Improvement of Asphalt Concrete Mixtures by Adding Pulverised Fuel Ash as Filler

Abbas Talib Al-Hdabi
Lecturer
Faculty of Engineering, University of Kufa
abbas.alhadabi@uokufa.edu.iq
alhudabi73@yahoo.com

Karar Shakir Dakhil
BSc student
Faculty of Engineering, University of Kufa

Hussain Ameen Qasim
BSc student
Faculty of Engineering, University of Kufa

ABSTRACT

Consuming of by-product or waste materials in highway engineering is significant in the construction of new roads and/or in renovations of the existing ones. Pulverised Fuel ash (PFA), which is a by-product material of burning coal in power stations, is one of these materials that might be incorporated instead of mineral filler in hot asphalt mixtures.

Two types of surface course mixtures have been prepared one with conventional mineral filler i.e. ordinary Portland cement (OPC) while the second was with PFA. Several testings have been conducted to indicate the mechanical properties which were Marshall Stability and Indirect Tensile Strength tests. On the other hand, moisture damage and ageing have been evaluated by indicating Index of retained strength (IRS) and Long Term Aging (LTA), respectively.

In accordance to the experimental investigation, the new hot asphalt mixtures i.e. with PFA mineral filler are comparable with conventional mixture and comply with the requirements which are recommended for surface course by the Standard Commission for Roads and Bridges (SCRB) in Iraq.

Key words: mineral filler, hot asphalt mixtures, PFA, mechanical properties, durability.

خواص الخلطات الاسفلتية المحتوية على مسحوق رماد الوقود كفلر

عباس طالب الهدابي
مدرس
كلية الهندسة-جامعة الكوفة

كرار شاكر داخل
طالب دراسة اولية
كلية الهندسة-جامعة الكوفة

حسين امين قاسم
طالب دراسة اولية
كلية الهندسة-جامعة الكوفة

الخلاصة

تعتبر عملية استخدام المواد الناتجة بصورة عرضية او المخلفات من الصناعات المختلفة في هندسة الطرق من الامور ذات الفائدة الكبيرة عند انشاء طريق جديد اواعادة تاهيل اي طريق منشاء سابقا. الرماد المتطاير الناتج من حرق الفحم الحجري بمحطات الطاقة الكهربائية هو احد هذه المواد والتي من الممكن ان يستخدم كبديل للمواد المالئة في الخلطات الاسفلتية الحارة التي تمثل احدى مكونات الخلطة الاسفلتية ذات الكلفة العالية.

في هذه الدراسة تم تهيئة نوعين من الخلطات الاسفلتية الحارة، الاولى تمثل الخلطات التقليدية التي تحتوي على السمنت كمادة مالئة اما الثانية فقد تم انتاجها باستخدام الرماد المتطاير بدلا عن السمنت. تم اجراء عدد من التجارب المختبرية لتحديد الخواص الميكانيكية وهي ثبات مارشال وفحص قوة الشد الغير مباشر. اما الديمومة لهذه الخلطات فتم تقييمها بايجاد الاضرار بسبب الغمر والكلل على المدى الطويل.

بحسب الفحوصات التي تم اعتمادها، تم استنتاج كون الخلطات المستدامة والتي تم تحضيرها باستخدام الرماد المتطاير تملك خواص جيدة مما يجعلها تحقق المتطلبات الهندسية للخلطات الاسفلتية الحارة والخاصة بالطبقة السطحية علاوة على كونها مقاربة او افضل من الخلطات التقليدية.

الكلمات الرئيسية: المادة المالئة، الخلطات الاسفلتية الحارة، الرماد المتطاير، الخواص الميكانيكية، الديمومة.

1. INTRODUCTION

Hot asphalt mixtures, which are being made and laid at high temperatures, often use asphalt cement to bind the aggregate substances. Although asphalt cement is manufactured to have a range of viscosities, the grades used in the structural layers of roads are approximately solid at ambient temperatures. In order to mix with the aggregate mixture, asphalt cement must first be liquefied by heating.

The mineral aggregate comprising coarse and fine constituent acts as the structural skeleton of the pavement **Read and Whiteoak 2003**. Moreover, mineral filler tends to stiffen the asphalt cement by dispersing fine materials in it. Several materials such as limestone dust, fine sand, lime and cement are normally used as mineral filler in Hot Asphalt Mixtures (HAMs). It's worthy to mention that cement and lime are costly and used efficiently for other purposes.

Using of waste powders as mineral filler in HMA have been investigated previously by several researchers. Phosphate waste filler **Katamine 2000**, recycled waste lime **Hwang et al. 2008**, and waste ceramic materials **Baoshan et al. 2009** have been studied as mineral filler. It was concluded that these waste materials could be incorporated in HAM without any significant drop in its performance.

The filler has the ability to improve the resistance of particle to move within the mix matrix and/or works as an active material when it interacts with the asphalt cement to enhance the properties of the mastic **Anderson 1987**. Furthermore, elastic modulus of HMA can be improved by incorporation of mineral filler. However, high quantity of filler may produce weak mixtures due to increment of the required amount of asphalt cement to cover the aggregate particles **Elliot et al. 1991, Kandhal et al. 1998**.

Pulverised Fuel Ash (PFA), can also be known as 'fly ash', is a waste generated in thermal power plants resulting from the burning of coal in the coal-fired furnaces. The idea of sustainable solutions for fly ash is directly linked with technologies with aligned vision for environment, economy and social goals **Kumar et al. 2007**. The environmental impact of fly ash in terms of its massive generation, large usage of land for disposal and, short and long term impact on surrounding areas is well known. There is an increasing interest in the bulk utilization of fly ash. Fly ash is a silico-aluminate material consisting of SiO_2, Al_2O_3, Fe_2O_3, as the major constituents.

Currently, there is an increasing interest in the utilization of waste materials which is one of the main target schemes for the environmentally friendly processes. In the case of construction industry, there was a growing trend towards use of waste as supplementary cementitious materials. In the asphalt-concrete mixtures, it is used as mineral filling to fill the voids and connect coarse aggregates by meeting conditions prescribed by ASTM D242 and AASHTO M-17 standards, as well as an addition to asphalt cement **Butul 2000, ASTM D242 2004, AASHTO M-17 2007, Simms 1998**.

Tapkin 2008, stated that using of fly ash in asphalt mixtures is attractive due to the performance improvement, cost reduction and environment impact decrease. While **Sobolev et al. 2013** conducted a research study to assess the interaction between fly ash and various kinds of asphalts and reported the main enhancements achieved in the critical characteristics of asphalt concrete. Also, they concluded that the rheological characteristics of asphalt mastics and asphalt concrete mixtures have been improved by fly ash addition. Furthermore, the resistance to the aging was enhanced due to the longevity increment of pavement infrastructure by decreasing aging-related cracks.

Another study investigated the possibility of incorporating fly ash in hot asphalt mixtures depending on Marshall mix design **Mistry and Roy 2016**. They stated that addition of 4% of fly ash to the dense asphalt macadam instead of hydrated lime, which is the conventional mineral filler in India, provides a significant economy of asphalt in the produced asphalt mixtures. Also, they indicated that filler modification by fly ash provides superior strength with lesser deformation in comparison with untreated mixtures.

In Iraq, there are few studies which were conducted on the characterization of asphalt and asphalt concrete with fly ash such as **Sarsam and Lafta 2014** and **Asmael 2010**. The latter, conducted a detailed lab research to investigate the performance of asphalt mixtures with different types of filler i.e. Portland cement, fly ash and silica fume. He concluded that, asphalt mixtures with silica fume (among the selected filler materials) has most workability and highest indirect tensile strength results. On the other hand, **Sarsam and Lafta 2014** attempted to prepare modified binders for asphalt mixtures by incorporating of fly ash, sulfur and silica fume (with three different percentages) into 40-50 and 60-70 penetration grade asphalt cement. The penetration, ductility and softening point tests were conducted for the modified binders before and after thin film oven test. They reported that the penetration value of the binders decreased for all percentages of additives except when adding sulfur to 40-50 penetration grade asphalt cement.

Therefore, the main objective of this investigation is to study the properties of traditional hot asphalt concrete mixtures which are suitable for surface courses in Iraq with PFA as mineral filler. According, two types of mixtures, one with conventional mineral filler i.e. OPC and the later with PFA, have been prepared and evaluated with different type testing.

2. MATERIALS

The materials that have been used in this research i.e. coarse and fine aggregate, asphalt cement and filler comply with the requirements which are approved by the State commission for Roads and Bridges specifications in Iraq **SCRB 2003**.

2.1 Coarse and Fine Aggregates

The coarse aggregate which used in this study were crushed quartz which is collected from one of the hot mix plants at Al-Najaf city, Iraq. On the other hand sand was used as fine aggregate. The physical properties of the coarse aggregate and fine aggregate are presented in **Tables 1 and 2,** respectively.

2.2 Asphalt Cement

A 40–50 penetration grade asphalt cement has been used in this study to investigate the performance of hot asphalt mixtures. The physical properties of this asphalt are shown in **Table 3**.

2.3 Mineral Filler

Two sets of samples have been prepared to cover this investigation. The first set was prepared with conventional mineral filler i.e. OPC which is collected from new Kufa cement factory. While the second set was prepared with PFA as filler which in turn has been collected from one of the power generation plants in UK.

Table 4 shows the chemical composition of the used PFA. The particle size distribution analysis of PFA indicates that the mean diameter (d50), d10 and d90 are 14.02, 0.952 and 34.26µm, respectively. Moreover, the particles of PFA has almost spherical shape and the specific surface area is 490 m^2/Kg.

2.4 Gradation and samples' preparation

The selected gradation of coarse aggregate, fine aggregate and mineral filler is shown in **Fig. 1** which comply with the specification for roads and bridges for type IIIA surface course mixtures with 12.5 mm maximum size **SCRB 2003**.

As per the selected gradation, asphalt mixtures have been prepared in accordance to ASTM D D6926 ASTM Standards 2010. The aggregate were separated depending on their size and a total weight of 1200 gm for each sample was heated in the oven at 150ºC before mixing with 40–50 grade asphalt cement. In turn the asphalt cement was kept at 150ºC in the oven before mixing with the aggregate. The whole materials were mixed thoroughly until the aggregate particles being coated with asphalt cement then compacted by an automatic compactor with 75-blows for each side. Three specimens for each test were prepared with different mineral fillers i.e. OPC and PFA.

3. TEST METHODS

The mechanical properties were assessed by conducting Marshall and Indirect Tensile Strength tests to investigate the performance of HAM with PFA filler and compare the results with conventional HAM i.e. with OPC filler,. While the durability of these mixtures were assessed by indicating the Index of Retained Strength (IRS) and the long term aging.

3.1 Marshall Test

Marshall test has been conducted to indicate Marshall Stability (MS) and flow in accordance to ASTM D6927 ASTM Standards 2010. This method describes the resistance to plastic flow of a cylindrical specimen with 2.5 in. height and 4 in. diameter of asphalt mixtures loaded on the lateral surface of specimen by means of Marshall apparatus with a constant rate of 50.8 mm/min and a temperature of 60 ºC until the maximum load is reached. Accordingly, the maximum load resistance (Marshall Stability) and the corresponding strain (flow) values were documented.

3.2 Indirect Tensile Strength Test

The Indirect Tensile Strength (ITS) test was conducted as per ASTM D 4123. The experimental method used to determine the tensile strength of Marshall Sample is based on loading it diametrically in compression with a constant rate of 50.8 mm/min. The ITS can be determined as shown below:

$$ITS = \frac{2 \times P_{max}}{\pi\, H\, D} \tag{1}$$

where: ITS is in kPa, P_{max} is the maximum applied load, kN, H is the height of the specimen, m and D is the diameter of the specimen, m.

3.3 Index of Retained Strength

Index of Retained Strength (IRS) test was conducted in accordance to ASTM D1075 to assess the moisture damage of the prepared mixtures. This test is recommended to indicate the loss of cohesion that is resulting from the existence of water. In addition to MS, this property is adopted in the SCRB specifications for asphalt mixtures used as surface course, more specific, IRS must be more than 70%. The method of mixing, the dimension of the specimens and the number of blows by compaction hammer were as described for Marshall Test in 3.1 and its value can be calculated by applying Eq. (2).

$$IRS = \frac{S_2}{S_1} \times 100\% \tag{2}$$

where: IRS = Index of Retained Strength, %
S_1= MS of the dry specimens (the samples were immersed in water bath for (30-40 minutes) at 60ºC before testing for MS at 60°C), KN
S_2= MS of the wet specimens (the samples were immersed for 24 hours at 60ºC before testing for MS at 60°C), KN.

3.4 Long Term Aging

Long Term Ageing (LTA) demonstrates age hardening through road life. As adopted by the Strategy Highway Research Program (SHRP) A-003A, the compacted samples are cured in an oven at 85°C for 2 or 5 days to simulate 5 or 10 years' age hardening in the pavement, respectively **Kliewer et al. 1995**.

In this study, the whole samples are conditioned in an oven at 85°C for 5 days to simulate the age-hardening effects after 10 years. Then the samples were tested in accordance with ASTM D6927, ASTM Standards 2010, to indicate MS values after ageing. Also, Mean Marshall Stability Ratio (MMSR) has been considered as the ratio between MS after ageing and MS before ageing.

3.5 Density and air voids analysis

Dry bulk density has been determined in accordance to ASTM D2726, while the other volumetric properties i.e. Air Voids (AV), Voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA) were determined as per ASTM D3203. Also, the equations below have been used:

$$G_{mb} = \frac{dry\ weight}{SSD\ weight - weight\ in\ water} \tag{3}$$

where: G_{mb} represents bulk specific gravity and SSD represents the weight of the saturated-surface dry samples, gm.

$$Air\ voids, \% = \left(1 - \frac{G_{mb}}{SG_{max}}\right) \times 100\ \% \tag{4}$$

where: SG_{max} is the maximum specific gravity for the mixture.

$$VMA = 100\% - \frac{G_{mb} \times P_s}{G_{sb}} \tag{5}$$

where: Ps is aggregate percentage in the total mix and G_{sb} is aggregate bulk specific gravity

$$VFA = \frac{(VMA - AV)}{VMA} \times 100 \tag{6}$$

4. RESULTS AND DISCUSSION

As per ASTM D6927 - 10, Marshall Mix Design Method, the optimum asphalt cement has been determined as 5.5% by total weight of aggregate for the two types of mixtures i.e. with OPC and PFA mineral filler. Marshal Stability (MS) and Indirect Tensile Strength (ITS) have been conducted to investigate the mechanical properties of HMA with PFA, while the durability of these mixtures has been assessed by Index of retained Strength (IRS) and Long Term Aging (LTA).

4.1 Marshall Properties results

Figs. 2─4 present Marshall results which are MS, Marshall flow and Marshall stiffness. It is clearly shown from Fig. 2 that MS increased slightly when the conventional mineral filler i.e. OPC has been replaced with PFA. The same trend can be observed in Marshall stiffness which is shown in **Fig. 4**. While, from **Fig. 3** it can be reported that there is a respectable decrease in Marshall flow for the new mixtures i.e. HAM with PFA. Moreover, the produced mixtures with OPC and PFA filler comply with the SCRB specifications by means of Marshall properties.
This improvement in Marshall properties for mixtures with PFA can be attributed to that PFA particles act as a reinforcing material to the asphalt cement and increase its stiffness. Furthermore and for the given gradation of aggregate and asphalt cement content, fine PFA caused more stiffening for asphalt cement in comparison with OPC which is coarser than it.

4.2 Indirect Tensile Strength results

Fig. 5 displays the average results of ITS test for the surface course mixtures with different mineral filler i.e. OPC and PFA. There is a substantial increase in ITS results when OPC was replaced by PFA, almost 35% increase. Several points might led to this performance such as the high stiffness of the produced mastic from asphalt cement and PFA and the way of testing samples in the indirect tensile technique. Incorporating of PFA particles may also increase the shear strength of the modified binder which will increase the resistance to the applied load.

4.3 Volumetric properties of asphalt mixtures

These properties have been determined by means of specifying specific gravity, air voids, Voids in Mineral Aggregate (VMA) and Voids Filled with Asphalt (VFA). **Figs. 6–9** show these parameters for the control mix i.e. with OPC and the other one which is prepared with the by-product material PFA. It can be indicated from these figures that the change in the volumetric properties i.e. bulk density, air voids, VMA and VFA is not significant when the conventional mineral filler was replaced with PFA. Also, the air voids, VMA and VFA of these mixtures remain conform to the requirements which are adopted by SCRB standards for surface course asphalt concrete mixtures.

4.4 Durability of asphalt mixtures

Moisture sensitivity and aging are the main properties which describe the durability of hot asphalt mixtures. Moisture sensitivity was assessed by determining Index of Retained Strength (IRS), while Long Term Aging (LTA) has been conducted to assess the later.

4.4.1 Moisture damage

IRS test results for the conventional i.e. with OPC and the new i.e. with PFA mixtures are shown in **Fig. 10**. Moreover, **Fig. 10** shows Marshall Stability for these mixtures before and after exposing to moisture damage. There is less impact by moisture damage for the mixtures with PFA in comparison with the control mixtures as IRS increased from 73% to 80%. These results can be attributed to that the stiffness of the binder for the new mixtures is higher than that for the conventional mixtures, therefore resultant MS for wet samples is higher in comparison with the control mixtures.

4.4.2 Long term aging

The effect of aging on the performance of the conventional and the new mixtures has been assessed by means of Long Term Aging (LTA) and presented in **Fig. 11**. As revealed in this figure, there is a substantial increase in MS results for PFA mixtures after aging, almost 15% in comparison with those mixtures without aging. While there is no substantial difference between the results for OPC mixtures with and without aging (MMSR=99%). Accordingly it can be stated that the durability of sustainable HAM is more in comparison with the control mixtures.

5. CONCLUSIONS

An asphalt concrete mixture suitable for surface course is produced by using PFA as mineral filler. PFA is the residual solid material from the combustion of coal in coal-fired power stations and well known as waste material that normally needs to be reused in different industrial fields. Therefore, it has been used in this study as a replacement for OPC to produce the new hot asphalt mixture. The mechanical properties were evaluated by conducting Marshall Test and Indirect Tensile Strength. While, water sensitivity and long term aging have been investigated by Index of Retained Strength (IRS) and Mean Marshall Stability Ratio (MMSR), respectively. Below are the main concluded points:

1. By means of Marshall Test properties, hot asphalt mixtures with PFA are comparable with those with OPC.
2. Mixtures with PFA perform considerably better than the conventional hot mixtures when compared by ITS.
3. In terms of water sensitivity, IRS increased for mixtures with PFA in comparison with those with OPC. Also, these mixtures have improved their mechanical properties after aging when tested in accordance to Long Term Aging (LTA).
4. Asphalt mixtures' compatibility is not affected by PFA addition. Accordingly, the traditional procedures for mix design are applicable for asphalt mixtures with PFA.

REFERENCES

AASHTO M-17 2007. S*tandard specification for mineral filler for bituminous paving mixtures. Washington, DC 20001: American Association of State Highway and Transportation Officials; Report nr M-17-07.*

Anderson, D. 1987.*Guidelines for use of dust in hot mix asphalt concrete mixtures.* Proceeding Association of Asphalt Paving Technologists. Association of Asphalt Paving Technologists, 492-516.

Asmael, N. 2010. *Effect of Mineral Filler Type and Content on Properties of Asphalt Concrete Mixes. Journal of Engineering,* 16.

ASTM D242 ,2004. *Standard Specification for Mineral Filler for Bituminous Paving Mixtures. In: Annual book of ASTM standards*.

ASTM Standards , 2010. *Roads and Paving Materials. Annual Book of the American Society for Testing and Materials Standards. Section 4, Vol. 03-04.* Washinton, USA.

Baoshan, H., Qiao, D. and Edwin, B. 2009. *Laboratory evaluation of incorporating waste ceramic materials into Portland cement and asphaltic concrete.*" *Journal of Construction and Building Materials,* 23:3451-6.

Butul, B. 2000. *Performance characteristic of coal fly ash and wood ash-modified asphalt binder*. United States - Florida: Florida Atlantic University.

Elliot, R., Ford, M., Ghanim, M. and Tu, Y. 1991. *Effect of aggregate gradation variation on asphalt concrete mix properties*. *Transportation Research Record.* Washington, D.C.: National Research Council.

Hwang, S., Park, H. and Rhee, S. 2008. A *study on engineering characteristics of asphalt concrete using filler with recycled waste lime*. *Journal of Waste Management*, 28:191-9.

Kandhal, P., Lynn, C. and Parker, F. 1998. Ch*aracterization tests for mineral fillers related to performance of asphalt paving mixtures. In:* 98-2, R. N. (ed.) *National Centre for Asphalt Technology*.

Katamine, N. 2000. *Phosphate waste in mixtures to improve their deformation*. *Journal of Transportation Engineering*, 126:382-9.

Kliewer, J., Bell, C. and Sosnovske, D. 1995. I*nvestigation of the Relationship Between Field Performance and Laboratory Ageing Properties of Asphalt Mixtures (SHRPA - 003A), Engineering Properties of Asphalt Mixtures and the Relationship to their Performance, ASTM STP 1265Gerals A.*. Philadelphia: Hubber and Dale S. Decker, Eds. American Society for Testing and Materials.

Kumar, R., Kumar, S. and Mehrotra, S. P. 2007. T*owards sustainable solutions for fly ash through mechanical activation. Resources, Conservation and Recycling,* 52**,** 157-179.

Mistry, R. and Roy, T. K. 2016. *Effect of using fly ash as alternative filler in hot mix asphalt*. *Perspectives in Science,* *http://dx.doi.org/10.1016/j.pisc.2016.04.061*.

Read, J. and Whiteoak, D. 2003. *The Shell Bitumen Handbook.* 1 Heron Quay , London: Thomas Telford Publishing.

Sarsam, S. and Lafta, I. 2014. A*ssessment of Modified - Asphalt Cement Properties. Journal of Engineering*, 20.

SCRB 2003. *R9: Specifications for roads and bridges in Iraq*. Baghdad, Iraq.

Simms, S. A. 1998. *Use of coal fly ash in asphalt concrete mixes. Canada: DalTech - Dalhousie University (Canada).*

Sobolev, K., Flores, I., Bohler, J., Faheem, A. and Covi, A. 2013. A*pplication of Fly Ash in ASHphalt Concrete: from Challeng to Opportunities. World of Coal Ash Conference.*

Tapkin, S. 2008. *Improved asphalt aggregate mix properties by portland cement modification*. *Canadian Journal of Civil Engineering,* 35: 27-40.

Table 1. Physical properties of coarse aggregate.

Property	ASTM Designation	Test results	SCRB specifications
Bulk specific gravity	C 127	2.61	….
Apparent specific gravity	C 127	2.64	….
Percent wear by Los Angeles abrasion , %	C131	22.7	30 Max.
Soundness loss by sodium sulfate solution,%	C88	3.4	12 Max.
Flat and elongated particles ,%	C 4791	5	10 Max.
Degree of crushing, %	D5821	96	90 Min.

Table 2. Physical properties of fine aggregate.

Property	ASTM Designation	Test results	SCRB specifications
Bulk specific gravity	C127	2.64	….
Apparent specific gravity	C127	2.68	….
Sand equivalent, %	D2419	57	45 Min.
Angularity ,%	C1252	54	….
Clay lumps and friable particles, %	C142	1.85	3 Max.

Table 3. Physical properties of asphalt cement**.**

Property	ASTM Designation	Test Results	Requirements
Penetration at 25 ºC, 0.10 mm	D5	44	40-50
Ductility at 25 ºC , cm	D113	125	>100
Specific gravity at 25 ºC	D70	1.03	------
Flash point , ºC	D92	275	>232
Solubility in trichloroethylene, % wt	D2042	99.22	>99
Residue from thin –film oven test - Retained penetration , % of original -Ductility at 25 ºC, cm	D1754 D5 D113	 71 54	 >55 >25

Table 4. Chemical composition of PFA**.**

OXIDE	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	Loss on ignition
%	57.60	26.38	4.15	2.25	0.38	2.18	4.89

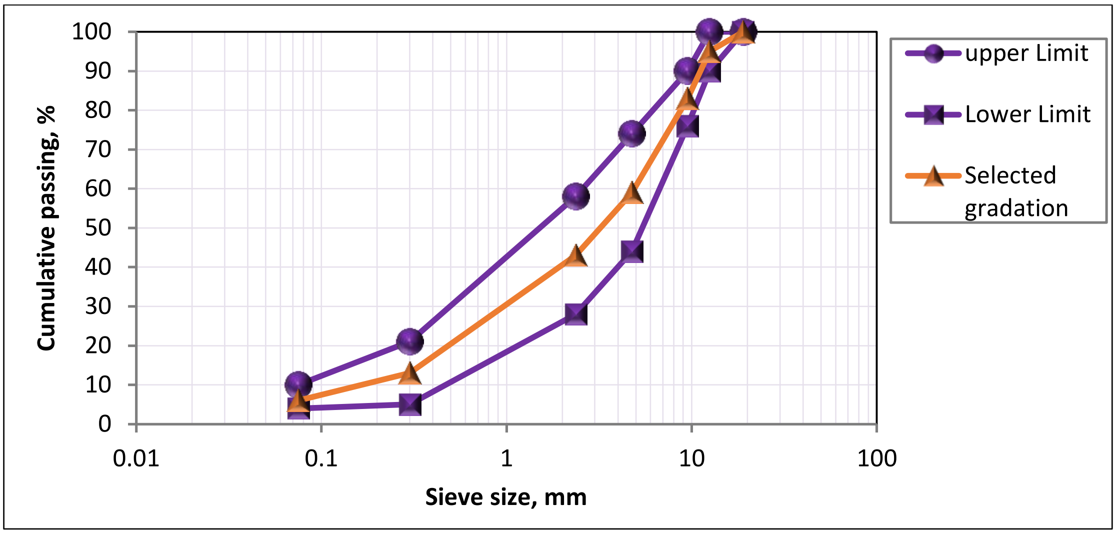

Figure 1. Type IIIA surface course hot asphalt gradation.

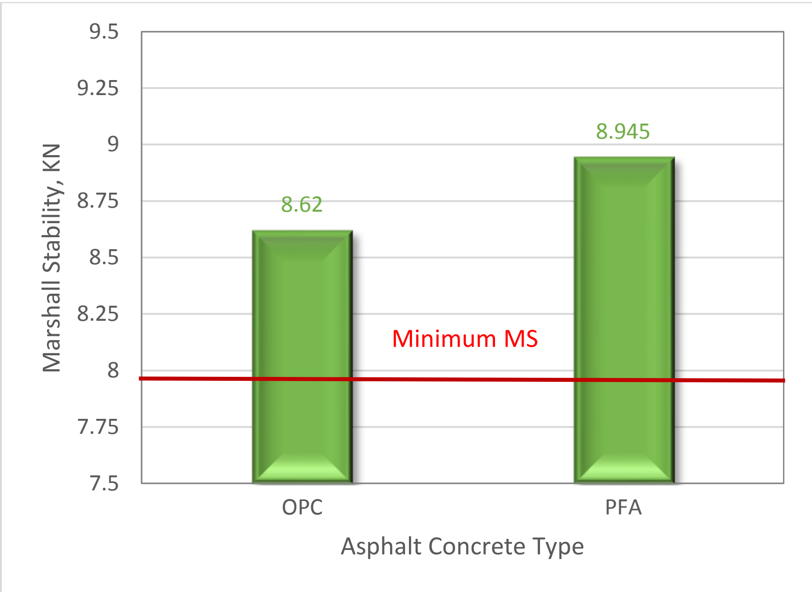

Figure 2. Marshall Stability results for OPC and PFA mixtures.

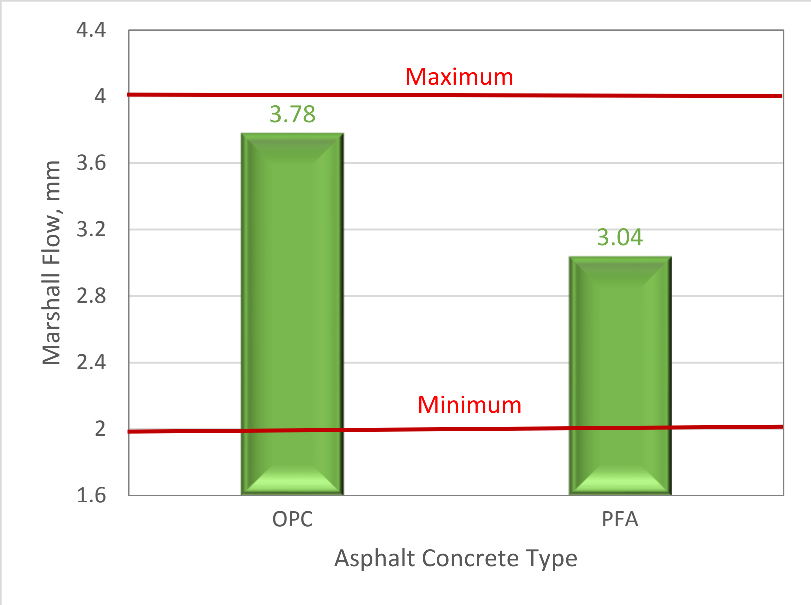

Figure 3. Marshall Flow results for OPC and PFA mixtures.

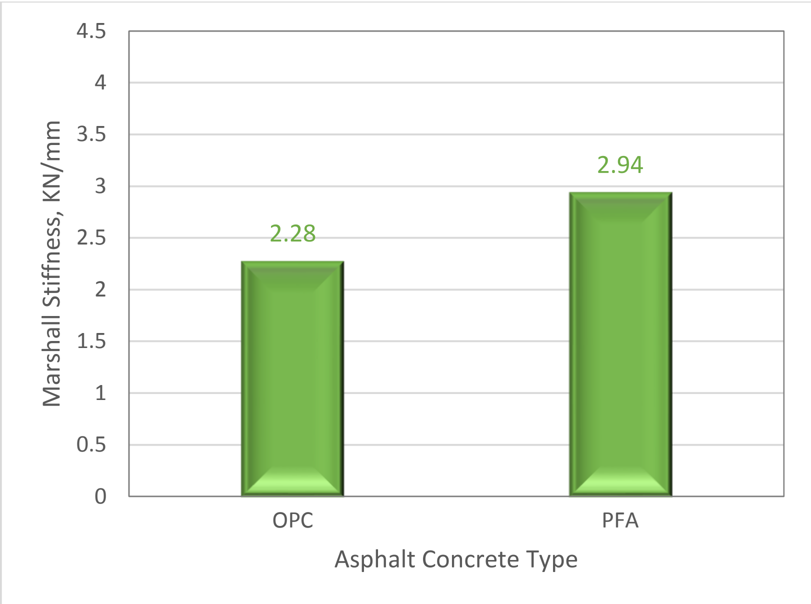

Figure 4. Marshall Stiffness results for OPC and PFA mixtures.

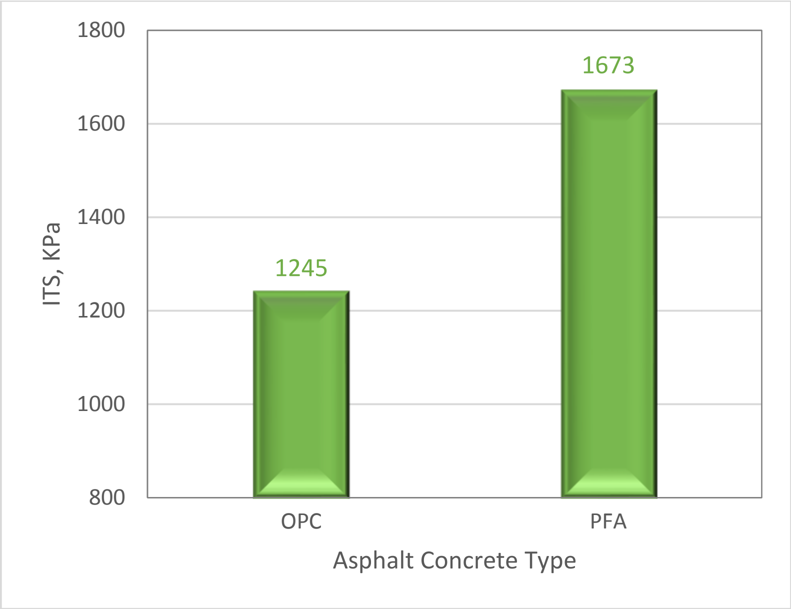

Figure 5. Indirect Tensile Strength results for OPC and PFA mixtures.

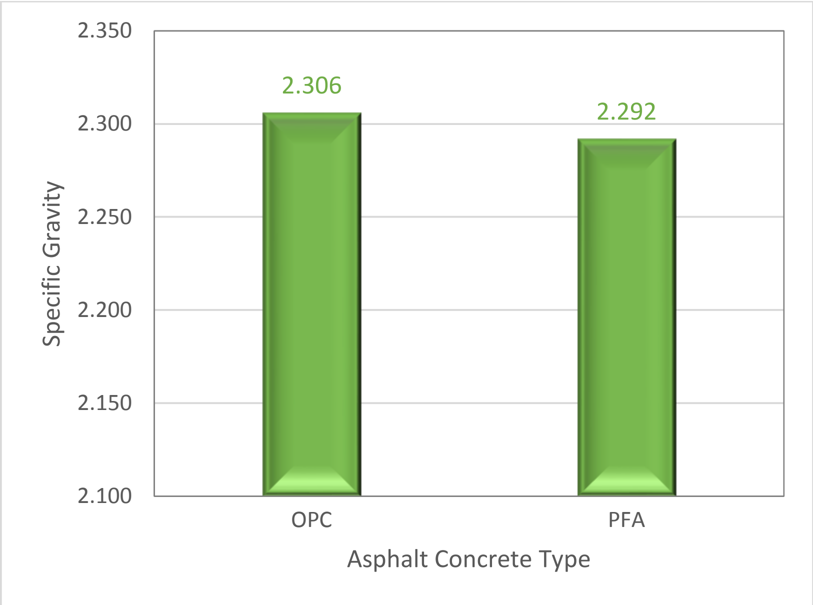

Figure 6. Specific Gravity results for OPC and PFA mixtures.

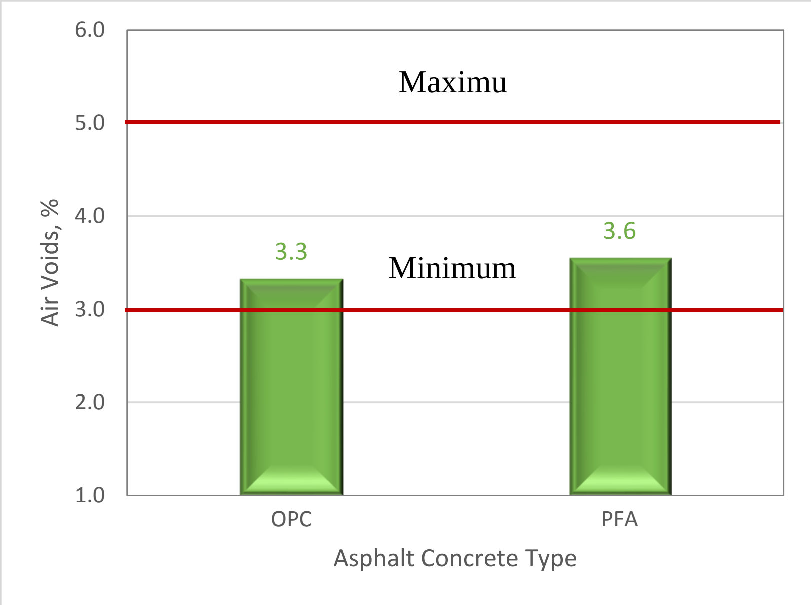

Figure 7. Air Void results for OPC and PFA mixtures.

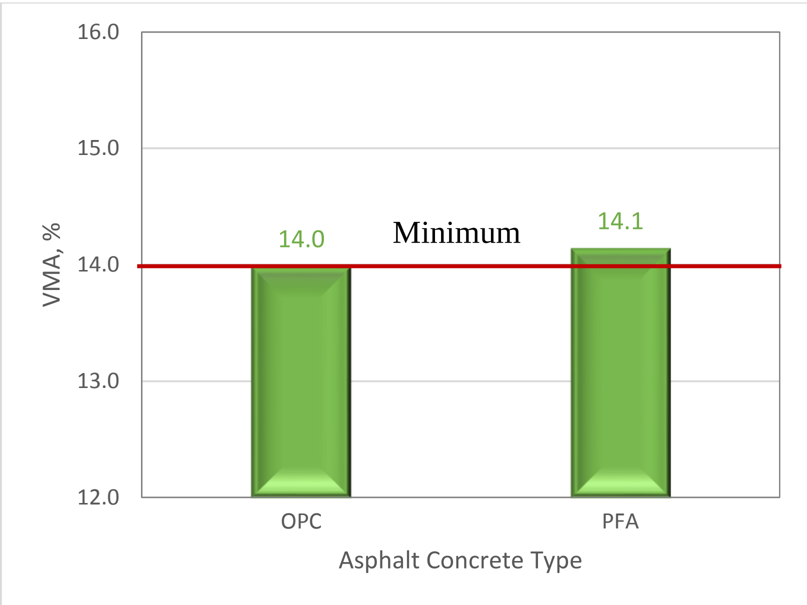

Figure 8. Voids in Mineral Aggregate for OPC and PFA mixtures.

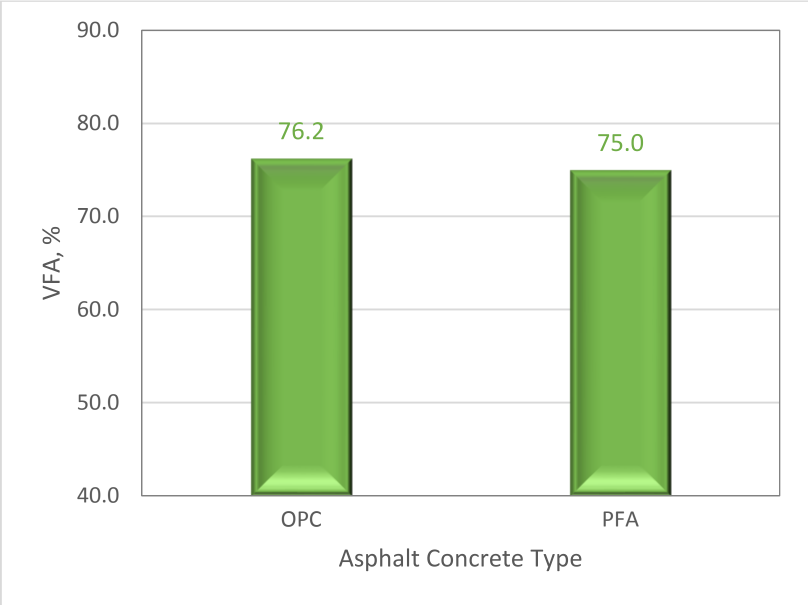

Figure 9. Voids Filled with Asphalt for OPC and PFA mixtures.

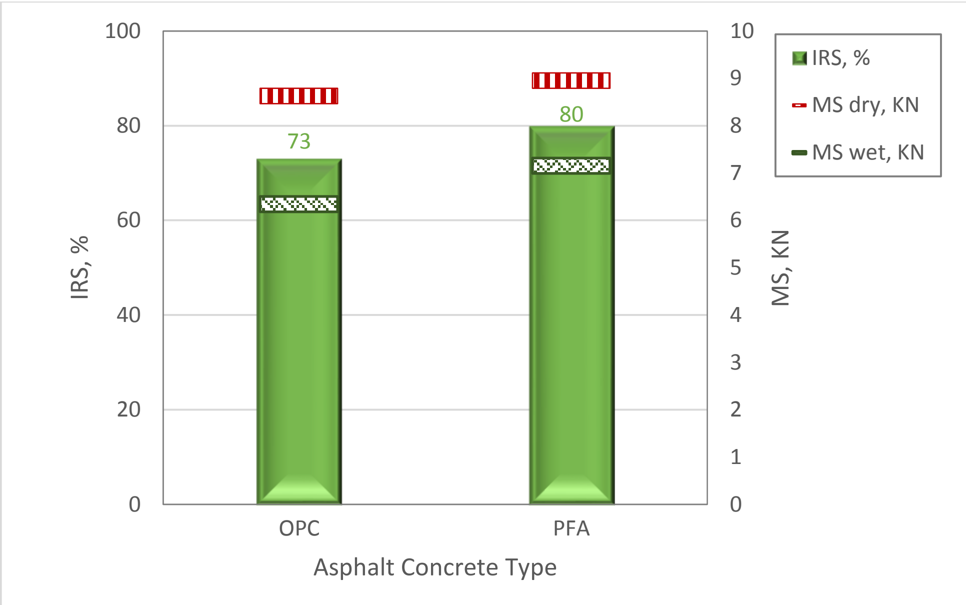

Figure 10. Index of Retained Strength for OPC and PFA mixtures.

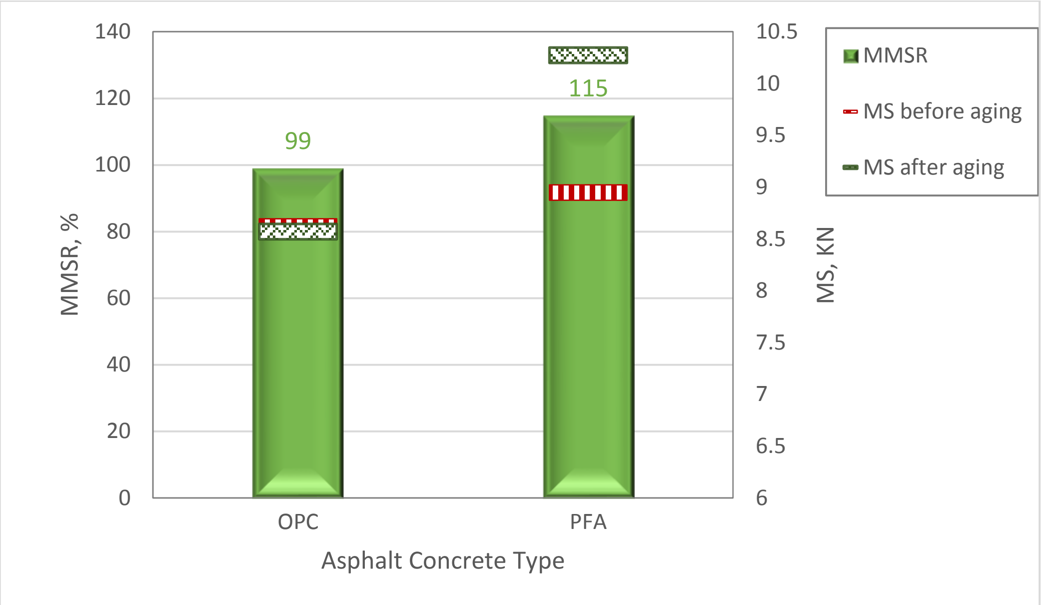

Figure 11. Effect of long term aging on OPC and PFA mixtures.