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The Effect of Adding Recycled Concrete Aggregates on Asphalt Mixture Modified with Tire Rubber Crumbs - An Experimental and Numerical Study

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Abstract

The accumulation of huge amounts of rubble and the worn-out tires that resulted from the severe damage to Syrian facilities because of the current war in Syria poses a serious environmental problem. In this research, therefore, asphalt mixtures containing recycled concrete aggregates and an asphalt binder modified with tire rubber crumbs were designed. It also determines the loading cycles until failure on fatigue and rutting of these mixtures by following numerical modeling and using the 3D-Move Analysis program. The results showed an increase in the optimal asphalt ratio, the proportion of air voids and flow with the increase in the proportion of recycled concrete aggregates in the asphalt mixture. Contrastingly, it showed a decrease in both volumetric density and stability with the increase in the proportion of these aggregates in the mixture. With modifying these mixtures with tire rubber crumbs, both of the percentage of air voids and stability increase, while the volumetric density and flow decrease. The results also showed an increase in the fatigue strength of the asphalt mixture with an increase in the proportion of recycled concrete aggregates, while the rutting resistance increased when the mixture was modified with tire rubber crumbs.

1. Introduction

Recycled concrete aggregates are known to be a granular material that is extracted from the demolition, removal and crushing and processing of concrete to be reused as a building material like natural stones [4]. However, these aggregates have different properties from natural ones, and this is largely due to the cement bond attached to their surfaces, which affects their properties. This clearly affects the properties and behavior of the asphalt mixtures in which these aggregates are involved as one of the components, unless specific steps are taken to take this into account in design and construction process [21].

In 1960 scrap tires were processed and used as a secondary material in paving, by two Swedish companies that produced asphalt mixtures with the addition of a small amount of crushed rubber resulting from scrap tires as a substitute for part of the aggregate in the asphalt mixture through a method known as "dry method" [16]. In the same period, Charles McDonalds in Arizona (USA) was the first to mix recycled tire rubber crumbs with bitumen for a reaction time ranging from (45) minutes to an hour. The method is known as the “wet method” [16].

There are two main methods for recycling scrap tires and converting them into crumbs of rubber: the first at normal temperature (Ambient) and the second after cooling (Cryogenic), and the treatment processes that are conducted on rubber tires differ according to each method [17]. In the (Ambient) method, scrap tires are ground at normal temperature (ambient temperature) to obtain shredded, irregularly shaped particles with relatively large surface areas to enhance interaction with bitumen. This is the most widely used and cost-effective method for treating expired tires [18]. In the (Cryogenic) method, liquid nitrogen is used to freeze recycled tire rubber, usually between (-87 °C) to (-198 °C), until it becomes brittle and fragile. Then a mill with a hammer is used to break the frozen rubber into soft particles with a relatively lower surface area compared with those obtained by (Ambient) method [18].

2. Literature Review

Fatigue is one of the less studied properties of asphalt mixtures containing recycled concrete aggregates. Pérez et al. concluded from the results of a three-point flexural stress test (according to the Spanish NLT-350 standard) that asphalt mixtures containing recycled concrete aggregates exhibit similar fatigue strength behavior to conventional mixes [13, 14]. Whereas, Shen et al. concluded that the asphalt mixtures in which recycled concrete aggregate powder was used as a filler have a higher fatigue life, based on the results of four-point fatigue tests at a temperature of (20 °C) according to specification (AASHTO T-321) [3]. Nejad et al. conducted an indirect tensile stress test at two temperatures (5, 40 °C) to analyze the fatigue life of asphalt mixtures containing recycled concrete aggregates; they found that replacing fine natural aggregates by up to (100%) the granular structure resulted in to improve fatigue life [11].

A review of research on permanent deformation of asphalt mixtures containing recycled concrete aggregates yields diverse conclusions. The results of some research showed that these mixtures give similar performance [12] or better [13, 15] compared to traditional asphalt mixtures. O the other hand, many researchers indicated that despite meeting the required specifications, the increase in the proportion of recycled concrete aggregates leads to a decrease in resistance to permanent deformation [8, 22]. A number of studies also unanimously agreed that the use of recycled concrete aggregates within the coarse field of the granular composition of the asphalt mixture led to better resistance to permanent deformation compared to mixtures of natural aggregates. Meanwhile, the mixtures containing recycled concrete aggregates showed -only within the fine field of the granular structure- less resistance to permanent deformation [23, 20, 19, and 6].

Muniz et al. studied the effect of total replacement of natural aggregates with recycled concrete aggregates asphalt mixture with the use of two types of asphalt binder (traditional asphalt binder and asphalt binder modified with rubber crumb). The results showed that replacing natural aggregates with recycled concrete aggregates improves the resistance of the asphalt mixture to repeated loading and permanent deformation. As for the asphalt mixture containing recycled concrete aggregates and a modified binder with rubber crumbs, it exhibited less fatigue life in the controlled stress test, while it gave better resistance to rutting [10]. Gopalam et al. also studied the effect of using asphalt binder modified with rubber crumbs on the performance of asphalt mixtures containing recycled concrete aggregates as a substitute for natural aggregates for the coarse part of the grain gradient, and the results showed that these mixtures show less tensile strength and greater resistance to rutting compared to conventional asphalt mixtures [5].

3. Research Goals

There are enormous challenges related to the accumulation of large quantities of concrete waste resulting from partial and total damage to concrete facilities, such as buildings and bridges in Syria in general and in Aleppo Governorate in particular, due to the large scale of destruction resulting from the war. On the other hand, the accumulation of large stocks of used rubber tires (scrap) causes environmental risks such as fires, health damages, pollution, etc., to cities, towns, and the areas surrounding their accumulation. The disposal of these tires in landfills is also a problem, as it is difficult to compress and stack them to reduce the size of landfills where are dumped, due to its rubber (elastic) nature.

Therefore, the main objective of the research is to design asphalt mixtures containing recycled concrete aggregates (RCA), which resulted from the ruins of the buildings of Aleppo Governorate, with the modification of these mixtures with tire rubber crumbs (TCR) according to the wet method. In addition, it also studies these mixtures on fatigue and rutting by predicting the responses in the pavement structure using numerical modeling in 3D-Move Analysis.

4. Materials and Research Methodology

To accomplish this research, recycled concrete aggregates resulting from the collection, processing, crushing and grinding of concrete debris were used for several buildings from different regions in Aleppo Governorate, including Hanano and Salah al-Din, as they are among the areas most exposed to destruction and contain large quantities of these debris.

As for the natural aggregates, they are local calcareous preparations available in Aleppo governorate. The general characteristics of each of the natural aggregates (NA) and recycled concrete aggregates (RCA) used in the research were determined as shown in Table (1) according to the international technical specifications for tests and materials [2].

Table 1 *Properties of NA & RCA*

Material		Apparent Specific Gravity	Bulk Specific Gravity (SSD)	Bulk Specific Gravity (Dry)	Effective Specific Gravity	Water Absorption (%)	ASTM Designation No. **[20]**
		Specific Gravity					
NA	Coarse	2.687	2.548	2.466	2.579	3.34	C127-88
	Fine	2.807	2.642	2.550	2.679	3.59	C128-97
	Filler	2.719	-	-	2.719		C128-97
RCA	Coarse	2.866	2.429	2.194	2.530	10.68	C127-88
	Fine	2.911	2.390	2.118	2.514	12.86	C128-97
	Filler	2.594	-	-	2.594	-	C128-97
		Los Angeles Abrasion (%)					
NA				33			C131-96
RCA				44.7			
		Sand Equivalent (%)					
NA				77			D2419-95
RCA		80					

The grain gradient of the aggregate materials was chosen with a maximum grain size of (19 mm) as shown in Figure (1) in accordance with the Syrian technical specifications specified for the requirements of the grain gradient for the pebble materials used for the wear layer [9].

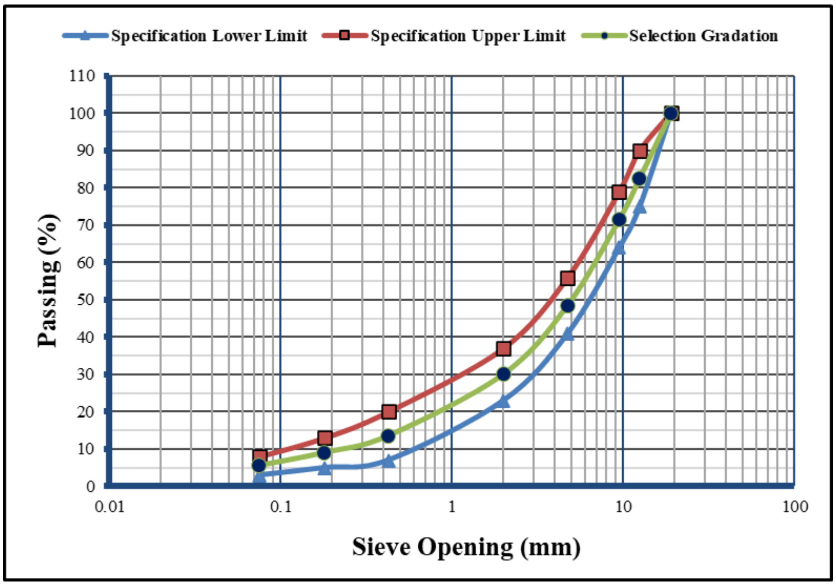

Fig. 1 *Aggregate Gradation for asphalt mixture*

As for the tire rubber crumbs, they are the result of recycling several spent rubber tires (scrap) according to the (Ambient) method. The properties of the granular composition and specific weight of these crumbs were also determined as shown in Table (2).

Table 2 *Properties of NA & RCA*

Gradation	
Sieve opening (mm)	Percentage of passage (%)
2 mm	100
1.7 mm	73.5
1.4mm	61

1mm	28.9
0.6 mm	10.3
0.3 mm	1.9
0.18 mm	0.5
0.15 mm	0
Specific Gravity	
0.97	

As for the asphalt binder preparations, they are from the Homs Refinery asphalt with stitching degree (AC 60-70), and the basic characteristics of the asphalt have been determined as shown in the table (3). Table (3) also shows the properties of the modified asphalt with increasing proportions of tire rubber crumbs. It should be noted that the modification of the asphalt binder with tire rubber crumbs was done according to the wet method at a mixing degree of (170 °C) and a reaction time of (60 min).

Table 3 *Properties of cement asphalt*

Characteristic	**ASTM Designation No.**	**Unit**	**Asphalt Cement**	**Asphalt Cement + TRC4%**	**Asphalt Cement + TRC8%**
Penetration (25°C, 100 gr, and 5sec)	D5	1/10 mm	67	60	50
Softening Point, (Ring and Ball)	D36	°C	49	53	56
Specific Gravity (25°C)	D70	-	1.033	1.028	1.025
Flash Point, (Cleveland open cup)	D92	°C	280	292	300

After determining the characteristics of the materials used in the research, the asphalt mixtures to be designed and studied were determined. Table (4) shows the asphalt mixture code and its components, whether from recycled concrete aggregates or modified rubber crumbs for the asphalt binder. It should also be noted that the replacement of natural aggregates with recycled concrete aggregates was done for the entire granular structure, including the fillers.

Table 4 *The different types of asphalt mixture*

Asphalt Mixture	**RCA (%)**	**TRC (%)**
NA	0	0
RCA20	20	0
RCA30	30	0
RCA30-TRC4	30	4
RCA30-TRC8	30	8

As for the numerical part of the research, the 3D-Move Analysis program was used to model a paving structure with a surface layer of asphalt concrete according to the specifications of the asphalt mixtures that were determined in the laboratory. 3D-Move analysis software was developed by the Asphalt Research Consortium (ARC). The program is based on 3D modeling and follows the defined layer approach (FLM) and includes the possibility of static or dynamic analysis. Through the 3D-Move analysis program, it is possible to predict the responses of the pavement to repeated loads (stresses, strains, and transitions), and the properties and behavior of the pavement materials, especially the asphalt layer, can be entered. The linear elastic behavior of the asphalt mixture or the viscous elastic behavior can be adopted, which is used in the research. The program is also characterized by allowing to enter data for materials with viscous elastic behavior, either based on the reciprocating test data or based on the model equations (Witczak Model equation), which is what was adopted in this research. Figure (2) shows the main interface of the 3D-Move Analysis program.

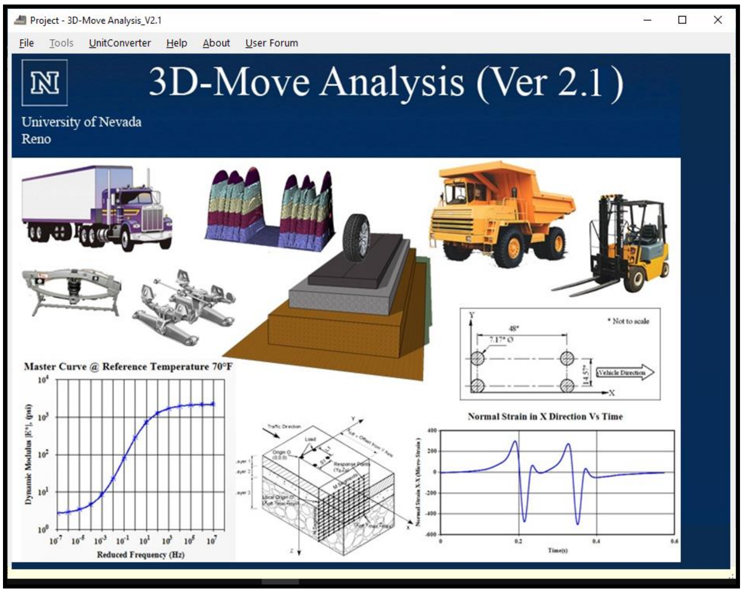

Fig. 2 *The main interface of 3D-Move Analysis*

5. Results and Discussion

5.1. Laboratory Experiments

Mixtures were designed according to Marshall Method standards, where six percentages of asphalt were added as a percentage of the weight of the asphalt mixture with finding the physical and mechanical properties of these mixtures, as shown in Table (5).

Table 5 *Basic characteristics of asphalt mixtures according to asphalt content*

Asphalt Mixture	Asphalt Content (%)	γmb (gr/cm³)	Pa (%)	V.M.A (%)	V.F.A (%)	Stability (KN)	Flow (mm)
NA	4.0	2.291	7.45	12.45	40.56	11.77	2.47
	4.5	2.327	5.31	11.62	54.49	14.44	2.82
	5.0	2.341	4.04	11.55	65.04	16.29	3.30
	5.5	2.366	2.31	11.07	79.17	15.10	3.62
	6.0	2.378	1.11	11.09	89.98	13.80	4.08
	6.5	2.370	0.76	11.88	93.58	12.30	4.51
RCA20	5.0	2.228	8.02	13.78	41.81	10.41	2.53
	5.5	2.247	6.56	13.48	51.38	12.60	2.87
	6.0	2.276	4.69	12.83	63.50	15.15	3.42
	6.5	2.315	2.37	11.80	80.05	13.78	3.75
	7.0	2.333	0.95	11.62	91.84	12.85	4.23
	7.5	2.322	0.72	12.50	94.29	10.70	4.68
RCA30	5.5	2.182	8.94	14.99	40.33	9.10	2.62
	6.0	2.198	7.65	14.83	48.47	11.23	2.95
	6.5	2.223	5.93	14.31	58.62	13.90	3.50
	7.0	2.264	3.54	13.20	73.24	12.69	3.81
	7.5	2.279	2.24	13.11	82.93	11.50	4.33
	8.0	2.271	1.93	13.89	86.12	9.68	4.74

The optimum asphalt ratio was determined for each asphalt mixture, and then the asphalt mixture (RCA30) was modified with two percentages of tire rubber crumbs with the percentage of asphalt in the mixture fixed. Table (6) shows the final volumetric and mechanical properties of asphalt mixtures.

Table 6 *Basic characteristics of asphalt mixtures*

Asphalt Mixture	Asphalt Content (%)	ɣmb (gr/cm³)	Pa (%)	V.M.A (%)	V.F.A (%)	Stability (KN)	Flow (mm)
NA	5.08	2.349	3.58	11.30	68.34	15.91	3.36
RCA20	6.17	2.290	3.86	12.44	69.01	14.76	3.61
RCA30	6.92	2.255	4.02	13.46	70.18	13.00	3.75
RCA30-CRM4	6.92	2.247	4.33	13.78	68.56	14.12	3.63
RCA30-CRM8	6.92	2.234	4.82	14.26	66.18	15.66	3.41

Figures (3) (4) (5) (6) (7) show an increase in the optimum asphalt ratio, the proportion of air voids, and flow with the increase in the proportion of recycled concrete aggregates in the asphalt mixture. Meanwhile, the volumetric density and stability decrease with the increase in the proportion of these aggregates in the mixture. This is mainly due to the cement bond attached to the surfaces of the recycled concrete aggregates, which has high porosity properties, which increases the specific surface of these aggregates and thus increases the optimum asphalt ratio required for the asphalt mixture, which also leads to an increase in the proportion of air voids in the asphalt mixture and a decrease in its density.

It should be noted that the increase in the specific surface of the recycled concrete aggregates is not due only to the cement bond attached to their surfaces, but also due to the possibility of fragmentation of these aggregates during the mixing and compaction works to prepare the asphalt mixture, taking into consideration that the factor of Los Angeles abrasion is high as is previously shown in Table (1).

However, when modifying the asphalt mixture (RCA30) with tire rubber crumbs, the percentage of air voids increases, while the density of the asphalt mixture decreases, mainly due to the decrease in both the workability and compaction efficiency of the mixture. When mixing the rubber crumbs with the asphalt binder at high temperatures, a non-chemical reaction occurs in which the essential oils of the asphalt are absorbed by the rubber crumbs, making them swollen and gelatinous, which leads to an increase in the viscosity of the asphalt binder, which reduces the sliding of the aggregates into each other (the increase in viscosity can be inferred from the increase in the liquefaction point as shown in Table (3)). The decrease in density can also be explained by the decrease in the specific weight of the rubber crumbs compared to the specific weight of the asphalt binder. As for the mechanical properties, the stability increases and the flow decreases with the increase in the proportion of rubber crumbs, and this is due to the increase in the hardness of the asphalt bond (the increase in the hardness can be inferred by the decrease in the value of the stitches as shown in Table (3)).

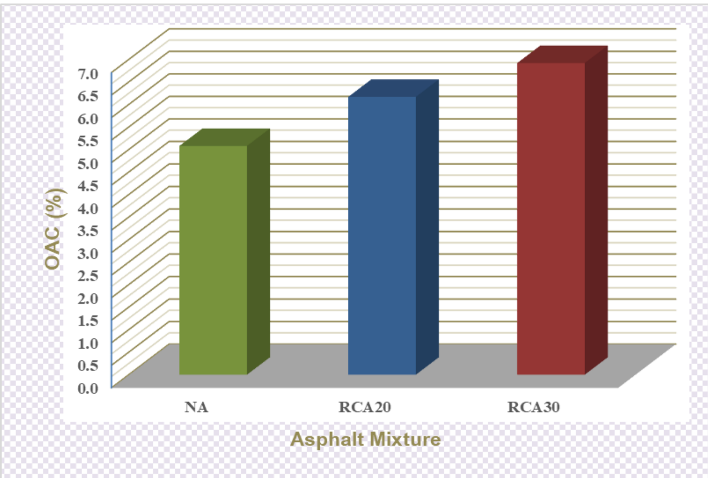

Fig. 3 *Comparison of optimum asphalt content of asphalt mixtures*

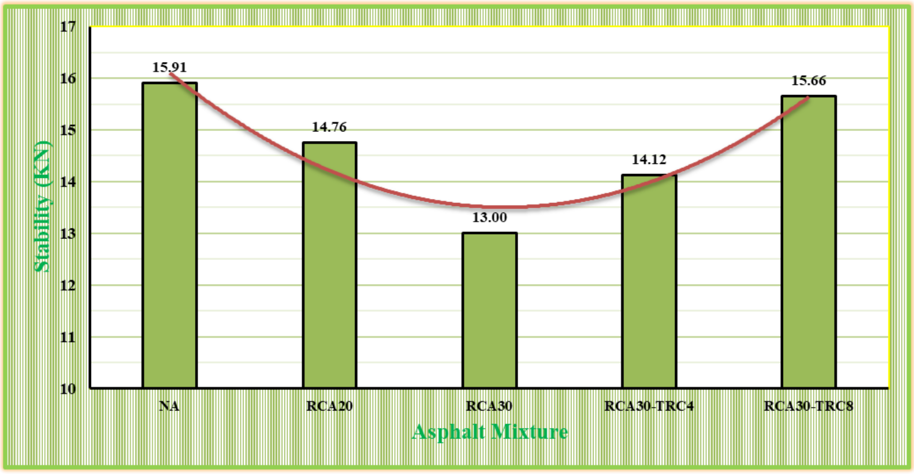

Fig. 4 *Stability comparison of asphalt mixtures*

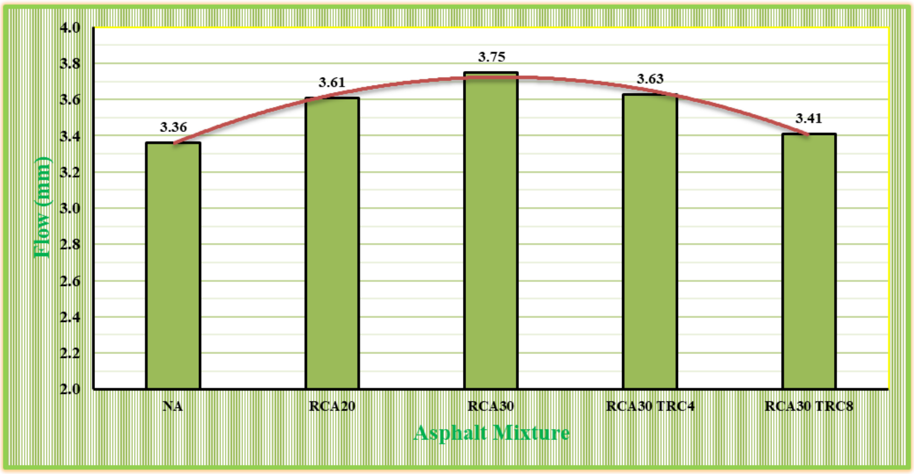

Fig. 5 *Flow comparison of asphalt mixtures*

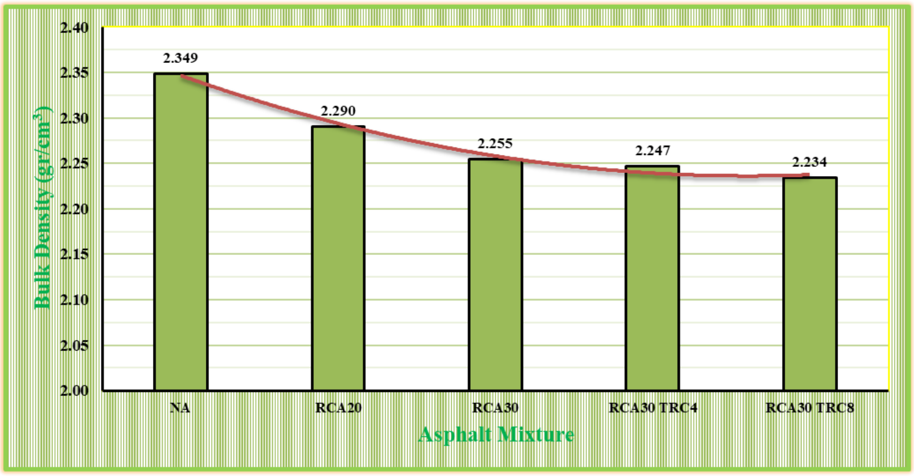

Fig. 6 *Bulk density comparison of asphalt mixtures*

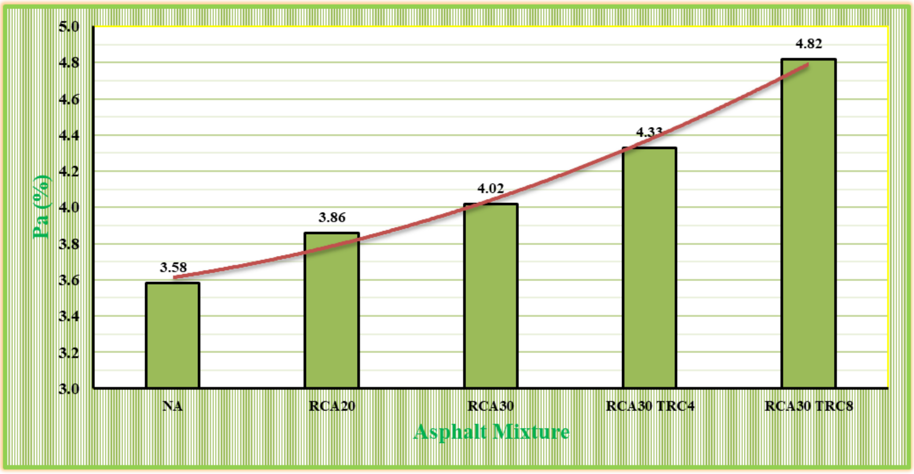

Fig. 7 *Comparison of air voids ratio of asphalt mixtures*

5.2. Numerical Modeling

Numerical modeling was done using 3D-Move Analysis software and according to the following considerations: The analysis type: dynamic.

The load is a single axle with a single tire with a weight of (80 KN). The load is distributed evenly within the load surface area of the tire and it is circular in shape with a radius (a = 12.6 cm). Figure (8) shows the load and the paving layers.

The following thicknesses and specifications have been assumed for the foundation layers and the support soil, as shown in Table (7).

Table 7 *Characteristics and specifications of (base-subbase-subgrade)*

Layer	Thickness	CBR	Poisson ratio	Density (gr/cm^3)
Base	2.0	65	0.35	19
Subbase	3.0	60	0.40	18.5
Subgrade	-	5	0.42	18

The asphalt mixture layer has variable specifications according to the asphalt mixtures that have been designed and their characteristics determined. The viscoelastic behavior of the asphalt aggregate layer was adopted and the dynamic coefficient was calculated using the program and through the Witczak Model according to the following equation:

$$|E^*| = 3.750063 + 0.02932\,(\rho_{200}) - 0.002841\rho_4 - 0.05809V_a - 0.802208\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34}}{1 + e^{[-0.603313 - 0.313351\log(f) - 0.393532\log(\eta)]}} \quad (1)$$

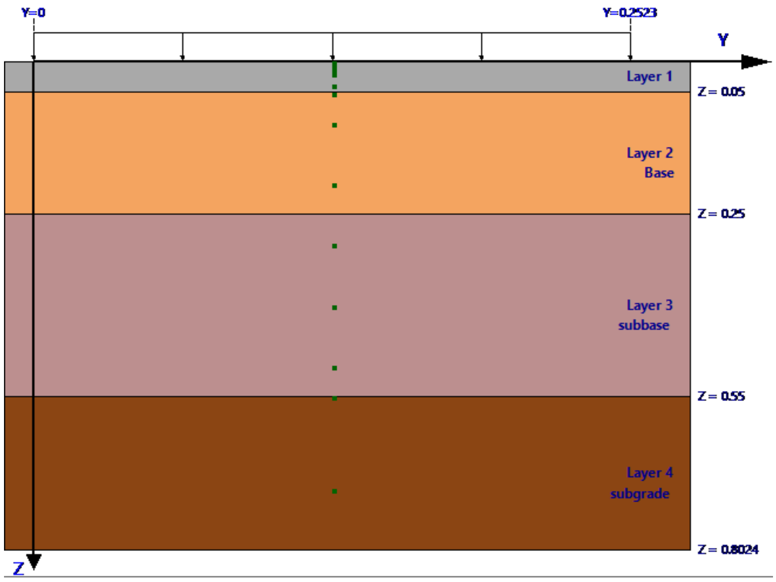

Fig. 8 *Load and pavement layers*

In the analysis of loads on the paving surface, two strains are important for design purposes: horizontal tensile strain (εt) below the asphalt aggregate layer and vertical compressive strain (εc) above the earthen floor. If the value of the horizontal tensile strain below the asphalt aggregate layer is large, cracks will occur in the paving and the paving will collapse due to fatigue, while if the value of the vertical stress strain above the earthen floor is large, permanent deformations will occur on the surface of the paving structure due to overloading the support earthen and the paving will collapse because of rutting [1].

The responses of the paving were established through numerical modeling using the 3D-Move Analysis program. The following two figures (9) and (10) show the horizontal tensile strains below the asphalt layer and the vertical compressive strains above the earthen floor, respectively.

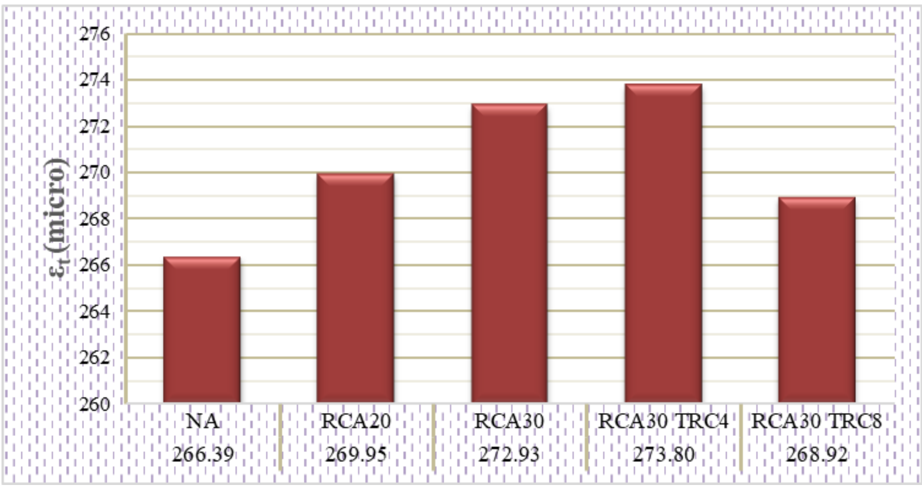

Fig. 9 *Comparison of the horizontal tensile strain at the bottom of the asphalt layer*

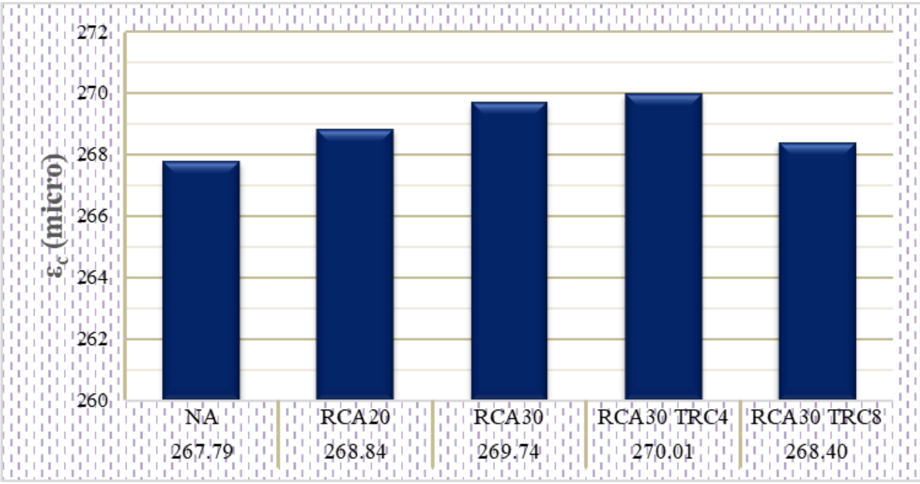

Fig. 10 *Comparison of the vertical compressive strain at the top of subgrade layer*

From Figure (9), it can be seen that the tensile stresses below the asphalt aggregate layer increase with the increase in the proportion of recycled concrete aggregates in the asphalt mixture to reach the highest value in the asphalt mixture (RCA30) compared to the reference mixture, and then it decreases with the increase in the percentage of tire rubber crumbs when adjusting the aforementioned mixture with these crumbs. As for Figure (10), it can be seen that the pressure strains above the earthen floor increase with the increase in the percentage of recycled concrete aggregates in the asphalt mixture to reach the highest value in the asphalt mixture (RCA30) compared to the reference mixture, then it decreases with the increase in the percentage of tire rubber crumbs when adjusting the aforementioned mixture with these crumbs.

Several fatigue and rutting models have been developed to relate the strains measured to the number of load repetitions until paving failure. Most fatigue failure models take the following form [7]:

$$N_f = f_1(\varepsilon_t)^{-f_2}(E_1)^{-f_3}$$

While rutting models usually take the following form:

$$N_d = f_4(\varepsilon_c)^{-f_5}$$

The values of the coefficients shown in the above equations usually vary according to the material properties, environmental conditions, traffic, and failure limits determined by the organization based on the research it has conducted in this regard. The values of the coefficients given by the Asphalt Institute were adopted to calculate the number of load times until failure, whether on fatigue or rutting, and they are as follows (f_1=0.0795), (f_2=3.291), (f_3=0.854), (f_4=1.365*10^{-9}), (f_5=4.477). Figures (11) and (12) show the permissible loading cycles until pavement failure on fatigue and rutting, respectively, for asphalt mixtures.

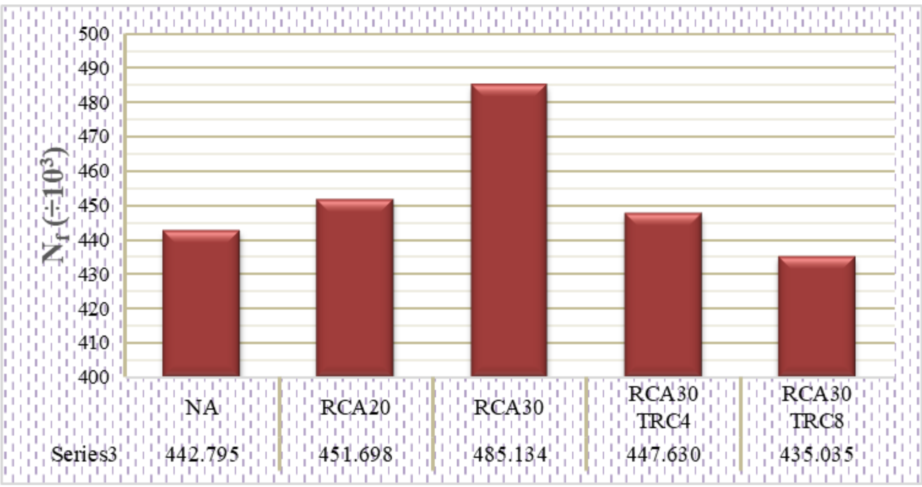

Fig. 11 *Comparison of loading cycles until failure on fatigue for asphalt mixtures*

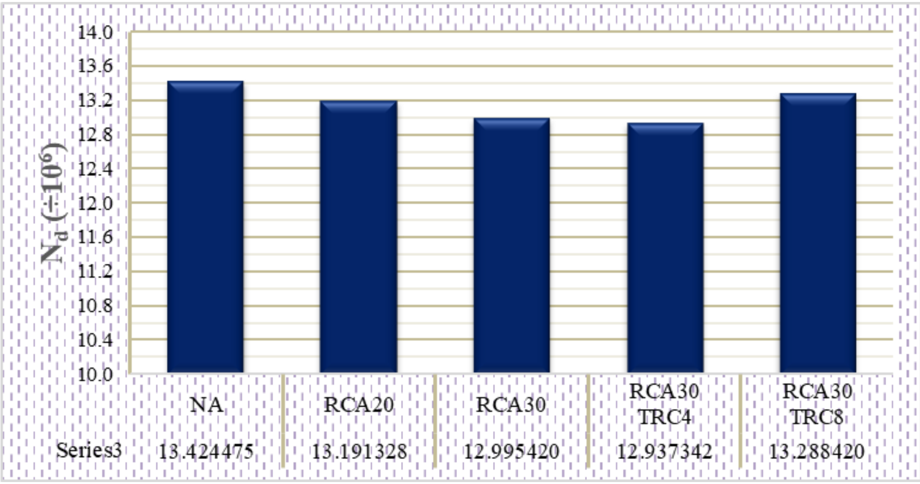

Fig. 12 *Comparison of loading cycles until failure on rutting for asphalt mixtures*

From Figure (11), it can be seen that the permissible load cycles until failure on fatigue increase with the increase in the percentage of recycled concrete aggregates in the asphalt mixture to reach the highest value in the asphalt mixture (RCA30) compared to the reference mixture, as this is due to the increase in the ductility of the asphalt mixture due to the increase in the content of the optimum binder, then it decreases with the increase in the percentage of tire rubber crumbs when the aforementioned mixture is modified with these crumbs. As for Figure (12), it can be seen that the permissible loading cycles until failure to rutting decreases with the increase in the percentage of recycled concrete aggregates in the asphalt mixture to reach the highest value in the asphalt mixture (RCA30) compared to the reference mixture, and then it increases with the increase in the percentage of tire rubber crumbs when modifying the aforementioned mixture with these crumbs; this is due to the increase in the hardness of the asphalt mixture.

6. Conclusion

In this research, the basic properties of asphalt mixtures containing recycled concrete aggregates modified with tire rubber crumbs were determined, and the number of permissible loading cycles until failure on fatigue and rutting was determined. The results can be summarized as follows:

- The optimal asphalt ratio, the proportion of air voids, and the flow increase with an increase in the proportion of recycled concrete aggregates in the asphalt mixture, while the volumetric density and stability decrease with an increase in the proportion of these aggregates in the mixture.
- When modifying the asphalt mixture containing recycled concrete aggregates with tire rubber crumbs, the percentage of air voids and stability increases, while the volumetric density and flow of the mixture decrease.
- The fatigue strength of the asphalt mixture increases with the increase in the proportion of recycled concrete aggregates, while the rutting resistance increases when the mixture is modified with tire rubber crumbs.

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