether substituting with an OPC filler can enhance asphalt-concrete mixtures' rigidity when made with low-quality aggregates and B60/70 bitumen. OPC filler substitute was selected since it enables the application of inferior aggregates and binders, maintaining the HMA's good rigidity levels and rutting resistance. This mixture improves the stability of the HMA and its resilience against shear failure at elevated temperatures. The superpave mix design methods used in the current study are new to various hot, arid, and developing countries. However, research demonstrates that these new designs demonstrate improved durability results compared to the MM (i.e., the most prevalent mix-design method used at present). The four mixtures' performances are assessed using the tensile modulus and wheel track tests. Specifically, to determine the OPC's effect on the pavement mixes' performance in high temperature climates, four diverse amounts of OPC (including 0%, 2%, 4%, and 6%) are used as alternative fillers in four different mixtures. The resulting pavement's structural capacity is also shown to significantly improve as the cement content embedded in the asphalt concrete increases.

EXPERIMENTAL PROCEDURE AND MATERIAL

MATERIAL

In this study, asphalt mixtures with a nominal maximum aggregate size of 10 mm, called "ESG10," which is normally used as for surface and binder layers, according to the Ministry of transportation of Quebec (MTQ 2016). Also, B60/70 bitumen is one of the components in the mixture, with OPC used as the filler. The main variable in the four mixtures is the percentage content of the filler. To guarantee a low-cost result, 20% of the mix consists of sand. Also, 74% consists of two types of finely grained, manufactured granite aggregate of between 0 to 5mm and 5 to 10mm. The optimum bitumen content of B60/70 is 6% used in the mixture.

AGGREGATE

As presented in Figure 1, sieving was used to separate the aggregate particles by the two required size ranges. Then, the proposed asphalt mixture was combined with the approved aggregates gradation. Next, we tested and summarized the aggregate's fundamental properties. Figure 1 shows that the used aggregate gradation is from between 0 mm to 10mm.

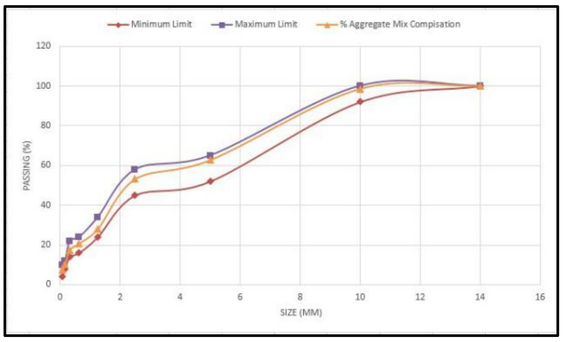

FIGURE 1. Aggregate gradation curves of the mix Portland cement

The filler used in the present study is OPC, which is a common construction material locally made and consumed in Libya. Table 1 presents the properties of the OPC additive material.

TABLE 1. Chemical composition of OPC (Guha and Assaf 2020)

Compound	%
Loss on Ignition (LOI)	7.91
SiO2	20.6
CaO	62.8
MgO	2.0
Al2O3	4.3
Fe2O3	3.15
Na2O	0.81
K2O	0.29
SO3	2.65
Materials not solvent	1.02

BITUMEN

Most road projects in developing countries are constructed using a penetration grade bitumen, consisting of B60/70. The B60/70 is recommended to be mixed at 156°C and compacted at 143°C. Table 2 shows the properties of the binder used here.

TABLE 2. Chemical composition of bitumen B60/70

Bitumen composition	Limitation	Lab result of B60/70
Specific Gravity	T228	1.03
Flash point, °C	T48	302
Mass Loss, %	T240	0.07
Penetration at 25°C, dmm	T316	64.7
Ductility at 25°C, cm	T51	143
Softening point, °C	T53	51.7

EXPERIMENTAL PROCEDURE

WHEEL TRACKING TESTER (WTT)

The WTT is a laboratory for analyzing bituminous mixtures' rutting resistance under various pressure conditions and temperatures. In accordance with the EN 12697-22 (Ministère des Transports, Québec MTQ, 2016) standard, this process simulates the many conditions pavement experiences. To induce permanent deformation, bituminous mix specimens are exposed to various passes of a tire that is mounted on a carriage, moving back and forth (see Figure 2). When testing two specimens under the same conditions (i.e., temperature and pressure) they can be placed in the same WTT at once, using two different supports.

For the wheel tracking test, a tire is repeatedly passed over a pavement sample's center twice per second. To achieve sample loading, a tire pressure of 600 kPa and a load of 500-N is applied to the sample. Each slab's dimensions are 500 × 180 × 50-100 mm. A steady temperature of 60°C is applied to all samples throughout the tests to simulate a high temperature climate. The samples were compressed and assessed using the WTT (Figure 2) and are consistent with the (MTQ 2016), see table 3. Once we completed the mix design experiments and their analyses, we created two pavement slabs for each mix design (i.e. each cement percentage has two samples – 0%, 2%, 4%, and 6%).

TABLE 3. Specifications for the WTT (Almadwi and Assaf 2021)

Thickness	Layer type	Cycle Number	Max Rutting (%)
-	Subbase base	10,000	≤10
6-8	Base course	30,000	≤10
3-4	Wearing course	1,000	≤10
		3,000	≤20
8-10	Base course	30,000	≤8
	high modulus for rut resistance		

To define deformation and find the average rut-depth, 15 measurements were taken for each sample - 120 total for the four mixes. The depth was established by loading samples at all repetitions and checking them against the same specifications and standards. We made the first sample measurement after 1000 cycles at an ambient room temperature of 60°C. The following measurements were made after the next 3000, 10,000, and 30,000 cycles.

The indirect tensile stiffness modulus (ITSM) test

Following EN 12697-26 standards, the ITSM test was performed to calculate the HMA samples' stiffness modulus. Specifically, each sample was tested at -5°C, 10°C, and 25°C to investigate the temperature sensitivity of the modulus. Similar to the rutting test, each mix variety was tested using two samples. Each sample was 100 mm wide and 63.5 mm in height. Moreover, for six hours prior to the test, the samples were stored in the ITSM at the particular temperature under investigation. Figure 2 illustrates the test procedures. The equation below is for calculating the stiffness modulus:

$$\mathrm{Sm} = \frac{F \times (\mu + 0.27)}{h \times Z}$$

where, Sm stands for the stiffness modulus, MPa; N; μ refers to the Poisson ratio (i.e., 0.25, 0.30, and 0.40 at -5°C, 10°C, and 25°C, respectively); F is the peak load; h refers to the specimen height in mm; and Z refers to the deformation in the horizontal plane in mm.

WinJulea SOFTWARE

The WinJulea is pavement thickness design software developed by US Army Corps of Engineers (USACE). This software calculates the stresses, strains and deflections anywhere on or under the pavement for any applied load or set of loads. The input values include pavement materials design parameters, coordinates of the applied load/s and coordinates of points where the operator requires the stresses, strains and/or deflections.

RESULTS AND DISCUSSION

RESULTS OF THE RUTTING TESTS

A total of 16 samples were used to evaluate the four mixes, with each mix-percentage having four slabs. All samples' rutting depths were established at 1000, 3000, 10,000 and 30,000 passes. Table 4 shows that, compared to samples with a lower cement content, rut depths are lesser for the mixes that had higher cement percentages. After the test, the average of different samples was used by the loading system to determine the rutting. Once 30,000 repetitions were achieved, the sample with 0% cement (i.e., the control mix) showed the greatest rutting, while the 6% cement mix (i.e., the highest percentage tested) had the least rutting. Moreover, the rutting test very clearly highlighted the OPC ratio's influence on the rutting performance. Finally, regarding the various OPC filler percentages (i.e., 0%, 2%, 4%, and 6%), the rut depth was lessened with an equivalent asphalt filler reduction.

TABLE 4. Thickness of each samples' rut depth (%)

Asphalt	PG 60/70				MTQ 4202, ESG10 Standard
Content (%)	0% Cement	2% Cement	4% Cement	6% Cement	
1000 Cycles	5.75	5.12	4.92	4.00	≥ 10
3000 Cycles	8.42	7.49	6.95	5.41	≥ 15
10000 Cycles	12.76	11.42	10.35	7.55	-
30000 Cycles	20.63	15.49	13.26	9.88	-

Each samples' average rut depth values were determined in accordance with the MTQ 4202, ESG10 standard. As demonstrated in Figure 2, the standard requires that each sample shows under 10% rutting from its original height after 1000-3000 tire passes. These findings show that adding cement to the mixture (especially at increasingly higher percentages) results in progressively less rutting.

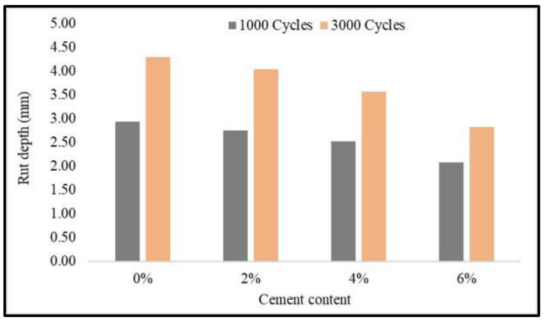

FIGURE 2. Rutting test preformed at 60°C rutting depth values for each mix

RESULTS OF THE ITSM TESTS

ITSM tests were carried out to investigate resilient modulus on 12 samples for the four mixes, with all three mix-percentages (i.e., -5°C, 15°C, and 25°C) having three samples each. At each temperature, all samples' resilient modulus was superior to the control, and increased with each rise in OPC percentage. As the temperature was increased, each mix's resilient modulus decreased. This was done to show the linear relationship between the cement percentages and the resilient modulus (i.e., with each cement percentage increase is a comparative increase in resilient modulus). Furthermore, each sample's resilient modulus increased as the temperature was reduced, and the lab results showed that the addition of OPC improved the mix's final quality. However, as Figure 3 demonstrates, because of the modulus's different values at various temperatures, the resilient modulus is unable to run comparative analyses on the mixtures.

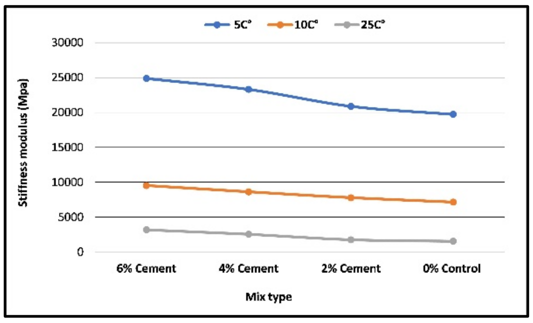

FIGURE 3. Average ITSM test results for all cement mixtures

In order to assess the impact of OPC as a filler in asphalt mixes, on the pavement lifetime before rupture, a throughout mechanistic analysis is presented in. Eight (8) scenarios are compared: the top layers of the analyzed structures are respectively composed of 75 mm and 100 mm of asphalt concrete with different percentages of OPC as filler (0%, 2%, 4% and 6%). The modulus for each asphalt concrete mix is presented in Figure 5 and rounded up in Table 5 below:

TABLE 5. Elastic modulus for each asphalt concrete mix

Asphalt concrete with	Modulus (25C°)
0% cement	1500 MPa
2% cement	2000 MPa
4% cement	2500 MPa
6% cement	3000 MPa

This asphalt concrete layer covers a 300-mm granular base composed of 50% of natural sand and 50% of manufactured sands, deploying a CBR of 52 (Amhadi and Assaf 2019), i.e an elastic modulus of 520 MPa.

The subbase is composed of natural desert sand, deploying a CBR of 12 (Fattah, Joni, and Ahmed 2016), i.e an elastic modulus of 120 MPa.

The structural design of the pavement needs to verify four (4) modes of failure: Failure in tension at the bottom of the asphalt concrete; Failure in compression at the top of the asphalt concrete; Failure in compression at the top of the granular base; Failure in compression at the top of the subbase.

For the two (2) alternatives proposed *(75 mm and 100 mm of asphalt concrete)*, graphs showing the number of allowable repetitions of an 8-ton axle load for all modes of failure versus the percentage of OPC added (0%, 2%, 4% and 6%) are proposed in Figures 4 and 5 below.

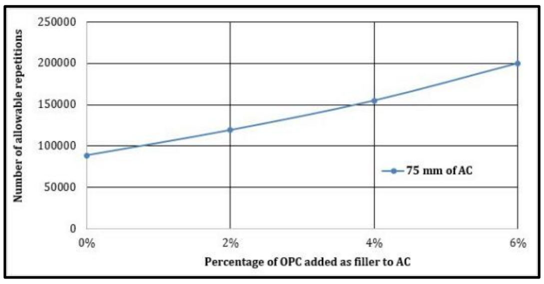

FIGURE 4. Number of allowable repetitions of an 8-ton axle load for all modes of failure versus the percentage of OPC added as filler to AC (75 mm)

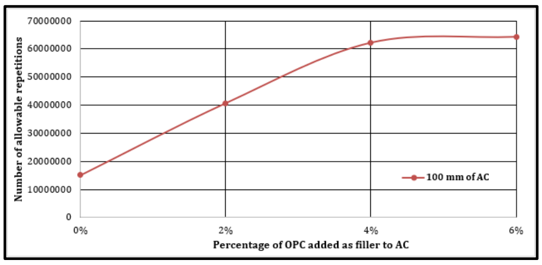

FIGURE 5. Number of allowable repetitions of an 8-ton axle load for all modes of failure versus the percentage of OPC added as filler to AC (100 mm)

As shown in figures 5 and 6, for an asphalt top layer of 75 mm, between 0% and 6% OPC adding as a filler to the asphalt mix, the number of allowable repetitions is more than doubled; for an asphalt top layer of 100 mm, between 0% and 7% OPC, the pavement life time is 4 time longer.

The number of allowable repetitions of an 8-ton axle load, and therefore the life time of a pavement structure, is substantially increased as the cement content is increased.

CONCLUSION

The present study investigates the use of OPC in HMA at various percentages (i.e., 0%, 2%, 4%, and 6%) to determine its range of road surface performance under typical environmental conditions. In particular, laboratory tests were conducted on various HMA mixtures with a range of OPC percentages from zero to six. Ultimately, percentages were identified based on the mix's total weight and the test results are as follows: As OPC is increased, rutting is reduced. The 6% OPC mixtures demonstrate the best performance of all the samples and are recommended in this study for hot regions.

Adding OPC to HMA enhances pavement stability and reduces flow, resulting to decreased rutting. Thus, OPC improves the final mix's overall strength. As the temperature applied to each mix was increased, their resilient modulus decreased. By contrast, each sample's resilient modulus increased as the temperature was reduced. Therefore, the lab results indicate that the addition of OPC improves a pavement's final quality. These findings are based on figure analyses that demonstrate how adding 6% OPC to HMA is recommended in hot and arid countries since it is a low-cost method of strengthening asphalt in such areas.

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DECLARATION OF COMPETING INTEREST

None

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