Effects of Iron Ore Tailing on Performance of Hot-Mix Asphalt

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Márcio Muniz de Farias
University of Brasília

Hugo Alexander Rondón-Quintana
Universidad Distrital Francisco José de Caldas

Effects of Iron Ore Tailing on Performance of Hot-Mix Asphalt

Juan Gabriel Bastidas-Martínez[1]; Jose Camapum de Carvalho[2]; Leda Lucena Cristhiane[3]; Márcio Muniz de Farias[4]; and Hugo Alexander Rondón-Quintana[5]

Abstract: In Brazil, large quantities of iron ore tailings (IOT) are produced as a result of iron mining, which may affect the environment negatively. This work evaluated the use of IOT in hot mix asphalt type C (HMA-C). For this purpose, IOT was incorporated as a filler (at 1% in relation to the total mass of HMA-C). The hot asphalt mix with IOT (called HMA-IOT) was designed and compared with a control HMA-C. The behavior of the mixtures under monotonic (indirect tensile strength, ITS, and the Marshall stability test), under dynamic (fatigue and resilient modulus tests), and static (static creep test) loading conditions was evaluated. Also, the resistance to induced moisture damage (tensile strength ratio, TSR) was calculated. As a general conclusion, it was shown that the use of IOT in HMA improves its mechanical response without increasing mixing and compaction temperatures and using less effective asphalt binder content. This could provide a new form of environmentally safe disposal of IOTs. **DOI:** 10.1061/(ASCE)MT.1943-5533.0004034.

Author keywords: Iron ore tailings (IOT); Recycled material; Asphalt binder; Hot mix asphalt (HMA).

Introduction

Iron ore is the main materials used in the steel industry. This material is extracted from natural rocks with a predominance of iron oxides, such as magnetite, hematite, goethite, and siderite, among others (Kumar et al. 2015; Clout and Manuel 2003; Legodi and de Waal 2007). Iron is considered one of the most widely used minerals in the world (Dauce et al. 2019). Its extraction is carried out from the deposits by means of open-pit or underground activities. Subsequently, the iron ore beneficiation process is carried out from washing, crushing, grinding, homogenization, classification, and concentration activities, among others. As a waste material from this process, the iron mining residue, or iron ore tailings (IOT), is obtained. Finally, the iron ore extracted through industrial processes is transformed into different products from the steel industry. Worldwide, an estimated 800 billion tons of material to obtain iron is processed, from which approximately 230 billion iron ore can be extracted. The reserves are in countries such as China, Brazil, Australia, India, Russia, South Africa, Ukraine, the United States, and Canada, among others. In 2019, the production of iron ore reached 2.5 billion tons (Christopher 2019).

Iron mining in Brazil is an important activity that represents approximately 88% of the primary products exported and 4% of the Gross Domestic Product (Fontes et al. 2019). Even though iron mining contributes to economic and social development, great environmental impacts are generated during its extraction, which may negatively affect the preservation and conservation of the environment. Among the main potential environmental impacts generated are the contamination of water sources, air pollution, the destruction of ecosystems, and the generation of waste or tailings. On the other hand, there are effects on topography and relief, such as removals, landslides, or mass erosions. Therefore, IOTs are considered an environmental problem due to the large amounts generated and the large number of heavy metals they contain (Maiti et al. 2005). In Brazil, an approximate production of 379,000 t of IOT per day is estimated (Fontes et al. 2019). In 2016, the annual production of 184 million tons of IOT was reported (Fontes et al. 2018). The amount of IOT corresponds to half of the total amount extracted during mining operations approximately (Fontes et al. 2019). It is estimated that in the production of one ton of beneficiated iron ore, 400 kg of IOT are discharged (Dauce et al. 2019). According to data from the State Environmental Foundation of Brazil, the reuse rate of IOT is less than 10% (Carrasco et al. 2017). Otherwise, the presence of heavy metals in IOTs makes their use in the steel industry unfeasible.

Currently, IOTs are mainly used in the construction of containment dikes or dams. However, this type of use has produced some environmental catastrophes, recording the loss of human beings and animals and irreversible damage to the environment (Carrasco et al. 2017). Among the main dam breaking accidents with IOTs are the following: Anshan from Liaoning Province in China in 2007, killing seven people (Li et al. 2010); and in Brazil, the Bauxite dams in Barcarena, Pará state in 2009, Funda in Mariana in 2015, Bento Rodrigues in 2017, and Brumadinho in 2019 in the State of Minas Gerais. The previous accidents report more than 300 people

[1]Associate Professor, Faculty of Engineering, Universidad Católica de Colombia, Diagonal 46A #15B–10, Bogotá DC 110231, Colombia (corresponding author). ORCID: https://orcid.org/0000-0002-6818-0322. Email: jgbastidas@ucatolica.edu.co

[2]Full Professor, Faculty of Technology, Faculty of Engineering, Universidade de Brasília, Campus Universitário Darcy Ribeiro, CEP 70910-900, Brasília-DF, Brazil. Email: camapum@unb.br

[3]Full Professor, Departamento de Engenharia Civil, Faculty of Engineering, Universidade Federal de Campina Grande, Rua Aprígio Veloso 882, Universitário, Campina Grande-PB 58428-830, Brazil. Email: edach@uol.com.br

[4]Full Professor, Faculty of Technology, Universidade de Brasília, Campus Universitário Darcy Ribeiro, CEP 70910-900, Brasília-DF, Brazil. Email: muniz@unb.br

[5]Full Professor, Facultad del Medio Ambiente y Recursos Naturales, Universidad Distrital Francisco José de Caldas, Avenida Circunvalar sede Vivero UD, Bogotá DC 110131, Colombia. ORCID: https://orcid.org/0000-0003-2946-9411. Email: harondonq@udistrital.edu.co

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as dead and missing. More statistics on the accidents of dams built with IOTs can be consulted in the study by Wallingford et al. (2019). Other forms of use of IOTs are in the open-type sludge pool (Krivenko et al. 2019), recovery of degraded areas (Zhang et al. 2006), production of fertilizers (Maiti et al. 2005), and iron ore and metals extraction by magnetism processes (Li et al. 2010; Sirkeci et al. 2007; Zhang et al. 2020a). Given the large amounts of residues produced, the IOT can provide a variety of applications to replace stone aggregates for concrete and mortars, among others (Fontes et al. 2019). In this sense, the main applications make its use feasible as aggregates in concrete for rigid pavements and structural elements (Ananthayya and Vijay 2014; Gayana and Chandar 2018; Krivenko et al. 2019; Kumar et al. 2014; Ma et al. 2016; Shetty and Nayak 2014; Swetha et al. 2015; Uchechukwu and Ezekiel 2014; Ugama et al. 2014; Umara et al. 2016), cementitious materials (Fontes et al. 2018; Huang et al. 2013; Luo et al. 2016), mortars (Carrasco et al. 2017), subgrade of pavements (Bastos et al. 2016; Osinubi et al. 2016), soil improvement (Osinubi et al. 2015; Yohanna et al. 2019), aggregates and fillers in asphalt mixture (Wang et al. 2016; Widojoko 2013), prefabricated elements (Kuranchie et al. 2016; Sant´ana Filho et al. 2017; Ullas et al. 2010; Yisa et al. 2016), industrial ceramics (Fontes et al. 2019; Yao et al. 2015), polymers for water treatment (Duan et al. 2016), and paints (Galvão et al. 2018), among others. According to Zhang et al. (2013), residues with high iron, silica, and calcium contents, such as IOTs, can be used for the production of cement clinker.

Besides, IOTs can also be studied as a filler for the production of asphalt mixtures, helping to reduce the large amounts of waste produced and minimizing the carbon footprint and environmental impacts (Choudhary et al. 2020). The amount of filler in the hot mix asphalt (HMA) is relatively low (approximately 4% to 8% in mass); however, this material makes up between 70% and 90% of the surface area of the aggregate (Dan et al. 2014; Veytskin et al. 2015). In this sense, numerous studies have been supported with the aim of evaluating the chemical, physical, and rheological characteristics of the interaction between fillers and asphalt binders (Bastidas-Martínez et al. 2021; Huang et al. 2009; Zhang et al. 2020a, b). Some clay-based chemicals have been used in the new generation of asphalt additives (Ziari et al. 2014). The principal studies describe the use of hydrated lime (Lesueur and Little 1999), diatoms (Cong et al. 2012), montmorillonite (Fang et al. 2012), nano titanium dioxide (Hassan et al. 2011), nano clays (Jahromi and Khodaii 2009; Rasouli et al. 2018), bentonite (Ziari et al. 2014), tourmaline (Wang et al. 2015; Ye et al. 2019), phosphorous slag superficially treated (Qian et al. 2018), nanoceramics (Hussein et al. 2017, 2021), amorphous carbon from paraffin residue (Rodgers et al. 2010), metallic iron oxides (Giuffrè et al. 2018), and nanomaterials (Chen and Zhang 2012), among others. These works report the use of fillers as additives of asphalt modifiers by the wet process and asphalt mixtures via the dry process. The presence of filler particles generally provides increases in the stiffness of the asphalt binder, which is evidenced by variations in its physical and rheological characteristics. Furthermore, the authors report improvements in some characteristics of the asphalt mixes—mainly an increase in resistance to permanent deformation.

The main purpose of the present study was to evaluate the response that a determined HMA undergoes when manufactured with the additional incorporation of IOT as a mineral filler (1% with relation to the total mass of the mixture, 12 g). This IOT increased the total filler by 7.05%: conventional filler (6%) + IOT filler (1.05%). Only the additional content of a 1.05% alternative filler was evaluated to assess if a small content of IOT generates significant changes in the resulting HMA. This paper studies the technical feasibility of using IOT as additional filler material in HMA to find safe final disposal for these by-products and to contribute to the preservation and conservation of the environment. The hypothesis that supports this study is based on the properties of hematite (IOT's predominant mineral): low absorption, high thermal conductivity, and heat capacity, which can facilitate the workability and compaction process of HMA. In the literature reviewed, there was no information found matching the way this material was used in this academic work. Thus, this could be a new and alternative technique for disposing of IOTs.

Methodology

Materials

The asphalt binder AC 50/70 (0.1 mm penetration range, according to ASTM D5) and natural aggregate (limestone generally used for construction of HMAs in Brasilia D.F., Brazil) were characterized following a standard DNIT 031 (DNIT 2006). The test performed on the AC 50/70 were penetration (ASTM 2013), softening (ASTM 2006), penetration index (NTL 1988), viscosity (ASTM 2015), flashpoint (ASTM 2019), ductility (ASTM 1999), specific gravity (AASHTO 2018b) and the Rolling Thin-Film Oven Test RTFOT (ASTM 2012). The test performed on the natural aggregate were Abrasion in Los Angeles (AASHTO 2002b), Specific gravity—absorption (fine) (AASHTO 2000), Specific gravity—absorption (coarse) (AASHTO 1991), Specific gravity of filler (AASHTO 2003), Sand equivalent (AASHTO 2002a), Soundness using magnesium sulfate (AASHTO 1999), Shape index (DNER 1994b), Plasticity index (ASTM 2000), Fractured particles (ASTM 2001) and adhesion of aggregate to bituminous

Table 1. Test results properties AC 50/70

Test	Process	Unit	Specification	Result
Test on the original asphalt				
Penetration	ASTM D5	0.1 mm	50/70	51
Softening point	ASTM D36	°C	46 minimum	52.0
Penetration index	NTL-181	—	−1.5 to +0.7	−0.69
Viscosity at 135°C	ASTM D4402	cP	274 minimum	337
Flashpoint	ASTM D3143	°C	235 minimum	339
Ductility	ASTM D113	cm	100 minimum	>105
Specific gravity	AASHTO D 70	—	—	1.020
Test on the residue after rolling thin film oven (RTFOT)				
Penetration, in % of the original value	ASTM D5	%	55 minimum	82
Increase in the softening point	ASTM D36	°C	8 maximum	7.5
Mass loss	ASTM D2872	%	0.5 maximum	0.1

Table 2. Test results properties aggregates

Test	Process	Specification	Result
Abrasion in Los Angeles	AASHTO T 96	50% maximum	21.8%
Specific gravity—absorption (fine)	AASHTO T 84	—	2.61%–1.5%
Specific gravity—absorption (coarse)	AASHTO T 85	—	2.58%–0.85%
Specific gravity of filler	AASHTO T 100	—	2.72
Sand equivalent	AASHTO T 176	55% minimum	66%
Soundness using magnesium sulfate	AASHTO T 104	12% maximum	7%
Shape index	DNER-ME 086	0.5 minimum	0.7
Plasticity index	ASTM D4318	Not plastic	Not plastic
Fractured particles	ASTM D5821	85% minimum	91%
Adhesion of aggregate to bituminous material	DNER-ME 078	Satisfactory	Satisfactory

material (DNER 1994a). The properties of the asphalt binders and aggregates are shown in Tables 1 and 2, respectively. The values meet the requests of the DNIT (2006) specification to manufacture HMAs.

The IOT was obtained from a mine positioned in the state of Rio Grande do Norte (Brazil). The maximum particle size of the IOT was 0.075 mm [all material passing sieve No. 200 in a particle-size distribution test, ASTM D6913 (ASTM 2017b)]. The specific gravity by AASHTO T 100 (AASTHO 2003) of the IOT is 4.09. The chemical composition of IOT obtained by X-ray fluorescence tests is presented in Table 3. Based on X-ray diffractometry (XRD) tests, 83.95% of the content is hematite, 8.59% silica, 6.48% alumina, and the rest comprise other minerals in a smaller proportion.

Table 3. Composition of IOT

Oxide	IOT (%)
Fe_2O_3	83.95
SiO_2	8.59
Al_2O_3	6.48
Others	0.98

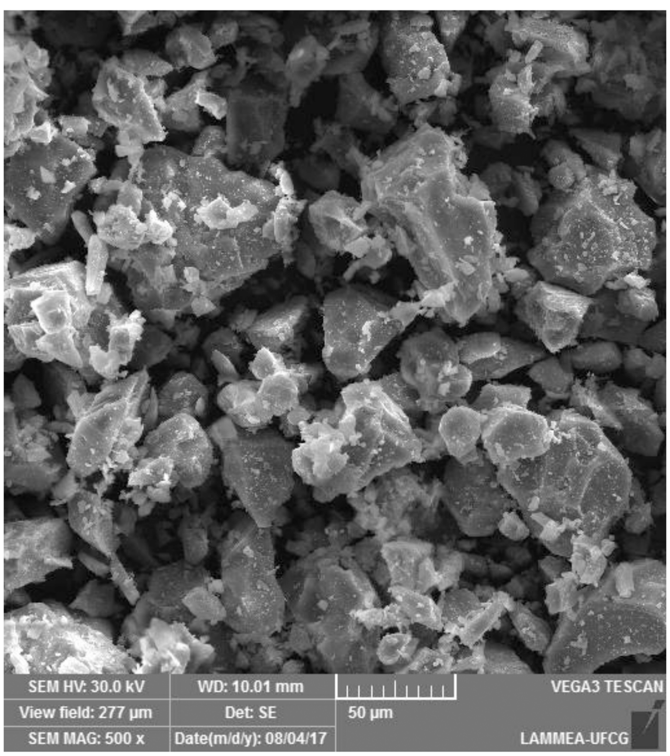

Fig. 1. IOT 500x.

These values are consistent with those described in the literature for the chemical composition of hematite (Gencel 2011; Gencel et al. 2010; Giuffrè et al. 2018). Hematite is the most stable iron oxide, it has high resistance to corrosion, and it is biocompatible, low cost, nontoxic, and ecological (Cornell and Schweramann 1996; Deraz and Alarifi 2012; Tadic et al. 2014). Additionally, analysis was performed with a scanning electron microscope (SEM) in a HI 99121 microscope to evaluate the shape and surface of the IOT particles under 500x magnifications (Fig. 1). In terms of the IOT particle size and shape, a predominance of angular particles with a cubic tendency can be evidenced.

HMA-IOT Manufacturing and General Methodology

Initially, each asphalt binder content of 3.2%, 3.6%, 4.0%, 4.4%, and 4.8% was mixed with 1% of IOT (12 g, relative to the total mass of the mixture). Both materials were blended at a speed of 4,000 rpm (using high-cut mixing equipment) for 5 min at 150°C. Blending times and temperatures were obtained through trial and error and using the following as the main criteria: (1) avoid asphalt binder aging and (2) achieve a complete coating of aggregates. Then, the asphalt mix was manufactured using the asphalt binder blended with IOT, which was called HMA-IOT. The mix designs (determination of the optimal asphalt content, OAC) were carried out by means of the Marshall test AASHTO T 245 (AASHTO 2015). After that, indirect tensile strength (ITS) tests from AASHTO T 283 (AASHTO 2018a) were carried out to evaluate the resistance of mixtures under monotonic loading. Later, its properties under cyclic loading (fatigue from UNE 12697-24 and resilient modulus from ASTM D 4123) were studied. Finally, static creep tests (NF P 98-250-2) and the resistance to induced moisture damage by means

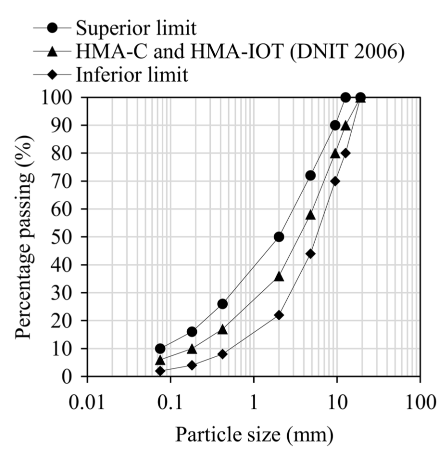

Fig. 2. Particle size distribution of HMA-C and HMA-IOT.

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of the modified Lottman test methodology of AASHTO T 283 were evaluated. All these tests are described subsequently.

Marshall and Indirect Tensile Tests

The control HMA-type C (HMA-C) and HMA-IOT were designed based on the Marshall test (AASHTO T 245). A total of 75 blows per face were used to compact the samples. The granular size distribution of the HMAs is presented in Fig. 2 in accordance with DNIT (2006). To obtain the OAC, three Marshall samples were manufactured and tested for each percentage of asphalt binder in mass (varying between 3.2% and 6.0%). The mixing and compaction temperatures of HMA-C and HMA-IOT were 150°C and 140°C, respectively. These temperatures were defined for the viscosities of AC 50/70 of 0.17 and 0.28 Pa·s (170 and 280 cP), respectively. Additionally, the following volumetric and physical parameters were obtained from the Marshall tests: air voids in volume (Va), voids filled with asphalt (VFA), voids in mineral aggregate (VMA), stability Marshall (S), flow (F), and the S/F ratio or Marshall quotient.

Using the OAC determined in the Marshall test, three Marshall samples were manufactured for each type of mixture (HMA-C and HMA-IOT) to measure the indirect tensile strength (*ITS*) by diametral compression, following the guidelines established by ASTM D6931 (ASTM 2017a). Each sample was exposed to the application of monotonic loading at a deformation speed of 50 mm/min until rupture at a temperature of 25°C. Additionally, the vertical displacement at rupture was determined (mm) to determine the stiffness (in the indirect tensile mode) of the material (K) by means of the load/displacement ratio (kN/mm). Finally, the toughness (W) of the material was calculated through the stress-strain curve area (for a level of a 4% strain).

Resilient Modulus

On the control HMA-C mixture and the HMA-IOT, resilient modulus tests under cyclic loading by diametral compression were performed. The tests were carried out at a temperature of 25°C, and a loading frequency of 1 Hz in a universal testing machine (UTM), following the guidelines established in ASTM D 4123. Each load cycle consists of a load period of 0.1 s and 0.9 s of recovery. The magnitude of the applied load was 1,200 N (less than 30% of the strength obtained in the ITS by diametral compression). The resilient modulus of three Marshall samples for each asphalt mixture was measured.

Fatigue Resistance

On the control HMA-C mixture and the HMA-IOT, fatigue resistance tests under controlled-stress loading were carried out using a UTM machine (UNE-EN 2018). A temperature of 25°C and stresses level corresponding to 10%, 20%, and 30% of the ITS were used. Stresses were applied using a haversine waveform with a loading frequency of 1 Hz (0.9 s corresponding to the resting time and 0.1 s corresponding to the time of the load application). Thus, 18 samples (3 controlled stress levels × 3 replicates × 2 types of mixtures) were used for the fatigue resistance tests. The fatigue was defined by the number of load applications that caused the complete rupture (N_f).

Static Creep

The static creep tests were performed to evaluate permanent deformation. On the control HMA-C mixture and the HMA-IOT, static creep tests were carried out following NCHRP (2002) guidelines. This test was performed using UTM equipment. The vertical stress, creep, and recovery time was 100 kPa, 3,600 s, and 900 s, respectively. Prior to the tests, the samples were preconditioned in a thermostatic chamber for 4 h at a temperature of 25°C (test temperature). The static creep test was performed on three Marshall samples for each HMA studied.

Modified Lottman

On the control HMA-C mixture and the HMA-IOT, modified Lottman tests (AASHTO T 283) were performed to assess the potential for induced moisture susceptibility. The samples were compacted until reaching air voids between 6.0% and 8.0%. Initially, three Marshall samples of each HMA were tested under dry conditions (IT_d). Before, three samples of each HMA were submerged in water to a saturation level between 55% and 80%. Then, each sample of HMA was subjected to freezing at −18°C and heating cycles of 60°C according to the specification. Finally, on each sample, the ITS was performed at a temperature of 25 °C (IT_w). With the test results and using the ratio IT_w/IT_d, the resistance to moisture damage parameter *TSR* in the percentage was calculated.

Results

Marshall and ITS Tests

Figs. 3–8 and Table 4 present the results of the Marshall and ITS tests, respectively. The OAC for the HMA-C and HMA-IOT mixes

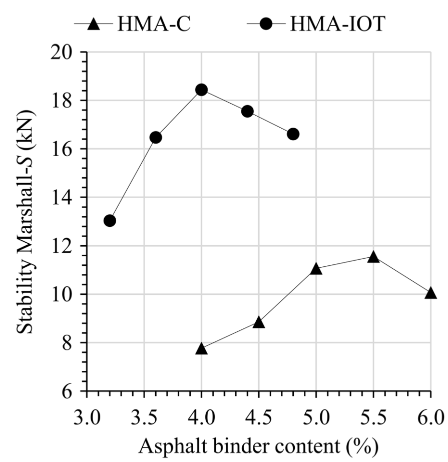

Fig. 3. Evolution of S with asphalt binder content.

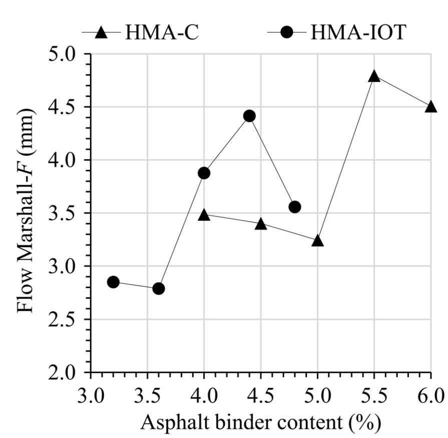

Fig. 4. Evolution of F with asphalt binder content.

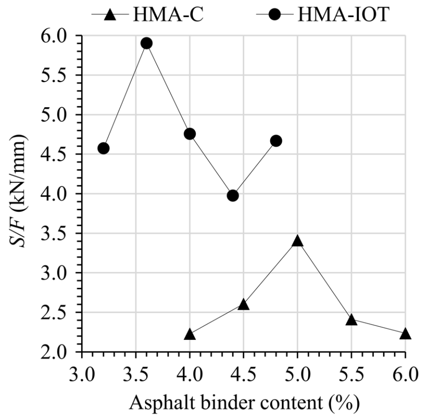

Fig. 5. Evolution of S/F ratio with asphalt binder content.

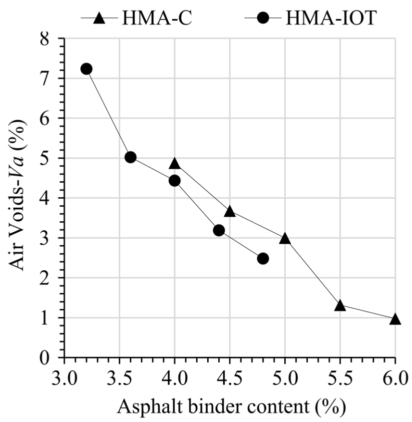

Fig. 6. Evolution of Va with asphalt binder content.

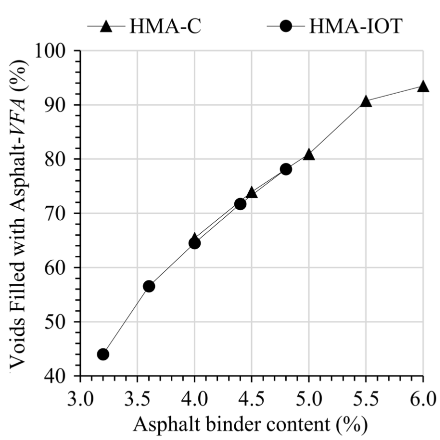

Fig. 7. Evolution of VFA with asphalt binder content.

were 5.0% and 4.0%, respectively. These OACs were chosen based mainly on the S and S/F values and meeting the following criteria established by DNIT (2006): minimum S of 5,000 N, Va between 3% and 6%, and VFA between 65% and 82%. The VMAs did not meet the minimum values (15%) established by DNIT (2006). However, to compare the behavior of the mixtures and not change their aggregate and/or gradation, this parameter was not considered with regard to establishing the OAC. Similar Va and VFA values are observed in both mixtures when the same contents of the

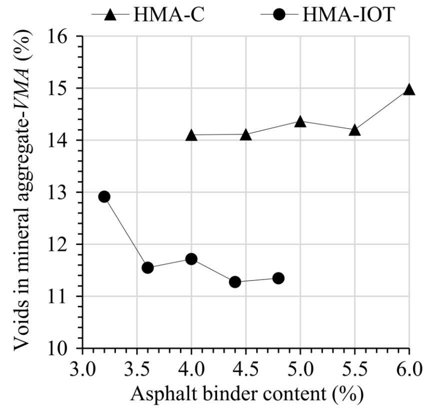

Fig. 8. Evolution of VMA with asphalt binder content.

Table 4. ITS test results

HMA	Asphalt (%)	Va (%)	ITS (kPa)	Displacement (mm)	K (kN/mm)	W (kN · mm)
HMA-C	5.0	3.0	850.0	4.9	4.1	2,511.8
HMA-IOT	4.0	4.6	1,171.3	6.0	5.3	3,452.4

asphalt binder are used (Figs. 6 and 7). However, the Marshall resistance of the HMA-IOT mixes is greater (Figs. 3 and 5).

It is observed that the HMA-IOT mixture manufactured with the OAC shows an increase in the characteristics S, S/F, ITS, K, and W with respect to the control mixture. The S, S/F, ITS, K, and W increased approximately 60%, 73%, 38%, 29%, and 37%, respectively. These increases occurred despite the higher Va and lower VMA and VFA in the HMA-IOT. These volumetric changes (Va, VMA, and VFA) were obtained due to the reduction of the asphalt binder content. The increases in resistance under monotonic load could be attributed to the increase in the internal cohesion and adhesion between the aggregate particles (including IOT) and the covering asphalt binder. Other aspects to consider that perhaps influenced the reported results are described subsequently:

- AC 50/70 is an electrically nonconductive material (Giustozzi et al. 2018). By introducing IOT particles, which have high electrical conductivity due to the presence of iron, a modified asphalt with stable electrical conductivity is generated, producing magnetization of the material. This is a characteristic of metallic elements, which can provide greater adhesion, cohesion, and, consequently, greater stiffness and strength in the asphalt mix. This was evidenced by Hamedi (2018) when using iron oxide nanoparticles in an asphalt mix.
- Due to the angularity in the shape of the IOT particles, a better *interlocking* provided greater stiffness of the asphalt mixture under the action of monotonic loads. This effect occurs despite the low content of IOT used (1%, with relation to the total mass of the asphalt mixture).
- Fe_2O_3 is a material with high hardness and mechanical resistance, as it is explained in the literature (Hamedi 2018; Kalkattawi et al. 1995). Additionally, hematite has high thermal conductivity (Akiyama et al. 1992; Mølgaard and Smeltzer 1971; Snow et al. 2010), which could help to improve the workability and compactness processes of the mixtures.
- The IOT used in the present study is mainly composed of hematite. This material has proven to be compatible with other binders, such as hydraulic cement. Some studies that evaluate the

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substitution of aggregates by hematite in concrete report benefits in terms of resistance under monotonic and dynamic load due to this material having good compatibility and adhesion with cement paste (Gencel 2011). It also helps to produce waterproof and radiation-resistant concrete (Kharita et al. 2008). Some studies even recommend subjecting hematites to high temperatures to make high-strength sintered steels (Tadic et al. 2014).

Resilient Modulus and Permanent Deformation

The resilient modulus is displayed in Table 5. The results of the static creep test are presented in Figs. 9 and 10. The HMA-IOT mixture tends to show higher stiffness under cyclic loading at 20°C than the HMA-C. The increment in resilient modulus was about 30%. For this reason, HMA-IOT mixture presents higher resistance to rutting with respect to the HMA-C. This is evidenced by the reduction of the maximum strain and the creep compliance of approximately 35% in relation to the control mixture. Besides, the asphalt mixtures HMA-C and HMA-IOT presented a recovery percentage of 23.2% and 28.1%, respectively, during the discharge phase of the test. In this sense, it is possible to show that the incorporation of IOT helped to increase the elastic recovery of the asphalt mixture. These increases in resilient modulus and permanent deformation resistance occur despite the higher Va content and the lower VFA in the HMA-IOT mixture compared to the control mix. However, it must be considered that the HMA-IOT mixture undergoes higher S and S/F values in the Marshall test, which is also an indicator of greater resistance to rutting.

Table 5. Test resilient modulus at 20°C

Mixture	Asphalt (%)	Va (%)	Resilient modulus (MPa)
HMA-C	5.0	3.0	3,655.0
HMA-IOT	4.0	4.6	4,739.0

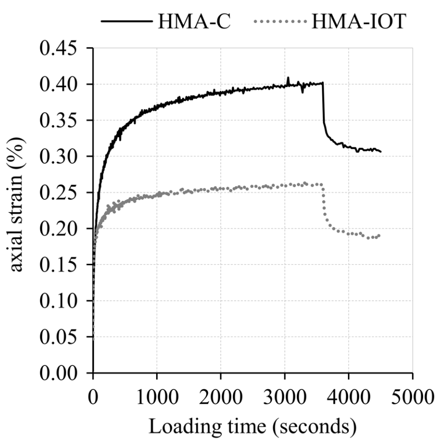

Fig. 9. Axial strain-static creep test results.

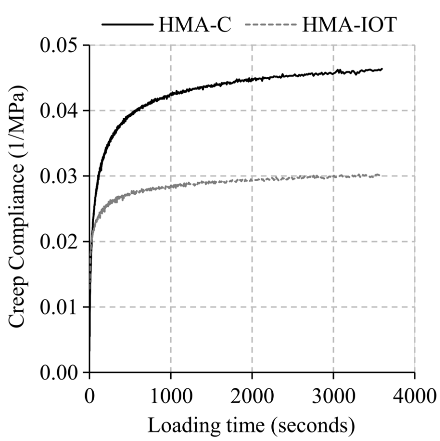

Fig. 10. Creep compliance-static creep test results.

Fatigue Resistance

Fatigue test results are presented in Fig. 11. A noticeable increase in fatigue resistance of an order of magnitude (10x) is observed when using IOT. These increases occurred despite the higher Va content and the lower VFA in the HMA-IOT mixture compared to the control mixture. In this sense, the amount of AC 50/70 and the IOT particles are enough to guarantee the cohesion between the particles in the HMA-IOT mixture. The increase in fatigue resistance is due to the increased stiffness of the asphalt mix, as well as in the mechanical behavior (S, S/F ratio, ITS, and resilient modulus) with respect to the control mixture. The increase in fatigue resistance can be related to the mixtures response to the type of loading (controlled-stress) because, as mixture stiffness increases with this type of loading, usually so does its service life and resistance to load fatigue, too (Di Benedetto et al. 2004; Muniz de Farias et al. 2018; Rondón-Quintana et al. 2020; Bharath et al. 2021).

Modified Lottman

The results of the modified Lottman test are presented in Table 6. It is observed that the presence of 1% IOT contributes to the increase of the resistance parameters IT_d, IT_w, and TSR of the HMA-IOT mixture. The preceding is an indicator of increased resistance to moisture susceptibility. The better response of the HMA-IOT

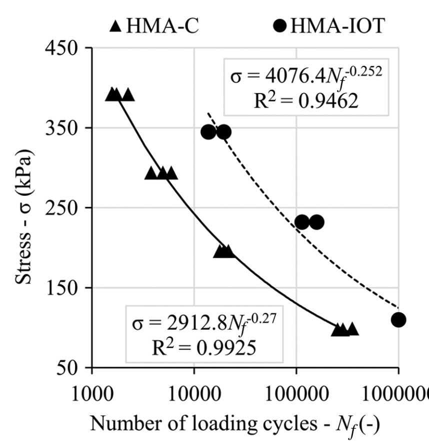

Fig. 11. Fatigue resistance.

Table 6. Moisture damage resistance—modified Lottman test

Mixture	Asphalt (%)	IT_d (kPa)	Va (%)	IT_w (kPa)	Va (%)	TSR (%)
HMA-C	5.0	792.5	6.3	660.5	6.3	83.3
HMA-IOT	4.0	1,171.3	6.5	1,007.3	6.4	86.0

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mixture in this test can be attributed to the high percentage of iron oxide in the IOT (83.95% hematite), as evidenced in the chemical and mineralogical characterization. According to Cala et al. (2019), the presence of some oxides, such as iron oxide, promotes resistance to moisture damage in the asphalt mix. The results are indicative that the presence of iron oxide in IOT could improve the adherence of asphalt mixtures.

Conclusions

In the present study, an HMA-IOT asphalt mix was manufactured to evaluate the mechanical behavior with respect to the HMA of control. Laboratory tests included the evaluation of the response to the action of monotonic load (Marshall, ITS), dynamics (resilient modulus and fatigue), and static (static creep), and, additionally, the susceptibility to moisture damage was evaluated. Based on the results, the following can be determined:

- The incorporation of 1% IOT in the HMA mixture significantly improves the mechanical behavior regarding the HMA-C control mix. It was observed that the HMA-IOT mixture presents a greater resistance under monotonic loads (greater S, S/F, ITS, K, and W), better performance under dynamic loads (greater resilient modulus and higher resistance to fatigue), and improved behavior under static creep conditions (reduction of the maximum deformation in the static creep test) with respect to the control mixture. Additionally, the IOT used in the present study is mainly composed of hematite, which had good compatibility and adhesion with asphalt binders. The presence of iron oxides in the IOT particles contributed to the increased resistance to moisture damage induced by the mixture. In this sense, it can be observed that the HMA-IOT mixture presented an increment in the IT_d, IT_{-w}, and TSR parameters with respect to the control mixture. This increment occurred despite the reduction of the effective content of the asphalt binder (AC 50/70), the increase in Va, and the reduction of VFA in the HMA.
- The incorporation of the IOT in the asphalt mixture in the way proposed in this study can be considered a viable technique from the technical, environmental point of view. In this sense, a new form of IOT waste disposal is proposed, which benefits the preservation and conservation of the environment in terms of solid waste management. However, additional studies are necessary to validate the technique (mainly long-term durability tests, use of IOTs from different sources and chemical-mineralogical composition, and use of different contents of IOT).

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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