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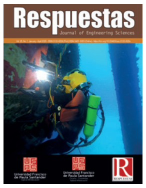

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RESPUESTAS

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Mechanical behavior of a hot micro agglomerate type mf-10 with recycled rubber grain

Comportamiento mecánico de un microaglomerado en caliente tipo mf-10 con grano de caucho reciclado

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ABSRACT

In Colombia, different investigations of hot dense asphalt mixtures with recycled rubber grain mixtures have been carried out, however, it is the first time that the mechanical behavior of a micro agglomerate with GCR additions is analyzed due to the unusual application of this type of Mix in road works. The main objective of the research is to analyze the mechanical behavior of a hot micro agglomerate type MF-10, through the transformation of recycled rubber grain, characterize the materials used as the GCR and the modified asphalt type III, design micro agglomerates with and without connection of hot recycled rubber grain type MF-10 using the Marshall methodology with IDU 2011 specifications and determine the optimal percentage of recycled rubber grain for a micro agglomerate that has a better mechanical performance. For the investigation the Marshall methodology was used to design the different mixtures of micro agglomerates with and without additions of GCR, the verification tests thereof which are: Adhesion, plastic deformation, fatigue laws, resilient module, dynamic module and coefficient of slip resistance. With the addition of recycled rubber-GCR grain, the mechanical behavior of the asphalt mixture is improved by improving its useful life as well as contributing to the environment by recycling disused tires. An improvement of the mechanical behavior of the micro agglomerate is obtained in terms of increased adhesion, decreased hollowness, greater fatigue resistance, better resilient modulus and increased coefficient of slip resistance. The results of the research affected the design and construction of Colombia's roads, being its main use the rehabilitation of layers of rolling, having as an agent improving the mixture, the recycled rubber grain.

Keywords:

Modified asphalt type III,
recycled rubber grain - GCR,
hot micro agglomerated,
resilient modules,
dynamic modules

RESUMEN

En Colombia se han realizado diferentes investigaciones de mezclas asfálticas densas en caliente con adición de grano de caucho reciclado, sin embargo, es la primera vez que se analiza el comportamiento mecánico de un microaglomerado con adición de GCR debido a la inusual aplicación de este tipo de mezcla en obras viales. El objetivo principal de la investigación es analizar el comportamiento mecánico de un microaglomerado en caliente tipo MF-10, mediante la incorporación de grano de caucho reciclado, caracterizar los materiales empleados como el GCR y el asfalto modificado tipo III, diseñar microaglomerados con y sin adición de grano de caucho reciclado en caliente tipo MF-10 mediante la metodología Marshall con especificaciones IDU 2011 y determinar el porcentaje óptimo de grano de caucho reciclado para un microaglomerado que presenta un mejor comportamiento mecánico. Para la investigación se empleó la metodología Marshall para realizar el diseño de las diferentes mezclas de microaglomerados con y sin adición de GCR, los ensayos de verificación de las mismas los cuales son: Adherencia, deformación plástica, leyes fatiga, módulo resiliente, módulo dinámico y coeficiente de resistencia al deslizamiento. Con la adición de grano de caucho reciclado- GCR se mejora el comportamiento mecánico de la mezcla asfáltica aumentando su vida útil además de contribuir al medio ambiente al reciclar las llantas en desuso. Se obtiene un mejoramiento del comportamiento mecánico del microaglomerado en cuanto a: aumento de adherencia, disminución del ahuellamiento, mayor resistencia a la fatiga, mejor módulo resiliente y aumento del coeficiente de resistencia al deslizamiento. Los resultados de la investigación contribuyen significativamente al diseño y construcción de las carreteras de Colombia, siendo su principal uso la rehabilitación de capas de rodaduras, teniendo como agente mejorador de la mezcla, al grano de caucho reciclado.

Palabras Clave:

Asfalto modificado tipo III,
grano de caucho reciclado – CR,
microaglomerado en caliente,
módulos resilientes,
módulos dinámicos.

Introduction

At present, there is an environmental problem related to waste that is not recycled and in turn is accumulated without any type of control; this is the case of car tires, their management generates great concern for their negative impact on the environment and human health, as they are considered solid waste and are generally buried, stored, incinerated and thrown into rivers and seas.

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The infrastructure and road construction sector, where GCR has been implemented as an asphalt mix improver either as an aggregate replacement (dry route) or as an asphalt cement modifier (wet route); Recently, asphalt mixtures have been evaluated with the addition of materials such as synthetic fibers [1], polyvinyl chloride PVC [2], and blast furnace slag [3], among others, in addition to improving the properties of the pavement, where better responses to thermal changes, increased fatigue strength, resistance to plastic deformation are achieved, increasing the life of the pavement and reducing maintenance costs during the service period of the structure. [4].

In response to the high levels of traffic and in order to contribute to the improvement of the mechanical properties of the pavement structure, the design of a discontinuous hot mix or hot micro-agglomerate was proposed, which is used to make a structural contribution to the wearing course, providing greater durability by presenting very good resistance to ageing, deformation and cracking, due to the type and quantity of binder used [5]. A microagglomerate contributes or restores pavement surface characteristics, its main use being in rehabilitation of wearing courses, with the rubber grain as a mix improvement agent. The analysis of a discontinuous mix or hot microagglomerate was proposed to establish the percentage of recycled rubber grain incorporated by dry route that would guarantee optimum performance of the mix with respect to its mechanical characteristics. To this end, we propose the design of four (4) mixtures type MF-10 made through the Marshall methodology, which was applied for the design of a conventional mixture and three (3) different mixtures with the addition of GCR by dry route, in variations of 0.5%, having mixtures of 0.5%, 1% and 1.5% modified with GCR.

In this article, the improvements in the mechanical behavior of micro aggregate asphalt mixtures are presented, such as fatigue resistance, increased rutting resistance [6], decreased thermal susceptibility, increased resistance to aging [7], reduced rolling noise by 1.5 to 2.0 dB [8] and increased pavement structure life.

This research project is registered with the Research Directorate of the Universidad Pedagógica y Tecnológica de Colombia - UPTC under code SGI-2543 and was carried out by the Road Infrastructure Research and Development Group - GRINFRAVIAL - of the UPTC's School of Transportation and Roads.

Materials and methods

To carry out the analysis of the hot discontinuous asphalt mix or micro agglomerate type MF-10 for a T2-T3 traffic level, initially the characterization of the materials that make up the mix was carried out, using the general technical specifications of materials and construction of the Institute of Urban Development of Bogota - IDU 2011.

Stone aggregate characterization

It is fundamental to characterize the stone aggregate for the design of the asphalt mix; in the fulfillment of the specifications it is necessary to have a demanding control with which the properties of the material are verified, in figure I the dosage for the micro agglomerate type MF-10 is evidenced for which stone aggregates of the department of Boyacá were used.

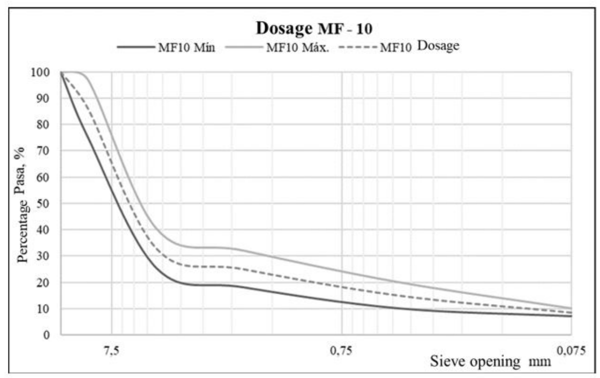

Figure 1. Particle size of the stone aggregate

Source: Authors based on IDU Technical Specifications, section 520-11.

Characterization tests

Once the granulometry and dosage of the stone aggregates had been defined, the laboratory tests were carried out for the coarse aggregate (Table I) and for the fine aggregate (Table II) in order to verify compliance with the requirements.

Table I. Characterization of coarse aggregate MF-10 mixture

TEST		TESTING STANDARD	REQUIREMENTS	OBTAINED	OBSERVATION
			T2-T3		
Hardness					
Wear out the Angels	Dry, 500 Revolution, % maximum	INV E-218	<30	19	COMPLY
Micro Deval, % Maximum		INV E-238	<25	10	COMPLY
10 % fine	Dry value, kN minimum	INV E-224	>75	146	COMPLY
Durability					
Losses in solidity test in magnesium sulphate % maximum		INV E-220	<18	5	CUMPLY
Geometry of Particles					
Mechanically Fractured Particles, % minimum	1 side	INV E-230	>75	100	CUMPLY
	2 sides		>60	96	CUMPLY
Flattening Rate, % maximum		INV E-230	<25	19	CUMPLY
Elongation Rate, % maximum		INV E-230	<25	20	CUMPLY

Table II. Characterization of fine aggregate mixture MF-10.

TEST	TESTING STANDARD	REQUIREMENTS	OBTAINED	OBSERVATION
		T2-T3		
Durability				
Losses in solidity test in magnesium sulphate % maximum	INV E-220	<18	4	CUMPLY
Geometry of Particles				
Angularity of the Fine Aggregate, % minimum	INV E-239	>45	48	CUMPLY
Cleaning				
Plasticity Index, % maximum	INV E-126	NP	NP	CUMPLY
Sand equivalent. Minimum %.	INV E-133	>40	52	CUMPLY

Characterization of asphalt cement

In the technical specifications of the Institute for Urban Development (IDU-2011) [9], it is proposed that the bituminous material for this type of mixture is polymer-modified asphalt cement. In the present investigation, the Type III asphalt binder was chosen for the design of the mix. For its characterization, the behavior of the binder was evaluated, according to the specifications as presented in Table III.

Table III. Characterization of type III asphalt binder.

Feature	Unit	Test Standard	TYPE III		Obtained	Observation
			Min.	Max.		
ORIGINAL ASPHALT						
Penetration	0.1 mm	INV E-706	55	70	59	CUMPLY
Softening point	°C	INV E-712	65	----	87	CUMPLY
Ductility	cm	INV E-702	15	----	29.5	CUMPLY
Elastic Recovery	%	INV E-742	70	-----	72.4	CUMPLY
Ignition point by open cup Cleveland	°C	INV E-709	230	-----	292	CUMPLY

The Brookfield rotational viscosity test was performed to obtain the mixing temperature (170°C) and the compaction temperature (150°C).

Characterization of the recycled rubber grain (GCR)

The recycled rubber grain GCR is a material obtained from the disused tires of motor vehicles [10]. For the design of the mixture with the addition of GCR, it was chosen to incorporate sizes belonging to the #10 and #40 sieves because, according to world literature, the maximum size of GCR directly influences its properties, and the smaller the rubber size (dust), the better the behavior of the mixture.

Chemical characterization of GCR

The tires contain a series of chemical components that influence the characteristics and behavior of the GCR obtained. Table IV shows these chemical components and their presence in percentage per tire [11].

Table IV. Chemical composition of the tires.

Element	% of composition
Carbon - C	70%
Hydrogen - H	7.0%
Sulphur - A	1.0%
Chlorine - Cl	0.5%
Iron - Fe	15%
Zinc oxide - ZNO	2.0%
Silicon dioxide - SiO_2	4.5%

Method of adding GCR to the asphalt mix

The addition of GCR to the batch mixture in this investigation was carried out by dry process. The dry process is the method by which the recycled rubber grain is mixed with the aggregates, prior to the addition of asphalt cement [12]. Although the rubber grains are treated as an aggregate, they cannot be considered an inert material as they interact with the asphalt mix binder. Figure 2 shows the incorporation of recycled rubber grains by the dry process [13].

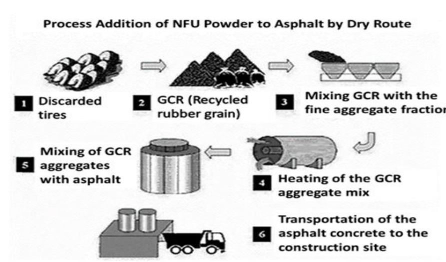

Figure 2. GCR incorporation process, by dry way.

Digestion time

It is a process to carry out an interaction between the asphalt binder and the GCR which is usually called "digestion" of the rubber. In the laboratory, digestion can be simulated by keeping the mixture in an oven, at a temperature in the range 150-170°C and a time of one to two hours, prior to mixing and compacting the test tube [14].

Methodology

To carry out the analysis of the mechanical behavior of the asphalt mixtures with and without the addition of GCR, after performing the characterization of the materials, the procedure indicated in Figure 3 was followed. For the Marshall methodology, 15 briquettes were made for each addition of GCR. In addition, 24 specimens were made for the adhesion test, 8 specimens for the determination of plastic deformation resistance, 32 briquettes for the determination of fatigue resistance, 24 briquettes for dynamic modulus tests, and two (2) specimens for the measurement of slip coefficient in dry and wet conditions.

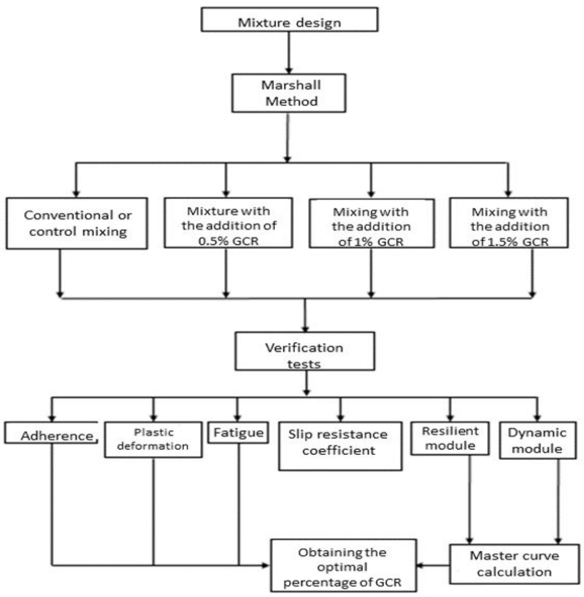

Figure 3. Methodology for obtaining the optimal percentage of GCR

Marshall method equations

The Marshall methodology considers the following design variables that are calculated by means of equations 1 to 9:

Bulk specific gravity of combined aggregate – Gsb

$$Gsb = \frac{100}{\frac{\%G}{Gsg}+\frac{\%F}{Gsf}+\frac{\%L}{Gsl}+\frac{\%GCR}{Gsgcr}} \quad (1)$$

Where,
G: Percentage of coarse aggregate.
F: Percentage of fine aggregate.
%L: Percentage of filler or mineral filler.
%GCR: Percentage of recycled rubber grain.
Gsg: Specific gravity of coarse aggregate.
Gsf: Specific gravity of fine aggregate.
Gsl: Specific gravity of filler.
Gsgcr: Specific gravity of recycled rubber grain.

Maximum Specific Gravity Rice – Gmm

$$Gmm = \frac{A}{A+B-C} \quad (2)$$

Where,
A: Dry sample mass (gr)
B: Vacuum pycnometer mass with the mixture and full of water (gr)
C: Water-filled vacuum pycnometer mass (gr)

Bulk Specific Gravity - Gmb

$$Gmb = \frac{Ab}{Bb-Cb(\frac{(Bb-Ab)}{Gp})} \quad (3)$$

Where,
Ab: Air dried briquette mass (gr)
Bb: Briquette mass with paraffin in the air (gr)
Cb: Briquette dough with paraffin dipped in water (gr)
Gp: Paraffin Specific Gravity

Effective specific gravity of the aggregate – Gse

$$Gse = \frac{100-\%\,Asf}{\left(\frac{100}{Gmmr}\right)-\left(\frac{\%Asf}{Gb}\right)} \quad (4)$$

Where,
Asphalt: Percentage of asphalt in the mix.
Gb: Specific gravity of the asphalt

Theoretical maximum specific gravity – Gmm

$$Gmm = \frac{100}{\frac{100-\%Asf}{Gse}-\frac{\%Asf}{Gb}} \quad (5)$$

Vacuum with air – Va

$$Va = \left(1 - \left(\frac{Gmb}{Gmm}\right)\right) * 100 \quad (6)$$

Asphalt volume absorbed – Vba

$$Vba = Gb * \left(\frac{Gse - Gsb}{Gse * Gsb}\right) * 100 \quad (7)$$

Effective asphalt content – Pbe

$$Pbe = \%\,Asf - \left(\frac{Vba}{100}\right) * (100 - \%Asf) \quad (8)$$

Dust ratio - R/p

$$R/p = \frac{\%\,Pasa\ \#\,200}{Pbe} \quad (9)$$

Master curve equations resilient module

To define the master curve of the resilient module, the following calculation expressions were used and are shown in equations 10 to 13.

Load application time – t

$$Log(t)=0.005*(h)-0.2-0.94*log(Vel) \quad (10)$$

Where,
t: Load application time, seconds
h: Asphalt layer thickness, cm
Speed: Design speed, Km/h

Load application frequency – F

$$Fr = \frac{1}{2*\pi*t} \quad (11)$$

Where,
Fr: Load application frequency, Hz

Equivalent or reference temperature – Tr

$$Tr = \frac{1}{\frac{1}{Te+273.15} - 4x10^{-5} * ln\left(\frac{Fr}{Fre}\right)} - 273.15 \quad (12)$$

Where,
Tr: Equivalent or reference temperature, °C
Tee: Test temperature, °C
Fr: Reference frequency, Hz
Fre: Test frequency, Hz

Resilient Module – Mr

$$Log(Mr)=k1[log(Trm)]^2+k2[log(Trm)]+k3 \quad (13)$$

Where,
Mr: Resilient Module, MPa
K1, k2, k3: Master curve calibration constants.
Trm: Temperature of the mixture - Tmix, °C

Master curve equations dynamic module

To define the master curve of the dynamic module, the following calculation expressions were used, which are shown in equations 14 to 18.

Asphalt Viscosity – η

$$log(log(\eta))=A+VTS*log(Trm) \quad (14)$$

Where,
η: Asphalt Viscosity, cP
Trm: Reference temperature Tmix, °R
A: Intercepting regression
VTS: slope of the regression curve

Temperature adjustment factor - Log(at)

$$log(at)=c(10^{(A+VTS*Log(Trm)}-10^{(A+VTS*log(Tro)}) \quad (15)$$

Where,
Log(at): Temperature adjustment factor
C: constant
Tro: Test reference temperature, °R

Load application time at the temperature of interest –Tr

$$log(Tr)=log(t)-log(at) \quad (16)$$

Where,
Tr: load application time at the temperature of interest
t: Load application time at test temperature
Horizontal translation coefficient – at

$$\log(at)=aT^2+bT+c \qquad (17)$$

Where,
at: Horizontal translation coefficient
a, b and c: Coefficients of regression
T: Test temperature, °F

Dynamic module - E*

$$Log(|E^*|) = \delta + \frac{\alpha}{1+e^{\beta+\gamma * log\,(tr)}} \qquad (18)$$

Where,
$|E^*|$: Dynamic module
δ: Minimum module value
$\delta+\alpha$: Maximum module value
β and γ: Parameters describing the shape of the sigmoidal curve

Results and analysis

Once the Marshall design was completed for each of the asphalt mixes, the values for the criteria required in the design specification were obtained. (Table V).

Table V. Marshall design results.

% GCR	0	0.5	1	1.5
Optimum % of Asphalt	5.5	5.8	6.1	6.3
Stability, N	11300	10520	8580	9995
% Voids with air	8	9	5.7	7.6
R/P dust ratio	1.6	1.56	1.6	1.7

The higher the GCR content of the asphalt mix, the higher the optimum percentage of asphalt is due to better interaction between the GCR and the other components of the mix.

The void to air ratio increases when the GCR ratio is 0.5% but decreases when the ratio is higher because of better interaction between the particles and thus decreases the void to air ratio of the asphalt mix.

The dust ratio decreases slightly with 0.5% GCR and remains constant until it reaches 1.5% addition values, for which the dust ratio increases because the effective weight of the asphalt and the absorbed asphalt is much higher.

The stability of asphalt mixes with GCR addition is decreased compared to the control mix because they contain a higher percentage of asphalt which leads to less load bearing capacity.

Verification Tests

After carrying out the Marshall design for each of the designed mixtures, the verification tests were carried out with which it was obtained (Table VI).

Table VI. Verification test results.

Item	Results obtained			
% GCR	0	0.5	1	1.5
Adherence %	81	85	90	97
Plastic deformation µm	2800	2730	2700	2600
Fatigue µm	1057	489	959	1201
Resilient module MPa	4872	4867	5191	6076
Dynamic module MPa	8790	7297	6717	8490
Slip resistance coefficient	0.65	0.66	0.68	0.69

The adhesion increases as the percentage of GCR added to the asphalt mix is higher, because the optimal percentage of asphalt also increases which generates a better coating of the particles and thus better adhesion between them.

The plastic deformation for GCR containing asphalt mixtures is lower because with percentages above 0.5% the rutting decreases considerably, this is because GCR provides a more solid mineral skeleton in which the air void percentages are lower as shown in Figure 4.

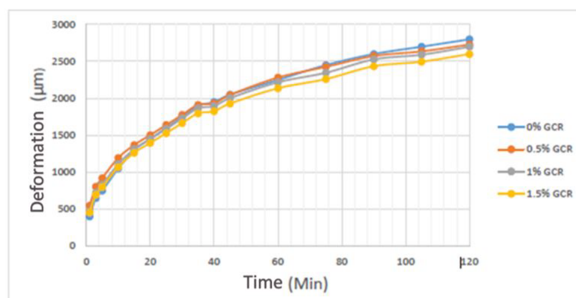

Figure 4. Plastic deformation.

For asphalt mixtures with an addition of 0.5% and 1% GCR, the deformations that they will withstand for a T2-T3 traffic level are less and this is due to the fact that the GCR particles present in the mixture behave in a way that is more susceptible to deformation by the action of traffic, but when the percentage of GCR is greater than 1. 3%, these particles interact with each other and in this way behave like a polymer, which allows a greater deformation by the action of vehicle loads.

Respuestas, 25 (1), pp. 6-14 , 2020, ISSN 0122-820X - E ISSN: 2422-5053

The deformation curves are shown in Figures 5 and 6.

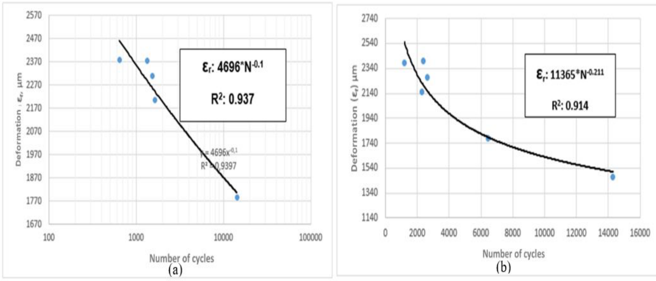

Figure 5. Deformation conventional mixture (a) and with 0.5% GCR (b)

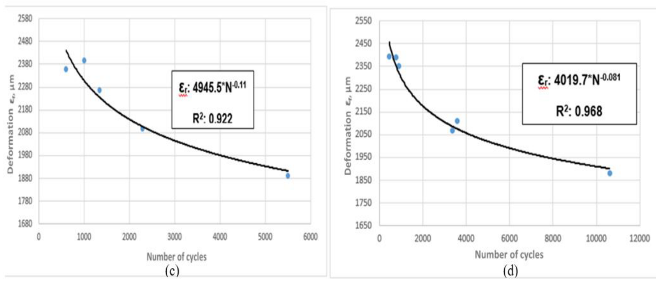

Figure 6. Deformation mixture addition with 1.0% (c) and 1.5% GCR (d)

The resilient module values were calculated for an estimated 10 cm thick asphalt pavement, an operating speed of 60 km/h and a weighted average annual air temperature of 13.3°C representative of the city of Tunja, Boyacá.

The resilient modulus of the asphalt mix increases when the GCR percentage is greater than 0.5%, due to the type of asphalt cement used to manufacture this mix since it provides this improvement when modified with polymer as shown in Figure 7.

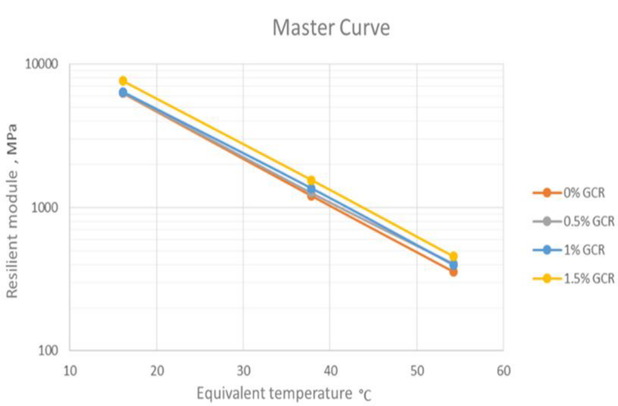

Figure 7. Resilient Module vs. Temperature master curves

The dynamic module (Figures 8 and 9) of the mixtures with addition of GCR does not present an improvement with respect to the control mixture, due to the fact that there is no clear trend in the behavior of the variable, so this variable will not be taken into account for the determination of the recommended percentage of GCR for a discontinuous mixture type MF-10.

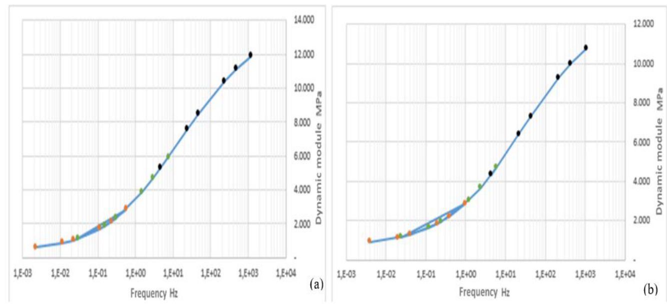

Figure 8. Master curves for conventional mixture dynamic module (a) and with 0.5% GCR (b).

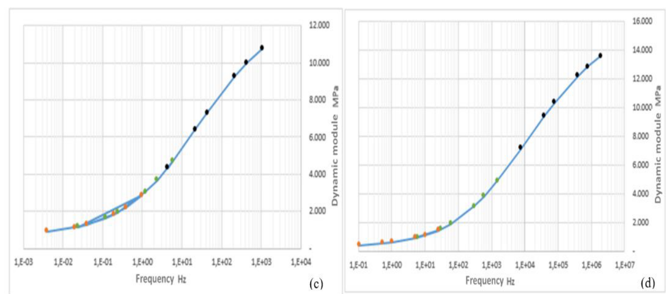

Figure 9. Master curve dynamic module with addition with 1.0% (c) and 1.5% GCR (d).

With the addition of GCR to the asphalt mix, the CRD is gradually improved which indicates that the higher the GCR content, the greater the slip resistance because GCR generates a surface with a greater micro texture.

Optimal percentage of recycled rubber grain for a hot mix type MF-10

The optimum percentage of GCR recommended for the MF-10 type hot mix is 1.4%, as it is the mid-point that contributes to the properties and behaviour of the mix by improving adhesion, rutting, fatigue, resilience modulus and the slip resistance coefficient compared to the conventional or control mix.

Once the evaluation of the different mechanical properties for each of the asphalt mixes analysed has been carried out, 1.4% GCR is considered as the optimum percentage of addition to a Type MF-10 asphalt mix, as shown in Figure 10.

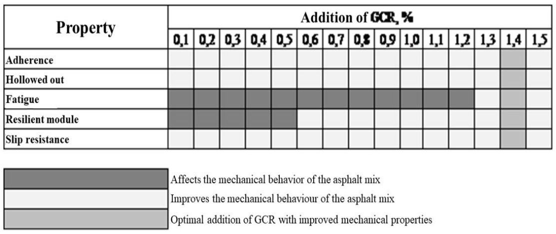

Figure 10. Obtaining the optimal percentage of GCR - MF-10 mixture

According to the results, this proportion presents the best performance of the asphalt mix, improving properties such as adherence, rutting, fatigue, resilient modulus and skid resistance, compared with the results obtained for asphalt mix without the addition of GCR or conventional, this in accordance with the requirements of the general construction specifications of the Institute of Urban Development of Bogota IDU-2011.

Conclusions

The materials used for the design of the MF-10 mixture were characterized meeting all the requirements of the general construction specifications of the IDU in its chapter 520-11. “Hot mix asphalt for wearing course”.

Likewise, the asphalt cement used in the design of the mixtures, which corresponds to a modified asphalt cement type III, was characterized and satisfactorily met the requirements of the IDU.

Four (4) MF-10 discontinuous mixtures were designed using the Marshall methodology, which was applied for the design of a conventional mixture and three (3) mixtures with the addition of recycled rubber grain in which the percentage of addition was varied having mixtures of 0.5%, 1% and 1.5% of this RGC.

The percentage of recycled rubber grain - GCR that is recommended for the design of a hot mix asphalt, type MF-10 micro agglomerate, to meet all the criteria and requirements specified by the IDU-2011 is 1.4% of the fine material that is between the sizes 2 mm and 0.075 mm which refers to the screens No. 10 and No. 40 respectively.

With the addition of recycled rubber grain -GCR, the mechanical behavior of the asphalt mixture is improved, increasing its useful life, as well as contributing to the environment by recycling disused tires. An improvement of the mechanical behavior of the micro agglomerate was obtained in terms of: increase of adherence, decrease of rutting, greater fatigue resistance, better resilient module and increase of the slip resistance coefficient.

The results of the research contribute significantly to the design and construction of the roads in Colombia, being its main use the rehabilitation of road surfaces, having as an improving agent of the mixture, the recycled rubber grain.

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Referencias

[1] O. Reyes and F. Reyes, “Comportamiento mecánico y dinámico de una mezcla asfáltica con adición de fibras”, *Ciencia e Ingeniería Neogranadina*, vol. 15, pp. 12-29, 2005. doi: 10.18359/rcin.1251

[2] H. Rondón, F. Reyes and B. Ojeda, “Comportamiento de una mezcla densa de asfalto en caliente modificada con desecho de policloruro de vinilo (PVC)”, *Ciencia e Ingeniería Neogranadina*, vol. 18, no. 2, pp. 29-43, 2008. doi: 10.18359/rcin.1487

[3] H. Rondón, J. Ruge, D. Patiño, H. Vacca, F. Reyes and M. de Farías, “Escoria de alto horno como sustituto de la fracción fina de agregados en una mezcla de asfalto”, *Revista de Materiales en Ingeniería Civil*, vol. 30, no. 10, 2018. doi: 10.1061/(ASCE)MT.1943-5533.0002409

[4] M. Ocampo, B. Caicedo and D. González, "Mezclas asfálticas mejoradas con caucho molido proveniente de llantas usadas". Universidad de Los Andes, Colombia, 2002.

[5] L. Salazar and L.Guillermo, "Formulación en laboratorio de microaglomerados discontinuos en caliente", etapa II, 2005.

[6] M. Karacasu, V. Okur and A. ER, "A Study on the Rheological Properties of Recycled Rubber-Modified Asphalt Mixtures", *The Scientific World Journal*, vol. 2015, no. 258586, 2015.

[7] Ministerio de fomento, Ministerio de medio ambiente, Centro de estudios y experimentación de obras públicas, "Manual de empleo de neumáticos fuera de uso en mezclas bituminosas". España, 2007.

[8] B. Vargas, "Introducción a la tecnología de los microaglomerados en frío y discontinuos en caliente. Universidad de Chile", Facultad de ciencias, física y matemáticas. Departamento de Ingeniería civil, Chile, 2000.

[9] Instituto de desarrollo urbano, "Especificaciones técnicas generales de materiales y construcción para proyectos de infraestructura vial y de espacio público", Cemento asfálticos modificado con polímeros. IDU, Sección, 202-211. 2011.

[10] C. Diaz and L. Castro, "Implementación del grano de caucho reciclado (GCR) proveniente de llantas usadas para mejorar las mezclas asfálticas y garantizar pavimentos sostenibles en Bogotá", Monografía de grado Ingeniero Civil, Universidad Santo Tomás, 2017

[11] E. Rodríguez, "Uso de polvo de caucho de llanta en pavimentos asfálticos", Boletín técnico. PITRA-Lanamme. UCR, 2016.

[13] Universidad de los Andes, "Estudio de las mejoras mecánicas de mezclas asfálticas con desechos de llantas-pista de prueba", Informe final contrato IDU-366-01. Alcaldía Mayor de Bogotá D.C. 2002.

[14] E. Rodríguez, "Uso de polvo de caucho de llanta en pavimentos asfalticos", Boletín técnico. PITRA-Lanamme UCR, 2016.