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RESEARCH ARTICLE

Construction Aggregates Potentiality in Humpata (Lubango Region, Angola)

Potencial en áridos para la obra civil en Humpata (región de Lubango, Angola)

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Key points:

Identification of lithologies with potential for primary sand and crushed stone in the Humpata area, close to Lubango, Angola

Alluvial sand near Humpata constitutes an annually renewable resource in fine to coarse aggregates suitable for construction

Dolomitic limestone and granite show the highest potential for crushed stone being suitable for use in the most frequent applications

ABSTRACT

In the Humpata area, near Lubango (southwest Angola), igneous, metamorphic, volcano-sedimentary, and carbonate rocks outcrop, with ages ranging from Paleoproterozoic to Mesoproterozoic. Elluvial-alluvial Cenozoic deposits of sands, clayey silts with gravels, and ferralitic armour overlie these lithologies. The aim of this study is to identify mineral raw materials for construction aggregates to supply nearby Lubango area and provide a first characterisation of their potential as raw material. Natural primary aggregates are here classified into sand and gravel, and crushed stone. Regarding characterisation of sand and gravel potential, the mineralogy of selected alluvial sand samples, particle size classification, and the respective cumulative distribution curves were studied. The analysed sands are fine, coarse, and fine to coarse-grained aggregates, suitable for construction in bituminous mixtures for roads and plaster. Use in concrete will need mixing with coarser sand. Considering the proximity to Lubango and the accessibility to raw material, the lithologies with the greatest potential for crushed stone are granites and dolomite limestones. Other lithologies such as dolerite also have potential for construction raw materials. Samples of granite, dolomite limestone, and dolerite aggregates were characterised through their granulometric curve, particle shape, and physical tests: water absorption, density, and the fragmentation resistance test. Overall, these tests revealed an adequate behaviour of the samples in relation to the analysed properties, suggesting the possibility of using these aggregates in the most frequent applications.

Keywords: Aggregates; Sand; Granite; Limestone; Dolerite

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Puntos clave:

Identificación de litologías con potencial para arenas y gravas, y áridos de machaqueo en la zona de Humpata, cercana a Lubango, Angola

La arena aluvial en Humpata constituye un recurso renovable en forma de áridos finos a gruesos aptos para la obra civil

La caliza dolomítica y el granito muestran el mayor potencial como áridos de machaqueo siendo adecuados para uso en la obra civil

RESUMEN

En la zona de Humpata, cerca de Lubango (suroeste de Angola), afloran rocas ígneas, metamórficas, vulcano-sedimentarias y carbonatadas (Paleoproterozoico al Mesoproterozoico). Depósitos cenozoicos eluvio-aluviales y corazas ferralíticas se superponen a estas litologías. El objetivo del trabajo es identificar materias primas para los áridos de obra civil que abastecerán la zona de Lubango y proporcionar una primera caracterización de su potencial como materia prima. En cuanto a la caracterización del potencial de arenas y gravas, se estudió la mineralogía de muestras de arena aluvial, su clasificación granulométrica y las respectivas curvas de distribución acumulativa. Las arenas analizadas son áridos finos, gruesos y de grano fino a grueso, aptos para la obra civil en mezclas bituminosas para carreteras y yesos. Para su uso en morteros será necesario mezclar con arena más gruesa. Considerando la proximidad a Lubango y la accesibilidad a la materia prima, las litologías con mayor potencial para áridos de machaqueo son los granitos y las calizas dolomíticas, aunque otras litologías como la dolerita también tienen potencial como materia prima para la obra civil. Se caracterizaron muestras de áridos de granito, caliza dolomítica y dolerita mediante su curva granulométrica, forma de las partículas y ensayos físicos: absorción y densidad de agua, y resistencia a la fragmentación. En general, estos ensayos revelaron un comportamiento adecuado de las muestras con relación a las propiedades analizadas, sugiriendo la posibilidad de utilizar estos áridos en las aplicaciones más frecuentes.

Palabras clave: Áridos; Arena; Granito; Caliza; Dolerita

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1. Introduction

The construction aggregates sector is an important part of most modern developed economies. They are essential to building and maintaining what is literally the physical fabric of buildings and infrastructure that our society depends on (BGS, 2013). However, the unit value of these materials is very low, meaning minimal transport is convenient between the place of exploitation and the place of consumption.

In this work, natural aggregates of primary origin, obtained directly from mineral raw materials, are classified into two groups: sand and gravel (sedimentary deposits of sand and gravel), and crushed stone (obtained by crushing natural materials such as compact rocks, pebbles, and which require more complex extraction and treatment methods).

The main parameters that define the quality of aggregates are particle size and shape, physical and mechanical properties, and durability. It is essential that the aggregate presents general properties, such as quality (complying with normative specifications); quantity (deposit with reserves for 20 to 30 years); selling markets; basic physical and mineralogical characteristics (such as density, abrasion, and compositional uniformity); transportation costs between production and competitive consumers.

The study area located in the region of Humpata City (Southwest Angola) is crossed by an important interprovincial road (EN 280) and, being very close to the city of Lubango currently the second with the major urban area and population in Angola (The World Fact Book, 2022), with access to the railway, it is implicit the special importance of identifying construction raw materials.

This article's goal is to highlight the occurrence of mineral raw materials for construction aggregates and provide a first characterisation of their potential. The identification of sand for aggregates assumes special relevance due to the scarcity of this type of aggregates, mainly associated with river sediments, in the studied region, and generally in south-western Angola. Due to the prevailing climatic characteristics, most river courses in this part of the country have a torrential regime, which does not benefit the accumulation of sand.

Most of the potential areas for aggregate extraction are located close to Humpata city and the main road, so the road network (mostly gravel roads) allows easy access, which is an important factor for the resources flow and transport.

This study is part of the mapping and characterisation work on rocks with suitability for use as aggregates carried out for IGEO, within the scope of the Chart of Rocks and Industrial Minerals of Angola (CARMINA) subproject, of the PLANAGEO project, which was accomplished in 2022. The target area of the study corresponds to CARMINA sheet 355-B, Humpata.

2. Geological setting

The study area (Fig. 1) is located on the Humpata plateau, where an extensive volcano-sedimentary sequence of Paleoproterozoic age, the Chela Group (Correia, 1976), unconformably overlies a gneissic-migmatitic and granitic basement of Paleoproterozoic age as well (e.g., Carvalho & Alves, 1993; Silva, 2009; Pereira *et al*., 2013a). The dolomitic Leba Formation (Vale *et al*., 1973; Correia, 1976) lies discordantly on the Chela Group. Dolerites and microgabbros crosscut all the units mentioned above, and are usually designated as Humpata doleritic sills, since they are installed preferentially on the stratigraphic discontinuity between the Chela Group and the Leba Formation.

The granitic and gneissic-migmatitic basement comprise units of ortho-derived gneiss with different degrees of migmatization, collectively described as a Suite of inhomogeneous granites, orthogneisses, and migmatites from the Lubango-Chibia region (Silva *et al*., 2021). The suite corresponds to leucocratic granitoids, sometimes evidencing deformation and very heterogeneous. It reveals a close spatial and/or genetic association with gneissic and migmatite rocks, with which the granitoids generally have diffuse contacts. Two subunits of this suite occur in the area: biotitic granites (± muscovite), variably foliated, and biotitic granites (± muscovite), porphyroid, foliated. The first one outcrops in the sub-plateau region, west and southwest of the Chela Escarpment, flanking the sedimentary sequences of the Chela Group. The second subunit crops out approximately 4 km west of the Humpata City, forming the granitic bedrock on which the metasedimentary sequence of the Chela Group unconformably rests.

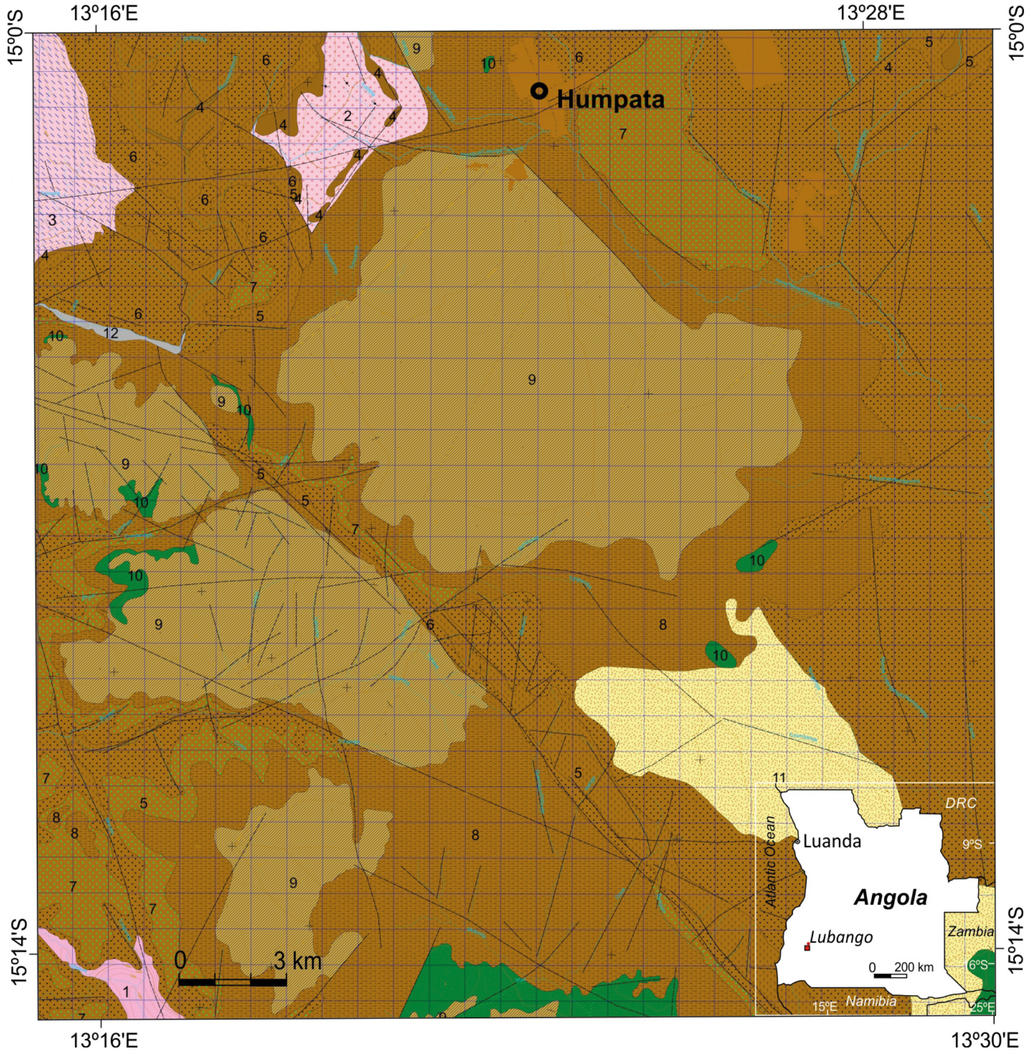

Figure 1. Study area corresponding to the sheet 355-B (CARMINA) geological map, according to the mapping of sheet D-33/T Chibia, scale 1: 250,000. Location map of the study area (small red square) in Angola (Figure 1 lower right corner). Map legend: Suite of inhomogeneous granites, orthogneisses and migmatites from the Lubango-Chibia Region: [1] Biotite (± muscovite) granites, variably foliated; [2] Biotite (± muscovite) granites, porphyroid, foliated. Late Eburnean acid plutonic suite from the Lubango-Chibia region: [3] Medium-grained biotite (±muscovite) granites. Chela Group: [4] Tundavala Formation (quartzites and metarenites with basal conglomeratic layers); [5] Humpata Formation (whitish and reddish volcanoclastites); [6] Bruco Formation (sandstones and siltstones; conglomerates); Cangalongue Formation ([7] Sandstones; [8] Pelites). [9] Leba Formation (dolomitic limestones with stromatolites). [10] Humpata basaltic suite (dolerite sills, mostly olivinic). Surface deposits: ([11] Ferralitic armour; [12] Alluvial deposits [sands, clayey silts, and gravels)].

Figura 1. Área de estudio correspondiente al mapa geológico de la hoja 355-B (CARMINA), según el mapeo de la hoja D-33/T Chibia, escala 1: 250.000. Mapa de ubicación del área de estudio (pequeño cuadrado) en Angola (esquina inferior derecha de la Figura 1). Leyenda del mapa: Suite de granitos, ortogneises y migmatitas no homogéneas de la región de Lubango-Chibia: [1] granitos biotiticos (± moscoviticos), de foliación variable; [2] Granitos biotiticos (± moscoviticos), porfídicos, foliados. Suíte plutónica ácida del Eburneano tardío de la región de Lubango-Chibia: [3] granitos biotiticos (± moscoviticos) de grano medio. Grupo Chela: [4] Formación Tundavala (cuarcitas y metarenitas con capas conglomeráticas basales); [5] Formación Humpata (vulcanoclastitas blanquecinas y rojizas); [6] Formación Bruco (areniscas y limolitas; conglomerados); Formación Cangalongue ([7] areniscas; [8] pelitas). [9] Formación Leba (calizas dolomíticas con estromatolitos). [10] Suite basáltica de Humpata (nivel de dolerita, en su mayoría olivínicos). Depósitos superficiales: ([11] coraza ferralítica; [12] Depósitos aluviales (arenas, limos arcillosos y gravas)).

In the Chela Group, the following formations are individualized from the base to the top (Pereira *et al*., 2006, 2013a, 2013b):

Tundavala Formation – presents great lithological homogeneity, being made up of a sequence of metric layers with variable thickness of compact coarse quartzite, and slightly recrystallized quartzic and arkosic metarenites; the upper limit corresponds to the transition from sandstone lithologies to fine pyroclastic lithologies.

Humpata Formation – conformably overlies the Tundavala Formation and consists of whitish and reddish volcanoclastites. The colours are varied, being common red, beige, and grey tuffs. Macroscopically, they are rocks that sometimes, due to their very fine granularity, resemble chert – when silicified – or, alternatively, mudstones when highly altered. The top of the unit is marked by an erosional unconformity where the Bruco Formation rests.

Bruco Formation – essentially corresponds to a monotonous sandstone set, macroscopically very homogeneous. Overlying a thin and discontinuous conglomeratic basal facies (generally ≤ 2 m), or volcanoclastites, there are sandstone layers, sometimes conglomeratic, with large-scale cross-stratification. The sandstones are made up of medium to coarse grains of quartz and feldspar, with a silica cement, generally presenting light to beige colours, sometimes with yellowish tints. The grains are rounded to sub-rounded evidencing textural maturity of the sediments.

Cangalongue Formation – at the base of the sequence there is a conglomerate followed by red sandstone levels; this is followed by silt-clay rocks of a very homogeneous red colour, with yellowish tints and small intercalations of compact ferruginous sandstone layers showing parallel horizontal lamination, at the top. The formation is limited above by an important lithological discontinuity defined by the abrupt transition of the red lutites, to the dolomitic limestones with stromatolites of the Leba Formation that overlies the Chela Group, through a low-angle angular discontinuity (Vale *et al*., 1973).

The Leba Formation is made up of a sedimentary set of carbonate rocks of the dolomitic limestone type, grey in colour; the layers are centimetre to metric thick interbedded with centimetre-thick layers of chert, finely laminated. Stratification is generally sub-horizontal. The formation presents intense jointing, generally perpendicular to the stratification. Lenticular layers of calcitic carbonate occur within the dolomitic carbonate. These layers' thickness can reach 20 m. The abundant presence of organo-sedimentary structures of the stromatolite type, within dolomite rocks, is characteristic of this formation (Correia, 1976).

The occurring surface deposits relate to colluvial-alluvial ferricrete type armour or laterite type armour, known as ferralitic armour (Pliocene – Pleistocene) and alluvium (Holocene) limited to valley forms regionally known as "mulolas" ("dry riverbeds"). These are shallow incisions, never exceeding ten meters deep. Its width can, however, exceed hundreds of meters. They are seasonal rivers, only during the rainy season, fed from the plateau area. These are quite heterometric deposits, being able to coexist gravel and coarse sand deposits or only coarse to medium sand deposits.

3. Methodology

The fieldwork constituted the fundamental basis of the present study, carrying out a first recognition of the characteristics of the different outcropping lithologies. Data and sample collection, whenever justified, was carried out at previously selected points in accordance with the defined CARMINA methodology, although some points had to be replaced due to lack of access to the location.

The identified and classified resources for construction aggregates were treated separately in two sets: resources for sand and gravel, and for crushed aggregates (crushed stone).

The study of the samples encompassed those analysis and tests considered the most relevant in the characterisation of construction aggregates, except for compressive strength test, which was not accomplished in this first classification. This study was carried out in the laboratory, on selected samples of sand and compact rock, respectively for natural and crushed stone; those samples were collected in deposits or massifs with higher potential for possible exploitation and use. Accessibility of the resource was always a main factor considered.

The laboratorial study concerning sand and gravel comprised mineralogical analysis of the selected sand samples with binocular lens and visual estimation of sphericity and roundness, according the Krumbein-Sloss chart (Krumbein and Sloss, 1963; ISO 13503-2, 2006), determination of particle size distribution by sieve analysis (250 g sample for a maximum aggregate dimension of 4 mm), with a motor operated sieve shaker using the sieve sizes: 0.063, 0.09, 0.125, 0.18, 0.25, 0.425, 0.5, 0.63, 0.71, 1, 1.4, 2, 2.8, and 4 mm; the NP EN 933-1 (2014) was followed and the respective cumulative distribution curves were drawn.

Samples of dolomitic limestone, granite, and dolerite were selected for crushed stone characterisation tests. Preparing the aggregate for testing involved the prior manual crushing of 20 kg of each sample with a sledgehammer to obtain fragments fitting the feed opening (100×100 mm aperture) of the jaw crusher model SP100×100 (Xamen Cheng Gong Mining Equipment, Co., Ltd.) to manufacture 5/25 mm crushed stone.

Physical-mechanical testing included particle size and shape analysis, determination of water absorption, density, and resistance to fragmentation (Los Angeles test) of the aggregates.

The sieving analysis was carried out for determining the aggregate particle size distribution in accordance with NP EN 933-1 (2014) and drawing the respective cumulative distribution curves. The particles were sieved with a motor operated sieve shaker using the sieve sizes of 0.075, 0.125, 0.25, 1, 2, 4, 4.75, 6.3, 9.5, 12.5, 22.4, 25, 31.5, 37.5, 50, and 75 mm. As none of the sample material was retained above the 31.5 mm sieve, the mass of aggregate tested was 12 kg (in accordance with the standard).

To determine the water absorption and density, both in accordance with NP EN 1097-6:2016, 7 kg test-specimens were used; the density was determined using the wire basket method.

The resistance to fragmentation of the aggregates was determined using a Los Angeles abrasion machine Proeti AR150 (Los Angeles test). For the procedure, following NP EN 1097-2 (2002), 5 kg test-specimens were used in the cylinder with abrasive (11 steel balls) and in the end, the mass of material retained on the 1.6 mm sieve was recorded.

Apart from mineralogical and shape analysis of sand and petrographic description of a thin section of granite, which was carried out in the National Laboratory of Energy and Geology (LNEG), in Portugal, all analysis and tests were carried out in Angola, at the IGEO Geoscientific Laboratory, in Congenge (Lubango).

4. Results and discussion

The proximity of Humpata to the city of Lubango justifies the need to develop work in this region aimed at identifying areas for the exploration of construction aggregates and their characterisation.

In the studied region, the raw materials with the greatest potential for aggregates are sand and gravel, and granite, limestone, and dolerite for crushed stone. The scarcity of sandy deposits with adequate particle size distribution, and quality for construction, particularly of a fluvial origin, is common in vast regions of south-western Angola, meaning that the identification of this kind of deposits with extractive potential is of particular importance.

The presented results constitute a preliminary indication of the potential of the aggregates studied for various construction materials, as the tests carried out do not allow for a more conclusive characterisation. In addition to the limited number of samples, analyses, and characterisation tests performed, which constitute the main limitations of this study, other raw materials would be important to characterize, namely the quartzites of the Bruco Formation. However, this work provides an initial characterisation of raw materials from this region, which were considered to have greater potential, with a view to their use as aggregates.

4.1. Sand and gravel

The resources for sand and gravel are found in the alluvium located in the northwest of the studied area, in the Humpata-Lubango sector, next to the main road or close to it, with access via trails. They consist of sand and sand with gravel, which occurs in the riverbed and floodplain of the Calunga and Leba rivers, less than 2 km from Humpata and 16 km from the city of Lubango, via the national road EN280, so the economic potential is high.

The deposits reach thicknesses of up to 3 m and are explored seasonally in the dry season, but in the rainy season, the important solid load carried by the rivers replenishes the resource, so despite the exploration taking place in an unsuitable location (water course or its vicinity), the impact of exploitation fades every year. It is important to note that the almost absence of impact is also due to the artisanal exploitation method practiced, with scattered extraction points. The predominantly quartz sands resources for aggregates can therefore be considered high and annually renewable, making the exploitation sustainable.

Table 1 shows the particle size classification of the selected sand samples and Figure 2 shows the respective cumulative particle size curves. There is a predominant, but variable, distribution in the samples across particle size classes from fine to coarse sand. The curves distribution has a parabolic trend, revealing sorted compositions (some range in grain size), with inflection points separating vertical and very slightly inclined sections (grain size gaps). The sand grains roundness varies slightly. In the samples illustrated in Figure 3, considering as standard Krumbein (1941), the sands are preferentially sub-rounded in sample 8, with coarser sand, and sub-rounded to sub-angular in sample 7, with finer grain; according to Krumbein (1941), the sphericity is moderate in both with a visually estimated average sphericity of 0.5 - 0.8 (Krumbein & Sloss, 1963; ISO 13503-2, 2006) (figs. 3a and b). The mineralogical observation with binocular lens shows essentially quartz sands, made of pink and hyaline quartz, and quartzite, sometimes with impregnations of iron oxides, few lithic grains and feldspar, and rare mafic minerals. The occurrence of (little) whitish silty-clay matrix added to the concavities of the grains is not significant.

Classification	Size range (µm)	Sample 4 (%)	Sample 6 (%)	Sample 7 (%)	Sample 8 (%)
Gravel	>2000	0.9	2.8	1.6	6.1
Very coarse sand	2000-1000	3.2	8.4	7.3	13.8
Coarse sand	500-1000	22.9	16.9	32.4	26.6
Medium sand	250-500	33.8	16.1	31.3	18.2
Fine sand	125-250	31.7	34.2	23.6	23.8
Very fine sand	63-125	2.8	12.4	2.2	4.3
Silt and clay	<63	4.6	8.4	1.5	6.8

Table 1. Particle size classification of selected sand and gravel samples.

Tabla 1. Clasificación granulométrica de muestras seleccionadas de arena y grava.

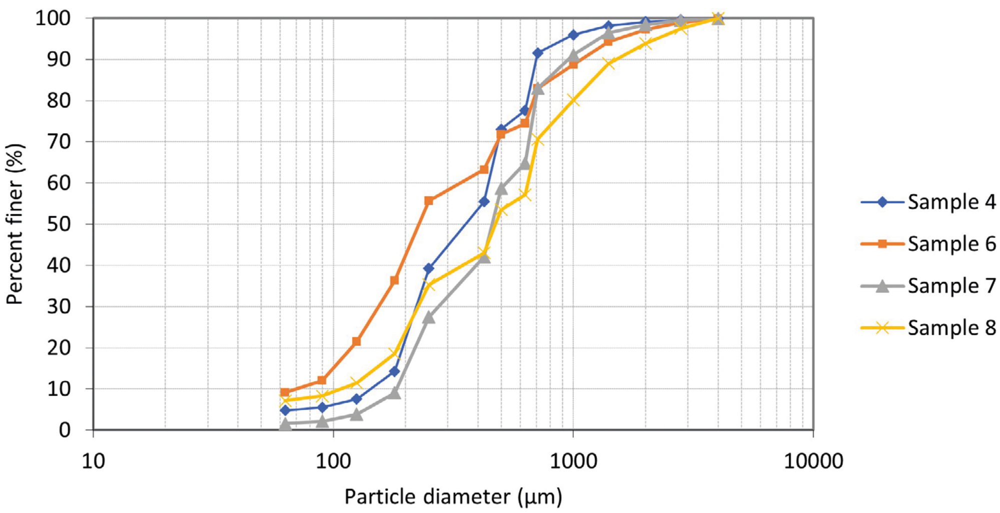

Figure 2. Cumulative particle size curves of the sand samples.

Figura 2. Curvas de distribución granulométrica de las muestras de arena.

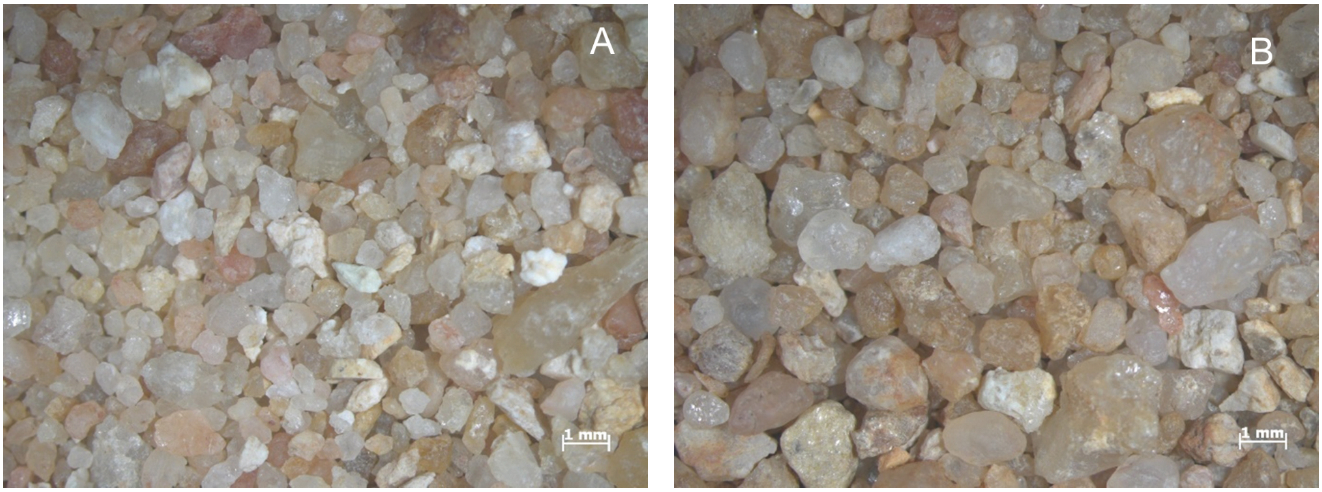

Figure 3. Bulk samples with magnification 1.0 × 1.0 (obj). a) Sample 7; b) Sample 8.

Figura 3. Muestras completas (tal cual) con aumento de 1,0 × 1,0 (obj). A) Muestra 7; B) Muestra 8.

Thus, in dimensional terms, the analysed sands are fine grained aggregates, suitable for construction in bituminous mixtures for roads and plaster. Regarding other common uses in construction, such as mortars or concrete, combination with coarser size aggregate would be required. For proper use in cement mixtures, the sand must be clean, the grains must not be coated with clay, carbonate, iron hydroxides, and must not contain more than 5% of silt and clay (Velho *et al*., 1998). The predominantly sub-rounded grains of these sands are an advantage, helping to reduce cement consumption. The quartz composition helps physical and mechanical properties, and durability. The samples of these sands revealed an average value of 5.7% for the particle size fraction <0.063 mm, which reflects their low silt and clay content, constituting an added value for the resource.

Sands with a silt-clay matrix will be more suitable for filler or filling of road base layers.

4.2. Crushed stone

At the time of the fieldwork, there was only one quarry with intermittent activity exploiting dolomitic limestone (Leba Formation) for crushed stone, but the potential for this use is also high in other lithologies, such as granites and dolerites. The most favourable and attractive lithologies from the economic point of view, due to the shorter distance to the large consumer centre of Lubango and the national road EN280, are granites (about 3 km from EN280) and dolomitic limestones (3 to 6 km from EN280 depending on the outcrops), however, other potential raw materials are the ferralitic armour (surface deposits) and dolerite sills of the Humpata Basalt Suite, which are still at economically viable distances, though with difficult access.

All these lithologies can provide quality crushed stone, except for the ferruginous crust, with strong limitations.

4.2.1. Dolomitic limestones (Leba Formation)

Dolomitic limestones constitute highly fractured rocks, being less hard than granitic rocks, which is an economic advantage in the aggregate manufacturing process; on the contrary, the frequent presence of veins, sometimes calcitic masses, is penalizing and generates heterogeneity due to differences in mechanical competence. Also, as an important drawback the clay filling of the joints causes excess of fine particles. Dolomitic limestones have good possibilities of use as armourstone, gravel, granular sub-bases, road layers, and ballasts. The resources are very high.

4.2.2. Granites (Suite of inhomogeneous granites, orthogneisses, and migmatites from the Lubango-Chibia region)

Due to their physical properties (competence, impermeability, hardness, and density), granites provide excellent crushed stone for use in construction, for example in concrete (Antolik & Jóźwiak-Niedźwiedzka, 2021). The studied granite in the Humpata outcrops is included in the Biotitic granites (± muscovite), porphyroid, foliated subunit, but macroscopically it appears as an isotropic rose granite, predominantly coarse-grained, porphyroid, with pink K-feldspar, presenting sericite and epidote as biotite and plagioclase alteration minerals. Excluding their ornamental potential as these granites are highly fractured, they have possibilities for use as construction aggregates, from large-size crushed stone, gravel, granular sub-bases, tread layers, ballasts, armourstone, railway ballast, etc. The assessment of these granite aggregates regarding its application in bound state, particularly in concrete, would require investigating their susceptibility to the alkali-silica reaction (ASR). Despite the quality of granite aggregates, alkaline reactivity is a problem that does not affect granites in certain regions, while other lithotypes in different areas are reactive (Fernandes *et al*., 2012), which can cause damages in concrete structures (e.g., Broekmans *et al*., 2009; Fernandes *et al*., 2012; Ferraz *et al*., 2017). Studies considering ASR in Angola are inexistent particularly those considering Paleoproterozoic granites. The microscopic study of this lithotype revealed granitic rock with a granular, medium to coarse-grained, hypidiomorphic texture, rich in subhedral to euhedral plagioclase crystals, intensely saussuritized. Potassium feldspar is a frequent mineral, forming interstitial anhedral crystals of perthite microcline. Granophyric textures of quartz intergrowth are sometimes observed in the microcline. A megacrystalline generation of perthitic potassium feldspar is also common. Quartz is abundant, often in polycrystalline aggregates with slightly serrated contours and undulatory extinction; sometimes they are very fractured (microcracks) and have internal deformation lamellae. Biotite is the dominant mineral, but much of it occurs in crystals partially to fully pseudomorphised to chlorite. Accessorily, subhedral and anhedral hornblende crystals occur, sometimes twinned. Some features identified in quartz by petrographic analysis - serrated contours, undulatory extinction, microcracks, and deformation lamellae, are supposed to contribute to the potential alkali reactivity of the granite (e.g., Fernandes *et al*., 2012; Ferraz *et al*., 2017). Considering the dimensions of the outcropping massif, approximately 1 by 6 km, the resources are high.

4.2.3. Ferralitic armour (Surface deposits)

The compact ferralitic armour extensively outcropping in the SE quadrant of the area are a source of crushed stone. The cementation of mineral and lithic components by high amounts of iron oxides and hydroxides, leads to the formation of hardened layers, with the appearance of a clast-supported, moderately calibrated conglomerate (3 mm to 5 cm).

This lithology does not provide usual aggregates and tends to disaggregate, originating gravel size clasts, but it requires crushing treatment, which is why it was included in the crushed stone type. The ferralitic armour aggregates are preferably coarse and originate extensive granulometry. They are frequently used in unpaved roads when they are available in the surrounding areas. Despite the drawbacks this raw material presents, such as the high percentage of silt and clay size particles, high porosity, and Fe oxides content, and therefore, not constituting suitable aggregates for quality mortars or concrete, ferralitic deposits are useful in regions where better-quality aggregates are not accessible. As advantages, ferralitic deposits are frequent, the quantities are satisfactory, their exploitation is simple, and the treatment to obtain aggregates is more economical when compared to that required for crystalline rocks. The field work carried out showed that these deposits outcrop in a vast area with variable thicknesses reaching 10 m, thus demonstrating a high volume of resources.

4.2.4. Dolerites (Humpata basaltic suite)

Dolerites are compact, unaltered crystalline rocks of high hardness and fine grain size, which is an advantage, meaning that, like granites, they make excellent crushed stone. Dolerites are more susceptible than granites to volume variations due to changes in the physical environment and alteration.

4.2.5. Characterisation of selected lithologies

The information about the aggregate granulometric curve is essential to quickly assess its granulometry and any deficiencies it may have in terms of certain granulometric fractions, for example the lack of particles of a given size range, essential for establishing the adequate amount for concrete and mortars.

The particle size distribution curves of the aggregates of samples from the three lithologies are shown in Figure 4. The very similar distributions have a uniform trend, characteristic of crushed stone. The silt and clay content (<0.075 mm) is very low (< 1%).

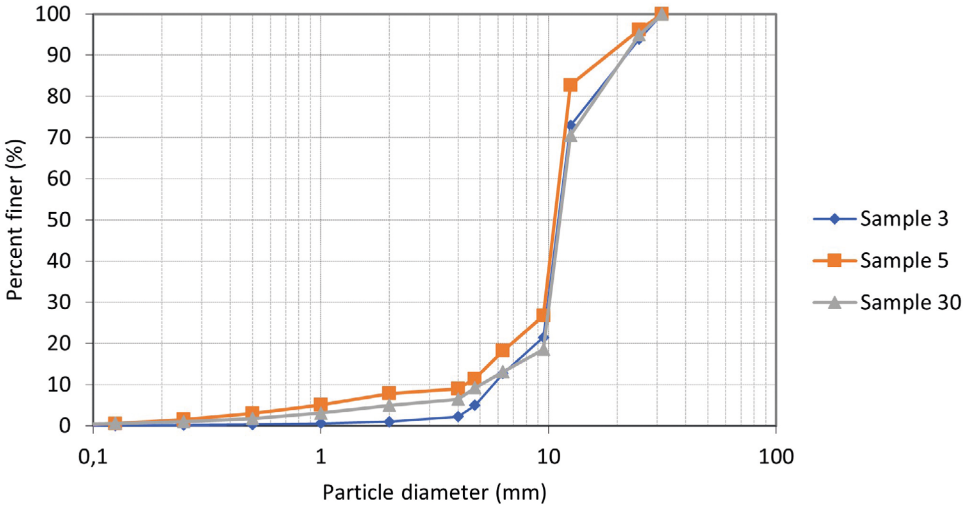

Figure 4. Cumulative particle size curves of rock samples for crushed stone. Dolomitic limestone (sample 3); granite (sample 5); dolerite (sample 30).

Figura 4. Curvas de distribución granulométrica de muestras de roca para áridos de machaqueo. Caliza dolomítica (muestra 3); granito (muestra 5); dolerita (muestra 30).

The geometrical properties of the studied aggregates were not tested according to the standards, and therefore shape indices were not determined. A visual appreciation of the three samples (Fig. 5), showed a predominance of angular faces more pronounced in dolerite than granite and limestone. All the aggregate particles present a rough surface texture and a predominantly cubic to irregular shape, with flaky or elongated particles being less represented compared to the former.

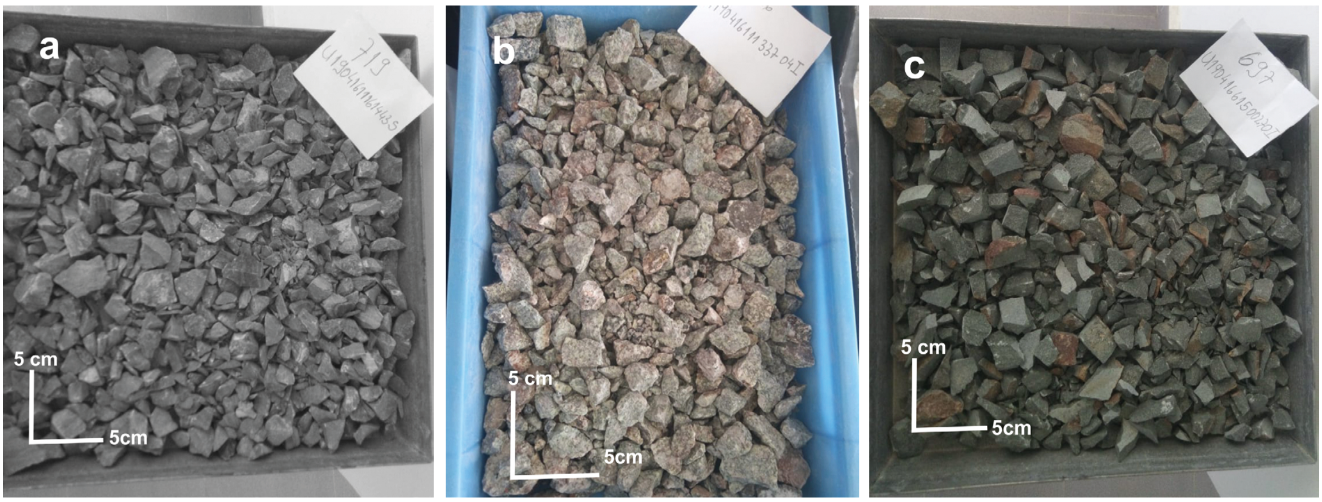

Figure 5. Samples for crushed stone. a) dolomitic limestone (sample 3); b) granite (sample 5); c) dolerite (sample 30).

Figura 5. Muestras de roca triturada para áridos de machaqueo. a) caliza dolomítica (muestra 3); b) granito (muestra 5); c) dolerita (muestra 30).

Water absorption and density are directly related to the porosity of the aggregate, so its knowledge is essential for its characterisation. A high porosity value may indicate, in some cases, a high weathering level. On the other hand, when aggregates are used with a binder, this can lead to higher consumption of the binder, making it advisable to limit the water absorption values of aggregates, such as those used in the manufacture of bituminous mixtures for road layers. The values obtained for water absorption are below 0.5%, except for dolerite (0.7), satisfying specifications for main uses of aggregates, such as bituminous mixtures (EN 13043, 2013; INIR, 2012a), armourstone (EN 13383-1, _2002). Regarding density, the results obtained are in line with usual values for limestone and granitic aggregates; the porosity has very low values, even for the dolerite aggregate, indicating a sufficiently high resistance for the same applications mentioned above for water absorption (Table 2).

Sample	Density (g/cm^3)	Water absorption (%)	Resistance to fragmentation (LA)
3 (dolomitic limestone)	2.79	0.0	18.5
5 (granite)	2.65	0.1	19.1
30 (dolerite)	2.74	0.7	15.9

Table 2. Test results for the density, water absorption and resistance to fragmentation of crushed stone of dolomitic limestone, granite, and dolerite samples.

Tabla 2. Resultados de los ensayos de densidad, absorción de agua y resistencia a la fragmentación de áridos triturados de muestras de caliza dolomítica, granito y dolerita.

The study of rocks and, ultimately, the aggregates obtained from them, from the point of view of their resistance, implies their hardness. This parameter plays a decisive role in abrasiveness, which in turn plays an important role in the tests currently used in the laboratory to determine the mechanical quality of aggregates. The resistance to fragmentation test results for the three lithologies (Table 2), always presenting Los Angeles (LA) coefficient values < 20%, indicate a high resistance of these aggregates to wearing and the aggregate strength. Concerning this parameter, those values satisfy most frequent applications, such as bituminous mixtures for road layers (EN 13450, 2002; INIR, 2012a), and also meet more demanding specifications, such as those concerning aggregates for railway ballast (EN 13450: 2002).

A	Density		Water absorption (%)	
Lithology	Granite	Limestone	Granite	Limestone
n	49	31	81	46
Min	2.62	2.65	0.2	0.4
Avg	2.67	2.70	1.2	2.0
Max	2.74	2.72	2.9	4.8

B	LA_{20}	LA_{25}	LA_{30}	LA_{35}	LA_{40}	LA_{50}
Total %*	3	10	12	26	37	12

* Percentage of the total sum of reported cases by the producers.

Table 3. Performance values declared by producers, for granite and limestone aggregates produced in Portugal (based on Castelo Branco, 2009): A. Total of declared cases (n), minimum (Min), average (Avg), and maximum (Max) values of density and water absorption; B. Declared performances (by LA categories), of granite aggregates, regarding resistance to fragmentation (Los Angeles abrasion test).

Tabla 3. Valores de rendimiento declarados por los productores, para los áridos graníticos y calizos producidos en Portugal (basado en Castelo Branco, 2009): A. Total de casos declarados (n), valores mínimos (Min), medios (Avg) y máximos (Max) de densidad y absorción de agua; B. Prestaciones declaradas (por categorías LA), de los áridos graníticos, en cuanto a resistencia a la fragmentación Los Ángeles.

Considering the results obtained, aggregates made with the sampled lithologies, in which concerns the studied properties (density, absorption/porosity, and resistance to abrasion) are suitable for main applications either in unbound state – used as, e.g., road base, ballast, or in bound state – e.g., bituminous mixes, concrete. The suitability of aggregates from the studied lithologies for the aforementioned applications is, however, conditioned by other properties that were not addressed in this study, particularly those measuring the strength of the aggregates (e.g., compressive strength).

Currently, there is no data on the characterisation of aggregates in the region of Angola studied or even in its wider surroundings, so it is not possible to establish comparisons. Making a tentative comparison between the values of density, water absorption, and resistance to fragmentation of aggregates produced in Portugal (Table 3, Castelo Branco, 2009) and the values obtained in this work for the granite and limestone lithologies (Table 2), it can be observed that regarding the granite aggregate, the density values are within the normal values of aggregates produced in Portugal, but the water absorption is lower and the resistance to fragmentation is higher than the most frequent values for this parameter in Portuguese granites, which is an indicator of the soundness and strength of the aggregate studied. Regarding the dolomitic limestone establishing comparison is difficult, because Portuguese Mesozoic limestone exploited for aggregates usually has a higher calcite and/or clay/silt content. The dolomitic limestone aggregate studied has higher density and much lower water absorption value, indicating a higher strength than the one of average limestone aggregate.

5. Conclusions

The identification and characterisation of mineral resources for construction aggregates in the proximity of large urban centres such as Lubango is a primary need, especially regarding sand and gravel, as the Southwest region of Angola is generally quite deficient in this type of aggregates.

The sand and gravel deposits are confined to the floodplains of the main watercourses, but the resources can be considered significant, as they are exploited seasonally in a relatively artisanal way, causing little impact. These are predominantly fine aggregates, quartz sands with fine to coarse grain sizes suitable for use in bituminous mixes for road layers, but other frequent applications such as mortars, and concrete, will require improving the grain size distribution of sand.

Rock resources for crushed stone in dolomitic limestones, granites, and dolerites were identified and some key properties characterised. Aggregates produced from the ferralitic armour may also be used, with limitations to less demanding uses.

Dolomitic limestone and granite have high potential in terms of the resource itself and location. The former is intensely fractured and being a rock less hard than granite, the aggregate manufacturing is less expensive. However, granite constitutes a better-quality aggregate, more homogeneous, and without the fine particles content that the dolomitic limestone can present due to the clay amount in open joints. The results of analyses and tests carried out on the samples of dolomitic limestone, granite, and dolerite revealed favourable properties and did not show significant differences between these lithologies, suggesting that the aggregates produced from dolomitic limestone, granite and dolerite are suitable for use in the most frequent applications.

Following this work, it would first be important to complement the general characterisation of the studied lithologies, in terms of the mechanical performance of the aggregates produced (e.g., compressive strength and shape tests) and resistance to weathering (e.g., salt crystallization tests). For granites, aiming for their application in concrete, it would be valuable to test the rock's susceptibility to ASR phenomena. This study would allow, based on the performances of these raw materials, to know their viability for the various segments of construction.

Authorship contribution statement

José Vítor Lisboa: Writing - Original Draft, Investigation, Conceptualization, Methodology, Visualization, Supervision, Project administration, Formal analysis.
Álvaro Oliveira: Resources, Data Curation, Investigation, Validation, Writing - Review & Editing.
Jorge Fernández: Methodology, Writing - Review & Editing.
José Feliciano Rodrigues: Methodology, Writing - Review & Editing.
José Manuel: Writing - Review & Editing.

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