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Research Paper

Challenges and Opportunities for the Use of Asphalt Mix Prepared with Ceramic Solid Waste in Emerging Countries

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This research demonstrates the feasibility of using ceramic waste as a substitute for aggregates in asphalt mixtures prepared with locally available materials in Spain and Colombia. To achieve this, the asphalt mixtures were prepared following the design standards, test methods, practices, and specifications associated with quality assurance for asphalt materials. Test specimens were prepared using 30% and 35% ceramic waste as a substitute for aggregates. The results indicate that when the aggregates and binder meet the quality standards required for asphalt mixture design, the inclusion of classified ceramic waste as recycled aggregate, despite being considered inappropriate or critical material, provides mechanical benefits to the tested mixtures.

As a result, this study provides relevant information to companies engaged in asphalt mix production, highlighting potential business opportunities in adopting such technological initiatives. Additionally, taking advantage of tax exemption policies established to incentivize environmentally sustainable practices can further enhance the feasibility and attractiveness of these initiatives.

Keywords: environmental sustainability infrastructure; development; asphalt.

1. Introduction

Improving the surface conditions of urban or rural roads is carried out through engineering works that involve a variety of materials, including natural material (simple affirmed), concrete, cobblestones, asphalt, or a mixture of these distributed throughout length and width of the road. In all cases, design criteria must adhere to technical specifications that consider the conditions of use and the corresponding traffic loads during the useful life of the road. This study analyzes the alternative use of ceramic waste in road construction, focusing on its use in flexible pavement [1], which requires the built structure to accommodate deflections occurring in the ground due to vehicle passage [2]. To achieve this, mixtures were produced according to the standards of Spain and Colombia, demonstrating that it is possible to prepare these mixtures in both countries. In addition, the study provides relevant information on the main challenges for the implementation of these asphalt mixtures prepared using ceramic waste in emerging countries such as Colombia.

An asphalt mixture, composed of aggregates and bitumen or binder, protects the subgrade that receives the load from vehicle traffic and responds to stability and flow parameters as well as void content, guarantying safety for users and durability of the pavement [3]. The design of this mixture is implemented at production plants, where the asphalt mixture is prepared and then transported to the construction site. At the site, paving machines lay the mixture, and rollers compact it to the thickness specified in the design.

1.1. Classification of asphalt mixtures

Asphalt mixtures can be classified according to the gradation of aggregates as hot mix asphalt with continuous , discontinuous, and open porous gradation. Another classification is based on the texture, including mega-texture, macro-texture, or micro-texture. Additionally, asphalt mixtures are categorized according to quality criteria established by designers. For all types of asphalt mixture prepared, it is necessary to mix (in percentage terms) a proportion of aggregate matrix and bitumen or binder. Following technical guidelines established during the design phase and ensuring proper pavement construction help minimize structural damage, allowing greater comfort for users and lower maintenance costs for authorities. Around 95% of the asphalt mixture is made of aggregates, and due to the excessive consumption of this material, there is growing interest in reusing waste as a substitute for aggregates in asphalt mixtures.

2. Industrial waste reuse

The rapid expansion of urban areas has led to a concerning increase in population density [4]. Consequently, this growth has triggered numerous challenges, including mobility problems, water and soil contamination, and landscape degradation due to improper waste disposal practices [5]. These issues have led to significant environmental and social impacts [6].

Projections indicate that waste production could reach a staggering increase of 1.39 billion tons between 2016 and 2050 under a business-as-usual scenario [6].

This alarming figure has motivated the establishment of national policies focused on enhancing solid waste management and promoting innovative solutions like reuse and recycling [7]. Embracing these sustainable practices aligns with the principles of the circular economy, a commitment shared by both the Ministry of the Environment of Spain and the Ministry of Sustainable Development of Colombia.

The alternative of using industrial waste, particularly that which currently has no economic value for third parties [8], has given rise to various studies conducted by universities or through collaborations between universities, the state, and private companies. These efforts respond significantly to Objective 12: Responsible Production and Consumption made explicit in the Sustainable Development Goals Report by United Nations, in which it is emphasized that the recycling and reusing of industrial waste is important.

2.1. Residues incorporated in the preparation of asphalt mixtures

The quest for substances that enhance the durability of asphalt mixtures used in pavements includes research on bitumen modification, substitution of a fraction of the aggregate, or both. For instance, authors in [9] found that incorporating elastomeric polymers improved the pavement's resistance to permanent deformation and wear. Moreover, such mixtures offer the advantage of lower working temperatures compared to conventional asphalt. This characteristic makes them easier to install on-site, as they can be utilized in various types of asphalt plants, thus contributing to a reduction in emissions released into the atmosphere [9, 10].

Similarly, asphalt mixtures containing plastics contribute to mitigating the negative environmental impacts associated with the production and use of traditional mixtures [11]. It is worth mentioning that Colombia has specifications that address the utilization of recycled materials such as rubber granules and polymers [12].

Another promising residue being tested is iron powder, which, when added in percentages of 8 and 12%, exhibited a remarkable increase in fatigue capacity by 100 and 150%, respectively [13].

Regarding the inclusion of ceramics as a residue, research conducted in [14] has verified its positive contribution to the mechanical resistance of asphalt mixtures when used as a substitution for up to 30% of ceramic over the total mass of aggregates [1]. Furthermore, studies demonstrated the advantageous performance of bitumen with a reasonable addition of recycled ceramic aggregates in low-volume roads [15].

Similarly, hot discontinuous mixes prepared with aggregate replacements of 20% and 30% exhibited deformations up to 9.8% lower than those reported in conventional asphalt mixes placed on low-traffic roads [16]. This indicates better resistance to cracking, deformation, and favorable dynamic behavior [17]. Moreover, even greater resistance to fatigue and plastic deformation was observed with substitutions of up to 40% of the aggregate [18].

Additionally, replacing up to 20% of the aggregate with ceramic residue as an aggregate in hot mix asphalt improved the elastic modulus and stability by 13.5% and 25%, respectively, compared to the control sample [16]. Other studies have shown that adding 2.5% of filler or mineral residue improved the response to indirect traction, flow number, and dynamic modulus [17]. Furthermore, the fiber of this type of residue exhibited favorable behavior as bitumen reinforcement, providing greater stiffness [18, 19].

Incorporating such residues into asphalt mixtures requires following a specific design process, along with quality control tests to ensure the desired properties of the asphalt. Existing evidence indicates that using asphalt mixtures with ceramic aggregates is well-suited for roads with medium to low traffic volumes. However, it is essential to continue research to verify the technical and economic feasibility [15, 20] and address any weaknesses identified in this recycling process [21].

Globally, there is a significant interest in promoting sustainability by incentivizing the use of environmentally friendly materials. Notably, in countries such as Spain and Colombia, companies engaged in financing or conducting research in this area could be eligible for tax exemptions. This incentivizes the adoption of innovative and sustainable practices in construction and encourages further progress in the field.

2.2. *Ceramic waste during the production process at Cerámica Italia*

The ceramic production process at the Cerámica Italia plant, in the city of San José de Cúcuta (Colombia) is summarized in Fig. 1. The ceramic production process encompasses many of the stages outlined in [22] as follows:

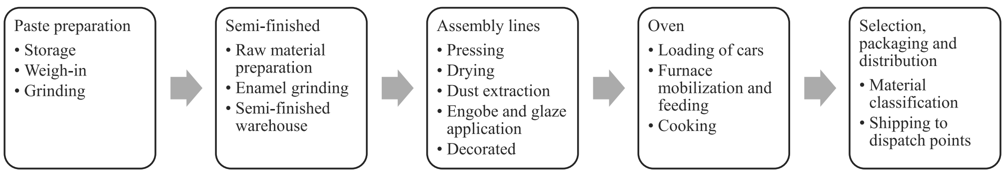

FIG. 1. Diagram of the ceramic production process.

Specifically, during the selection and packaging stage, the material is classified using established standards for quality assurance and it is organized by labeling the boxes as first, commercial, second, third, or broken material [32].

Material classified as broken or critical is reprocessed. Around 1200 tons/month of this type is reprocessed in Colombia and used for the formation of internal roads [23]. This presents an opportunity for using it in the preparation of asphalt mixtures. That fact really motivated this study validating the technical and economic results of preparation of the mixture in a developed country like Spain and an emergent country as Colombia.

3. Methodology

The mechanical quality of asphalt mixtures prepared with ceramic waste as an aggregate substitute is thoroughly examined, following the design standards from Spain and Colombia. In this comprehensive approach, the aggregates and bitumen are carefully characterized, and the optimal percentage is determined using the Marshall method. For a clearer overview of the key stages involved in this process, refer to Fig. 2.

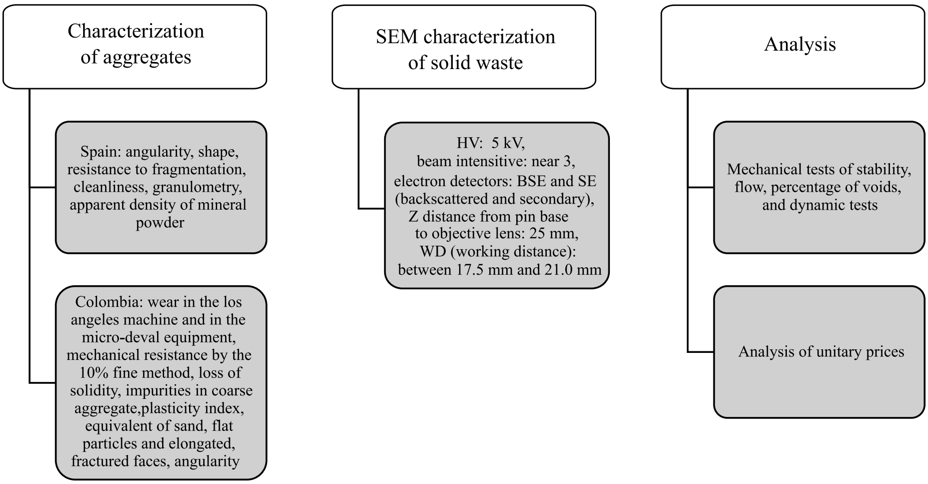

Fig. 2. Stages for carrying out the study
(Note: SEM (scanning electron microscope) characterization).

In Spain, the aggregates were provided by Pavasal company in Cheste, Valencia, while the 35/50 type binder, indicating penetration test results between 35 mm to 50 mm, was supplied by Repsol company. The ceramic waste used in this part of the study was supplied by the Becsa company. In Bucaramanga, Colombia, the aggregates were provided by Sánchez Constructora Ltda., sourced from the Chicamocha river. The 60/70 type bitumen, indicating penetration test results between 60 mm to 70 mm [32], was obtained from Asfaltart company, and the ceramics were sourced from Cerámica Italia company in San José de Cúcuta. The tests in Spain were conducted at the Roads laboratory of the Polytechnic University of Valencia and the Pavements laboratory of the Pavasal company. In Colombia, the tests were carried out at the Geotechnics and Pavements laboratory of the Universidad Pontificia Bolivariana, located in the city of Bucaramanga.

To select the appropriate hot asphalt mixture, asphalt cement with a maximum aggregate size of 22 mm for wearing surface (AC22Bin S) was chosen for Spain, and a hot mix design with maximum aggregate size of 25 mm MSC 25 was selected for Colombia. In both cases, ceramic residue was incorporated at replacement rates of 30% and 35% relative to the aggregate portion. Additionally, a control mixture (without ceramic waste) was prepared as a baseline to facilitate a comparison of the mechanical behavior of the composite material prepared with the different replacement proportions.

A total of 15 specimens were prepared for each mixture, employing asphalt percentage variations of 0.5%, ranging from 4% to 6%. The objective was to determine the optimal asphalt percentage, following Standard 542 of the General Technical Specifications for Road and Bridge Works- PG-3 in Spain and the Technical Specifications of the National Institute of Roads in Colombia. Each specimen was compacted with 75 blows on each side, and subsequently, several key properties were evaluated for both the control (standard mixture) and the mixtures with substitutions. These properties included bulk density, maximum specific weight, apparent density, stability, and flow number.

4. Results

4.1. Behavior of the asphalt mix tested in Spain

As shown in Table 1, the aggregates utilized in the mixture preparation were thoroughly characterized, confirming their compliance with the required quality

Table 1. Qualification of the aggregates used in the preparation of the asphalt mixtures in this study.

Characterization of natural aggregates	Requirement PG-3	Complies with PG-3
Sieve analysis of fine and coarse aggregates	Sieves compliance	Yes
Sand equivalent value	>40	Yes
Resistance of coarse aggregate to degradation by abrasion and impact in the Los Angeles machine (rolling/intermediate/base)	<20/35/30%	Yes
Fractured particles (rolling/intermediate/base)	Minimum 75/60/60	Yes
Flattening index	<20%	Yes

standards. Similarly, the penetration and ring and ball tests conducted on the binder verified its compliance with the specifications for the AC 35/50 classification (see Table 2). Furthermore, the scanning electron microscopic (SEM) test revealed notable predominance of oxides, silicon, and aluminum, as well as textural irregularities that could potentially enhance friction and adhesion with the bitumen (Fig. 3).

Table 2. Classification of the binder in Spain.

Asphalt characterization	Standard	Value	Complies with PG-3
Penetration at 25°C (0.1 mm)	UNE EN 1426	44	35/50
Softening point °C	UNE EN 1427	54.4	Yes
Penetration index	UNE EN 12591	−0.45	Yes

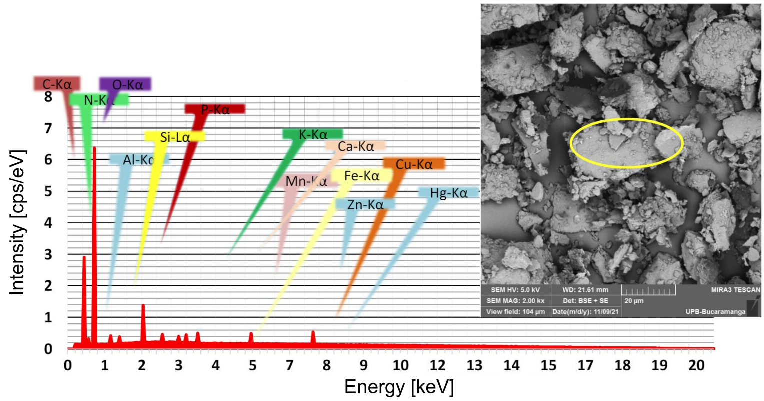

FIG. 3. Microscopic image with 2000 X magnification of the aggregate from Cheste, Spain, and its characteristic X-ray spectrum.

The characterization of the ceramic residue demonstrated compliance with the specified requirements for aggregates established in the Technical Specification Sheets PG-3 (see Table 3).

Table 3. Qualification of the ceramic waste of the company Becsa, Spain.

Test	Limit proposed by the standard (rolling/intermediate/base)	Ceramic grinding	Compliance with PG-3
Fragmentation resistance	<20/35/30%	27%	Yes
Aggregate surface cleaning	Maximum 0.5%	0.2	Yes
Sand equivalent	>40%	86	Yes
Flattenning index	Maximum 20	0.5%	Yes
% Fracture in coarse aggregate	Minimum 75/60/60	100%	Yes
Mineral filler density	0.5–0.8 g/cm^3	NA	NA

Regarding the asphalt content and its impact on stability and flow, the control mixture exhibited an optimum asphalt percentage of 4.2%. In contrast, the mixtures prepared with 30% and 35% substitution levels had higher asphalt percentages of 4.6% and 4.7%, respectively (Table 4).

Table 4. Results Marshall asphalt mix design in Spain.

Parameter	Limit	Control value	30% value	35% value
Bulk density [kg/m^3]	–	2475	2291	2282
Maximum bulk density [kg/m^3]	–	2590	2483	2560
% Voids in the mixture	4–7	4.0	7.0	7.03
% Aggregates voids	≥ 14	14.0	16.56	18.17
Marshall stability [kN]	>12.5–8	21.4	14.88	18.26
Flow [mm]	2–4	2.4	2.04	2.8
Filler/binder ratio	1.1	1.2	1	1.11
Optimum asphalt binder [%]	>4	4.2	4.6	4.7

To estimate the costs of preparing the asphalt mixture, we referred to the Bank of Prices and Technical Conditions of the Community of Valencia CICCP for the year 2022. The relevant information is available at: https://tinyurl.com/2udpatj3. Table 5 provides a comprehensive price comparison.

4.2. The behavior of the asphalt mix tested in Colombia

The aggregates used in the mixture preparation were thoroughly characterized, and the results demonstrate their compliance with the quality standards as specified by the Colombian technical standards of the National Institute of Roads (see Table 6). Moreover, the binder used in the asphalt mixture passed both penetration and ring and ball tests, confirming that it meets the required specifications for asphalt with a 60/70 classification. Additionally, the SEM test revealed textural irregularities that could enhance friction and adhesion with the bitumen. The predominant elements found were oxygen, silicon, and aluminum, which is consistent with the typical mineralogical composition of construction aggregates (see Fig. 4).

The quality of ceramic residue was assessed, and the material was found to meet the criteria required for the design of asphalt mixtures, as specified by the Colombian technical standards of the National Institute of Roads (see Table 7).

In Fig. 5, the compliance of various aggregate proportions and their corresponding aggregate-ceramic residue mixes is shown.

Table 5. The analysis of unit prices per m^3 of asphalt mix in Spain.

Item	Unit.	Control (4.2% asphalt)			
		Qt.	Adit.	Unit. val. [€]	Total value [€]
Asphalt cement 35/50	kg	97.44	5%	0.2991	30.6
Coarse aggregate	m^3	0.36	5%	9.63	3.64
Fine aggregate	m^3	0.85	5%	3.21	2.86
Ceramic waste					
Equipment	Global				1.43
Material transportation	Global				3.6
Workforce	Global				5.94
Taxes and administration	–				5.00%
Total [€]	–				50
Item	Unit.	30% replacement/4.6% Asphalt			
		Qt.	Adit.	Unit. val. [€]	Total value [€]
Asphalt cement 35/50	kg	106.7	5%	0.2991	33.52
Coarse aggregate	m^3	0.226	5%	9.63	2.29
Fine aggregate	m^3	0.536	5%	3.21	1.81
Ceramic waste		0.328	5%	0	0
Equipment	Global				1.43
Material transportation	Global				4
Workforce	Global				6
Taxes and administration	–				5.00%
Total [€]	–				51.5
Item	Unit.	35% replacement/4.7% Asphalt			
		Qt.	Adit.	Unit. val. [€]	Total value [€]
Asphalt cement 35/50	kg	109	5%	0.2991	34.24
Coarse aggregate	m^3	0.207	5%	9.63	2.09
Fine aggregate	m^3	0.509	5%	3.21	1.71
Ceramic waste		0.387	5%	0	0
Equipment	Global				1.43
Material transportation	Global				4
Workforce	Global				6
Taxes and administration	–				5.00%
Total [€]	–				51.9

Regarding, the impact of asphalt content on stability and flow characteristics of asphalt mixtures, the results revealed that the control mixture demonstrated an optimum percentage of asphalt at 5%. Similarly, for mixtures prepared with

Table 6. Qualification of the aggregates used in the preparation of the asphalt mixtures in Colombia.

Characteristics	Standard INV	Maximum	Minimum	Value	Compliance
Resistance to degradation in the Los Angeles machine [%]	E-218	35	–	25.38	Yes
Abrasion degradation on the Micro-Deval equipment [%]	E-238	30	–	6.91	Yes
Mechanical resistance by the method of 10% fines Dry value [kN] Wet/dry ratio [%]	E-224	–	110 75	211.2 64.8	Yes
Losses in solidity test in magnesium sulfate, fine and coarse aggregates [%]	E-220	18	–	17.5	Yes
Impurities in coarse aggregate [%]	E-237	0.5	–	0.41	Yes
Plasticity index [%]	E-125 & E-126	NP	NP	0	Yes
Sand equivalent [%]	E-133	–	50	64.92	Yes
Flat and elongated particles [%]	E-240	10	–	1.25	Yes
Fractured faces [%]	E-227	–	75	94.67	Yes
Angularity of the fine fraction [%]	E-239	–	40	42.83	Yes

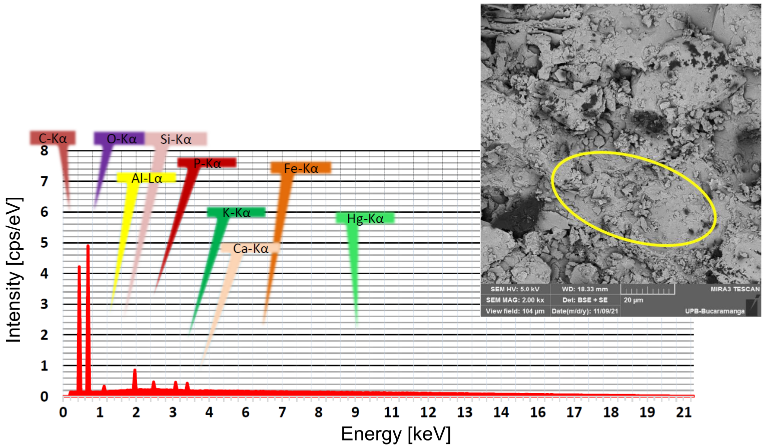

FIG. 4. Microimage with 2000 X magnification of Colombian aggregate and its characteristic X-ray spectrum.

30% and 35% substitution levels, the optimum percentages of asphalt were found to be 5.2% in both cases (Table 8).

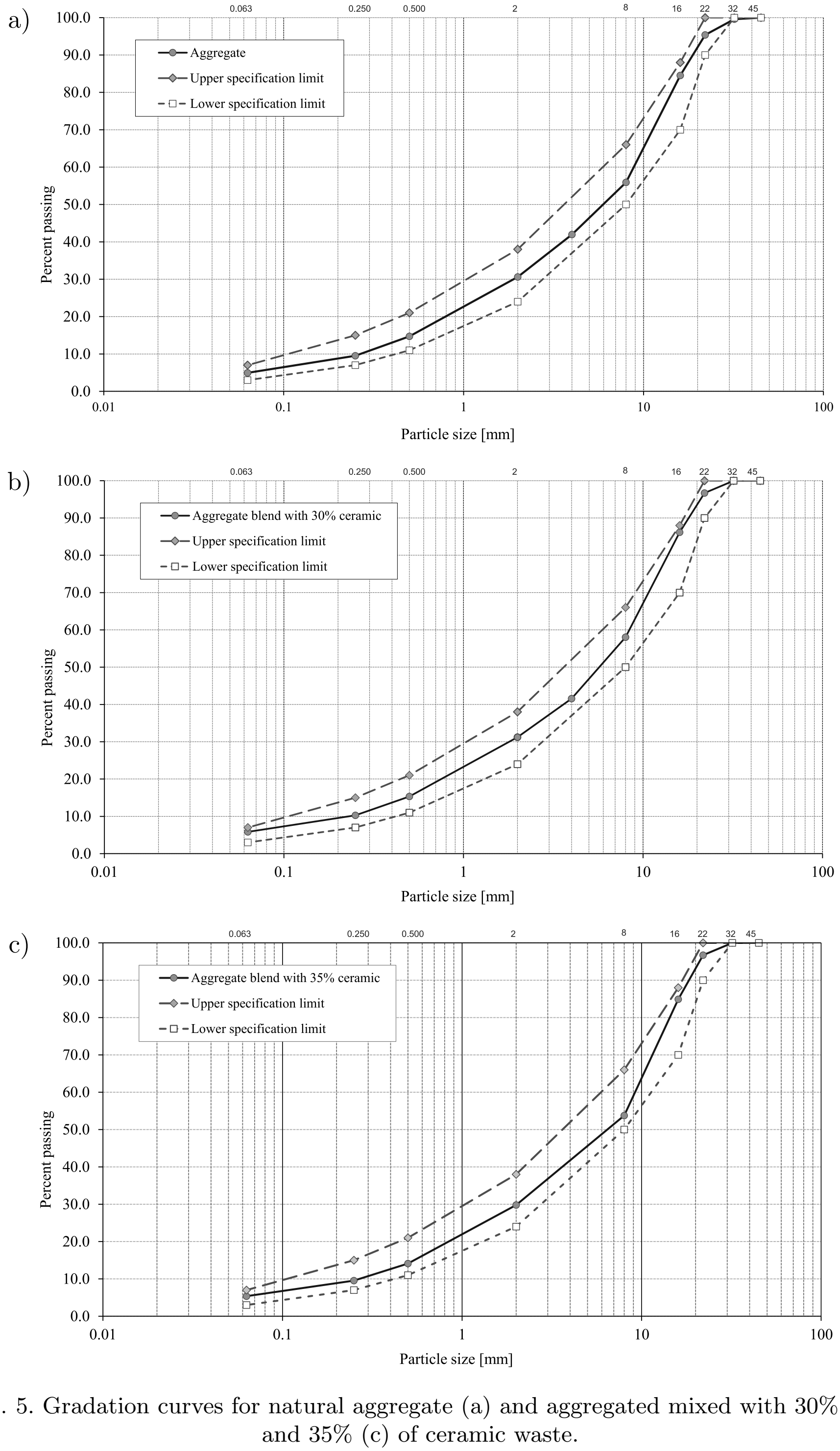

FIG. 5. Gradation curves for natural aggregate (a) and aggregated mixed with 30% (b) and 35% (c) of ceramic waste.

Table 7. Qualification of ceramic waste from the Cerámica Italia company in San José de Cúcuta.

Characteristic	Standard INV	Maximum	Minimum	Value	Compliance
Resistance to degradation in the Los Angeles machine [%]	E-218	35	–	26.98	Yes
Abrasion degradation on the Micro-Deval equipment [%]	E-238	30	–	8.00	Yes
Mechanical resistance by the method of 10% fines Dry value [kN] Wet/dry ratio [%]	E-224	–	110 75	267.0 107.1	Yes Yes
Losses in solidity test in magnesium sulfate, fine and coarse aggregates [%]	E-220	18	–	16	Yes
Determination of Surface Cleanliness of Coarse Aggregate Particles	E-237	0.5	–	0	Yes
Impurities in coarse aggregate [%]	E-125 & E-126	NP	NP	0	Yes
Plasticity index [%]	E-133	–	50		Yes
Sand equivalent [%]	E-240	10	–	0.5	Yes
Flat and elongated particles [%]	E-227	–	75	100	Yes
Fractured faces [%]	E-239	–	40	36.62	No

Table 8. Results of Marshall asphalt mix design in Colombia.

Parameter	Limit	Value	Value with replacement 30%	Value with replacement 35%
Bulk density [kg/m^3]	–	2250	2160	2073
Maximum bulk density [kg/m^3]	–	2467	2320	2340
% Air voids	4–7	5.9	7.0	7.0
% Aggregates voids	$\geq$14	16.83	14.02	14.84
Marshall stability [kN]	>12.5	16.98	14.53	16.30
Flow [mm]	2–4	3.5	3.5	3.0
Sensibility [%]	>80	88.8	82.6	81.8
Filler/binder ratio	1.1	1.2	1.1	1.1
Optimum asphalt binder [%]	>4.0	5.0	5.2	5.2

To estimate the costs of asphalt mixture preparation in Colombia, we utilized price data from a company specializing in road paving in Bucaramanga. Table 9 presents a comprehensive price comparison of the materials used and the total cost estimated cost for each asphalt mixture.

Table 9. Analysis of unit prices per m^3 of asphalt mix in Colombia.

Item	Unit.	Control (5% asphalt)			
		Qt.	Adit.	Unit. val. [€]	Total value [€]
Asphalt cement 35/50	kg	116	5%	0.2991	36.43
Coarse aggregate	m^3	0.36	5%	9.63	3.64
Fine aggregate	m^3	0.84	5%	3.21	2.83
Ceramic waste					0
Equipment	Global				25.11
Material transportation	Global				12.94
Workforce	Global				0.88
Taxes and administration	–				9.55%
Total [€]	–				89.64
Item	Unit.	30% replacement/5.2% asphalt			
		Qt.	Adit.	Unit. val. [€]	Total value [€]
Asphalt cement 35/50	kg	120.64	5%	0.2991	37.89
Coarse aggregate	m^3	0.2247	5%	9.63	2.27
Fine aggregate	m^3	0.5325	5%	3.21	1.79
Ceramic waste		0.326	5%	0	0
Equipment	Global				25.11
Material transportation	Global				12.94
Workforce	Global				1
Taxes and administration	–				9.55%
Total [€]	–				88.74
Item	Unit.	35% replacement/5.2% asphalt			
		Qt.	Adit.	Unit. val. [€]	Total value [€]
Asphalt cement 35/50	kg	122.1	5%	0.2991	38.35
Coarse aggregate	m^3	0.2057	5%	9.63	2.08
Fine aggregate	m^3	0.5059	5%	3.21	1.71
Ceramic waste		0.385	5%	0	0
Equipment	Global				25
Material transportation	Global				12.94
Workforce	Global				1
Taxes and administration	–				9.55%
Total [€]	–				88.82

5. Discussion

The global production of solid waste varies widely in quantity and composition depending on economic conditions and community lifestyles where waste is generated [25]. Over time, inadequate waste generation and disposal have become a global problem [26] due to improper practices and a lack of planning for treatment and disposal strategies [27]. It is crucial for emerging countries to address the issue of waste disposal and propose solutions in line with their technological capabilities, focusing on mitigating negative environmental impacts [27]. Colombia, like other countries, faces significant challenges in incorporating waste into the production chain. Some of these challenges include:

- The practice of open-air waste disposal continues to persist [24].
- There is an absence of specific policies and established guidelines for the proper disposal and treatment of recovered waste [24, 25].
- Tax incentives for industries that implement waste reuse or recovery practices are either scarce [30] or non-existent in certain regions [25].
- The rising demand for ceramic products has led to increased landfill waste, prompting research institutes to develop effective recycling methods for ceramic materials [31].
- Obsolete infrastructure [25] and a lack of technology contribute to delays in waste collection.
- The implementation of sustainable practices faces delays [27].
- There is limited awareness and promotion of the benefits of reusing materials [27].
- The implementation of research results from universities is limited [27].

The study found that the characterization of the aggregates and recycled ceramic waste used in the mixture met the requirements specified in the General Technical Prescription Specifications for Road and Bridge Works of the Ministry of Public Works in Spain and the General Specifications for Road Construction of the National Institute of Roads in Colombia. Additionally, it was verified that the bitumen in both countries fell within the expected quality range for asphalt.

Moreover, the study demonstrated the viability of incorporating industrial ceramic waste as a constituent of asphalt mixtures, supported by the results of stability and flow tests conducted in [28]. The tests conducted in Spain revealed that the optimum asphalt percentages were 4.6% and 4.7% when substituting aggregate with ceramic waste at 30% and 35%, respectively. Similarly, in the Colombian mixtures, the optimum asphalt percentage was 5.2% with the same substitution percentages for both mixtures. These findings align with a previous study conducted in [29], where asphalt percentages ranged from 4.8% to 5.2%.

The results strongly support the practicality of incorporating ceramic industrial grinding mixed with locally available materials in Europe and Latin America for asphalt production, in line with the United Nations' Sustainable Development Goals aimed at promoting international commitment to recycling and reuse [34, 35]. Additionally, this approach offers significant cost advantages, with production costs for this type of asphalt mixture being considerably lower in Spain and Colombia, resulting in savings of up to 3 euros and 8.78 euros per m^3 of asphalt mix, respectively, in these countries.

As a future work, it is recommended to conduct dynamic tests to verify the pavement's performance throughout its useful life and validate designs of asphalt mixtures suitable for secondary and tertiary roads. However, the widespread implementation of these tests may face challenges due to their high costs and time requirements [36], which could delay their adoption, especially in an emerging economy like Colombia.

6. Conclusion

The results of this study provide strong evidence for the possibility of using ceramic waste as a replacement for aggregate in asphalt mixtures. In the context of Colombia, where approximately 1200 tons of ceramic waste are generated monthly with an average density of 2 tons/m^3, there is a volume of 600 m^3 of ceramics available. This substantial quantity can be effectively utilized to produce 246 m^3 of asphalt mixture, with 30% of the aggregate replaced by ceramic waste.

Our study paves the way for local and national governments to propose strategies and regulations that encourage tax exemption for companies conducting research focused on the utilization of waste. In this way, the collaboration between academia, the state and the private sector is strengthened since universities and research centers have the most advanced equipment, companies provide the necessary inputs, and communities benefit from the solutions implemented through the right decisions made by government authorities.

The implementation of effective industrial waste management mechanisms for the ceramic industry, as well as the incorporation of quality controls in the production of asphalt mixtures, will contribute to the generation of jobs and environmental benefits from the reuse of inert waste. Although the mechanical behavior of the mixtures with ceramic waste designed under Marshal criteria has been verified, it is essential to carry out dynamic tests to evaluate the durability of these mixtures as part of future work.

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