Ceramic waste in semi-dense asphalt mixtures: alternatives for low-traffic roads in Colombia

Residuos cerámicos en mezclas asfálticas semidensas: alternativas para carreteras de bajo tráfico en Colombia

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Resumen

La condición de la infraestructura vial en zonas rurales es precaria en países en vía de desarrollo y es común encontrar vías construidas utilizando materiales como concreto y en escasas ocasiones con pavimento flexible. En este estudio se propone el aprovechamiento de residuos cerámicos como agregados en porcentajes del 30% y 35% en mezclas asfálticas semidensas preparadas según los estándares del Instituto Nacional de Vías en Colombia. Se realizaron ensayos Marshall, de susceptibilidad, deformación y módulos dinámicos encontrándose que los reemplazos al 30% presentaron el mejor comportamiento para vías de bajo tráfico.

Palabras clave:

Carretera; Cerámica; Vidrio; Residuo; Asfalto; Diseño de Mezcla; Desarrollo Rural; Desarrollo Regional; Reciclaje; Tráfico Rural; Mejoramiento.

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Abstract

The condition of the road infrastructure in rural areas is precarious in developing countries and it is common to find roads built using materials such as concrete and rarely with flexible pavement. This study proposes the use of ceramic waste as aggregates in percentages of 30% and 35% in semi-dense asphalt mixtures prepared according to the standards of the National Road Institute in Colombia. Marshall tests of susceptibility, deformation and dynamic modules were performed, finding that 30% replacements showed the best behavior for low traffic roads.

Keywords:

Road; Ceramic; Glass; Waste; Residue; Asphalt; Mix Design; Rural Development; Regional Development; Recycling; Improvement.

1. INTRODUCTION

The world population has shown an exponential growth [1] affecting the consumption of resources and therefore, the production of waste with the consequent problems associated with the disposal. That is the case in Colombia, where at least 22,270,338 tons of construction and demolition waste per capita are produced per year [2]. This country is behind several developing countries regarding density, specifications, and maintenance of the road system, affecting not only people's quality of life but also causing lost revenues [3]. Because of that, government agencies are encouraged to invest in public works [4] as such as highways, hospitals, schools, housing, sewer systems, waste water treatment systems, water supply systems, among many others [5]. It is a fact that transportation infrastructure is key to ensuring the development of economic and social activities and the cohesion of populations [6], however, the design and construction of these projects face difficult challenges such as shortage of materials.

Due to this fact, alternatives such as the return of materials to the production processes have emerged [7], recycling, reusal, disposal of non-recoverable material, the consumption of recycled material prepared with an industrial treatment, the reduction of resource consumption, [7] among other initiatives, are being used in the improvement of pavements. It should be noted that various methods can be used for the conditioning of the coating, such as hot dense mixes, hot open mixes, hot demi-dense mixes. This study focuses on the analysis of the behavior of hot dense mixtures in which ceramic industrial waste has been introduced. It must be made clear that in recycling new products are made [8] while in reuse, the same product is reused several times during multiple uses [9]. Considering that the activities of construction, maintenance and rehabilitation of roads depend on non-renewable resources [7], the incorporation of certain waste in road construction processes can generate significant benefits.

For example, waste and plastic residues have been used as a modifier in asphalt mixtures [10] and ceramic residues [11][12] with results that have shown up to 13.5% higher elastic modulus than a conventional asphalt mixture [13].

It is irrefutable that the progress of a region evidenced by different aspects and connectivity conditions makes part of them [14].

This connectivity is achieved by different terrestrial, aquatic, or aerial means, but terrestrial means consisting of roads and unpaved roads are the most common. Around 90% of the roads worldwide are paved using asphalt [15], which is why the consumption of different types of this product reaches 100M t annually worldwide [7].

In the case of Colombia, a developing country, the armed conflict for over a period close to six decades [16] has had an impact on socio-economic, political, and cultural conditions [17] mainly in the rural areas where around 60% of the population is located, they are to use tertiary roads in order to reach the main roads through the [18] [14].

The construction and maintenance of the main roads of Colombia is the responsibility of the Nation, the secondary roads are managed by the Departments and the municipalities are in charge of the tertiary roads [19]. There are 206,708 km of roads of which 142,284 km correspond to tertiary roads [20]. According to the National Planning Department of Colombia, about 70% of tertiary roads have some type of pavement (e.g. plate footprint concrete) with regular condition and the rest is natural or land not passable [21].

The objective of this research is to evaluate the mechanical behavior of hot semi-dense asphalt mixtures prepared with the replacement of 30% and 35% of stone material with ceramic waste. This alternative is presented as a solution for the disposal of this kind of waste in Colombia and for the improvement of mobility conditions on low traffic roads. The study responds to questions about the compatibility of the use of these waste as aggregate for binder by standardizing mechanical tests that allow the validation of the use in asphalt mixtures.

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2. METHODS

In this study the mechanical behavior of a semi-dense asphalt mixture of maximum size 25 mm (MSDC-25) was evaluated, with aggregates extracted from the source of "Pescadero", near the Chicamocha river 50 km far the city of Bucaramanga (Colombia), making a replacement of the stone material in percentages of 30 and 35% by ceramic waste. The used methodology is shown in Figure 1.

The preparation of the asphalt mix followed the General Specification of Highway Construction 450 (Hot asphalt gradation mixtures continues) of the National Road Institute of Colombia, INVIAS [22], a reference source that is organized in articles that follow the provisions established by international standards, including the American Standard Testing Methods.

The characterization of the stone, ceramic and bituminous material (Table 1) was carried out following the quality standards for it. Regarding binder material, the performed tests are suggested in the different standards of quality control, allowing
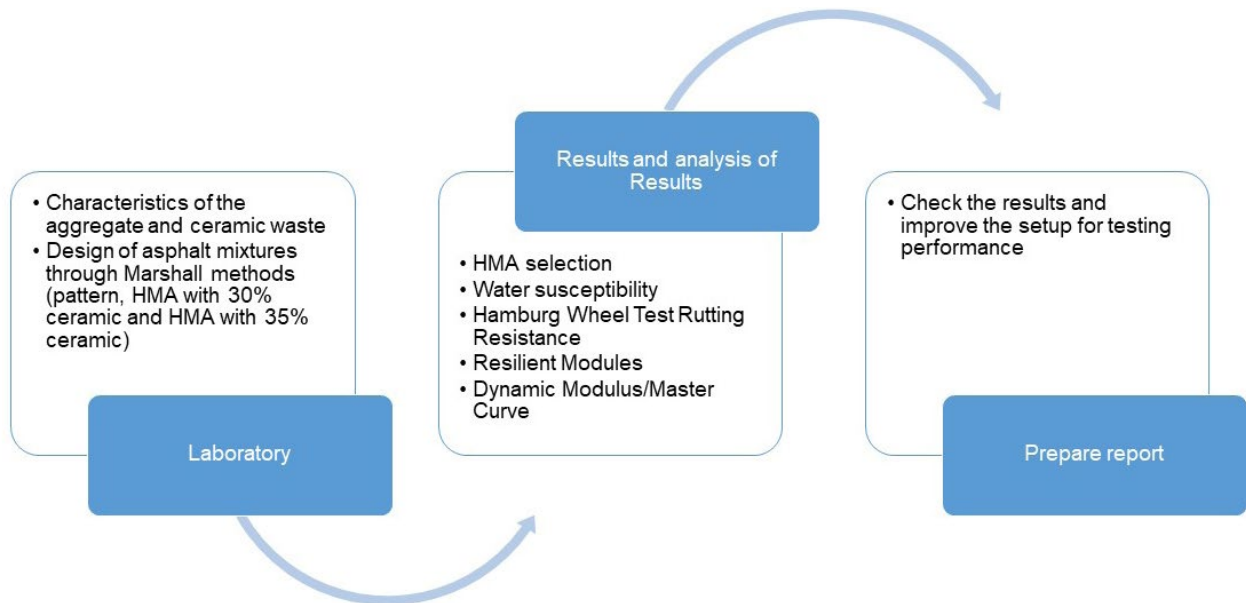

Fig. 1: Methodology

the characterization. Likewise, mechanical tests were performed on asphalt mixtures for the analysis of their mechanical behavior and the response to the effect of water.

Figure 2 shows the working formula of the standard granular material and the modified granular material according to the different ceramic proportions. In addition, the upper and lower limits recommended for this type of material are included. In Figure 2, the asphalt mixes were prepared according to the following considerations:

- Standard mix corresponds to 22% of ¾", 8% of ½" and 70% of sand.

- Material granular 1: 15.4% of ¾", 5.6% de ½" and 49% of sand, 9% of thick ceramic, and 21 % of ceramic sand

- Material granular 2 2:14.7% of ¾", 4.9% de ½" and 45.5% of sand, 10.5% of thick ceramic, 24.5 % of ceramic sand.

- Superior Limit for aggregates in asphalt mix according with Colombian´s standard (INVIAS).

- Inferior Limit for aggregates in asphalt mix according with Colombian´s standard (INVIAS)

Table 1. Aggregates and asphalt characterization standards

Aggregate Characterization				
Hardness				
Characteristics	ASTM and other standards	Norma INV	Maximum	Minimum
Resistance to degradation in the Los Angeles machine (% Losses) (500 rev)	ASTM C 131 -06	E-218	35	
Abrasion degradation in Micro-Deval equipment (%)	ASTM D6928-17, ASTM D7428-15	E-238	30	——
Mechanical resistance by the 10% fine method Dry Value (kN) Wet / Dry Ratio (%)	ASTM D 7428-08	E-224	——	——
Durability				
Lost in solidity test on magnesium sulfate, fine and coarse aggregates (%)	ASTM C 88-99a	E-220	18	——
Cleaning, coarse aggregate				
Organic Impurities in aggregate (%)	ASTM C40−04	E-237	0.5	——
Cleaning, combined gradation				
Plasticity Index (%)	ASTM D4318	E-125 y E-126	NP	NP
Sand Equivalent (%)	ASTMD2419	E-133	——	50
Particle geometry, coarse aggregate				
Flat and elongated particles (%)	ASTM D4791−10	E-240	10	——
Fractured faces (%)	ASTM D5821−13	E-227	——	75
Particle geometry, fine aggregate				
Fine Aggregate Angularity (%)	ASTM C1252	E-239	——	40
Density of aggregates				
Relative density of fine aggregate SH and Fine aggregate absorption (%)	ASTM C-128-01	E-222	——	——
Relative density of coarse aggregate SH and Absorption of coarse aggregate (%)	ASTM C-127-07	E-223	——	——
Asphalt Characterization				
Characteristics	ASTM and other Standards	Norma INV	Maximum	Minimum
Penetration, 0.1mm	ASTM D 5- 06	E-706	70	60
Softening point °C	ASTM D36/D36M-09	E-712	54	48
Indicator of Penetration	NLT 181/99	E-724	0.6	-1.2
Viscosity (60 °C), Pa-S	AASHTO T 316-06	E-717	different value for each asphalt——	0
Ductility, cm	ASTM D113-07	E-702	——	100
Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester	ASTM D 92-11	E-709	——	230

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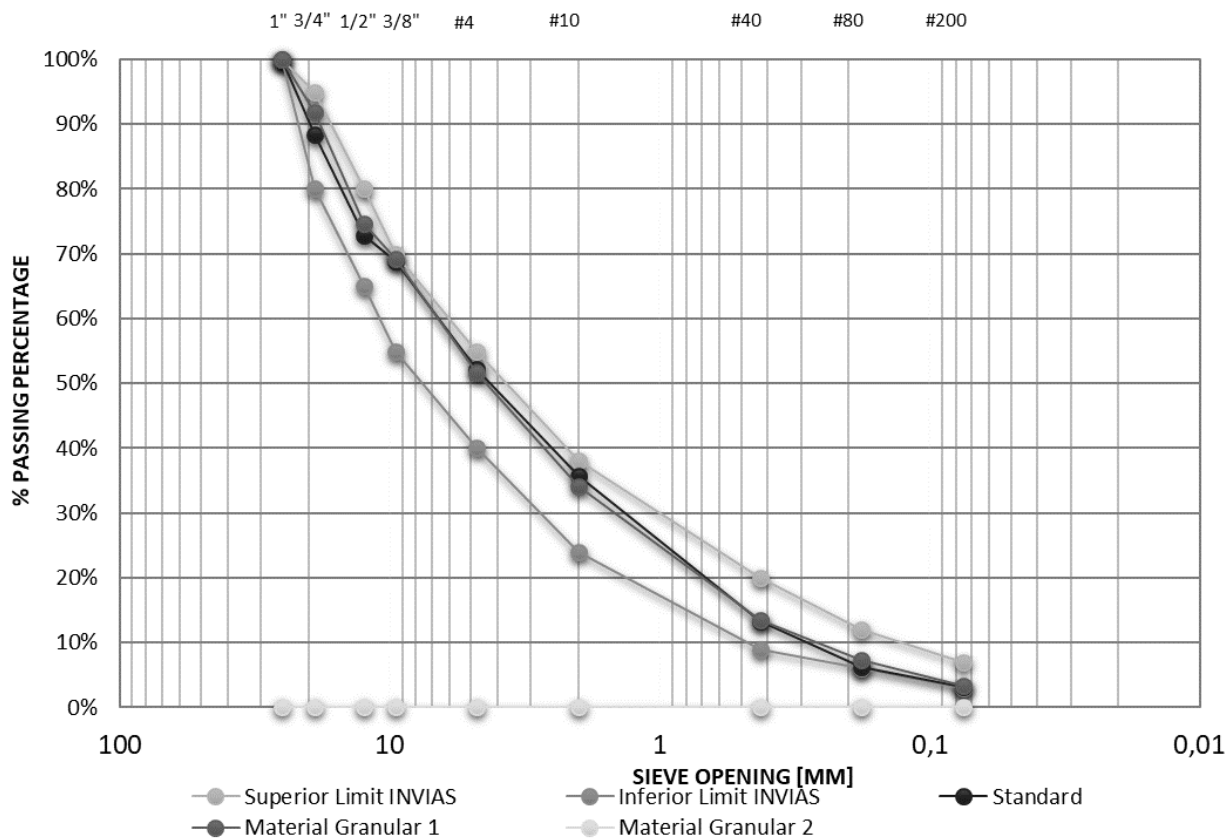
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Fig. 2: Formula Standard and Modified Asphalt Mixtures

For the design of the asphalt mixture, 15 specimens were prepared for each replacement percentage following INV E-748-13 (ASTM D6926-10 / ASTM D 6927-06) determining the optimum percentage of asphalt. Additionally, the Indirect tensile stiffness modulus test was carried out following the INVE-725-13 (ASTM D4867 / D4867 M-09), rut depth with the Hamburg wheel tracking (AASHTO T324-04) and the resilient modulus according to (UNE-EN 12697-26) [23] [24] and AASHTO T342 – EN 12697-26D where the behavior of the asphalt mixture is analyzed at two temperatures (10ºC and 30ºC) and three frequencies (10HZ, 5Hz. 2.5Hz).

3. RESULTS

The semi-dense asphalt mix consists of stone material and bituminous material. In this case, an inert ceramic residue is incorporated. The results of the characterization of the stone material and the bituminous material are summarized in Table 2 and compared with table 450-3 of the INV-13 standard, especially with Traffic Level 2, NT2 or Intermediate of the three Level of Traffic in Colombia.

Table 2. Results of aggregates and asphalt characterization standards

Material Granular			
Test (Unidad)	**Limit proposed by the standard (Intermediate layer NT2)**	**Natural aggregate**	**Ceramic aggregate**
Resistance to degradation in the Los Angeles machine (% Losses)	Max 35%	25,38%	27%
Resistance to degradation in the Micro-Deval apparatus (% Lost)	Max 30%	6.91%	8%
Determination of the value of 10% of fines (intermediate, NT2)	Dry value min 90 (KN)	210 KN	280 KN
* For NT2 there are no requirements for 10% fines *	Min Wet / Dry Ratio: 75 (%)	67%	93%
Aggregates solidity against the action of sodium or magnesium sulfate solutions (% Lost)	Max 18%	5.41%	10.54%
Surface cleaning in the aggregate (surface cleaning coefficient)	Max 0.5%	0.41	0.2
Liquid soil limit	Not Present	–	–
Sand equivalent	Min 50%	66	86
Proportion of flat and elongated particles 1: 5 ratio (%)	Max 10%	1.25%	0.50%
Fractured surfaces (%)	Min 75%	94.67%	100%
Angularity of fines (Percentage of uncompacted voids)	Min 40%	42.92%	36.62
Asphalt or Binder			
Test (Unidad)	Limit proposed by the standard (Asphalt 60-70)	Results	
Penetration (mm)	Between 60 and 70	63.5	
Softening point (°C)	Between 48 and 54	60	
Penetration rate	Between -1.2 and 0.6	1.66	
Absolute Viscosity at 60°C [P]	Min 1500	4334.8	
Ductility [cm]	Min 100	128	
Flash point [°C]	Min 230	280	

In relation to asphalt mixtures, the optimum asphalt content was determined considering the technical specifications for stability, flow (Figure 4) and percentage of air voids, reaching 6% asphalt as optimal for the control mixture and for 35% ceramic, 5.8% for 30% and 5.6% for 0% or Standard. (Figure 3 and Figure 4).
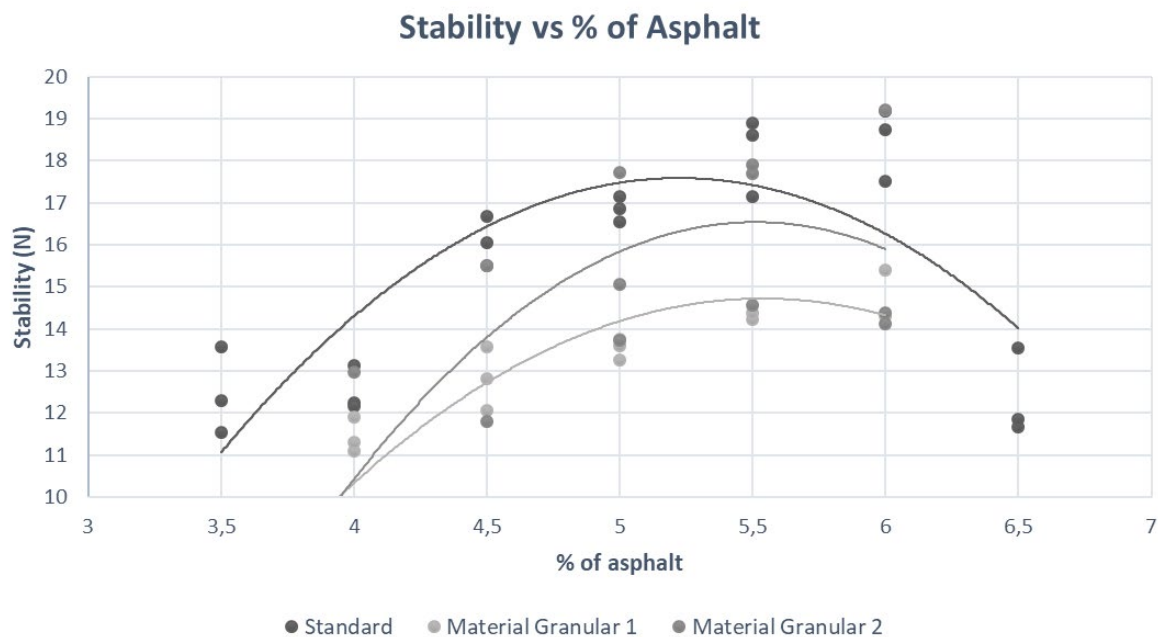
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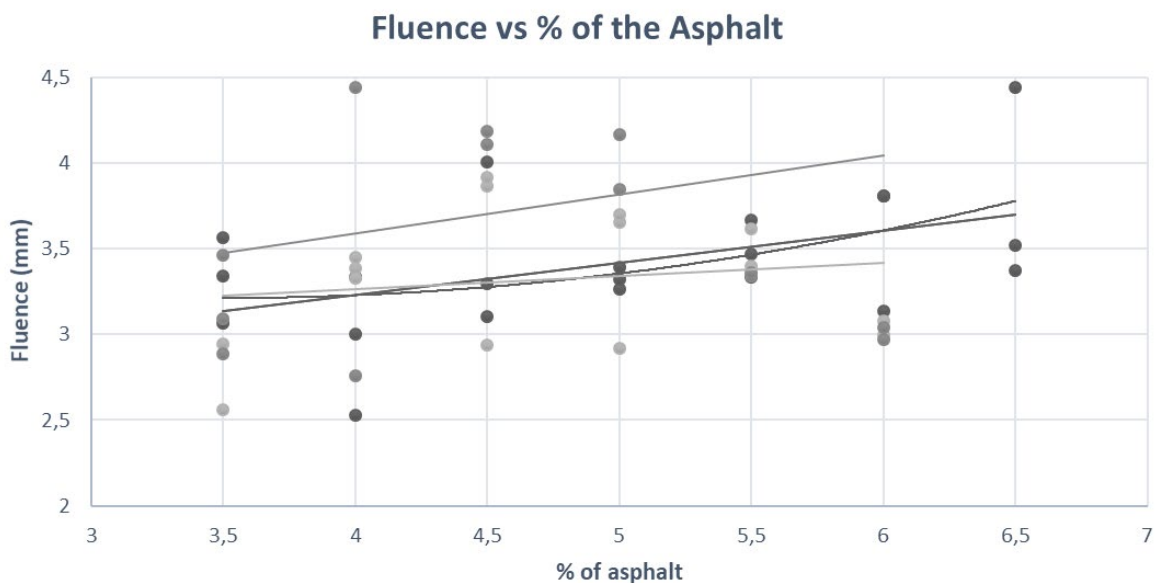
Fig. 3: Stability vs. % of asphalt

Fig. 4: Fluence vs % of asphalt Marshall Mix Design HMA

The results of the water susceptibility test of asphalt concrete mixtures is essential for making decisions regarding the use of the mixtures. Table 3 summarizes the behavior of the evaluated mixtures, which meet the standards required according to Art. 450 of the INVIAS standards [22] in table 450-11.

Table 3. Results of mix characterization aggregates and asphalt

Characteristic (Unit)	Limit proposed by the standard (NT2 intermediate layer)	Result of Design Marshall Standard HMA Optimal Asphalt	Result of Design Marshall HMA with 30% ceramic Optimal Asphalt	Result of Design Marshall HMA with 35% ceramic Optimal Asphalt
		5.60%	5.80%	6.00%
Compact (pushes/face)	75	75	75	75
Stability min (N)	7500	17418	14324	15900
Flow (mm)	2 a 4	3.46	3.03	3.77
Relation stability / flow	3 a 5	4.76	4,72	4,60
Air voids (%)	4 a 7	4.72	6,50	6,55
Voids in the aggregate mineral (%)	Mínimo 15%	15.97	16.64	15,56
Vacuum filled with asphalt (%)	65 a 78	70.36	66.89	69.94
Fill ratio / effective binder in weight	0.8 a 1.2	0.86	0,92	1,07

The results of the water susceptibility test of HMA by indirect tensile test are essential for making decisions regarding the use of the mixture. Table 4 summarizes the behavior of the evaluated mixtures, which meet the standards required according to Art. 450 of the INVIAS standards. The results were very similar in all mixtures.

Table 4. Evaluation of the water susceptibility of asphalt concrete mixtures using the indirect tensile test (tensile strength ratio (%))

Specification 450-13	Standard HMA	HMA with 30% ceramic	HMA with 35% ceramic
Min 80%	80.8%	80.9%	80.0%

As for the Hamburg Wheel Tracking Test (HWTT), it helps to evaluate the behavior of hot asphalt mixture to moisture susceptibility and rutting resistance of HMA. The result of the test is conditioned by the temperature, the stiffness of the asphalt cement, by the percentage of voids, number of load cycles, among others. Figure 5 allows comparing the response to the test in the three prepared asphalt mixtures. The asphalt mix with 30% ceramic was deformed 1 mm and that of 35% 1.12 mm that are increasing deformations but lower than those evidenced in the standard mixture (1.29 mm). It is

highlighted that these results are far from the maximum limit established by the specification, which indicates a very good performance of asphalt mix designs [34].

In relation to the dynamic module, a dozen specimens were made, four were evaluated at each temperature 10°C, 20°C, 30°C and 40°C. Table 5 shows the average behavior of the different mixtures. The asphalt mixture with 30% of ceramic has a better performance, while the mix with 35% ceramic has a behavior very similar to the standard HMA.

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The trend shows a differentiated increase and appropriate of the designs between the temperatures of test, indicating that, at a lower temperature, the modules are higher and at a higher temperature, the modules are lower. The 30% modified asphalt mix performs better compared to standard asphalt mix. Although the modified mixture with 35% obtained values slightly higher than the standard mixture. The difference of the averages of the dynamic modules with that of 30% varies between 35 and 54%, showing a marked superiority with the standard. The above coincides with the results obtained by Silvestre et al. [12] where they recommended using the 30% percentage and discarding the 50% percentage.

It is important to mention, this investigation included the mixture with 40% ceramic, but it was ruled out due to overflow of specimens and non-compliance with the design requirements.

The maximum difference of the modules of the standard mix and that of the 30% ceramic was located at a temperature of 10 ° C and was on average 54%. This indicates according to the dynamic modulus test, at the highest point of difference between the performance of the standard asphalt mix and the ceramic modified asphalt mix, it could work up to approximately 150% of the total capacity obtained for a standard mix. While in the 40 ° C scenario, the two mixes have yields with a 35% difference, the modified asphalt mix could average 135% of the capacity achieved by the standard asphalt mix. The behavior of the 35% modified ceramic mix was like that of the standard mix.

The designed mixtures shown that while the temperature increases, there was a decrease in the values of the modulus of rigidity. Moreover, the standard mixture presented a decrease with respect to the dynamic modules of the modified mixture with 30%,
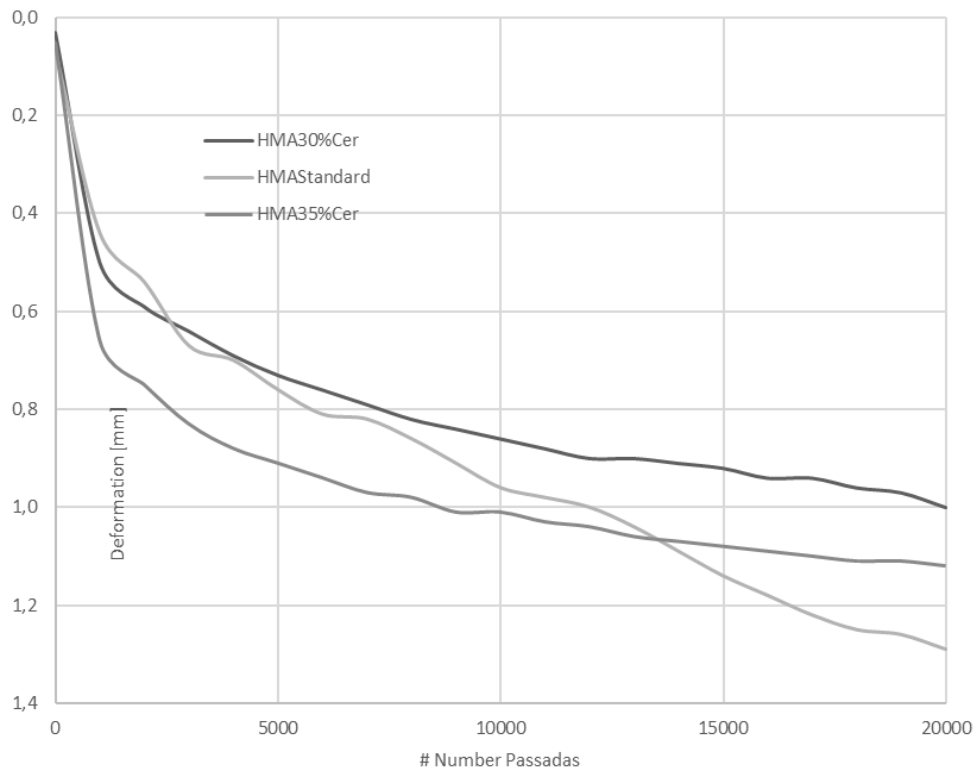

Fig. 5: HWTT responses in asphalt mixtures

fact that could be originated because of the ceramic residues with adequate characteristics to work on pavements.

For the highest frequencies, such as 25 Hz, the HMA specimens modified with 30% ceramics gave high values, like those obtained by Lara Ruiz, [31] in experimental data from tests of dynamic modules developed with different aggregates, including material from the same

department as those used in this research, so for future research it is recommended to consider fatigue tests to know the behavior to fracture. See Figure 6, 7, 8 show the behavior of the mixture under the action of loads, finding a higher dynamic modulus in the mixture with 30% ceramic residue (Table 5). On the other hand, it is convenient to emphasize that the results expressed here are consistent for the interaction of asphalt and aggregates used in this study.
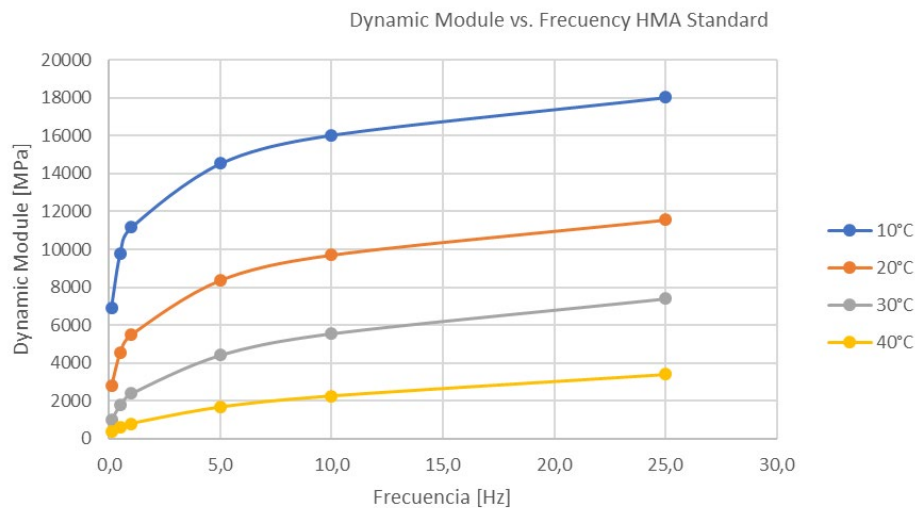

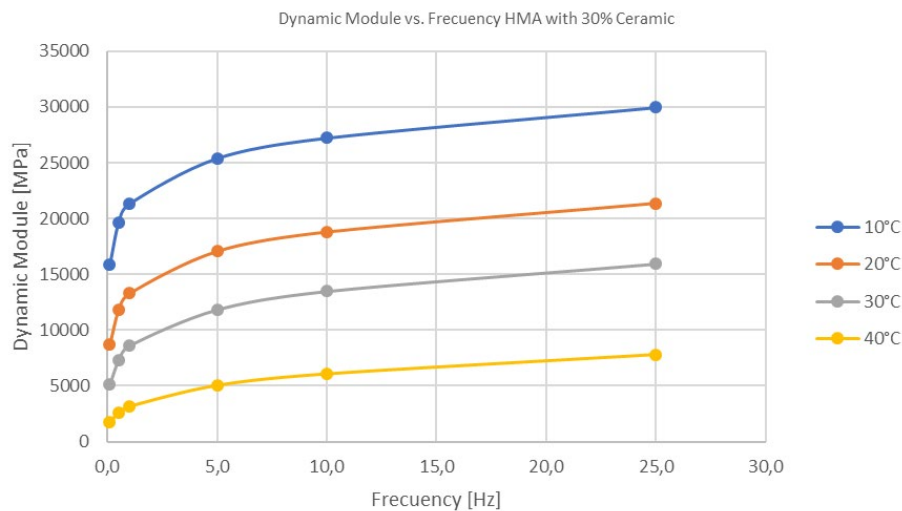**Fig. 6:** Performance of dynamics modulus HMA Standard

Fig. 7: Performance of dynamics modulus HMA with 30% Ceramic.

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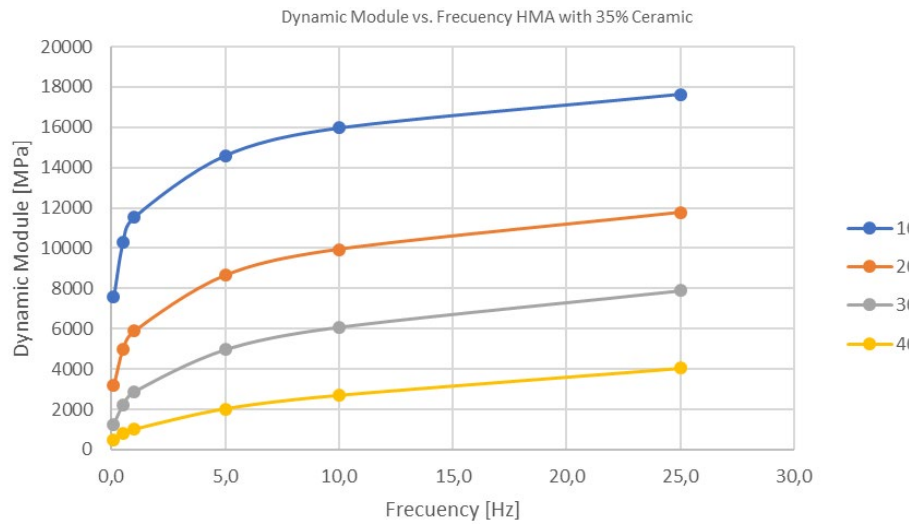
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Fig. 8: Performance of dynamics modulus HMA with 35% Ceramic.

Tabla 5. Results dynamic modulus (mpa) using test une-en-12697-26

HMA Standard Dynamic Module (MPa)						
Tempe-rature [°C]/Frecuency Hz	25	10	5	1	0,5	0,1
10	18036	16038	14534	11153	9800	6925
20	11554	9705	8376	5508	4564	2794
30	7403	5562	4423	2394	1794	992
40	3394	2256	1665	789	616	380
HMA with 30 % ceramic Dynamic Module (MPa)						
Tempe-rature [°C]/Frecuency Hz	25	10	5	1	0,5	0,1
10	29960	27218	25403	21326	19613	15824
20	21352	18782	17062	13291	11781	8699
30	15924	13475	11837	8619	7298	5135
40	7810	6081	5052	3167	2614	1707
HMA with 35 % ceramic Dynamic Module (MPa)						
Tempe-rature [°C]/Frecuency Hz	25	10	5	1	0,5	0,1
10	17642	15968	14600	11540	10272	7570
20	11768	9943	8655	5889	4965	3176
30	7886	6072	4960	2867	2207	1262
40	4037	2699	2029	1010	792	503

The usefulness of dynamic module trials is that they support the design and analysis of pavement structure performance. In most design methodologies, the dynamic modules resulting from the tests are used as input to know the performance of the layers.

Additionally, with the general sigmoidal equation and by means of the time-temperature overlay principle, the data of modules obtained from different temperatures and/or frequencies are adjusted to a master curve at a specific temperature, in this case 20°C (Figure 9, 10 and 11). In the horizontal axis, frequency (Hz) and the vertical axis Dynamic Modulus (MPa) The first figure is the standard HMA second figure is HMA with 30% ceramic and last is HMA with 35% ceramic.
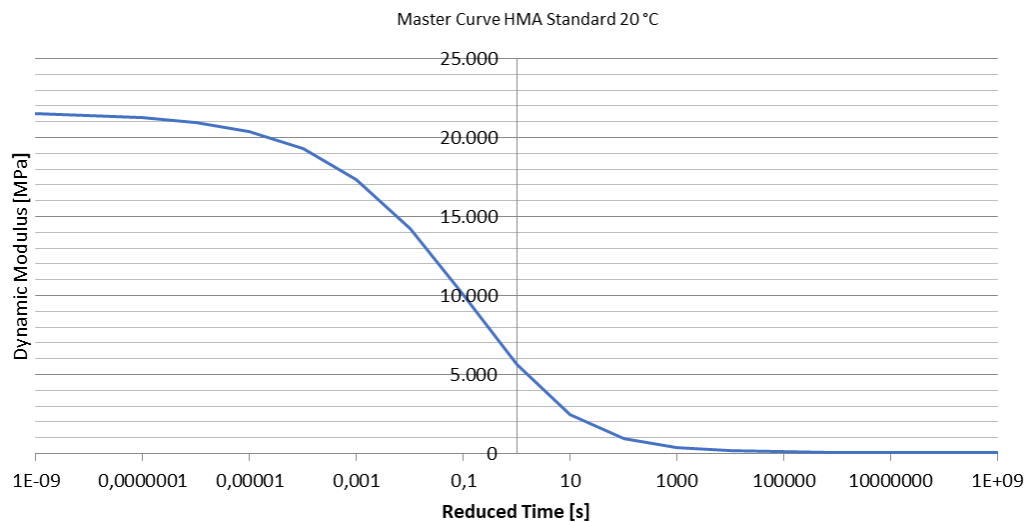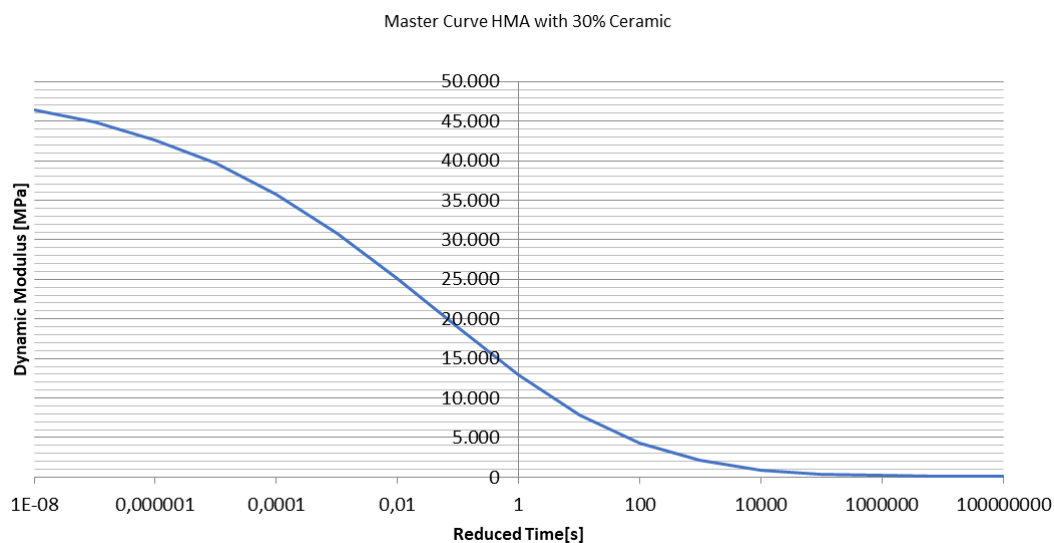

Fig. 9: Master Curve Standard HMA

Fig. 10: Master Curve HMA with 30% Ceramic

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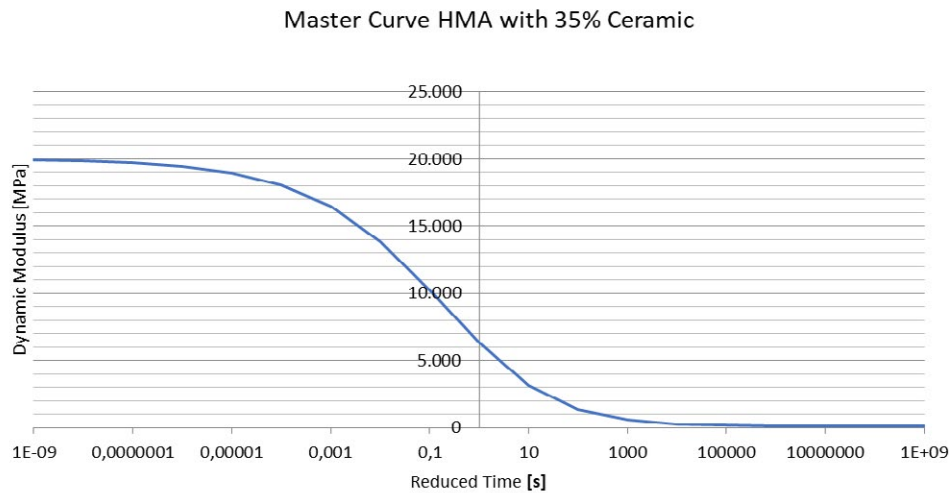
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Fig. 11: Master Curve HMA with 35% Ceramic

4. DISCUSSION

The waste utilization initiative is not recent. For example, there are traces of the use of ash dating from the second century BC, as well as the use of products such as steel and other metals that were recovered after the Second World War. More contemporary waste, such as glass that has been used in mixtures with substitutions between 15-40% [9] or brick that incorporated into the mixtures must have a compressive strength of not less than 41.4 MPa (6,000 psi) [25]. According to a report by The Federal Highway Administration (FHWA), it was estimated that, in the United States alone, a total of 123 million tons of construction waste was produced annually [26] Hence, inert waste reuse alternatives can contribute to the disposal solution of these materials. On the other hand, as it is well mentioned [8] a greater number of green publications are needed that reflect the benefits of materials generated with the use of waste from different industrial or domestic anthropic activities.

In this study, as in the one carried out by Silvestre et al. [12], it was established that a higher percentage of asphalt was required in Marshall's design for the modified asphalt mix than for the conventional asphalt mix and a better behavior of the mixture including ceramic in the test of determination of resistance to plastic deformation, among others. It is established that ceramic waste, widely used as modifiers in asphalt mixtures [27], [28], [29], and in particular, as a substitute for a percentage of the aggregate [30] can be used to the preparation of asphalt mixtures. In this way, it is ratified that the incorporation of recycled material into asphalt mixtures represents a significant contribution in the three E's: environmental, economics and engineering aspects [9].

This particular case of this study found that both the aggregates of the region and the ceramic material obtained from the Italian ceramic company presented characteristics that make its use feasible for the production of asphalt mixtures.

For practical purposes and a better approach to the production process of the mixtures, the granular material was separated into hoppers. As for the bituminous material, the increase in the percentage of asphalt required by the modified asphalt mixture can be explained in terms of the greater absorption of this product by the ceramics, with respect to aggregates of natural origin. On the other hand, both the conventional

and the modified mix met the maximum limit of plastic deformation (maximum 2.9 mm) and an adequate behavior of resilience at low temperatures.

5. CONCLUSIONS

The experimental work of selection and adjustment of the aggregate material, including that coming from natural conditions and the ceramic waste of the industry, was done by means of sand hoppers and thick hoppers distributed in the way as is done the production in plant of the asphalt mixtures. Both aggregate and bituminous material comply with the General Specification for Road Construction in its Article 410: "Supply of asphalt cement" that follow the standards of the American Standard Testing Methods and American Association of State Highway and Transportation Officials, AASHTO, and the Spanish Standardization Association, UNE.

Marshall's method was used to determine the optimal percentage of asphalt, finding that 5.6% corresponded to this value for the standard asphalt mixture, 5.8% for the 30% modified asphalt mixture and 6% for the modified mixture at 35%. Regarding the flow, it was found that both the standard and the modified asphalt mixtures ranged between 2mm and 4mm, as established in Art. 450 and the stability was also within the limits of the specification which translates into a better capacity in terms of which refers to the resistance of the traditional mixture or pattern against loads applied to it.

The water susceptibility test showed that all mixtures were at the minimum expected value for this test (80%), that is, in relation to this parameter the behavior is very similar in relation to the affectation generated by moisture to the performance of the conventional mixture. Regarding the Hamburg wheel, it was found that specimens with a high content of ceramic material sometimes disintegrated before completing the experimentation. However, the average behavior showed a plastic deformation below 2.9 mm. The resilient module test does not yield comparison

limits, but it was observed that the standard mixture behaved similarly to the modified mixtures 35% with ceramic.

From the study, it can be concluded, in general terms, that both the conventional asphalt mixture and the modified asphalt mixtures meet the mechanical conditions for use on medium to low traffic roads. However, the replacement of 30% of natural aggregates with aggregates of ceramic origin for an asphalt mix of the MSC-25 type that can be used in an intermediate layer of an asphalt pavement with an NT2 type transit is the most recommended for tertiary roads in Colombia.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest with any commercial institution or association.

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