Article

Mechanical Performance of Gilsonite Modified Asphalt Mixture Containing Recycled Concrete Aggregate

Daniel Alberto Zuluaga-Astudillo ^{1,*} , Hugo Alexander Rondón-Quintana ² and Carlos Alfonso Zafra-Mejía ²

¹ Especialización en Diseño y Construcción de Vías y Aeropistas, Escuela de Ingenieros Militares, Ejército Nacional de Colombia, Bogotá, DC 111611, Colombia

² Facultad del Medio Ambiente y Recursos Naturales, Universidad Distrital Francisco José de Caldas, Bogotá, DC 110321, Colombia; harondonq@udistrital.edu.co (H.A.R.-Q.); czafra@udistrital.edu.co (C.A.Z.-M.)

* Correspondence: daniel.zuluaga@esing.edu.co

Abstract: Hot-mix asphalts exposed to hot weather and high traffic volumes can display rutting distress. A material that can be used to increase the stiffness of asphalt binders is gilsonite. On the other hand, from an environmental point of view, the virgin natural aggregates of asphalt mixtures can be replaced with recycled concrete aggregates. For these reasons, this study modified the asphalt binder with gilsonite by wet-process to improve rutting resistance, and replaced (by mass and volume) part of the coarse fraction of the aggregate with recycled concrete aggregate in two hot-mix asphalts with different gradations. Unlike other studies, a larger experimental phase was used here. Marshall, indirect tensile strength, resilient modulus, permanent deformation, fatigue resistance, and Cantabro tests were performed. An ANOVA test was carried out. If the replacement of the virgin aggregate by recycled concrete aggregates was made by volume, both materials (gilsonite and recycled concrete aggregate) could be used in hot-mix asphalts for thick-asphalt layers in high temperature climates and any level of traffic. The use of both materials in hot-mix asphalts is not recommended for thin-asphalt layers in low temperatures climates. It is not advisable to replace the aggregates by mass.

Keywords: hot-mix asphalt; modified asphalt binder; gilsonite; recycled concrete aggregate RCA

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1. Introduction

1.1. Gilsonite Background

Gilsonite is a natural fossil resource that was discovered more than one century ago, hence, it has been broadly studied. It is a type of natural asphalt (generally solid) derived from petroleum, which has a predominantly dark brown color, and is found widely around the world. It is naturally produced through the penetration of oil or petroleum in rocks under combined actions of heat, pressure, oxidation, and microbe activity throughout millions of years [1]. It is a hard and brittle material [2], but it can easily be crushed into powder. It is also scientifically named uintaite [3–5]. This resinous hydrocarbon has been evaluated and used in different industrial processes [3,4,6,7]. Generally, it presents a carbon content superior to 70% and a low H/C ratio, which indicates a high degree of molecular condensation. It contains a large quantity of N, O, and S elements in which there are existing functional polar groups and a high presence of metallic elements. Upon carrying out SARA (Saturates, Aromatics, Resins, Asphaltenes)-fractions, gilsonite presents a high content of asphaltenes [4,8–12]. It is a material that is highly compatible with conventional asphalt binders [13,14]. Gilsonite is soluble in aromatic and aliphatic solvents, as well as in petroleum derivatives [4].

In pavements, gilsonite is a material used to modify the properties of asphalt binders. In particular, it is used to increase the stiffness and thermal susceptibility [5,15,16]. Therefore, it helps to increase the resistance of hot-mix-asphalts (HMA) to the phenomenon

of rutting in high temperature climates [1,17–29], increasing the Marshall stability and stiffness under a cyclic load (e.g., resilient modulus and dynamic modulus) and resistance to permanent deformations. There have also been reports of improvements regarding moisture damage resistance [1,2,5,16,24,28,30] and indirect tension resistance [5,31]. However, in low temperature climates, this may generate problems associated with thermal and fatigue-induced cracking [1,32–35]. Because of this, several studies have combined gilsonite with other conventional polymeric additives (e.g., styrene–butadiene–styrene (SBS), styrene butadiene rubber (SBR), and crumb rubber) in order to modify asphalt binders [1,31,36,37]. Additionally, in high addition percentages, it can considerably increase the viscosity of the asphalt binder, negatively affecting mix temperatures (workability) and compaction, increasing energy consumption and environmental pollution [1,2]. Despite the above, if the gilsonite dose is controlled up to a certain point, it may not exert a considerably negative influence upon the mentioned aspects [3,38]. On the other hand, in comparison with other modifiers, gilsonite offers advantages in terms of lower costs and increased ease of use [1,5,21,24,32,39].

1.2. Recycled Concrete Aggregate Background

During the construction process of roadway projects, large quantities of natural origin aggregates (NA) are consumed. This negatively impacts the environment. According to the authors of [39], roadway construction produces approximately 28% of the world's energy consumption and 22% of global CO₂ emissions. A way of reducing these impacts (reduction of the carbon footprint in the construction industry, conservation of natural resources, and reduction of hazardous emissions, among others) is replacing NAs with recycled concrete aggregates (RCAs). The latter is obtained from construction and demolition (C&D) waste (CDW), which has been increasing because of growth in the construction industry [40,41]. The authors of [42], referring to other researchers, mention that an average between 30% and 40% of the total solid waste material comes from C&D activities. Additionally, they mention that RCAs represent between 50% and 70% (in weight) of the total CDW. For these reasons, several studies have been carried throughout the world to evaluate the use of RCAs as a substitute for NAs. Some factors that limit the use of RCAs are (i) the need for using large spaces for their storage; (ii) experience in residue recycling operations, supervisors, and trained personnel are all required; (iii) it requires knowledge about waste material markets; and (iv) it requires a high degree of awareness regarding environmental and safety regulations [43].

The broadly identified problem in most RCA studies is that these are materials with a high degree of heterogeneousness, which present greater absorption and lower mechanical resistances than those of NAs [44–49]. This is mainly because of the adhered mortar attached to the RCA particles [50–52]. Additionally, RCAs present impurities such as bricks, roof tiles, ceramic, and organic materials, among others. Because of this, most part studies have focused on evaluating the behavior of RCAs as a substitute for NAs in the lower layers of pavement (e.g., subgrade, subbase, and base), which are exposed to less of the pressures produced by traffic [53]. However, the amount of RCA produced in the world already surpasses its common use (even in its use in pavement base and subbase), and therefore there is an existing need to broaden its use in asphalt mixes [47]. Additionally, differently to the use of RCAs in bases, subbases, or subgrades, in the context of asphalt mixes, there is an absence of the problem regarding the possible generation of lixiviates [54]. Despite the identified problems, some authors have mentioned that RCAs present particles with ideal shapes (fractured faces with low flattening and elongation indexes) that can help to generate a compact granular skeleton with good intergranular friction [55]. Furthermore, their greater porosity in comparison with NAs can help to improve adhesion to asphalt binders. RCAs have not only been experimentally characterized, but the complex failure processes of these materials have been simulated using the discrete-element method (DEM) [56].

Regarding asphalt mixes, studies have mainly focused on substituting (generally by mass) NA with RCA in different proportions (even replacing the totality of the aggregate),

and then measuring the changes that took place in the mixes, as well as their mechanical resistance. The literature is ambiguous regarding drawing conclusions related to the obtained results. While some studies have reported that the evaluated properties improve, others have concluded the opposite [48,57,58]. Furthermore, there is a great disparity about the recommendations regarding the replacement levels of NAs for RCAs in asphalt mixes [58]. Likewise, the behavior of mixes may change depending on the source from where the RCA was obtained [48]. Despite the above, most studies conclude the following: (i) mixes with RCAs show satisfactory results when they are placed in the asphalt layers of roadways with a low traffic volume, and (ii) it is necessary to use greater asphalt contents as the quantity of RCA used is greater [59]. Additionally, several studies have concluded that asphalt mixes that use RCAs comply with the design criteria of several countries, which enhances its use [60–65]. To reduce asphalt consumption and improve the properties of RCAs, some studies have conducted pre-treatment for these materials. For example, some studies have covered RCA particles with a slag cement paste [66], bitumen emulsion [43,67], silane-based water repellent agents [68], or a carbonation technique [69]. Others have applied combined coating techniques with additives such as Tite-BE and heating [46], while others have attempted to mechanically eliminate the adhered mortar [70]. States of knowledge regarding the topic of RCA pre-treatment can be consulted in the literature [71,72]. The authors of [72] mention that RCA pre-treatment methods are mainly classified into the following two types: the elimination of adhered mortar and reinforcement of adhered mortar. According to the authors of [71], it is much more effective and efficient from an energy standpoint to coat RCAs than to attempt to eliminate the adhered mortar.

1.3. Problem Statement and Objective

In Colombia, average annual temperatures above 24 °C cover almost 70% of the total area in the country. Moisture, in terms of average annual relative humidity, is above 60% [73]. Because of this, within a large part of the Colombian territory, the most common pavement distress type is rutting. This motivated the use of gilsonite in this study, with the purpose of stiffening the asphalt binder, thus attempting to increase rutting resistance for the two types of HMAs that are mostly used throughout Colombia (named MDC-19 and MDC-25, according to the authors of [74]). Additionally, for the case of Colombia, the use of RCAs as replacements for NAs in HMAs could be an interesting alternative, taking into account that projections for 2019–2024 indicate the use of 75 million tons of NAs for the construction of roadways [75]. In addition, a great portion of the national roadway network is comprised of unpaved roadways [76].

Few studies have combined the effects of modifying the asphalt binder with gilsonite and using RCAs as replacement for NAs in HMAs. The authors of [77,78] conducted limited experimental studies combining both effects, but in porous mixes. The authors of [79] conducted a study on an HMA; however, the scope of the experimental phase was also limited (only conducted using Marshall, indirect tensile strength (ITS), and Cantabro tests; used one gradation; and the substitution of NA with RCA was carried out according to mass). In addition, few studies have replaced the NA with RCA dosing according to volume; despite this, several researchers recommend doing so because it is more appropriate for these types of porous materials [59,80]. This is because RCA particles generally have a lower specific gravity than NAs, and when replacing according to mass, a greater amount of RCA particles that are to be coated with asphalt are introduced into the mix [81].

Given all of the above reasons, in contrast to other studies conducted on the topic, this study evaluated the combined effects of modifying asphalt cement (AC) with gilsonite through a wet process, and replaced (dosing by mass and by volume) part of the coarse fraction of NA with RCA in mixes of MDC-19 and MDC-25. Marshall, resilient modulus, and permanent deformation tests were carried out in order to evaluate the rutting resistance. Additionally, ITS, fatigue, and Cantabro tests were carried out to evaluate the durability related aspects. In order to know if changes in properties were statistically significant,

an ANOVA test was carried out with test F and a reliability level of 95%. The values of $F > F_{0.05}$ represented statistically significant variations.

2. Materials and Methods

2.1. Materials

In this research, an AC 60–70 (penetration grade in 0.1 mm) was used as asphalt binder, whose properties are shown on Table 1.

Table 1. General properties of asphalt cement (AC) 60–70.

Test	Method	Unit	Value
Tests on the original AC			
Penetration (25 °C, 100 g, 5 s)	ASTM D-5	0.1 mm	63.8
Softening point	ASTM D-36–95	°C	51.7
Absolut viscosity (60 °C)	ASTM D-4402	Poises	1690
Specific gravity	AASHTO T 228–04	-	1.012
Viscosity to 135° C	AASHTO T-316	Pa-s	0.35
Tests on the residue of AC after the RTFOT (Rolling Thin Film Oven Test)			
Mass loss	ASTM D-2872	%	0.57
Penetration (25 °C, 100 g, 5 s), in percentage of the original penetration	ASTM D-5	%	70
Increase on the softening point	ASTM D-36–95	°C	5

Gilsonite (Figure 1a) has a specific gravity of 1.03 g/cm³. Its penetration measured at 25 °C, according to the ASTM D-5 specification, is 0 mm/10 and its softening point, measured according to ASTM D-36, is 92 °C. Its particles pass through a sieve 40 (0.425 mm). The properties of NA aggregates (Figure 1b) and RCA (Figure 1c) are shown in Table 2. The specific gravity and abrasion wear resistance of NA is greater in comparison with RCA. This is mainly because of the presence of adhered mortar, the greater porosity, and absorption of the RCA, as described in the RCA background. It is worth highlighting that RCA particles present a better geometry (greater percentages of fractured faces and less percentages of elongated and flattened particles).

Figure 1. Materials: (a) gilsonite (G); (b) natural origin aggregates (NA); (c) recycled concrete aggregate (RCA).

Table 2. Properties of NA and RCA particles.

Test	Method	NA	RCA
Specific gravity/absorption—coarse	AASHTO T 84	2.65/1.8%	2.52/4.9%
Specific gravity/absorption—fine	AASHTO T 85	2.53/1.5%	2.48/5.2%
Los Angeles Machine, 500 revolutions	AASHTO T 96	22.7%	31.1%
Micro-deval	AASHTO T327	21.1%	29.0%
Fractured particles: 1 face	ASTM D 5821	87.6%	97.2%
Plasticity index	ASTM D 4318	No plastic	No plastic
Flattening index	NLT 354	6.5%	3.0%
Elongation index		8.2%	2.2%

2.2. Modification of AC 60–70

Gilsonite was added to the AC 60–70 through a wet process in a proportion of 10% with relation to the asphalt binder's mass. The temperature and time to mix both materials (AC 60–70 and gilsonite) was 160 °C and 10 min, respectively. This mix was performed using high shear mixer equipment at 3000 rpm. The addition percentage, temperature, and mix time were chosen based on the results of previous studies [22,28,82]. The modified AC was named AC/G/10%. The properties of AC/G/10% are presented in Table 3. It was observed that gilsonite notably increased the asphalt binder stiffness (reduces penetration, increases softening points and viscosity). This increase in stiffness was mainly due to the high content of asphaltenes in gilsonite [4,10–12], as well as its lower penetration and higher viscosity and softening point compared with AC 60–70 asphalt binder.

Table 3. Properties of AC/G/10%.

Test	Method	Unit	Value
Tests on the original AC			
Penetration (25 °C, 100 g, 5 s)	ASTM D-5	0.1 mm	42.0
Softening point	ASTM D-36-95	°C	75.6
Specific gravity	AASHTO T 228-04	-	1.014
Viscosity to 135 °C	AASHTO T-316	Pa-s	1.02
Tests on the residue of AC after the RTFOT			
Mass loss	ASTM D-2872	%	0.44

2.3. Mix Design Procedure

In this research, six types of mixes were designed and tested, which are described as follows:

- The MDC-19 and MDC-25 mixes were the control. These used AC 60–70 as a binder and 100% of their aggregates were NA. The gradation of these mixes is presented in Figure 2.
- The MDC-19-M and MDC-19-V mixes had the gradation of the MDC-19 mix; however, they used AC/G/10% as a binder and replaced 21% (particles retained in sieve 3/8" or 9.5 mm) of the NA with RCA. M or V indicate that the replacement was carried out by mass or volume, respectively.
- The MDC-25-M and MDC-25-V mixes had the gradation of the MDC-25 mix; however, they used AC/G/10% as a binder and replaced 24% (particles retained in sieve 1/2" or 12.5 mm) of the NA aggregate with RCA.

Considering that the gradation of RCA presented more than 90% of the material that was retained in a 3/8" sieve (9.5 mm), a replacement of 21% and 24% of the mass of NA with RCA was chosen for MDC-19-M and MDC-25-M, respectively. In other words, harnessing RCA was greater when replacing the coarse fraction of NA. Replacing this with particles of a smaller size would increase the costs, entailing an industrial process.

Additionally, particle sizes corresponding to the superior sieves were chosen on each mix to carry out the replacements ($1/2'' + 3/8''$ on MDC-19 and $3/4'' + 1/2''$ on MDC-25). In order to make the replacements according to volume for mixes MDC-19-V and MDC-25-V, the specific gravities of both aggregates (NA and RCA) were taken into consideration, and the guidelines recommended by the authors of [80] were followed.

Figure 2. Gradation of the MDC-19 and MDC-25 mixes.

The method used to design and obtain the optimal asphalt content (OAC) of mixes was the Marshall method. For this reason, the manufactured samples were Marshall type (cylindric samples compacted at 75 blows per face, with an approximate mass of 1200 g, and with approximate dimensions of 63.5 mm in diameter and 101.6 mm in height). Additionally, the recommendations of the AASHTO T-245 general guidelines were followed, and all mixes were manufactured under short-term oven aging (STOA) conditions following the protocols recommended by AASHTO R30 (before compacting samples, these were heated in a loose state for 2 h inside a conventional oven at 135 °C).

The compaction and mix temperature for the control mixes (MDC-19 and MDC-25) were 150 °C and 145 °C, respectively. These temperatures were chosen based on the viscosity vs. temperature curve obtained for AC 60–70 (viscosity of 170 ± 20 MPa·s for the mix temperature and 280 ± 30 MPa·s for compaction). For the other mixes, which used AC/G/10%, said temperatures were 165 °C and 160 °C, respectively. These last temperatures were not chosen based on viscosity curves vs. temperature, given that for the case of modified asphalt binders, this criterion is not realistic [22,83,84]. In this study's case, viscosity curves vs. temperature for AC/G/10% indicated the need for increasing both temperatures by more than 30 °C. For this reason, an increase of 15 °C was chosen to avoid aging and degradation of the modified asphalt binder's properties. Likewise, it was selected through trial and error, considering that the aggregate's particles were easily coated with the modified asphalt binder.

Regarding the mix design, four asphalt percentages per mix were used. Likewise, three samples per asphalt percentage were manufactured to obtain the volumetric and resistance parameters for the Marshall test. Stability and flow were obtained from a Marshall compression machine by applying a loading rate of 50.8 mm/minute (sample temperature was 60 °C).

2.4. Resilient Modulus, Permanent Deformation, and Fatigue Resistance

Using a Nottingham Asphalt Tester (NAT) machine, the stress–strain relationship of each asphalt mix was depicted through resilient modulus (RM) tests (ASTM D4123). The “half-sine” load type was applied under frequencies of 2.5 Hz, 5.0 Hz, and 10 Hz. The test temperatures were 10, 20, and 30 °C. Each RM was determined based on the average of results obtained on the three Marshall samples using the OAC.

Permanent deformation resistance tests were carried out using the NAT machine and following the UNE-EN 12697-25 standard. The test temperature was 40 °C. Initially, 600 cycles of preload (10 kPa) were applied for 20 min per sample. Posteriorly, 3600 load cycles under a stress of 100 kPa were applied. Vertical displacement was measured by using LVDTs (linear variable differential transformers). The load cycles were a square wave type with a frequency of 0.5 Hz. (1 s of load application and 1 s of rest per cycle). Each permanent deformation curve was determined by averaging the results obtained on the three samples.

Fatigue resistance was measured using the NAT machine (UNE-EN 12697-24). Controlled-stress was the indirect tensile load mode. The load frequency and test temperature were 10 Hz and 20 °C, respectively. Sample total rupture was the criterion used to obtain the failure number of cycles (N_f). Nine Marshall samples for each asphalt mix were tested to obtain each fatigue curve.

2.5. Indirect Tensile Strength (ITS) and Cantabro Tests

ITS tests were carried out on the mixes manufactured with the OAC obtained by design. In order to conduct this test, guidelines established in the AASHTO T 283 specification were followed. Three conditioned Marshall samples (C) were tested by type of asphalt mix and for another three under unconditioned samples (U). The air voids content of each sample ranged between $7 \pm 0.5\%$. Each sample was loaded radially at a speed of 50 mm/min, using a Marshall compression machine. The maximum load at fracture was measured at a temperature of 25 °C. The indirect tensile strength (ITS) under C (ITS-C) and U (ITS-U) conditions were obtained. Both parameters were calculated in percentage, using a tensile strength ratio ($TSR = (ITSC/ITSU) \times 100$).

The Cantabro test is broadly used to characterized open-graded type asphalt mixes. However, during the latest years, it has been used to provide information regarding aspects associated with durability in dense-graded type asphalt mixes [85,86]. The percent of weight loss (Cantabro loss (CL)) was calculated by applying 500 cycles in the “Los Angeles machine” (without steel spheres). Three samples were tested for the asphalt mix. The test temperature was a room laboratory temperature of 20 °C.

3. Results and Discussion

3.1. Marshall Test

The Marshall test results are shown in Figures 3 and 4. The OAC of the MDC-19, MDC-19-M, MDC-19-V, MDC-25, MDC-25-M, and MDC-25-V mixes is of 5.5%, 6.0%, 5.5%, 5.0%, 5.5%, and 5.0%, respectively (see Table 4). For the case of the MDC-19, MDC-19-V, MDC-25, and MDC-25-V mixes, the design criteria were fulfilled for any traffic level according to the authors of [74], while for the MDC-19-M and MDC-25-M mixes, these were only fulfilled for low traffic levels (80 kN equivalent single axle load (ESAL) $< 5 \times 10^5$). S, F, Va, VFA and VMA are stability, flow, air void content, voids filled with asphalt and voids in mineral aggregate, respectively.

The greater absorption of RCA particles and the greater viscosity and stiffness of the modified asphalt binder caused the mixes to undergo increases in Va and reductions in VFA. Despite the above, these volumetric changes were minor when the replacement of NA with RCA was carried out by volume. This occurred because of the entry of a lower quantity of RCA particles when replaced by volume. According to the ANOVA test, the mass and volume replacements of NA with RCA generated statistically significant volumetric changes. Additionally, based on the ANOVA test, a notable increase was observed in

the S and S/F parameters when the replacement was carried out by volume and when modified asphalt binder was used. This increase in resistance was mainly due to the greater stiffness of the modified asphalt binder. Contrary to the above, the replacement of NA with RCA according to mass produced mixes with a level of resistance under a monotonic load in the Marshall test that tended to be lower in comparison with the control mix. During the monotonic compression in the Marshall press, MDC-19-M and MDC-25-M mixes were more prone to failure because of the greater presence of mortar adhered to the RCA particles, and because of their greater porosity (higher V_a and lower VFA).

Figure 3. Marshall test results of MDC-19, MDC-19-M, and MDC-19-V: (a) V_a content; (b) VFA content; (c) stability—S; (d) S/F ratio.

Table 4. Values of Marshall test results in OAC.

Parameter	MDC-19 OAC = 5.5%	MDC-19-M OAC = 6.0%	MDC-19-V OAC = 5.5%	MDC-25 OAC = 5.0%	MDC-25-M OAC = 5.5%	MDC-25-V OAC = 5.0%
S (kN)	12.3	12.7	13.0	12.5	12.7	13.1
F (mm)	3.47	3.89	3.50	3.44	3.78	3.61
S/F (kN/mm)	3.53	3.26	3.71	3.65	3.35	3.64
V_a (%)	4.2	5.8	4.9	5.4	6.2	5.9
VMA (%)	16.6	18.9	17.1	16.6	18.2	17.0
VFA (%)	74.6	69.2	71.2	67.7	65.9	65.0

Figure 4. Marshall test results of MDC-25, MDC-25-M, and MDC-25-V: (a) Va content; (b) VFA content; (c) stability—S; (d) S/F ratio.

3.2. Resilient Modulus (RM) and Permanent Deformation Tests

The results of the RM tests are shown in Figures 5 and 6. According to the ANOVA test, the mixes that replaced the NA with RCA according to volume and used modified asphalt binder significantly increased their RM with relation to the control mixes. These increases were greater as the test temperature increased. The increase in RM was mainly due to the increase in stiffness of the modified asphalt binder.

On the other hand, when the replacement of the NA with RCA was carried out according to mass, the mixes that utilized modified asphalt tended to slightly increase the RM (except for MDC-19-M in 10 °C); however, said increases were not statistically significant according to the ANOVA test. On one hand, the modified asphalt binder helped to increase the RM in these mixes, but their greater porosity (greater Va and lower VFA), greater quantity of RCA particles to be coated with asphalt binder, and lower mechanical performance of RCA particles compared with NA, contributed to reducing it.

The permanent deformation test results are shown in Figure 7. It is observable that mixes with RCA and modified asphalt underwent a greater permanent deformation resistance in comparison with the control mixes. The above is consistent with the increase in stiffness of the modified asphalt binder. The replacement of NA with RCA according to volume helped to increase resistance to the phenomenon of rutting even more so, which was coherent with the increase of RM in these mixes. For the case of mixes where replacement was carried out according to mass, it is possible that the increase of number of contacts between particles could have helped to increase the permanent deformation resistance.

Figure 5. Resilient modulus MDC-19, MDC-19-M, and MDC-19-V: (a) 10 °C; (b) 20 °C; (c) 30 °C.

Figure 6. Cont.

Figure 6. Resilient modulus MDC-25, MDC-25-M, and MDC-25-V: (a) 10 °C; (b) 20 °C; (c) 30 °C.

Figure 7. Permanent displacement: (a) MDC-19, MDC-19-M, and MDC-19-V; (b) MDC-25, MDC-25-M, and MDC-25-V.

3.3. Fatigue Test

The results of fatigue tests are shown in Figure 8. An increase in fatigue resistance was observed in both gradations when NA was replaced with RCA according to volume and modified asphalt was used. This occurs because, generally, under stress-controlled conditions, the fatigue resistance of mixes increases with the increase in stiffness [52,77,87,88].

Other behavior was obtained when NA was replaced with RCA according to mass. The fatigue resistance of the MDC-19 control mix was similar to that of MDC-19-M. Regarding MDC-25, replacing NA with RCA according to mass reduced its fatigue life. The greater quantity of RCA particles to be coated with asphalt and the greater porosity and reduction of VFA could have influenced this response.

Figure 8. Fatigue curves: (a) MDC-19, MDC-19-M, and MDC-19-V; (b) MDC-25, MDC-25-M, and MDC-25-V.

3.4. Indirect Tensile Strength and Cantabro Tests

The results of the ITS and Cantabro tests are shown in Tables 5 and 6, respectively. Based on the ANOVA test, a notable reduction in the ITS-U, ITS-C, TSR, and ML parameters was observed when, in both gradations, the NA was replaced with RCA by mass and modified asphalt was used. The above is an indicator of loss of adherence, moisture damage resistance, and wear abrasion resistance. This was mainly due to the lower resistance to abrasive wear and crushing that RCA particles underwent. Additionally, gilsonite increased the viscosity of the modified asphalt binder, which could affect the adhesion between asphalt binder and aggregate. Despite this, both mixes of MDC-19-M and MDC-25-M presented TSR values that were superior to the minimum (80%) requirements of the [74] standard.

Table 5. Indirect tensile strength (ITS) test results.

Parameter	MDC-19	MDC-19-M	MDC-19-V	MDC-25	MDC-25-M	MDC-25-V
ITS-U (kPa)	1070.6	1026.7	1110.2	1111.4	1015.6	1151.9
ITS-C (kPa)	967.8	849.2	1002.3	958.9	827.7	1002.3
TSR (%)	90.4	82.7	90.3	86.3	81.5	87.0

Table 6. Cantabro test results.

Mass Loss—ML (%) at 500 Revolutions					
MDC-19	MDC-19-M	MDC-19-V	MDC-25	MDC-25-M	MDC-25-V
8.82	9.21	8.66	9.87	11.10	9.93

On the other hand, if replacement was carried out by volume, both ITS-U and ITS-C underwent statistically significant increases with relation to the control mixes (based on the ANOVA test). However, the TSR was similar, just like the ML. According to volume replacement, less RCA particles were introduced (compared with mass replacement), which could contribute to improving resistance in both tests.

4. Summary and Conclusions

Based on the results obtained, the following conclusions are drawn.

Just as was shown in the background information, gilsonite increases asphalt's stiffness, and RCA presents particles with a greater absorption and lower mechanical resistance in comparison with those of NA.

Replacing a mass of 21% (MDC-19) and 24% (MDC-25) for the coarse fraction of NA with RCA and using asphalt cement (AC 60–70) modified with gilsonite is not advisable, given that (i) it increases the asphalt binder content and porosity of mixes; (ii) the asphalt mix design allows for their use in roadways with low traffic volumes; (iii) it reduces resistance under a monotonic load (reduces S, S/F, ITS-U, and ITS-C parameters); (iv) reduces moisture damage resistance (reduces TSR) and abrasion resistance (increases ML); and (v) regarding MDC-19 gradation, it does not generate changes in fatigue resistance, but in MDC-25 it tends to reduce it. Despite the above, it could help to increase permanent deformation resistance in hot temperature climates and TSR values are coherent to the minimum values required by the standard.

Contrary to the above, replacing NA particles with RCA according volume and using modified asphalt could generate the following benefits: (i) it increases asphalt mix resistance under monotonic and cyclic loads (increases S, S/F, ITS-U, ITS-C, and RM parameters, as well as permanent deformation resistance and fatigue resistance under stress-controlled conditions), without increasing the asphalt binder content; (ii) the mix design allows for its use in roadways with any level of traffic; and (iii) in comparison with control mixes, it maintains its moisture damage resistance and abrasion resistance.

The previously described benefits of MDC-19-V and MDC-25-V mixes can be recommended for comprising the thick asphalt layers (greater than 4 inches) in hot temperature climate pavements. However, in low temperature climates and thin asphalt layers (less than 2 inches), the high stiffness of these mixes can cause fatigue cracking.

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