University of Baghdad
College of Engineering

Journal of Engineering

journal homepage: www.joe.uobaghdad.edu.iq

Volume 30 Number 1 January 2024

Evaluating the Moisture Susceptibility of Asphalt Mixtures Containing Aluminum Dross as a Filler

Sarah K. Ugla[1,*], Mohammed Q. Ismael[2]

Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
Sara.ugla2101m@coeng.uobaghdad.edu.iq[1],drmohammedismael@coeng.uobaghdad.edu.iq[2]

ABSTRACT

One of the most essential components of asphalt pavements is the filler. It serves two purposes. First, this fine-grained material (diameter less than 0.075 mm) improves the cohesiveness of aggregate with bitumen. Second, produce a dense mixture by filling the voids between the particles. Aluminum dross (AD), which is a by-product of Aluminum re-melting, is formed all over the world. This material causes damage to humans and the environment; stockpiling AD in landfills is not the best solution. This research studies the possibility of replacing part of the conventional filler with Aluminum dross. Three percent of dross was used, 10, 20, and 30% by filler weight. The MarshallMix design method was adopted to obtain the optimum asphalt content for the selected aggregate gradation. After that, the mixture was used to evaluate the moisture damage for controlandimproved mixtures. The compressive strength and tensile strength tests were used to estimate the moisture damage to the asphalt mixtures. It was observed that replacing a part of the limestone dust filler with Aluminum dross would improve moisture damage resistance. This was approved since the maximum increase in tensile strength ratio (TSR)was found to be 13.42% at 20% of AD, and the maximum increase in the index of retained strength (IRS)was found to be 8.73% at the same AD percent.

Keywords: Moisture Susceptibility, Aluminum Dross, Marshall Mix, Compressive Strength, Indirect Tensile Strength.

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2024.01.12

Article received: 22/04/2023
Article accepted: 21/10/2023
Article published: 01/01/2024

تقييم تحسس الرطوبة للخلطات الاسفلتية المحتوية على خبث الالمنيوم كمادة مالئة

سارة خالد عكلة[1,*]، محمد قادر اسماعيل[2]

قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

احد المكونات الاساسية في الخلطات الاسفلتية هو المادة المالئة. فهو مهم من ناحيتين: الاولى، يحسن قوة التماسك بين الركام والاسفلت. والثانية، يعمل على انتاج خلطة اسفلتية كثيفة قليلة الفراغات الهوائية، فالمادة المالئة تعمل على ملئ تلك الفراغات لتقليل تأثر الخلطة بضرر الرطوبة.خبث الالمنيوم الذي هو مادة عرضية ناتجة من اعادة صهر الالمنيوم ينتج بكثرة كل سنة، ان تراكم هذه المادة يسبب ضرر للانسان والبيئة. في هذا البحث تم دراسة امكانية استبدال جزء من المادة المالئة التقليدية المستخدمة في الخلطات الاسفلتية بمادة خبث الالمنيوم وتم استخدام ثلاث نسب 10، 20، 30% من وزن المادة المالئة. استخدمت طريقة مارشال لايجاد نسبة الاسفلت المثلى وبعد ذلك اجريت فحوص لتقييم تحسس الرطوبة للخلطة التقليدية والمعدلة, اختير فحص مؤشر الانضغاط و نسبة الشد غير المباشر لتقييم تحسس الرطوبة.وجد ان استبدال غبار حجر الكلس بخبث الالمنيوم يحسن من مقاومة الخلطة للرطوبة وقد تم اعتماد هذا الاستنتاج بسبب زيادة نسبة قوة الشد غير المباشر بمقدار 13.24% عن الخلطة المرجعية عند نسبة حبث المنيوم 20%. كذلك زيادة نسبة مقاومة الانضغاط بمقدار 8.73 % عن الخلطة المرجعية عند نفس النسبة لخبث الالمنيوم.

الكلمات المفتاحية: تحسس الرطوبة، خبث الالمنيوم، خلطة مارشال، مقاومة الانضغاط، مقاومة الشد غير المباشر.

1. INTRODUCTION

One of the primary causes of asphalt concrete (AC) pavement deterioration is moisture susceptibility, which reduces the durability of AC pavements. The combined effect of aggregate gradation and asphalt on moisture susceptibility is important to avoid and decrease premature failures of AC **(Maqbool et al., 2022).**In the presence of water, a loss of adhesion between the asphalt cement and the aggregate surface and a loss of cohesiveness within the binder can produce advanced deterioration in the durability of the asphalt pavement **(Nazal and Ismael, 2019).** Various additives, such as fibers, are used in asphalt mixtures to improve moisture damage resistance. (**Ismael and Mohammed, 2021)** modified the moisture susceptibility of warm mix asphalt (WMA) by employing 2, 4, and 6% polypropylene as a percent of asphalt cement in the control mixture (WMA). According to the TSR and IRS values, adding polypropylene fibers to the asphalt mixture increased its moisture resistance. **(Hamedi, 2017)** used alumina as a nanomaterial to modify the hot mix asphalt for moisture damage, and the followings were noticed:

- The addition of nanoparticles increased the value of TSR in tensile strength testing samples.

- The use of alumina nanoparticles reduced the debonding energy in the modified materials. This increases the thermodynamic stability of the asphalt binder-aggregate system and reduces the severity of stripping.
- The improved specimens had higher adhesion-free energy compared to the control specimens.

A different form of alumina waste was utilized by (**Ismael et al., 2022).** Alumina waste (Al) was added as a reinforcing agent at a percentage of 1–3% of the mixture's total weight, containing recycled concrete aggregate as coarse aggregate. Al improved the rutting resistance at all dosages but was at its best at 2% Al, which reduced rutting depth by 26%. This percentage also resulted in a 30% rise in the index of plastic deformation, a 16% increase in the resilient modulus, and a 23% increase in the flow number. The effect of different types of mineral filler on asphalt mixtures was studied by (**Sutradhar et al., 2015; Gürer and Selman, 2016; Wasilewska et al., 2017).**

During the Aluminum production process, a large amount of waste known as dross is created, which is used to recycle and re-extract residual Aluminum. Because dross has been discovered to be a hazardous waste for the environment, recycling or locking up this waste is necessary **(Satish and Neeraja, 2018).**

Currently, Aluminum dross is picked up in rotating kilns to extract the metal, and the resulting salt cake is transported to dumps, where it is covered to prevent leaching but still represents a threat to the environment due to the presence of fluorides and other salts. In addition, much energy is consumed in separating the Al from the dross; if the dross could be reused as a structural material in such a way, that energy might be saved **(Dai, 2012).**

The extraction of primary Aluminum dross produces a solid byproduct known as secondary Aluminum dross (SAD). SAD is composed of between 40 and 60 percent alumina, 10 to 30 percent Aluminum nitride, 5 to 15 percent salts, and other constituents. Salts contain sodium chloride, potassium chloride, and fluoride salts. The SAD is valued both as a resource and as a contaminant. SAD waste disposal in landfills demands a significant amount of space, results in the loss of a considerable amount of resources, and has a significant adverse impact on the environment **(Shen et al., 2021).**

(López et al., 2019) investigated the mechanical performance of RCA mixed with alumina wastes and compare it to that of artificial gravel. A trial section of the roadway was constructed to evaluate the road's performance under traffic conditions. After 28 days, the combined RCA/alumina mixture utilized in this investigation demonstrated a better load capacity (CBR = 105).

(Diab and Enieb, 2018) focused their research on understanding the mechanics of mineral fillers in the asphalt mixture and mastic scale. To better understand the possible processes between asphalt binder and mineral filler, researchers examined the physical properties of asphalt mixtures and mastics and performed a chemical analysis of the mastic scale. The asphalt binder was mixed with varying amounts of three different mineral fillers: hydrated lime, limestone dust, and cement bypass dust. This research shows that the type and amount of filler are crucial criteria throughout mix design to ensure the mixture's performance in field conditions because of the effect of mineral filler on the qualities of the asphalt mixture and mastic.

The possibility of using dross as a filler was studied by **(Udvardi et al., 2019).** The experimental results showed that Aluminum dross was a more sophisticated substance than the reference mineral filler based on its chemical composition. The particle size distribution of fillers is similar, but limestone powder includes finer particles, resulting in a greater specific surface area. According to the morphological tests, these fillers are suitable for asphalt mixtures.

(Busari et al., 2021) evaluated the modified engineering properties of a modified asphalt mixture using Aluminum dross as a filler. Three percent of dross was used, 10, 20, and 30% by the weight of the mixture. The results showed increased stability from the control mix when using 10 and 20% dross. The improved adhesion in the mixture may be responsible for the increased stability. Furthermore, using Aluminum dross is useful in surface course construction to decrease solid waste.

Asphalt-wearing course mixes with a nominal aggregate size of 11mm was prepared by (**Toth, 2017)** to evaluate the filler composition's impact with the same aggregate gradation, binder grade, and content. Basic performance tests were conducted to evaluate the possible performance of the asphalt mix after replacing limestone filler with dross. Limestone's stiffening impact is more significant at low temperatures (low frequencies) and decreases at high temperatures, which is an interesting result that permits further study. Substituting dross for limestone filler raises the asphalt mix's stiffness and phase angle. A reasonable option for future research is to use 50% of the filler; in other words, only a part of the filler is replaced with dross.

The main objective of this work is to develop a sustainable asphalt mixture that is less expensive than conventional asphalt mixtures and to eliminate waste materials that threaten landfill capacity and harm the environment. These waste materials were intended to improve the HMA's properties. SAD was used as a partial replacement for the conventional filler (limestone dust), and RCA was used as a partial replacement for coarse aggregate.

2. MATERIALS

All materials used are available locally and have been tested to comply with the Iraqi Specification for Roads and Bridges(SCRB) requirements.

2.1 Asphalt Cement

The 40/50 grade asphalt cement is used since its viscosity suits the Iraqi hot climate. It was supplied by the Al-Durra refinery in Baghdad city. The physical properties of asphalt cement following the Iraqi specification requirements **(SCRB R/9, 2003)** are given in **Table 1**.

Table 1. Asphalt cement properties

Test	Unit	ASTM	Value	SCRB
Penetration@ 25 ^{o}C	0.1 mm	D-5	46	40-50
SofteningPoint	°C	D-36	54	-
Ductility@ 25 ^{o}C	cm	D-113	130	>100
Rotational Viscosity @ 135 ^{o}C	Pa.s	D-4402	0.612	-
After the Film Oven Test		D-1754		
Retained Penetration@ 25 ^{o}C	%	D-5	61	>55
Retained Ductility@ 25 ^{o}C	%	D-113	75	>25

2.2 Aggregates

The crushed coarse and fine aggregate supplied from the AL-Nibaai quarry north of Baghdad was used. The sizes of coarse aggregate rangedbetween1/2`(12.5 mm) and No.4 sieve (4.75 mm) for the course, and the size of fine aggregate ranged between No.4 sieve (4.75 mm) and No.200 sieve (0.075 mm). Physical tests are accomplished on aggregate to characterize its properties, and the test results are given in **Table 2**. Aggregate gradation for the asphalt mixture was selected to meet the surface course's Iraqi specifications (SCRB R/9,2003). **Fig. 1** shows the aggregate gradation.

Table 2. Properties of coarse and fine aggregate.

Test	ASTM	Value	SCRB
Bulk Specific Gravity	C-127	2.63	-
Water Absorption, (%)	C-127	0.52	-
Percent Wear by Los Angeles Abrasion, (%)	C-131	19	30 max
Soundness Loss by Sodium Sulfate Solution, (%)	C-88	1.5	12 max
Fractured Pieces, (%)	D-5821	98	90 min
Fine Aggregate			
Bulk Specific Gravity	C-128	2.54	-
Water Absorption, (%)	C-128	0.81	-

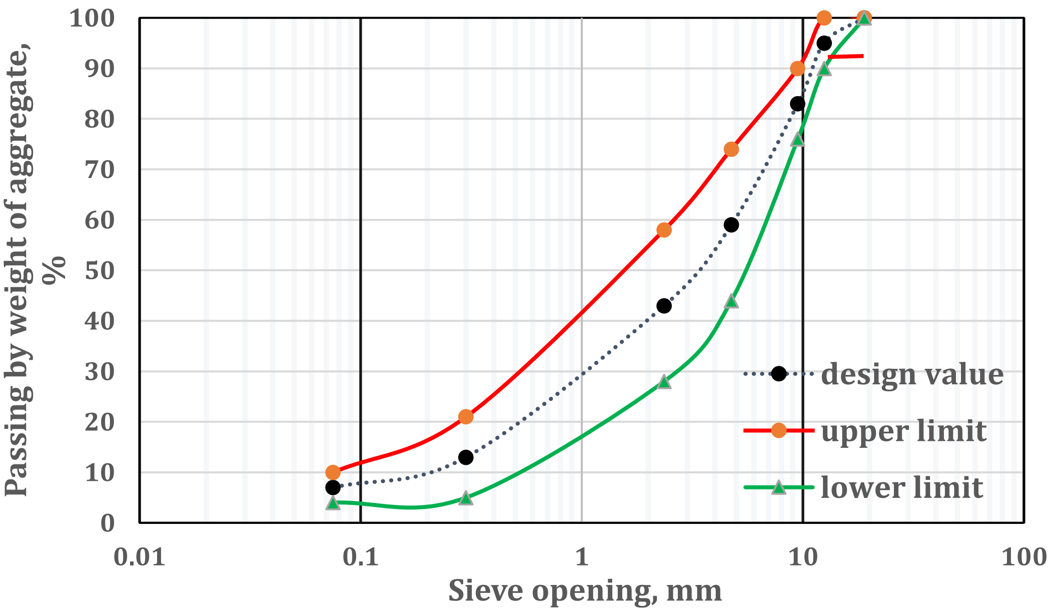

Figure 1. Gradation of combined aggregate.

2.3 Filler

The limestone dust from Amant-Baghdad is used as mineral filler, which is dry and clear from clay, lumps, and aggregation of dust and shavings. The filler was tested.

According to **(SCRB R/9, 2003),** the results are shown in **Table 3.** AD is used as a potential Asphalt filler from an open dumped site north of Baghdad. **Fig. 2** shows the Aluminum dross source.

Table 3. Limestone dust properties.

Property	Value	ASTM	SCRB
% Passing Sieve no.200	90	-	70% min
Specific Gravity	2.71	C-188	-

Figure 2. Aluminum dross.

Fig. 3 shows Aluminum dross filler, and **Fig. 4** shows the microstructure of filler as obtained by scanning electron microscopy (SEM). It is obvious that all particles have a diameter of less than 75 μm. Dross was subjected to the same testing as virgin filler. The test results for Aluminum dross are displayed in **Table 4**. Both fillers were sieved on No.200 (0.075m). The results of X-ray diffraction (XRD) test for compounds and phases performed on a collection of powdered dross for a range of particle sizes are given in **Table 5**.

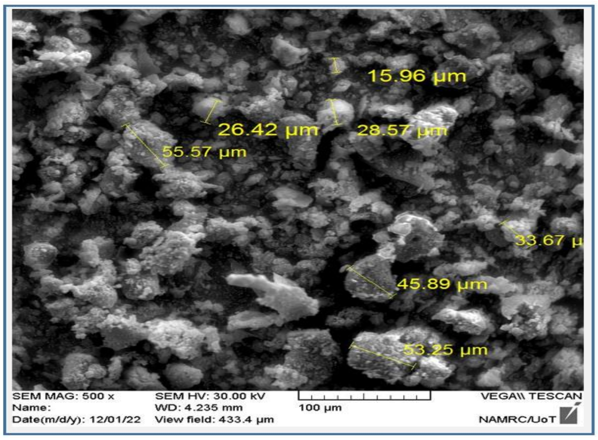

Figure 3. Aluminum dross filler. **Figure 4.** SEM image for Aluminum dross.

Table 4. Aluminum dross properties.

Property	Value	ASTM	SCRB
%Passing Sieve no.200	90	-	70% min
Specific Gravity	2.8	C-188	-

Table 5. Oxides concentration in Aluminum dross.

Elements (Oxide of)	Concentration (Wt. %)	Elements (Oxide of)	Concentration (Wt. %)	Elements (Oxide of)	Concentration (Wt. %)
Magnesium	7.312	Calcium	8.090	Phosphorus	0.190
Aluminum	60.250	Manganese	0.390	Lead	0.315
Silicon	6.552	Sodium	1.849	Barium	0.172
Sulfur	3.640	Copper	0.774	Iron	2.770
Chlorine	0.709	Titanium	0.587	Zinc	0.720
Potassium	0.400	Manganese	0.394		

3. EXPERIMENTAL WORK

The Marshall test was used first to determine the optimal asphalt content for asphalt cement **(Chelovian and Shafabakhsh, 2017; Abdi Kordani et al., 2021; Al-Saad and Ismael, 2022).** The Tensile Strength Ratio and the Index of Retained Strength were determined to estimate the asphalt mixture resistance to moisture damage. The indirect tensile and compressive strength tests were employed to determine these parameters.

3.1 Marshall Mix Design

The Marshall Design method was employed to obtain the OAC. (4-6)% asphalt cement percent applied according to (SCRB, R/9 2003). The test method described in (ASTM D6926) was adopted to prepare the cylindrical specimens, and after compaction was complete, the mold was transferred to a level surface and left to cool at room temperature for 20 hr before being taken. Three identical specimens with a height of 63.5mm and a diameter of 101.6 mm were prepared for the control mix and each percent of the Aluminum dross-modified mixture. After the specimen cooled, it was extracted from the mold. Then, the density of each specimen was determined as described in **(ASTM D2726, 2002).** After that, the specimen was conditioned for testing by placing it in a 60°C water bath for 30 min., as recommended in **(ASTM D6927, 2015)**. The guide rod was lubricated during this period, and the testing head was cleaned. The test's loading movement rate should be 2 ± 0.15 in/min (50 ± 5 mm/min). Finally, remove the testing sample from the water bath and remove the excess water with a towel, then place it in the Marshall Device immediately and record stability and flow readings. **Fig. 5** shows the Marshall Test specimen and device based on stability, flow, density, and air voids. The O.A.C. are obtained as shown in **Fig. 6.** The results of OAC are tabulated in **Table 6.**

Table 6. Marshall test results.

O.A.C (%)	Stability (kN)	Flow (mm)	Bulk density (gm/cm^3)	Airvoids (%)	V.M.A (%)	V.F.A (%)
4.9	9.22	2.58	2.323	4.01	15.59	74.28
SCRB (R/9) specification for surface coarse						
4-6	8 min	2-4	-	3-5	14min	-

Figure 5. Marshall stability and flow test.

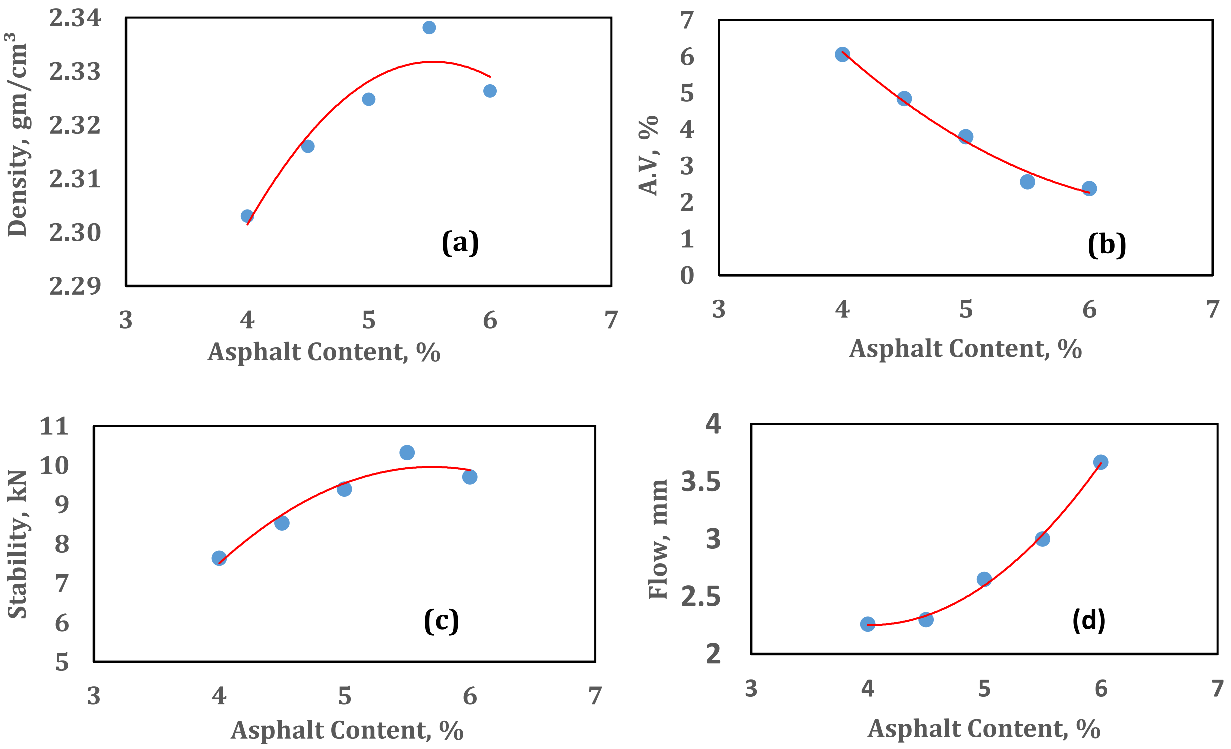

Figure 6. Change of Marshall properties for control mix with AC
a) Bulk density, **b)** Air voids, **c)** Stability, **d)** flow.

3.2 Indirect Tensile Strength

The test was utilized to evaluate the mixes' moisture damage resistance according to **(ASTM D6931, 2012)**. Before preparation of the specimen, the number of blows that produce 7% ±1 air voids were calculated, and the results are shown in **Fig. 7**. After that, the specimens were prepared and tested following the test method described in **(ASTM D4867, 2012)**. The tensile strength ratio is the average tensile strength for conditioned samples to the average tensile strength for unconditioned samples **(Ismael and Ahmed, 2019; Xiao et al., 2019).**

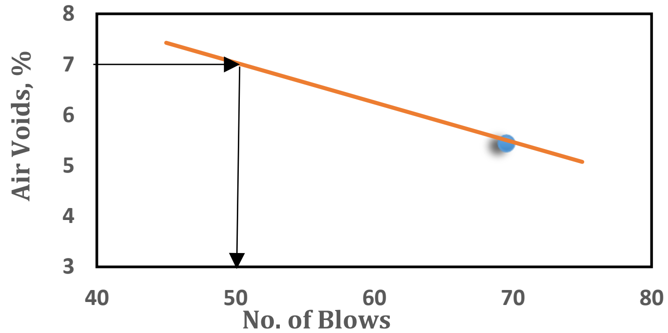

Figure 7. The relationship between No. of blows and the air voids percent.

$$I.T.S = \frac{2p}{\pi\ D\ t} \quad (1)$$

$$T.S.R = \frac{I.T.S\ \ c}{I.T.S\ \ u} \quad (2)$$

where:
I.T.S is indirect tensile strength, kPa
P is the ultimate applied load, N
D is the diameter of the specimen, mm
t is the thickness of the specimen, mm
I.T.Sc is indirect tensile strength for conditioned specimen, kPa.
*I.T.Su*is indirect tensile strength for unconditioned specimen, kPa
These specimens’ data are compared to determine the effect of the unconditioned and the conditioned mixes on mixture performance. **Fig. 8** describes the indirect tensile strength test steps.

Figure 8. The indirect tensile strength test.

3.3 Compressive Strength Test

The index of retained strength (IRS) has been utilized to evaluate a mixture's resistance to moisture damage. According to **(SCRB, 2007),** the minimum permissible value of the Index of Retained Strength is (70%), so mixtures with a lower IRS are more susceptible to moisture damage. This test was accompanied according to **(ASTM D1074, 1996)**. The prepared mixture is compacted by using a compressive device. Samples of 101.6 mm and a diameter of 101.6mm were prepared**(Ismael and Ismael, 2019; Raof and Ismael, 2019; Mawat and Ismael, 2020).**The specimens were cooled for24 hours before being tested for compressive strength at a rate of loading of 5.08 mm/min. The specimens were then positioned vertically such that the axial force could be applied to the specimen's initial surface untilit failed as described in **(Ismael and Khaled, 2019)**.The compressive strength test specimens are shown in **Fig. 9.**

Figure 9. Compressive strength test specimens.

4. TEST RESULTS

4.1 MarshallTest

The replacement of limestone dust in the asphalt mixture with Aluminum dross for the utilized dosage increased Marshall´sstability by (9.76, 24.18, and 21.8%), respectively. The largest increase in stability was observed at 20% dross content. This increase wascomplemented by a decrease in flowvalues of (4.65, 8.52, and 11.24%). The percent of voids in asphaltmixtures increases somewhat with the supplement of AD. The bulk density of asphalt mixtures containingAluminum drossfallsomewhat as the dross content increased. The rationale for these performances can be explained by the statement that the replacement of limestone dust with Aluminum drossincrease the asphalt absorption, resulting in anincreasein the volume of voids. The increasein percentage of the airvoid result in a decrease in the bulk density. The addition of AD increases the adhesion between aggregates andbitumen,causing anoticeablerising in Marshallstability. The test results are collected in **Table 7** and shown in **Fig. 10.**

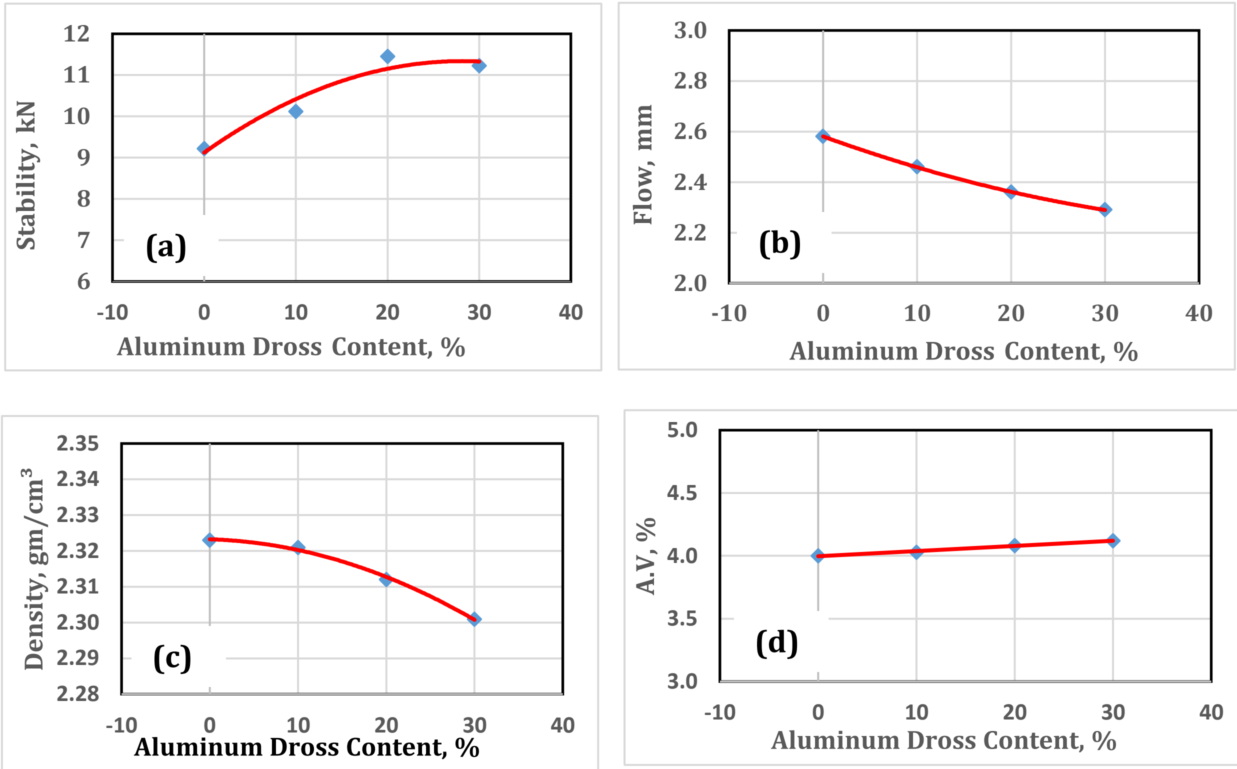

Figure 10. Effect of Aluminum dross on Marshall properties
a) Stability, **b)** Flow, **c**) Density, **d)** Air voids

Table 7. The effect of Aluminumdross on Marshall properties.

Dross (%)	O.A.C(%)	Stability (kN)	Flow (mm)	Density (g/cm^3)	A.V (%)	V.M.A (%)	V.F.A (%)
0	4.9	9.22	2.58	2.323	4.00	15.59	74.27
10		10.12	2.46	2.325	4.03	15.39	74.25
20		11.45	2.36	2.328	4.08	15.17	74.06
30		11.23	2.29	2.331	4.12	14.98	74.01

4.2 Tensile Strength Ratio

The replacement of a specific proportion of limestone dust with Aluminum dross in the asphaltmixtures improved dry and wet tensilestrength values together. As a result, T.S.R values increased, with the largest increase in the tensilestrength ratio occurring at 20% AD percent. The T.S.R value increased by 13.43% as compared to the control mix. This upgrade in moisturedamage resistance could be attributed to the increase in adhesionbetween the binder and the aggregate because Aluminum dross is a more complex material that strengthens the connection betweenthe aggregate surface and the asphaltcement film. **Table 8** and **Fig. 11** contain all of the necessary information for this test.

Table 8. The indirect tensile strength ratio results**.**

dross (%)	Dry I.T.S (kPa)	Wet I.T.S (kPa)	T.S.R (%)
0	1481.06	1194.15	80.63
10	1639.27	1371.74	83.68
20	1722.25	1575.08	91.45
30	1687.98	1519.66	90.03

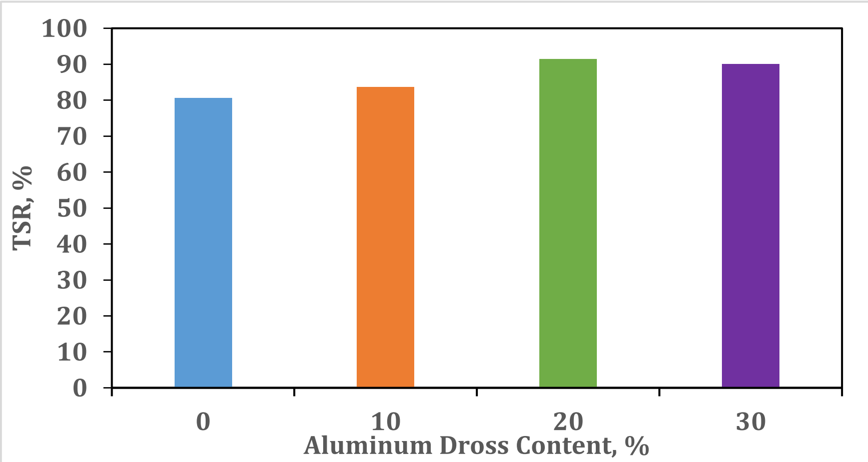

Figure 11. The effect of Aluminum dross on TSR.

4.3 Index of Retained Strength

With the same rising trend as the tensile strength ratio, replacing limestone dust with Aluminum dross in the asphalt mixture preparation improves the dry and wet compressive strength values. As a result, the magnitude of the Index of Retained Strength was also increased by 20% as best obtained results. The largest increase in I.R.S value above the control mix was 8.73%. The justification for this improved behavior is identical to the prior clarification. The test results are stated in **Table 9** and visually explained in **Fig. 12**.

Table 9. Compressive strength test results.

Dross (%)	Dry Compressive Strength (kPa)	Wet CompressiveStrength (kPa)	I.R.S (%)
0	5491.33	4343.40	79.10
10	6179.60	5205.17	84.23
20	8044.58	6918.44	86.00
30	7783.09	6575.54	84.48

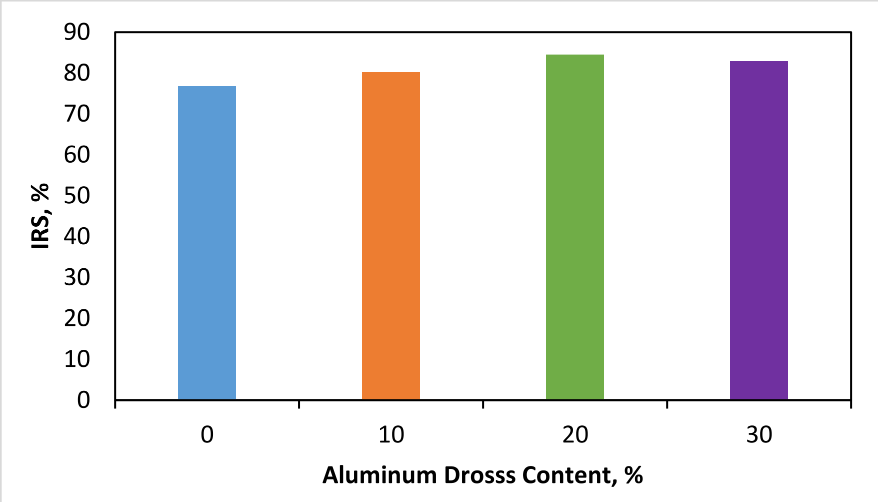

Figure 12. The effect of Aluminum dross on IRS.

5. STATISTICAL MODELLING

The model was built using the Statistical Package for the Social Sciences (SPSS) computer software version 26. This work uses the regression equation as the statistical prediction model. It represents the predictable changes in the response variable (dependent variable) as a function of the other variables (independent variables).

Before beginning the regression equation, the outliers and significant observations are examined using the (1.5 * IQR) criteria. The Kolmogorov-Smirnov test is then used to determine whether the variables are normally distributed. After the linear regression criteria were satisfied, the linear regression model was created using the inter technique, and all variables were included in the regression equation.

The dependent variables include compressive strength and tensile strength, while the independent variables are dross content%, stability%, and A.V%.

Table 10 shows the detailed of regression equation details.It is obvious that the increasing in stability and dross percent have a positive effect on both the compressive strength and the tensile strength while the increasing in air void percent has a negative effect on both dependent variables. **Fig. 13** shows the regression plot.

Table 10. The results of the final model.

Enter Regression Model 1	R^2	Adjusted R^2	Std.E.E
T. S = 1886.9 +2.4 dross% -131.5A.V%+ 60.8 Stability	0.928	0.861	47.961
Enter Regression Model 2	R^2	Adjusted R^2	Std.E.E
C. S =11982.7 +55.7 dross% - 1651.7 A.V% +373.1 Stability	0.993	0.987	150.49

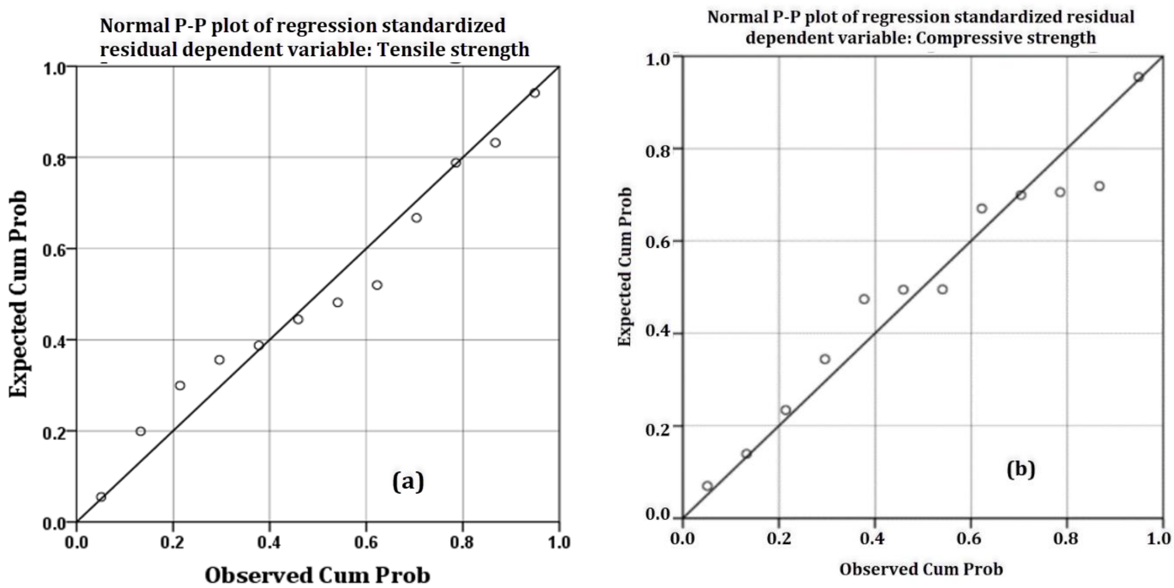

Figure 13. Regression model for: a) Tensile strength, b) Compressive strength.

6. CONCLUSIONS

This study adopted indirect tensile strength and compressive strength tests to evaluate the moisture damage resistance of the hot mix asphalt. The Marshall mix design method was also used, and from the experimental work, the following was concluded:

- The replacement of Aluminum dross with limestone dust by three percentages (10, 20, and 30) by the weight of filler obtained an optimum content of 20%. This amount improved the Marshal´sstability by 24.7%.
- Aluminum dross decreases Marshall flow; the maximum decrease is 17.8%, which takes place at 30% of AD, and the high absorption of Aluminum dross can explain this.
- The replacement of limestone dust with Aluminum dross slightly increases the air voids in asphalt mixtures. The highest increment value marked by 2.02% for 30% AD percent.
- Aluminum dross significantly raised the tensile strength ratio values. The best results were obtained with an Aluminum dross content of 20%. On this percent, the T.S.Rvalues for the modified mixtures were above the controlmixtures by 13.43%.
- By replacing limestone dust with Aluminum dross in the asphalt mixtures, the index of retained strength value increased. With a 20% lime percentage, the rise in I.R.Svalue over the control mix was 8.73%.
- From the results of tensile strength test and compressive strength test the following equation was built using SPSS software:

$$T.S = 1886.9 + 2.4 dross\% - 131.5 A.V\% + 60.8\ Stability \quad (3)$$

$$C.S = 11982.7 + 55.7\ dross\% - 1651.7\ A.V\% + 373.1\ Stability \quad (4)$$

NOMENCLATURE

Symbol	Description	Symbol	Description
AC	Asphalt concrete	HMA	Hot mix asphalt
AD	Aluminum dross	ITS	Indirect tensile strength
ASTM	American Society for testing and material	IRS	Index of retained strength
		P	Ultimate load failure
AV	Air voids, %	RCA	Recycled concrete aggregate
CBR	California bearing ratio	SAD	Secondary Aluminum dross
d	Particle diameter	T	Thickness of specimen
D	Diameter of specimen, mm	TSR	Tensile strength ratio

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