Journal University of Kerbala, Vol. 14 No.4 Scientific . 2016

EVALUATING HOT MIX ASPHALT CONTAINING WASTE AND BY-PRODUCT MATERIAL ASHES

تقييم خرسانة اسفلتية اسفلتية حارة تحتوي خبث مواد فضلات و مخلفات صناعية

Dr. Shakir Al-Busaltan
Lecturer, Department of Civil Engineering, University of Kerbala, Karbala, Iraq
shakerfa2003@yahoo.com,

Abstract

It is well observed that filler types play a significant role in properties of Hot Mix Asphalt (HMA), from one side. From other side, currently, massive quantities of waste or by-product materials are resulted from local and global industrial processes, municipals services, and mining. Such waste or by-product materials reached to massive levels which bring a harmful impacts on human being life. Thus, this research is an attempt to evaluate the volumetric and mechanical properties of HMA comprising different composition of waste and/or by-product as filler materials. Cement Kiln Dust (CKD) was suggested as a partially and completely replacement to Ordinary Portland Cement (OPC) in HMA, while other two fillers were selected, up to 30% to help in activating the CKD; namely Silica Fume (SF), and Rice Husk Ash (RHA). Traditional volumetric and mechanical properties were conducted to evaluate the designed HMA, while microanalysis techniques were used as tools to characterise different filler types. Results showed that CKD with at less15% SF, or 27.5% RHA could bring design HMA to satisfy the local specification requirements, where totally replacement of CKD will not satisfy the local specification. Furthermore, microanalysis properties of different filler types can be vital tool to explain the variation in HMA properties.

Keywords: Cement Kiln Dust**,** HMA, microanalysis techniques, Rice Husk, Silica Fume

الخلاصة

اصبح واضحاً ان الانواع المختلفة للمادة المالئة تلعب دورا مهماً في خواص الخلطات الاسفلتية الحارة، هذا من جهة. ومن جهة اخرى، حالياً هناك كميات هائلة من الفضلات و النواتج العرضية تنتج من عمليات التصنيع، الخدمات البلدية، والتعدين ، محليا وعالميا. والملاحظ وصول مستويات هذه المواد الى حدود قياسية جلبت اضرار على الحياة البشرية. وعليه، هذا البحث هو محاولة لتقييم الخواص الحجمية و الميكانيكية لخلطات اسفلتية حارة تحتوي مواد فضلات و/ او نواتج عرضية كمواد مالئة. غبار فرن السمنت تم اقتراحه ليكون كبديل جزئي او كلي عن الاسمنت البورتلاندي العادي في الخلطات الاسفلتية الحارة، بينما مادتين مالئتين ولحد 30% تم اختيارهما لتساعد على تفّعيل غبار فرن السمنت، وهاتين المادتين هما السيلكافيوم و غبث قشور الرز. استخدمت الفحوص الحجمية و الميكانيكية التقليدية في تقييم الخلطات الاسفلتية الحارة المصممة، بينما استخدمت تقنيات التحليل المايكروي كأداة في معرفة الخصائص المختلفة للمواد المالئة. اظهرت النتائج ان استخدام غبار فرن الاسمنت مع 15% سيلكافيوم او 27.5% غبث قشور الرز كحد ادنى ممكن ان تحقق متطلبات المواصفة المحلية، بينما استخدام غبار الفرن منفردا لا يحقق متطلبات المواصفات. كذلك خواص التحليل المايكروي لمختلف المواد المالئة يمكن ان تكون اداة فعالة في تفسير الاختلاف في خواص الخلطات الاسفلتية الحارة.

كلمات دلالية: غبار فرن السمنت ‘ الخلطات الاسفلتية الحارة‘ تقنيات التحليل المايكروي‘ غبث قشور الرز‘ سيلكافيوم

1. Introduction

Globally, several waste or by-product materials result from industrial processes, municipals services, and mining. Such waste or by-product materials reached to massive levels which bring a harmful impacts on human being life. Thus, significant attempts have been attained to minimize these materials impacts, especially on landfills. United Nations Environment Programme (UNEP) spent a high momentum on the reuse and recycle techniques, and flag it as a key strategy for more sustainable world [1]. Haas et al. [2] estimated the global recent recycled materials from waste by 4 gegatonnes per year, these materials represent about 6.5% of the total processed material in the global markets. However, part of such attempts have focused on reuse or recycle waste or by-product materials in construction processes; mainly because these processes consume a valuable amount of materials; e.g. recently asphalt mixture production touched the level of 650 million tonnes per year, about 17% is recycled from waste pavement materials [3].

Furthermore, to help easing landfill pressures, the use of waste or by-product materials as a replacement to primary materials, reduce the demand of extraction and processing of highway materials. In fact, this is an essential way of getting the paving industry on the rail of sustainable construction practices. Although it has been believed by wide range of paving specialists that it is more essential to focus on the lower pavement layers (which consume higher materials quantities) in replacement process, other researchers argued that the cost of transportation and processing of waste materials can only be justified in the use of surface paving layer [4].

In any case, partial or entire replacement of waste and by-product materials have added value characteristics to current paving industries. Where these replacements have been achieved either for coarse aggregate, fine aggregate or mineral filler. The most well-known coarse aggregate replacement have done with Reclaimed Asphalt Pavement (RAP). However, Zaumanis and Mallick [5] summarize the recent practices in utilizing RAP in HMA; they mentioned that 99% of the RAP is reused currently in the USA, where its percentage in the mix reached above 40% with comparative engineering properties to mix with virgin materials.

An example for fine aggregate replacement is the work achieved by Hassan [6], who proved that there is a high potential of resistance to moisture and ravelling of developed HMA when replacement 15 % of the fine aggregate of surface course layers, by the products of incineration of Municipal Solid Waste (MSW). Simultaneously, higher percentage, i.e. 20%, has proven for base course layer by the same research work. The advantages in mechanical properties performance of HMA comprising MSW over conventional HMA were confirmed also by Xue et al.[7].

Other research works were focused on mineral filler replacement. Sung Do et al. [8] suggested that the use of recycled waste lime which is a by-product of the production of soda ash ($Na2CO3$) as a replacement to conventional mineral filler of HMA. Their results demonstrated that HMA with such by-product materials explore superior improvement in stripping resistance and resistance to permanent deformation in high temperature in contrast to HMA comprised conventional filler. Superiority of fly ash, which is collected from thermal power plant, over the conventional mineral filler was proved by Sharma et al.[9]. Moreover, recycled brick powder [10],rice husk [11], coal waste [12], and Cement Kiln Dust [13] have been approved with the same superiority.

On the other hand, it has to said that Huang et al. [4] argued that it has to concern about use of Soild Waste Materials (SWM), such as waste glass, steel slag, tyres and plastics, due to the potential of producing environmental problems in road structures, such as run-off pollutants and leaching.

2. Research Aim and Scope

The current research work is aimed to investigate the potential of selective waste and by-product material as a filler for improving the mechanical and durability properties of HMA. These fillers include Cement Kiln Dust (CKD), Rice Husk Ash (RHA), and Silica Fume (SF). Although part of such materials were used individually through previous research works, it is the first time to use them collectively, as a filler in HMA, on the hope of increasing their validity by activate each other. However, to reach this aim, the attempt draw the following objectives:

- Investigating the efficiency of CKD as an entire replacement for OPC which used extensively to control the water sensitivity of local HMA
- Investigating the ability of SF to activate CKD to improve its validity as a filler for local HMA
- Investigating a cost alternative to SF with CKD, i.e. RHA.

3. Materials and Test Methods

3.1 Materials

Aggregates (course and fine) used in this research work were supplied from local Kerbala quarries. The materials properties requirements were compliance to the Standard Specification for Road and Bridge [14]. Tables (1 and 2) present the physical properties of coarse and fine aggregate used in this research work, respectively. The aggregates were sieved, separated and graded to compliance to the gradation required for surface layer according to the mentioned Iraqi specification. Simultaneously, asphalt binder was supplied from Al-Nasseria refinery, its properties are shown in Table (3).

Cement and Cement Kiln Dust were supplied from Karbala cement plant. Rice Husk Ash obtained from combustion of rice husk in the lab, then grinded and sieved on No. 200 sieve after burning. Silica Fume was a product of Conmix Company under trade name MegaAdd MS (D). Table (4) presents the chemical and physical properties of the mentioned filler materials according to the prevailing test methods.

Table 1: Physical Properties of Coarse Aggregates

Property	ASTM designation	Crushed Coarse agg.	SORB Requirement, (binder course)
Bulk specific gravity	C127	2.59	-
Apparent specific gravity	C127	2.63	-
Water absorption %	C127	1.32	-
Percent wear by los Angeles abrasion ,%	C131	7.2	35% Max
Soundness loss by sodium sulfate,%	C88	3.8	12% Max
Clay lumps,%	C142	0.03%	-
Flat and elongated particles,%	D4791	0.2%	10% Max
Passing sieve NO.200,%	C117	0.81%	-
Degree of crushing,%	---	99%	90% min

Table 2: Physical Properties of Fine Aggregates

Property	ASTM & AASHTO Designation	Fine agg.	SORB Specification for binder course
Bulk specific gravity	C128	2.65	-
Apparent specific gravity	C128	2.67	-
Water absorption,%	C128	0.4	-
Clay lumps , %	C142	1.8%	-
Passing sieve NO.200,%	C117	3.46%	-
Plasticity index, %	D 4318	NA	4% max
sand equivalent,	T 176	48%	45% min

Table 3: Properties of Asphalt Binder

Property	ASTM designation	Test results	SORB requirements
Penetration,100 gm. ,25°C,5sec (1/10 mm)	D5	43	40-50
Specific Gravity, 25°C (gm/cm3)	D70	1.03	-
Ductility, 25°C , 5 cm/min (cm)	D113	>100	>100
Flash point, (°C)	D92	323	>232
Softening point (°C)	D36	42	-
Solubility in trichloroethylene, (%)	D2042	99.4	>99
After Thin Film Oven test			
Penetration of Residue (%)	D 1754	67.4	>55
Ductility of Residue, (cm)		94	>25

Table 4: Chemical and Physical Properties of Fillers

Physical testing				
property	OPC	CKD	RHA	SF
Specific surface area (m^2/kg)	411	4850	5080	16430
Density (gm/cm^3)	2.987	2.556	2.24	2.170
Chemical testing (XRF)				
SiO2	24.911	17.011	91.892	94.765
Al2O3	2.327	3.653	0.831	0.432
Fe2O3	1.121	3.684	0.674	1.895
CaO	64.146	57.451	1.156	0.996
MgO	1.322	1.424	0.713	0.872
K2O	0.764	1.036	2.441	0.260
Na2O	1.713	0.143	0.012	0.889

3.2 Testing Methods

Microanalysis, mechanical, volumetric, and durability characteristics of the filler and designed HMAs are determined using the following testing methods:

1. **Scanning electron microscopy**: specimen of about 3 gm of each filler powder was mounted on specimen holder by adhesive film, then coated in gold to ensure high electron conductivity. Test conditions were performed with SEM resolution of 10 µm; high vacuum and test voltage 10-15 kV
2. **Chemical composition by XRF analysis:** specimen of about 10 gm of each filler powder was subjected to X-ray fluorescence spectrometer to determine the chemical compositions of the mentioned filler.
3. **Density and air voids:** three cylindrical specimens were prepared for each property, with 101.6 mm diameter x 63.5 mm height specimen, to determine bulk density according to ASTM D 2726 [15] and air void in total mix according to ASTM D 3203 [16].
4. **Resistance to plastic flow:** three cylindrical specimens were prepared for each property, with 101.6 mm diameter x 63.5 mm height, to determine Marshall stability and flow according to ASTM D 6927 [17]. results of this test is compared with the Iraqi specifications requirements.
5. **Indirect tensile strength:** three cylindrical specimens were prepared for each property, with 101.6 mm diameter x 63.5 mm height, to determine indirect tensile strength according to ASTM D 6931 [18].
6. **Index of retaining strength:** six cylindrical specimens were prepared for each property, with 101.6 mm diameter x 101.6 mm height, to determine retaining strength according to ASTM D

1075 [19]. Three specimens were conditioned and three left without conditioning. results of this test is compared with the Iraqi specifications requirements.

3.3 Test Plan

In order to evaluate the opportunity of using waste and/or by-product materials as a filler in HMA, firstly OPC was replaced in various ratios (25%, 50%, 75% and 100%) with CKD. Secondly, an attempt to activate CKD was achieved by replaced it in various ratios (7.5%, 15%, 22.5% and 30%) with SF, then with the same ratios with RHA; these replacement ratios base on the highest recommended ratio by previous research works [20-24]. Table 5 presents the test code of HMA for each mix ratio.

For each single aimed property three samples were prepared for testing according to the mentioned methods, except for retaining strength where six samples were prepared, three for conditioning and three for non-conditioning process. At the same time, density and air void were determined from prepared samples for the mentioned testing methods, and the average was adopted.

Table 5: Test Code of Prepared HMA

No.	Mix	The filler material percentages				Process aim
		OPC	CKD	SF	RHA	
1.	MO	100	0	0	0	OPC replacement by CKD
2.	MOC1	75	25	0	0	
3.	MOC2	50	50	0	0	
4.	MOC3	25	75	0	0	
5.	MC	0	100	0	0	
6.	MCS1	0	92.5	7.5	0	Activating the CKD by SF
7.	MCS2	0	85	15	0	
8.	MCS3	0	77.5	22.5	0	
9.	MCS4	0	70	30	0	
10.	MCR1	0	92.5	0	7.5	Activating the CKD by RHA
11.	MCR2	0	85	0	15	
12.	MCR3	0	77.5	0	22.5	
13.	MCR4	0	70	0	30	

MO (mix with OPC), MOC (mix with OPC and CKD), MC (mix with CKD), MCS (mix with CKD and SF), MCR (mix with CKD and RHA)

4. Results and Discussion

4.1 Microanalysis Testing Observations

Dry powder samples were prepared for SEM to observe the morphology and microstructure of different filler types, namely, OPC, CKD, SF and RHA. Scanning such fillers can yield a deeper insight into the possible effects of filler morphology and microstructure in HMA properties. Figure (1) shows the magnified prospective of the mentioned fillers. Additional, XRF analysis for the mentioned filler was conducted to determine the chemical composition elements; the results are shown in Table (4).

Form Figure (1-a) the OPC grains obviously can be described as angular shapes with sharp edges particles. Also, they looked flattened somehow and were gathered into a loosely plate-like structure, with more porous structure in comparative to other fillers. This is normal due to clinker grinding and crushing processes during cement manufacture.

CKD filler grains, Figure (1-b), also showed very less angular shapes and much smaller particles in contrast to OPC. Moreover, the grains were agglomerated in more compact clusters structure. The structure can also describe as porous structure. The less angular particle shape is reliable, as such powder is fly and escaped from the rotated kiln and no process of crashing or grinding were subjected to its particles.

On the other hand, SF morphology is almost spherical particles shape agglomerated in clusters, as can be seen in Figure (1-c). Oertel, et al. [25] suggested that during the producing of silicon metal or ferrosilicon at a temperature higher than 1000 °C in the electric arc furnace, the SF is formed as a by-product materials. During this process, SF particles are condensed and connected closely, accordingly, to clusters of several spheres by sintered joints through Si–O–Si bonds. In contrast, SF particles as can be shown in Figure (1-c) is the smallest among the selected filler in this research work.

Figure (1-d) shows the morphology and microstructure of RHA filler, where uneven particles shape can be recognized with non-angular edge. Also, there is high range of particle sizes. The biggest Particle look dense with high bulges on its outer surface. Moreover, its structure is porous with dissipated surface texture.

XRF analysis results, which illustrate in Table (4), demonstrate that both OPC and CKD are composed mainly (two third to half) from CaO with less composition of SiO_2, Al_2O_3, and Fe_2O_3. In contrast, SF and RHA is wholly composite from $SiO_{2,}$ with trace composition from other oxides. Accordingly, OPC and CKD is define as hydraulic materials where SF and RHA are defined as pozolanic materials. It is well-known by researchers that the specific quantities between the main said four oxides is after the activity of hydration process of the powder materials.

As a conclusion the high different in microanalysis properties of various filler used in this research works can be used to explain the variation in volumetric and mechanical properties of HMA. That will be a vital tool as will be shown hereafter.

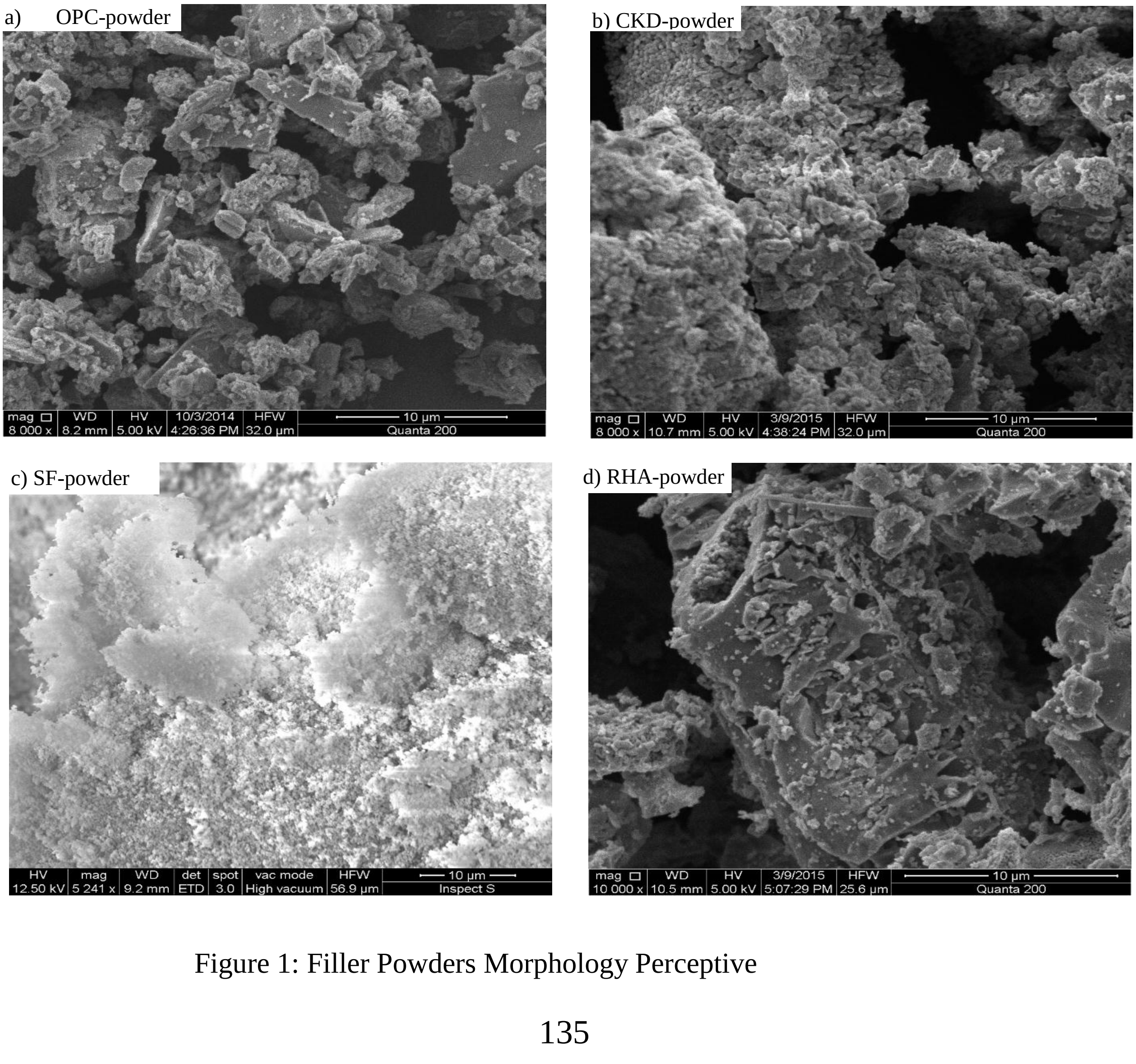

Figure 1: Filler Powders Morphology Perceptive

4.2 Volumetric Properties

The results of volumetric properties for the planned HMA are presented in Figures (2&3) for densities and air void, respectively, for various HMA with different filler compositions. As mentioned previously, the densities were determined according to ASTM D 2726, where air void was determined according to ASTM D 3203.

However, continuous replacement of OPC by CKD lead to continuous increase in densities and decrease in air void. As example, 50% replacement showed 0.9% increase in density and 9.21% decrease in air void. In fact, this is could be a result of different reasons. Firstly, the lowest density of CKD in contrast to OPC (as can see in Table (4)) provide higher quantities of smallest particles (as can see in Figure (1)) help in more compact mixture skeleton. Secondly, the angular shape particle of the OPC in contrast to CKD (as can see in Figure (1)) increase the viscosity of the asphalt mastic and dissipate the compaction effort.

Simultaneously, continuous partially replacement of CKD with SF, up to selected replacement percentage, i.e. 30%, demonstrate continuous increase in densities and decrease of air void of HMA. For example, 22.5% replacement of CKD by SF, resulted in 1.22% increase in density and 7.38 % drop in air void in contrast with HMA comprising CKD filler. It might be a result of incorporating very fine materials (as can see in Table (4) and Figure (1)) which occupied the tiny voids in the mixture skeleton. Furthermore, low density of SF in contrast to CKD (as can see in Table (4)) offers further particles in the mix.

The same trend is recognized when continuous replacement of CKD by RHA is achieved, but with less rate of increment in densities and decrease in air void. Microanalysis explanation can used here as well, where lower density of the RHA offers higher particle quantities in contrast to CKD, but the bigger particle in contrast to SF decrease the rate.

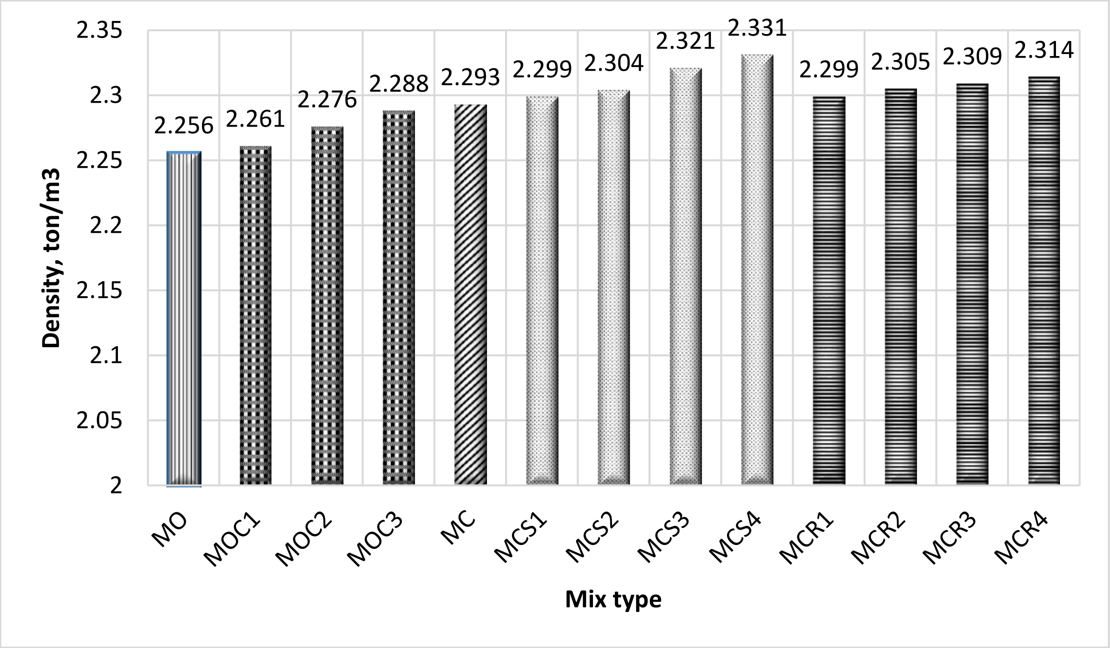

Figure 2: Comparison of Density for HMA Comprising Different Filler Compositions.

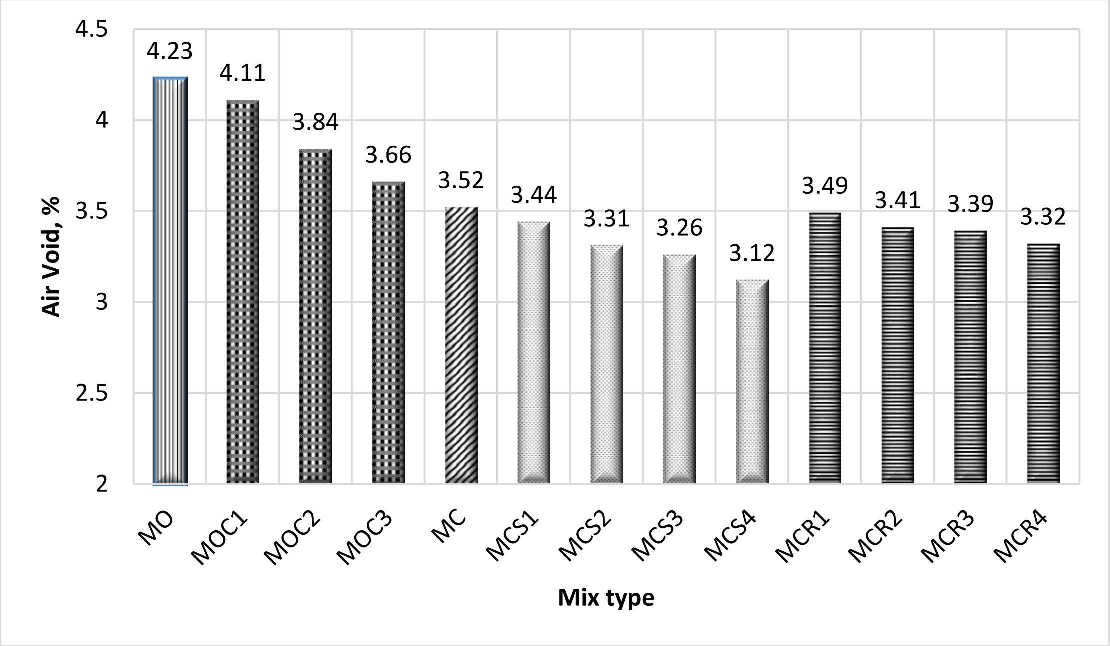

Figure 3: Comparison of Air Void for HMA Comprising Different Filler Compositions.

4.3 Marshall Stability and Flow

Marshall stability and flow of HMA comprising different filler compositions are demonstrated in Figures (4&5), respectively. Form these results, it can be said that all results satisfied the related requirements of Marshall stability and flow stated by Iraqi specifications [14].

However, continuous replacement of OPC by CKD resulted in continuous drop in Marshall stability (ranged from 2.78-20.36%) and increase in Marshall flow (ranged from 4.23-15.7%). This is could be a result of microstructure properties of OPC which provide an angular shape particles that facilitate better reinforcement of asphalt mastic. So, replacing these particle by less angular shape particles weakening the resistance to deformation of such mastic.

Results showed that the continuous replacement of CKD by SF (from 7.5% -30%) led to increase in Marshall stability (ranged from 3.08- 24.44%) and decrease in Marshall flow (ranged from 8.09-27.94%) in contrast with HMA comprising pure CKD. This might be a result of high surface area of fine particle of SF, which strengthen the asphalt mastic and improve the resistance to deformation.

On the other hand, continuous replacement of CKD by RHA (from 7.5% -30%) managed to rise in Marshall stability (ranged from 1.54- 17.56%) and decrease in Marshall flow (ranged from 5.74-18.53%) in contrast with HMA comprising pure CKD. The same explanation to what happened with SF can be adopted here; the different in surface area and particle size, of course, after the variations in results.

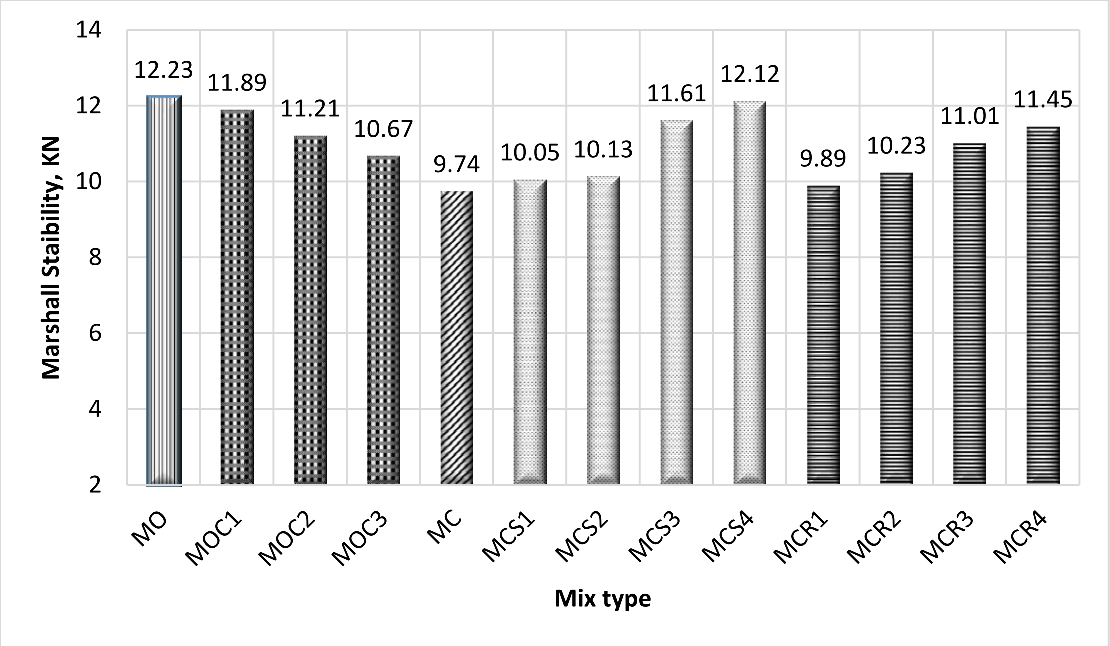

Figure 4: Comparison of Marshall Stability for HMA Comprising Different Filler Compositions.

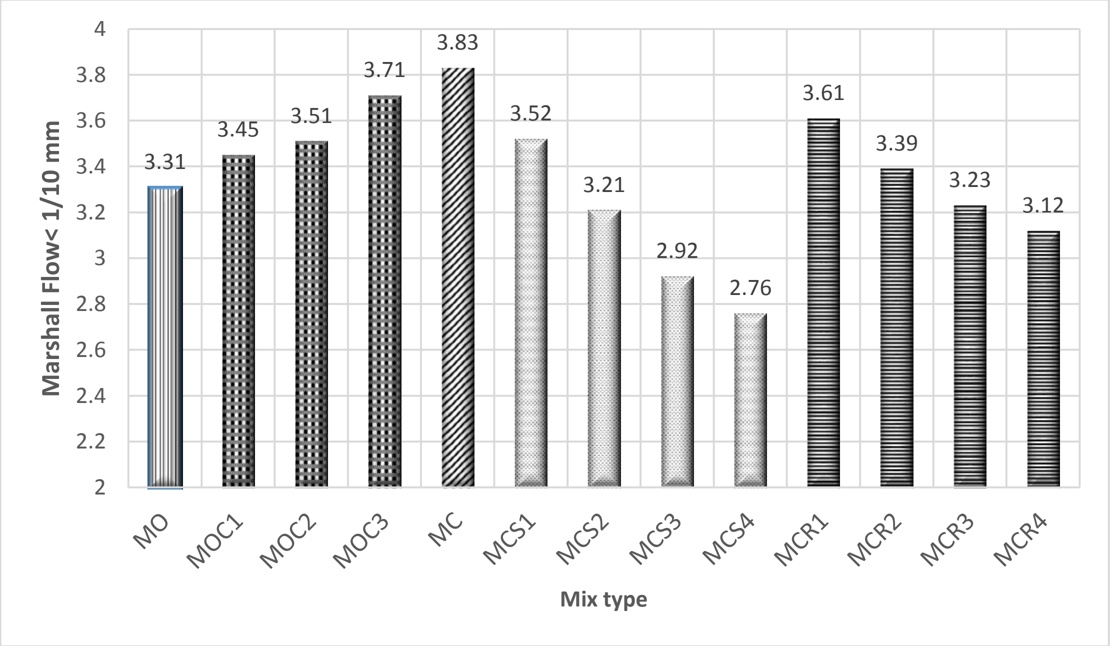

Figure 5: Comparison of Marshall Flow for HMA Comprising Different Filler Compositions.

4.4 Indirect Tensile Strength

Figure (6) presents the effect of filler types on Indirect Tensile Strength (ITS) of HMA. It is evident from this Figure that OPC has the superior value of ITS in comparison with other designed mixtures. When OPC is replaced by a range of CKD (25-100%), ITS values are dropped continually; the reduction ranged from 5.35-26.44 %. Similar to that when continuous partially replacement (from 7.5-30%) of CKD with SF and RHA, individually, continuous improvements can be recognized and it ranged from (7.27-35.27%) for different mixtures comprising SF, and (5.2-17.98%) for different mixtures comprising RHA. In fact, the same explanation for resistance to deformation which mentioned in the previous section can be adopted. In other word the physical properties of the filler plays the vital role in enhancing the mastic by reinforce it either by angularity of the particles and/or increase in the fine particles.

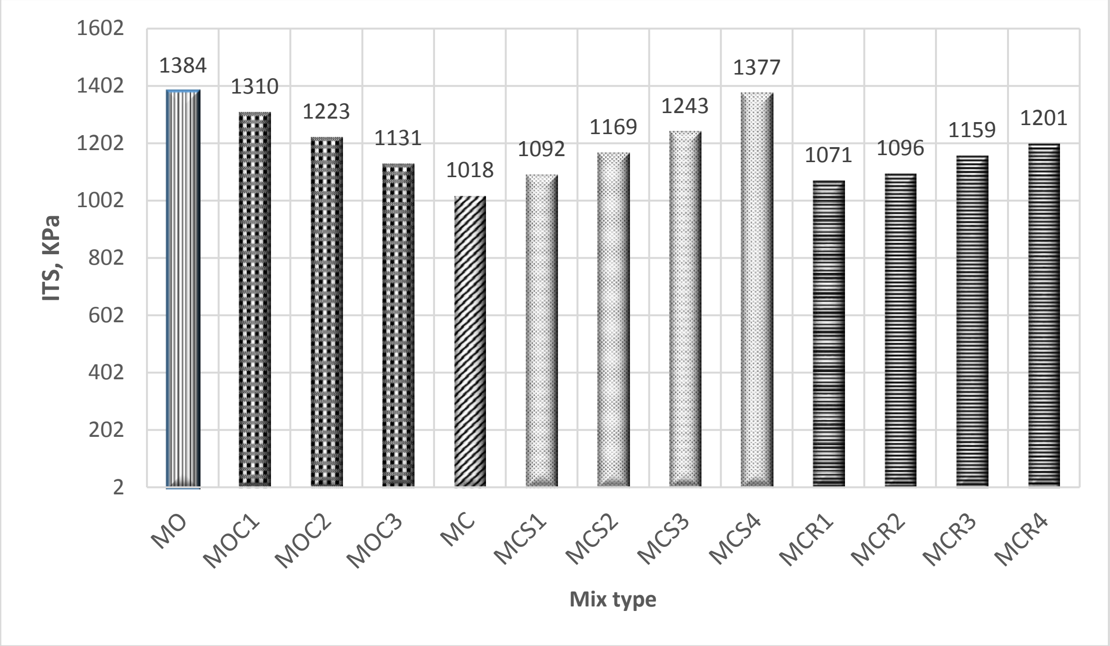

Figure 6: Comparison of Indirect Tensile Strength (ITS) for HMA Comprising Different Filler Compositions.

4.5 Water Sensitivity

Durability expressed in Index of Retaining Strength (IRS) for various designed mixtures are presents in Figure (7). The minimum value of this index is 70%, as stated by the valid Iraqi specifications [14]. Thus, this being the excuse for local agencies to use OPC to prevent stripping as local aggregate is entirely hydrophilic materials. Results showed that continuous replacement of OPC by CKD drop the IRS value to critical stages when 75% or more of OPC were replaced. In other words, the hydraulic properties of CKD is not enough to resist the stripping forces under specified condition of ASTM D 1075.

However, when SF being introduce with CKD, results showed at least 15% of the CKD should be replaced by SF to satisfy the specification requirements. While more than 22.5% (actually 27.5%) of RHA should be replaced with CKD to satisfy this requirement. Results confirm that both SF and RHA can activate CKD successfully within oily media; i.e. asphalt cement coated particles.

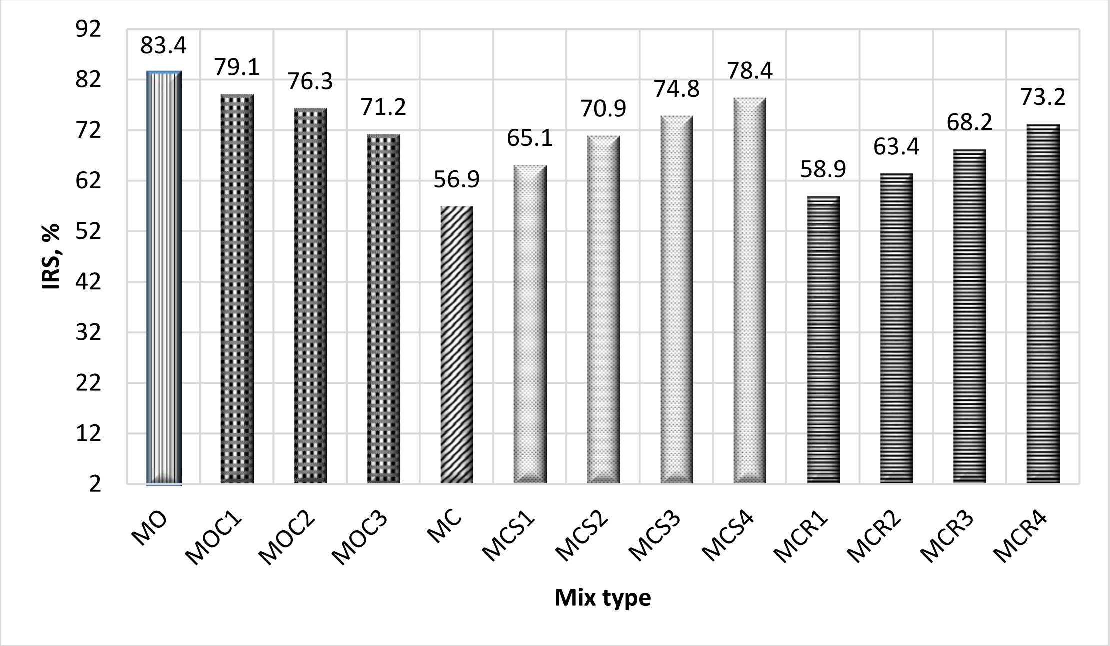

Figure 7: Comparison of Index of Retaining Strength (IRS) for HMA Comprising Different Filler Compositions.

5. Conclusions

The following can concluded from the results of this research work:

1. Physical and chemical properties of different filler types are reflected on volumetric and mechanical properties of HMA comprising such filler types.
2. Partial or total replacement of OPC with CKD in preparation of HMA are conserved the Marshall Stability and flow values within the specification requirements.
3. Although replacement of CKD can offer an acceptable engineering properties in term of Indirect Tensile Strength, Marshall Stability and flow, activators have to add with CKD to satisfy the durability requirements. However, minimum percentages of 15% and 27.5% are suggested for SF or RHA, respectively, where the rest percentage is CKD to touch the lower level of Index of Retaining Strength.
4. Utilising waste and/or by-product material in preparation of HMA could be a vital alternative to material has bring high impact on environment. Furthermore, more benefits could achieved in term of cost impact.
5. Microanalysis techniques could be useful tools to explain the variations in the volumetric and mechanical properties of HMA.

6. References

1. GEO5, Global Environmental Outlook 5-Environment for the future we want, I. 978-92-807-3177-4, Editor 2012: Nairobi:United Nations Environment Program.
2. Haas, W., et al., How Circular is the Global Economy?: An Assessment of Material Flows, Waste Production, and Recycling in the European Union and the World in 2005. Journal of Industrial Ecology, 2015. **19**(5): p. 765-777.
3. EAPA, ASPHALT IN FIGURES, 2015: EUROPEAN ASPHALT PAVEMENT ASSOCIATION, Brussels - Belgium.
4. Huang, Y., R.N. Bird, and O. Heidrich, A review of the use of recycled solid waste materials in asphalt pavements. Resources, Conservation and Recycling, 2007. **52**(1): p. 58-73.

5. Zaumanis, M. and R.B. Mallick, Review of very high-content reclaimed asphalt use in plant-produced pavements: state of the art. International Journal of Pavement Engineering, 2015. **16**(1): p. 39-55.
6. Hassan, H.F., Recycling of municipal solid waste incinerator ash in hot-mix asphalt concrete. Construction and Building Materials, 2005. **19**(2): p. 91-98.
7. Xue, Y., et al., Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: Pavement performance and environmental impact. Construction and Building +
8. Sung Do, H., P. Hee Mun, and R. Suk keun, A study on engineering characteristics of asphalt concrete using filler with recycled waste lime. Waste Management, 2008. **28**(1): p. 191-199.
9. Sharma, V., S. Chandra, and R. Choudhary, Characterization of Fly Ash Bituminous Concrete Mixes. Journal of Materials in Civil Engineering, 2010. **22**(12): p. 1209-1216.
10. Chen, M.-z., et al., Utilization of recycled brick powder as alternative filler in asphalt mixture. Construction and Building Materials, 2011. **25**(4): p. 1532-1536.
11. Sargın, Ş., et al., Evaluation of rice husk ash as filler in hot mix asphalt concrete. Construction and Building Materials, 2013. **48**: p. 390-397.
12. Modarres, A., M. Rahmanzadeh, and P. Ayar, Effect of coal waste powder in hot mix asphalt compared to conventional fillers: mix mechanical properties and environmental impacts. Journal of Cleaner Production, 2015. **91**: p. 262-268.
13. Modarres, A., H. Ramyar, and P. Ayar, Effect of cement kiln dust on the low-temperature durability and fatigue life of hot mix asphalt. Cold Regions Science and Technology, 2015. **110**: p. 59-66.
14. State Orgnization of Roads and Bridges, GENERAL SPECIFICATION FOR ROADS AND BRIDGES, 2003: Ministry of Housing and Construction, Iraq.
15. ASTM, Standard Test Method for Bulk Specific Gravity and Density of Non-Absorptive Compacted Bituminous Mixtures, 2005: D 2726, American Aociety for Testing Material, West Conshohocken, PA 19428-2959, United States.
16. ASTM, Standard Test Method for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures, 2005: D 3203, American Aociety for Testing Material, West Conshohocken, PA 19428-2959, United States.
17. ASTM, Standard Test Method for Marshall Stability and Flow of Bituminous Mixtures, 2005: D 6927, American Aociety for Testing Material, West Conshohocken, PA 19428-2959, United States.
18. ASTM, Standard Test Method for Indirect Tensile (IDT) Strength of Bituminous Mixtures, 2012: D 6927, American Aociety for Testing Material, West Conshohocken, PA 19428-2959, United States.
19. ASTM, Standard Test Method for Effect of Water on Compressive Strength of Compacted Bituminous Mixtures, 2011: D 1075, American Aociety for Testing Material, West Conshohocken, PA 19428-2959, United States.
20. Ismail, M.S. and A.M. Waliuddin, Effect of rice husk ash on high strength concrete. Construction and Building Materials, 1996. **10**(7): p. 521-526.
21. Roy, D.M., P. Arjunan, and M.R. Silsbee, Effect of silica fume, metakaolin, and low-calcium fly ash on chemical resistance of concrete. Cement and Concrete Research, 2001. **31**(12): p. 1809-1813.
22. Rodríguez de Sensale, G., Strength development of concrete with rice-husk ash. Cement and Concrete Composites, 2006. **28**(2): p. 158-160.
23. Gastaldini, A.L.G., et al., Chloride penetration and carbonation in concrete with rice husk ash and chemical activators. Cement and Concrete Composites, 2007. **29**(3): p. 176-180.
24. Jo, B.-W., et al., Characteristics of cement mortar with nano-SiO2 particles. Construction and Building Materials, 2007. **21**(6): p. 1351-1355.
25. Oertel, T., et al., Primary particle size and agglomerate size effects of amorphous silica in ultra-high performance concrete. Cement and Concrete Composites, 2013. **37**: p. 61-67.