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Research article

Geomechanical characterization of samples in the pilot zone of Bogotá, Colombia, to determine its potential as aggregates for construction

Caracterización geomecánica de muestras en la zona piloto de Bogotá, Colombia, para determinar el potencial como agregados para la construcción

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Abstract

The purpose of this project is to evaluate and determine potential areas for the exploitation of a mineral resource, considering that materials suitable for construction are a strategic line for the development of the country. In this sense, the pilot zone of Bogotá defined by a radius of 200 km around Bogotá was evaluated, in which lithostratigraphic units with potential for stone aggregates in areas free of mining licenses were studied through geotechnical testing of samples. A total of 198 samples were collected, which underwent the process of size reduction or crushing. Subsequently, granulometry tests were conducted to classify the samples by size, and finally, wear tests (hardness) and sand equivalent tests (cleanliness) were carried out. Once the tests were performed, the results were interpreted to define the potential use of this material as coarse aggregates (sizes in the range of 75 to 4.75 mm) and fine aggregates (sizes in the range of 4.75 to 0.075 mm), according to the *General Construction Specifications* of the National Highway Institute of Colombia (Invías). In terms of hardness and cleanliness, 60% of the samples collected in the pilot zone of Bogotá can be used to produce aggregates. A total of 118 potential sites for the exploitation of coarse aggregates and 19 potential sites for the exploitation of fine aggregates were defined.

Keywords: Bogotá pilot zone, hardness, cleanliness, construction materials, geomechanical tests.

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Resumen

Este proyecto tiene como propósito evaluar y determinar zonas potenciales para la explotación de este tipo de recurso mineral, considerando que los materiales aptos para la construcción son un renglón estratégico para el desarrollo del país. En ese sentido, se evaluó la zona piloto de Bogotá definida por un radio de 200 km alrededor de Bogotá, en la cual se estudiaron las unidades litoestratigráficas con potencial para agregados pétreos en áreas libres de licenciamiento minero, mediante muestreos para ensayos geotécnicos. Se recolectaron 198 muestras, a las cuales se les realizó el proceso de reducción de tamaño o trituración; posteriormente se ejecutó el ensayo de granulometría para clasificar las muestras por tamaños, y finalmente se realizó el ensayo de desgaste (dureza) y ensayo de equivalente de arena (limpieza). Una vez realizados los ensayos, se interpretaron los resultados para definir el uso potencial como agregados gruesos (tamaños en el rango de 75 a 4,75 mm) y agregados finos (tamaños en el rango de 4,75 a 0,075 mm), de acuerdo con las Especificaciones generales de construcción del Instituto Nacional de Vías de Colombia (Invías). En términos de dureza y limpieza, el 60 % de las muestras recolectadas en la zona piloto de Bogotá se puede usar para la producción de agregados. Se definieron 118 sitios potenciales para explotación de agregados gruesos y 19 sitios potenciales para explotación de agregados finos.

Palabras clave: Zona piloto de Bogotá, dureza, limpieza, materiales de construcción, ensayos geomecánicos.

1. Introduction

The objective of this project is to evaluate and determine potential areas of exploitation of construction materials, which constitute a strategic line for the development of the country. This project follows the methodology of Fuentes et al. (2020) for the prospecting of construction materials in Colombia. The geomechanical characterization of the samples taken in the field in the framework of the construction materials project is presented below.

A total of 198 representative samples, each weighing 80 kg, were processed to carry out the geomechanical characterization through crushing, size classification, and wear performance and sand equivalent testing.

The characterization of the materials was performed with the following tests: density indices, wear on the Los Angeles machine, micro-Deval, sulfate fastness, shape indices (elongation and flattening), fractured faces, durability-sag, sand equivalent, methylene blue and alkali-silica reaction (Montero et al., 2009). The project included the performance of wear and sand equivalent tests, which were the most important analyses in terms of distinguishing coarse aggregate and fine aggregate.

Initially, granulometric analysis testing of the coarse and fine aggregates was conducted (Standard INV E-213, Invías, 2013), to classify the crushed material of a sample into varied sizes or sieves to determine the portion of gravels, sands, and fines, as well as to obtain the fractions of certain sieve sizes for the execution of other tests.

The second test corresponds to the wear or the determination of the resistance to the degradation of the coarse aggregates using the Los Angeles machine (Standard INV E-218 and

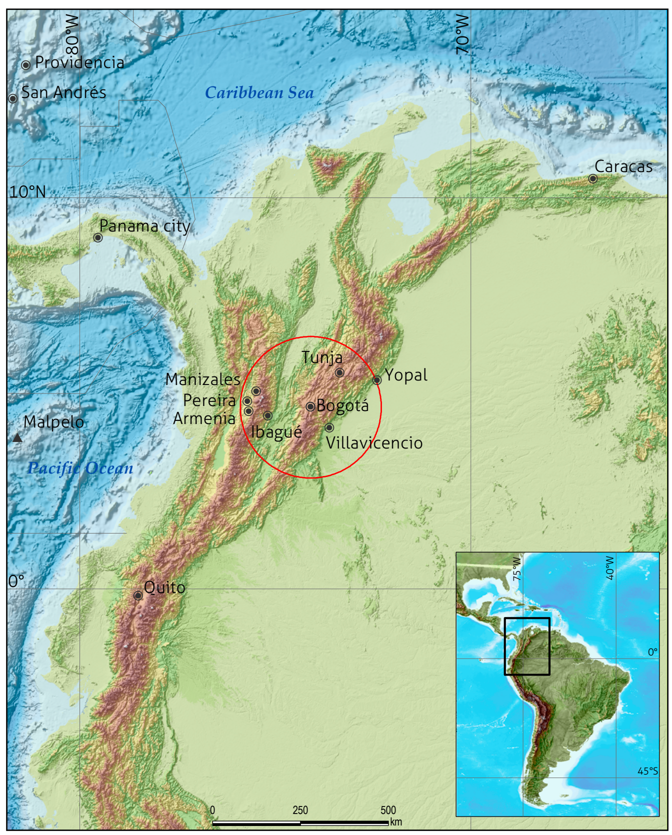

Figure 1. Geographical location of the pilot zone of Bogotá

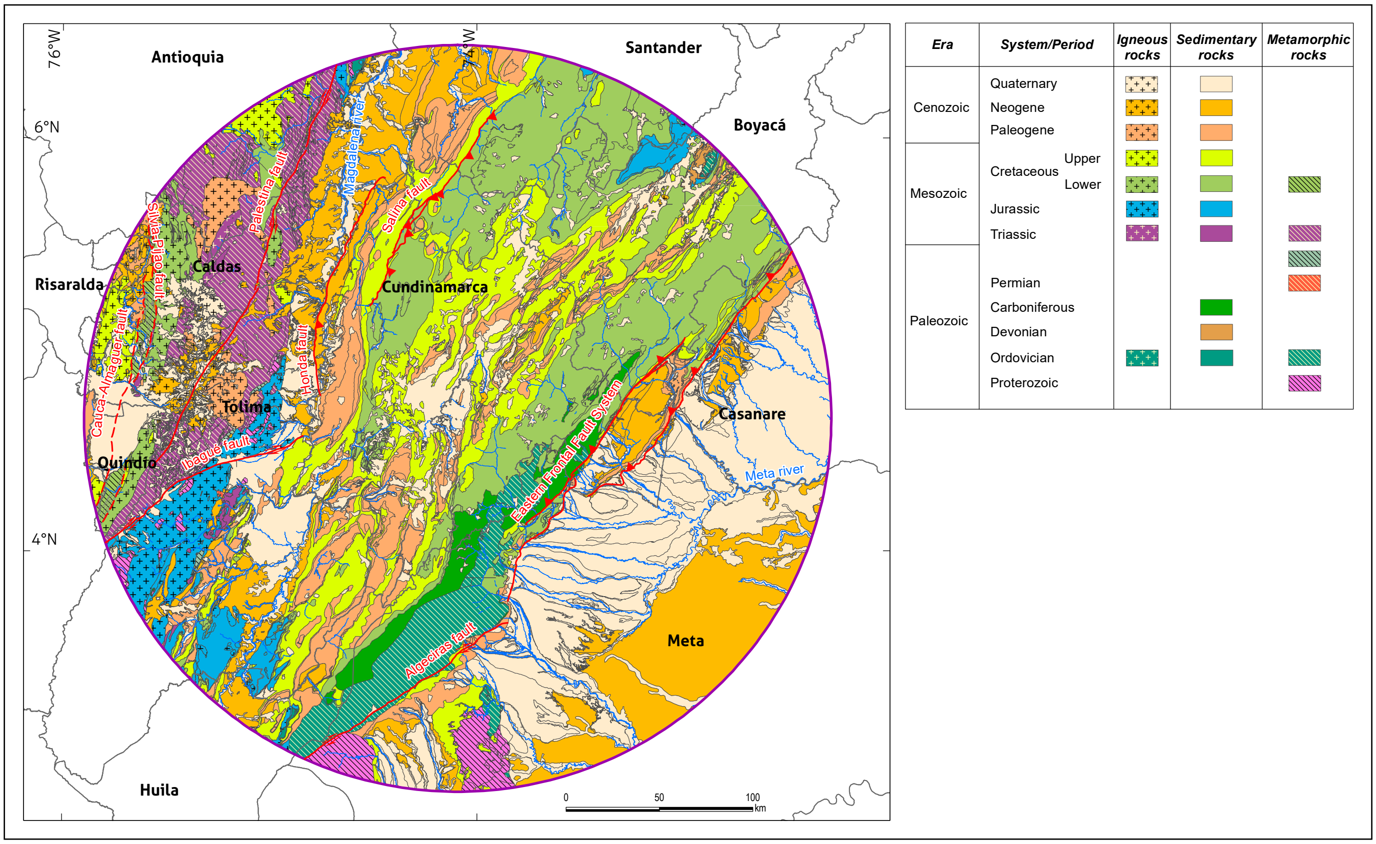

Figure 2. Chronostratigraphic geological map of the pilot zone of Bogotá
Source: taken and modified from Gómez et al. (2015).

E-219, Invías 2013), in which the loss of resistance of a material under an abrasive load and continuous movement is classified. The type A granulometry was defined, which represents the granulometries of granular materials, asphalt mixtures, and hydraulic concrete, established in the *General Construction Specifications* of the National Highway Institute of Colombia (Invías).

The last test was carried out on samples of fine aggregate, the product of secondary crushing: the sand equivalent test (INV E-133, Invías, 2013). This test represents the percentage of the fine silty sand portion in relation to the fine clay portion, which has a harmful nature, because the minerals present can generate volumetric changes or accelerated weathering of the remaining granular material and thus affect the quality and stability of the work where it is used.

2. Geological setting

2.1. Location of the study area

The study area is called *the pilot zone of Bogotá*, defined by a radius of 200 km around the city, which has the highest demand for construction materials in Colombia. This zone includes part of the departments of Cundinamarca, Tolima, Boyacá, Santander, Meta, Casanare, Antioquia, Quindío, Risaralda, Caldas, and Huila (Figure 1).

2.2. Regional geology

The pilot zone of Bogotá contains rocks from the Eastern Cordillera, Central Cordillera, Middle and Upper Magdalena Valley, and Eastern Plains, with Precambrian, Paleozoic, Mesozoic, and Cenozoic ages, which correspond to igneous, metamorphic, and sedimentary rocks (Figure 2).

Structurally, in the southeastern sector, a system of faults of the Eastern Cordillera and the Algeciras fault is present; in the western part, the Cauca-Almaguer, Silvia-Pijao, Ibagué, Honda, Palestina and La Salina faults are present.

3. Method

Geomechanical characterization begins with the process of size reduction or crushing of the collected samples to carry out laboratory tests and measure the properties of hardness (wear test) and cleanliness (sand equivalent test) depending on the type of rock.

Once these tests were performed, the results were interpreted to define the potential use of this material as coarse aggregates (sizes in the range of 75 to 4.75 mm) and fine aggregates (sizes in the range of 4.75 to 0.075 mm), according to the *General Construction Specifications of* Invías. Below is a flow chart that identifies the work stages (Figure 3).

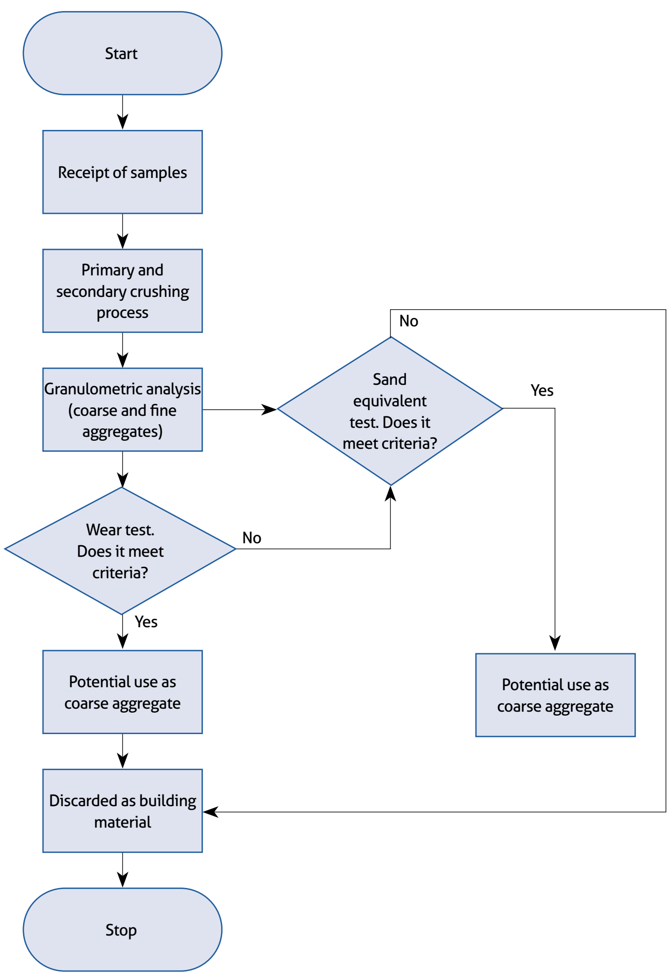

Figure 3. Process for geomechanical analysis of samples

3.1. Crushing process

The crushing process (Figures 4 and 5) is a physical transformation of stone materials without altering their mineralogical composition, hardness and durability and was necessary because the collected samples were larger than those required to perform laboratory tests (sizes between 75 and 0.075 mm).

Initially, the primary crushing was carried out by means of a jaw crusher made up of two plates facing each other, one fixed to the system and the other with a movement that oscillates back and forth. This first crushing reduced blocks or clasts of the rock up to 30 cm in size, as mentioned above. Due to the oscillatory movement of the plates, some samples tended to leave the aggregates with an elongated shape, for which a secondary crushing was necessary by means of an impact mill, made of rotating plates that hit the material against fixed plates, to correct and mold the aggregates into a cubic shape, which generates a better bond between aggregates and prevents them from fracturing easily due to the flat or elongated shape. Similarly, the impact mill reduced the size of the aggregates to produce coarse and medium sands.

3.2. Laboratory tests

The crushed samples were subjected to the geomechanical tests standardized by Invías or the Colombian Institute of Technical Standards and Certification (Icontec) (Table 1).

Figure 4. Primary and secondary crushing laboratory of the Servicio Geológico Colombiano
a) Jaw crusher; b) impact mill.

Figure 5. Samples collected from the field and after the primary crushing process

Table 1. Laboratory tests performed

Property	Test	Norm
Distribution	Granulometric analysis of coarse and fine aggregates	INV E-213 NTC 77
Hardness	Resistance to degradation of coarse aggregates by means of the Los Angeles machine	INV E-218, INV E-219 NTC 93, NTC 98
Cleaning	Sand equivalent in soils and fine aggregate	INV E-133 NTC 6179

3.2.1. Granulometric analysis of coarse and fine aggregates

This test determines the percentage distribution of the sizes (Invías, 2013) of the materials that have undergone a crushing process (sizes of gravels, sands, silts, and clays), and that are used as aggregates of granular materials, asphalt mixtures and hydraulic concrete. As mentioned above, the distribution of the crushed material in varied sizes or sieves was determined, 3", 2 ½", 2", 1 ½", 1", ¾", ½", $^{3}/_{8}$", #4, #10, #20, #40, and #200, with the #4 sieve dividing the gravel and sand portions and the #200 sieve dividing the sand and fine portions.

This size distribution is also necessary to obtain the fractions retained or the fractions that pass through a certain sieve, required for the execution of other tests (Figure 6).

3.2.2. Determination of the wear resistance of coarse aggregates

This test quantifies the loss of resistance of a material under an abrasive load and continuous movement and is the indicator of the material's hardness, an inherent property. This test is carried out in a *machine called the Los Angeles machine* (Figure 7), where a quantity of material classified by size and controlled weight is placed in a drum with an abrasive load for a time. Subsequently, the material is removed from the drum, and the sieving process is carried out: in this work, a sieve with an opening of 1.7 mm was used. Thus, the material disintegrated by the abrasive load was determined by the weight difference (Invías, 2013).

The parameters of the wear test, such as the type of granulometry, the amount of aggregate in a sieve, the number of revolutions and that of spheres that simulate the abrasive load, were defined in the test standard based on the predominant proportion of material that is retained in a range of sieves.

The granulometry that is further studied was chosen to be like that of the aggregate that will be used in the development

Figure 6. Granulometry test: Mechanical sieve, sieves and samples classified by size

Figure 7. Wear test on the Los Angeles machine
This figure shows the spheres that simulate the abrasive load on the material, the material before the test and the disintegrated material once the test is performed.

of the infrastructure work. In our case, type A granulometry was defined, which represents the granulometries of granular materials, asphalt mixtures and hydraulic concrete established in the *General Construction Specifications* of Invías.

To obtain the wear percentage, the dry mass after the test is subtracted from the mass of the initial dry sample, previously sieved by a 1.70 mm sieve in this work, and this product is divided by the initial mass (Invías, 2013).

3.2.3. Sand equivalent in soils and fine aggregates

This test determines the relationship between the amount of sand, silts and clays present in a fine portion smaller than 4.75 mm (Figure 8). This represents the percentage of the fine silty sand portion in relation to the fine clay portion, which has a

Figure 8. Sand equivalent test
Specimens in the same test to determine an average value of sand equivalent readings

Table 2. Minimum requirements of the aggregates according to the use

Test	Affirmed (Art. 311)	Granular subbase (Art. 320), Class			Granular base (Art. 330), Class			Asphalt concrete (Art. 450) R/I/B			Hydraulic concrete (Art. 500)
		C	B	A	C	B	A	NT1	NT2	NT3	
Los Angeles machine wear (maximum%)	50	50	50	50	40	40	35	25/35/-	25/35/35	25/35/35	40
Sand equivalent (minimum%)	-	25	25	25	30	30	30		50	50	60

R: Surface layer, top layer of asphalt mix; I: Intermediate layer, middle layer of asphalt mix underlying the surface layer; B: Base layer, lower layer of asphalt mix underlying the intermediate layer; Class A: Material for transit NT3; Class B: Material for transit NT2; Class C: Material for transit NT1; NT3: NEE <500,000; NT2: 500,000 ≤ NEE ≤ 5,000,000; NT1: NEE> 5,000,000; NEE: Number of equivalent axles of 8.2 tons.
Source: Adapted from General construction specifications (Invías, 2013).

harmful nature because the minerals present can generate volumetric changes during a change in the hydric state or due to accelerated weathering of the coarse and fine granular material or by interfering between anthropic chemical compounds (cement minerals), which can affect the quality and stability of the work where the material is used.

This test consists of taking a quantity of fine aggregates and a quantity of flocculating solution in a graduated cylinder and shaking the mixture so that the sand particles separate from the clay material. Subsequently, the mixture is irrigated with an additional amount of flocculating solution to force the clay material to remain in suspension. After a period of sedimentation, the heights of the flocculated clay material and the sand in the specimen are determined.

The sand equivalent is determined by dividing the sand reading by the clay reading (Invías, 2013).

3.3. Potential use

The initial criterion for analysis is resistance to degradation (wear), in which the sample must obtain a maximum wear value of 50% to be classified as a material suitable for construction. If the material does not meet this condition, through the granulometry results, it must be verified that the percentage that passes sieve #4 (4.75 mm) is greater than 60%, and the equivalent test of sand.

Once the results of the wear tests or sand equivalent have been obtained, the potential use is determined by verifying if the requirements established in the *General Construction Specifications* of Invías (Table 2) are met, classifying the coarse and fine aggregates suitable for the production of a hydraulic concrete, asphalt mixture (rolling, intermediate, and base types), granular base, granular subbase or affirmed material.

4. Results

A total of 198 samples were processed, which were crushed and classified by size of gravels, sands, and fines by means of the granulometry test. Subsequently, wear and sand equivalent tests were carried out, depending on the matrix (coarse or fine) predominant in each sample.

Of these 198 samples, 131 corresponded to sedimentary rocks (66%), 36 to igneous rock samples (18%), 19 to metamorphic rocks (10%) and 12 to unconsolidated deposits, such as river alluvium (6%) (Figure 9).

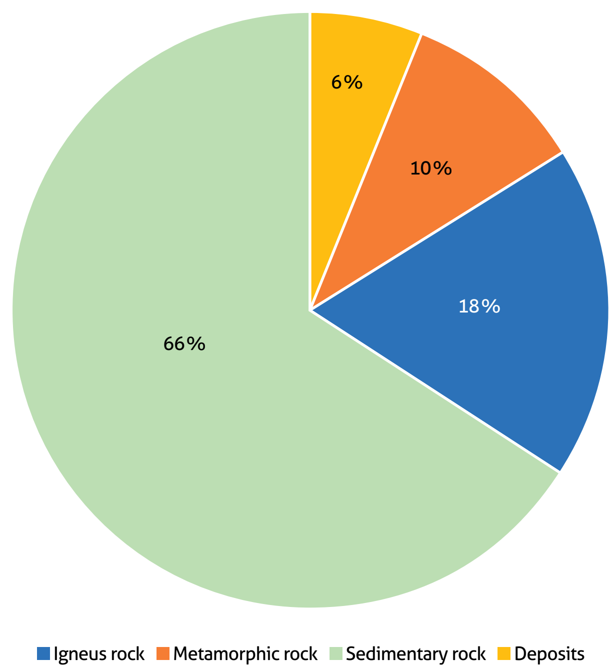

Figure 9. Distribution of the type of rocks in the sampling carried out

It is evident that 66% of the samples are sedimentary rocks because a large part of the pilot zone of Bogotá is in the eastern mountain range, formed by this type of rock.

Regarding the tests, 162 wear tests were carried out, of which 118 showed satisfactory preliminary results (wear less than 50%) to produce coarse aggregates suitable for use in granular subbases and bases, asphalt mixtures and hydraulic concrete (Appendix 1).

On the other hand, 37 sand equivalent tests were carried out, of which 19 showed satisfactory preliminary results (sand equivalent greater than 30%) to produce fine aggregates suitable for use in granular subbases and bases, asphalt mixtures and hydraulic concrete.

Appendices 1 and 2 show the location of the collected samples, the geological unit to which they belong, their classification by type of rock, and the results of the wear and sand equivalent tests.

5. Discussion

In general, it was identified that the sedimentary rocks undergo the greatest loss of resistance measured by the wear test: of 102 samples evaluated of this type of rock, 35, which are equivalent to 34%, are not suitable for producing construction materials. The samples from unconsolidated deposits (27%), igneous rocks (16%) and metamorphic rocks (6%) follow in that order (Figure 10).

In terms of cleanliness (sand equivalent test), the sedimentary rocks are 50% unsuitable for fine aggregates due to the percentage of clay minerals that compose it, which are inadequate due to the quality of the sands (Figure 11).

For igneous rocks, saprolite samples were tested, and more than 50% do not comply due to the clay fraction product of the weathering of the feldspathic minerals.

On the other hand, the laboratory tests allowed us to classify the geological materials into coarse and fine aggregates suitable to produce asphalt mixtures, hydraulic concrete, and granular bases and subbases, in accordance with the requirements of the *General Construction Specifications* of Invías. Table 3 shows the classification of all the samples analyzed.

In terms of hardness, it is evident that igneous and metamorphic rocks are more stable than sedimentary rocks, which have a wide variation in resistance. Regarding the cleaning property, no certain behavior is observed for any type of rock among the evaluated samples, furthermore, the number of samples to represent a specific behavior is limited.

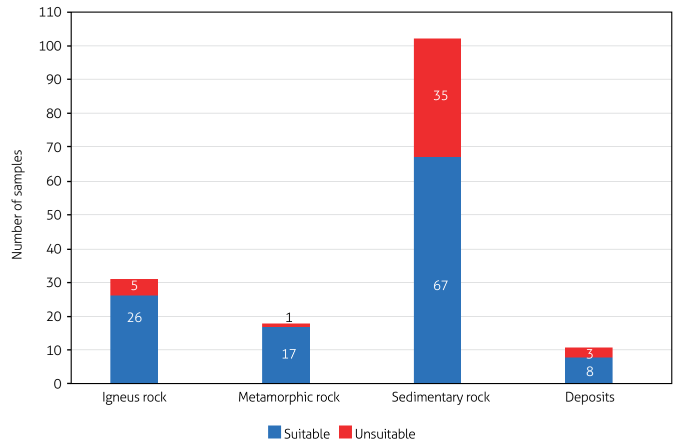

Figure 10. List of suitable and unsuitable samples of the wear test according to the type of rock

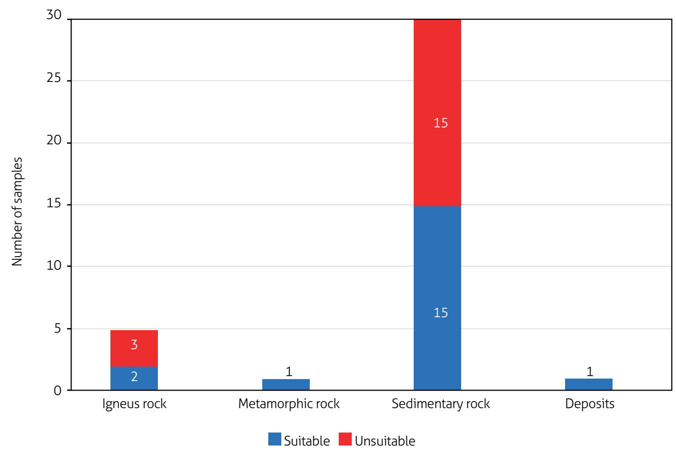

Figure 11. List of suitable and unsuitable samples of the sand equivalent test according to the type of rock

Table 3. Classification of samples based on their size, strength, or cleanliness

Classification according to material specifications	Percentage of samples
Coarse aggregate suitable to produce asphalt mixtures and hydraulic concrete	38%
Fine aggregate suitable to produce asphalt mixtures and hydraulic concrete	6%
Coarse aggregate suitable to produce granular base	15%
Fine aggregate suitable to produce granular base	2%
Coarse aggregate suitable to produce granular subbase or affirmed material	7%
Fine aggregate suitable to produce granular subbase	2%
Unsuitable material	30%

Regarding the type of rock, Figure 12 shows the classification of coarse aggregate samples based on the wear test results, and Figure 13 shows the classification of fine aggregate samples based on the sand equivalent results.

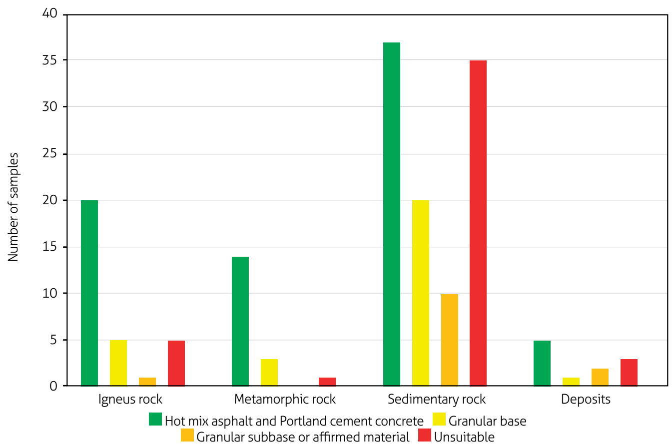

Figure 12. Distribution of coarse aggregate samples according to the wear result and the type of rock

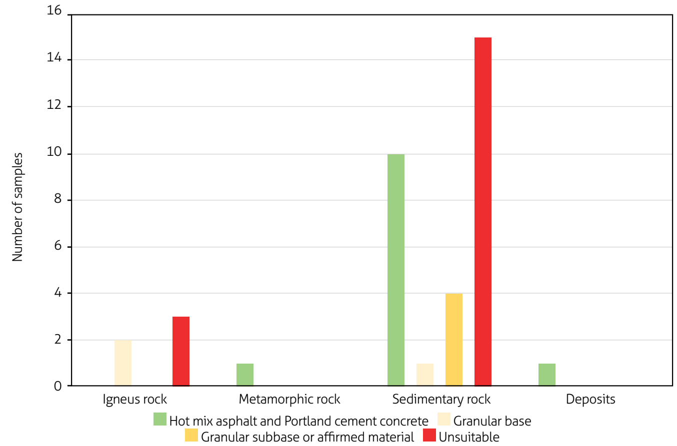

Figure 13. Distribution of fine aggregate samples as a function of the sand equivalent result and the type of rock

Figure 14 presents the location of the samples in the pilot zone of Bogotá, which is subdivided into four subzones formed as concentric circles (red dashed lines) around the city of Bogotá, to show the samples closest to the material consumption center.

It was identified that from the subzone between 50 and 100 km from the city of Bogotá, enough samples present favorable results to produce asphalt and hydraulic concrete and are thus suitable to produce granular materials (granular base, granular subbase and affirmed material).

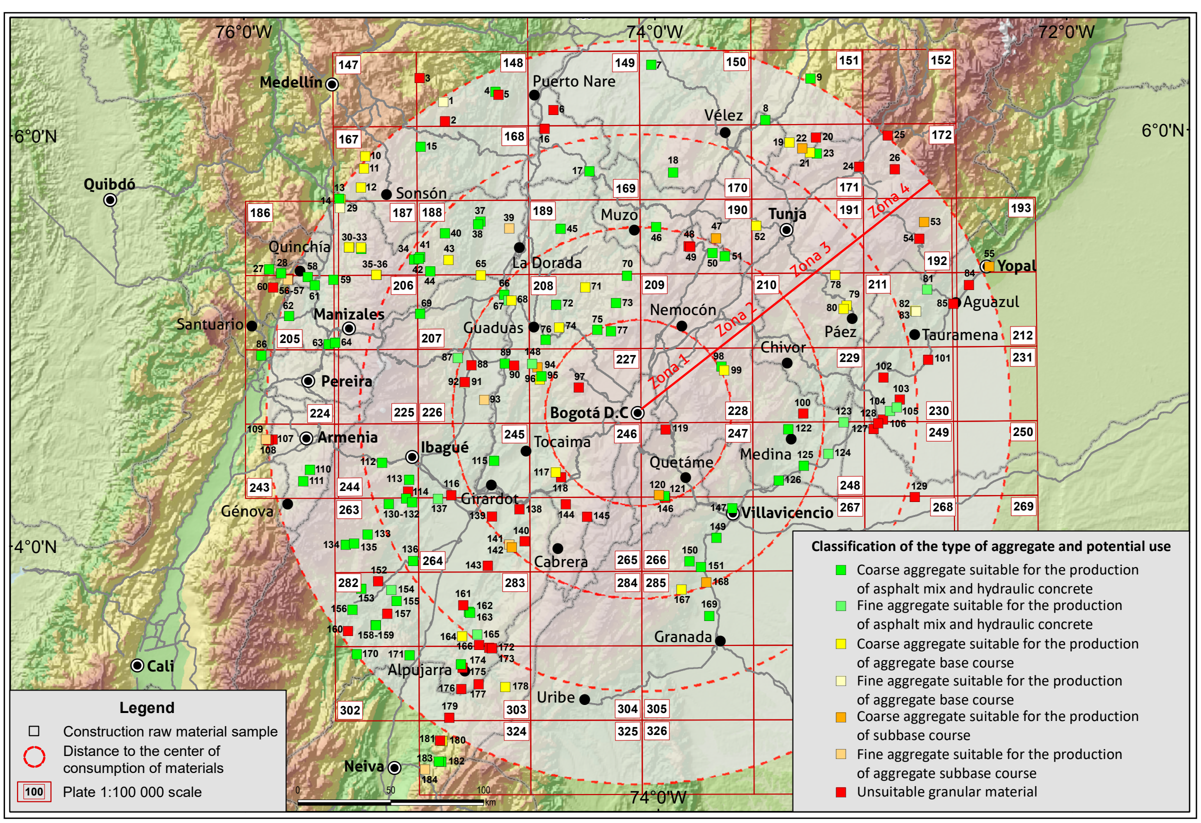

Figure 14. Potential use of the analyzed samples obtained in the pilot zone of Bogotá

6. Conclusions

According to the results obtained, igneous and metamorphic rocks are more resistant to wear in the Los Angeles machine.

Regarding the sand equivalent test, the samples that offer adequate cleanliness in the production of fine aggregates are weakly cemented clastic sedimentary rocks, with little clay matrix, and unconsolidated deposits (river sands).

Wear and sand equivalent tests show that 60% of the samples collected in the pilot zone of Bogotá can be used to produce aggregates for construction.

In the pilot zone of Bogotá, the subzone defined between 50 and 100 km from the city presents a convenient number of samples that present adequate results for the production of asphalt mixtures, hydraulic concrete and granular materials (granular base, subbase granular and affirmed material), which thus constitutes a possible area of interest for the production of construction materials that could be used in future infrastructure projects in this city and its surroundings.

7. Acknowledgments

The authors thank Dr. Gloria Prieto Rincón, former director of the Directorate of Mineral Resources of the Servicio Geológico Colombiano (SGC), for the unconditional support of the activities carried out in the Project of Investigation and Exploration of Construction Materials in Colombia in the Pilot Zone of Bogotá; to Mr. Miguel Ángel Chaves Camacho for the technical support in the execution of the geomechanical tests in the Geotechnical Laboratory required by our project; to the SIG engineer Hernán Guillermo Cifuentes, for the elaboration of the figures and location of the samples. Finally, we also thank the anonymous reviewers for their comments and suggestions.

Supplementary Data

Supplementary data for this article can be found online at https://doi.org/10.32685/0120-1425/bol.geol.49.2.2022.618

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