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Geo-resource mapping in the Lakhssas plateau and Ifni massif, Morocco: a geomatics and geotechnical perspective

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INTRODUCTION

The progress of modern societies is intrinsically linked to the construction and civil engineering industries, which are major consumers of materials derived from quarries, particularly aggregates, sand, and gravel. However, like any industrial activity impacting the environment, quarrying raises concerns regarding its potential negative effects on ecosystems, biodiversity, and landscapes. In the face of growing challenges related to sustainable development, it is imperative to adopt innovative approaches for responsible geo-resource management, minimizing environmental disruption, and preserving geological heritage.

It is within this context that the in-depth study conducted on the Lakhssas Plateau and the Ifni Massif, located in the western Anti-Atlas of Morocco, takes place. This region, rich in potential geo-resources, has experienced a proliferation of quarries developed without prior optimization studies, posing risks to the environment. This study aims to create a geotechnical map for the sustainable exploitation of geo-resources in this area, leveraging the capabilities of Geographic Information Systems (GIS).

The primary objective is to identify and quantify the potential resources of the Lakhssas Plateau and the Ifni Massif, while guiding operators towards the most suitable areas for opening new quarries, in compliance with environmental regulations and the preservation of geological heritage. This approach seeks to strike a balance between meeting the demands of the construction industry and safeguarding the ecological integrity of the region. By providing a scientifically robust framework for quarry development, the study aims to minimize environmental impacts while ensuring the long-term availability of essential construction materials.

Ultimately, this study serves as a decision-support tool for stakeholders involved in quarry operations, providing them with accurate and up-to-date information on available resources, their quality, and their location. This informed decision-making process is crucial for fostering a more sustainable and responsible approach to resource extraction in the region.

MATERIALS AND METHODOLOGIES

This study employed an integrated, multidisciplinary approach, combining geotechnical expertise with the powerful tools of Geographic Information Systems (GIS). This methodology was structured around the following key phases:

- **Collection and Compilation of Existing Data:** The initial phase focused on assembling a comprehensive dataset of georeferenced and structured information covering various aspects of the study area. Geological maps from the Geological Survey of the Ministry of Energy and Mines were digitized, georeferenced, and compiled to establish a precise and exhaustive cartographic base. Lithological, petrographic, geochemical, and geotechnical data from bibliographic sources and previous studies were also collected and integrated into a spatial database. A high-resolution Digital Elevation Model (DEM) (30-meter) was utilized to extract topographic information, including elevation, slope, and aspect. This foundational dataset provided a critical framework for subsequent analyses.
- **Strategic Field Sampling Campaign:** A meticulously planned field sampling campaign was conducted to ensure representative coverage of the main geological units present within the study area. A rigorous protocol was followed during sample collection to maintain sample integrity and ensure data quality. Multiple samples were collected from each rock outcrop to account for lithological variability. The samples were then sealed in airtight bags to preserve their integrity until laboratory analysis. This careful approach to sample acquisition and handling aimed to minimize potential biases and maximize the reliability of the resulting data.
- **Laboratory Geotechnical Analyses (Characterization of Material Properties):** A comprehensive suite of laboratory geotechnical tests was performed to determine the physical and mechanical properties of the various rock types. Tests were conducted in accordance with current European

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(AFNOR) and Moroccan standards, ensuring comparability and reproducibility of results. The primary tests included:

- **Los Angeles Abrasion Test:** To assess aggregate resistance to fragmentation and abrasion.
- **Micro-Deval Test:** To measure aggregate resistance to wear under the combined action of water and abrasion.
- **Bulk Density Determination:** To calculate the mass per unit volume of the rocks.
- **Porosity Determination:** To evaluate the volume of voids within the rock.
- **Water Absorption Coefficient Determination:** To quantify the rock›s capacity to absorb water. These tests provide essential data for characterizing the suitability of the materials for various engineering applications.

- **Integration and Spatial Analysis within a GIS (QGIS):** All collected and generated data (cartographic data, geotechnical analysis results, topographic information) were integrated into a Geographic Information System (QGIS), a powerful and flexible open-source software platform. This platform facilitated:

  - Efficient data structuring, organization, and management.
  - Visualization of data through thematic maps.
  - Execution of complex spatial analyses (overlaying information layers, area calculations, proximity analyses).
  - Classification of zones according to their exploitation potential, combining geological and geotechnical data.
  - Production of clear and informative summary maps to aid decision-making. The use of QGIS provided a robust framework for spatial data management and analysis, ultimately contributing to a more comprehensive understanding of the geotechnical potential within the study area.

RESULTS

Analysis of the geotechnical testing data enabled characterization of the primary rock types present within the study area:

- **Carbonate Rocks (limestones and dolomites):** These are characterized by a relatively high density (ranging from 2.6 to 2.74 t/m^3), low porosity, and low water absorption. Their resistance to wear (measured by the Micro-Deval test) and fragmentation (Los Angeles abrasion test) varies, but generally falls between 15% and 35%. These rocks are primarily utilized as aggregates in road construction and concrete production. The variability in their resistance properties, however, necessitates careful selection based on the specific intended application.
- **Igneous Rocks (granites, basalts, diorites and granodiorites):** These rocks exhibit higher densities (greater than 2.6 t/m^3), very low porosity and water absorption, and generally high resistance to wear and fragmentation. This robust geomechanical profile makes them highly sought after for manufacturing paving stones, kerbstones, facade cladding, and other applications demanding high durability. The specific mineralogical composition within this group influences the final engineering performance and should be considered during material selection.
- **Detrital and Volcaniclastic Rocks (sandstones, conglomerates, breccias and tuffs):** This lithological group displays variable density (typically between 2.5 and 2.7 t/m^3), higher porosity and water absorption compared to igneous and carbonate rocks, and generally lower mechanical strength. Their geotechnical properties often dictate their use as fill materials, in foundation construction, and

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as sub-base layers in road construction. Further investigation into the cementation and grain size distribution is crucial for optimizing their utilization in specific engineering contexts.

Spatial analysis of the compiled data facilitated the production of a geotechnical potential map for the study area, delineating five potential classes: high, medium, low, very low, and null. The spatial distribution reveals the following:

- **High potential zones:** These are primarily concentrated around the Ifni inlier, where the most resistant igneous rocks outcrop. This geological context offers significant opportunities for quarrying and the extraction of high-quality construction materials.
- **Medium and low potential zones:** These correspond to areas dominated by carbonate and detrital rocks, where resistance properties exhibit greater variability. Project development in these areas requires a more detailed site-specific geotechnical investigation to assess suitability for various engineering applications.
- **Very low and null potential zones:** These are predominantly located in alluvial plains, where unconsolidated materials and soils prevail. These areas present significant geotechnical challenges for construction and require specialized engineering solutions.

Quantitatively, this study demonstrates that approximately 72% of the study area possesses an exploitable potential ranging from low to high. This finding underscores the significant resource potential within the region, but emphasizes the need for careful planning and management to ensure sustainable development and minimize environmental impact.

DISCUSSION

The results obtained in this study are generally consistent with data reported in the scientific literature, supporting the reliability of the employed methodology. However, some variations were observed in the values obtained for impact and wear resistance. These discrepancies likely stem from the inherent variability in rock properties, the nuances of experimental methods, and the influence of weathering parameters, particularly fracturing, which can affect rock strength unevenly within a given formation. Further investigation into the microstructural characteristics of the rocks could provide additional insights into these observed variations.

The adopted geomatics approach offers a powerful tool for identifying, characterizing, and quantifying resources. Moreover, integrating a digital elevation model would introduce another valuable layer of analysis, enabling a more refined assessment by considering factors such as the complexity of exploitation. This would be particularly relevant for evaluating the feasibility and cost-effectiveness of potential quarry sites in challenging terrain.

Spatial analysis within a GIS framework also presents significant potential for scenario simulation, incorporating various environmental factors such as transportation and the presence of sensitive habitats. Such simulations could inform decision-making processes by evaluating the potential impacts of different exploitation strategies and identifying optimal solutions that balance economic development with environmental protection.

This integrated approach to geo-resource management not only allows for the identification of suitable locations for quarry development but also facilitates the optimization of operational costs. By combining geological, geotechnical, and topographic data within a GIS, a comprehensive understanding of the resource potential and associated challenges can be achieved, promoting sustainable and responsible resource utilization.

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CONCLUSIONS

This study successfully demonstrated the effectiveness of a multidisciplinary approach, integrating geotechnical expertise with the capabilities of GIS, for the sustainable management of quarry resources. The results provide a solid foundation for strategic planning of mineral resource exploitation in the Lakhssas Plateau and Ifni Massif.

The generated geotechnical potential maps constitute a valuable tool to guide the decisions of public authorities and industry stakeholders towards rational and responsible resource utilization. By targeting high-potential zones and considering environmental constraints, the negative impacts of extractive activities can be minimized while maximizing economic benefits. This balanced approach is essential for ensuring long-term sustainability.

However, it is important to acknowledge that this study represents a preliminary stage and warrants further investigation and refinement. Specifically, the following recommendations are proposed:

- Increase the density of the sampling network: This will refine the characterization of rock properties and reduce uncertainties associated with data interpolation, leading to a more accurate assessment of the resource potential.
- Conduct petrographic and geochemical analyses: These analyses will provide a deeper understanding of the rock formation processes and their inherent properties, informing more effective material selection and utilization.
- Perform more sophisticated mechanical tests (triaxial tests, creep tests, etc.): These advanced tests will enhance understanding of rock behavior under stress, crucial for designing safe and stable quarry operations.
- Implement an environmental monitoring system: This system will track the impacts of extractive activities, enabling adaptive management strategies and mitigating potential environmental damage.
- Expand the study to a larger scale: Including pedological and hydrological studies within the area will provide a more holistic understanding of the potential impacts of new quarry development, allowing for more informed and sustainable land-use planning.

Furthermore, these recommendations should be incorporated into future reforestation planning maps, ensuring that resource extraction and ecological restoration efforts are harmonized. This integrated approach is vital for minimizing environmental disruption and promoting sustainable land management practices.

Ultimately, this work contributes to a sustainable development framework, promoting more responsible geo-resource management practices in the Lakhssas Plateau and Ifni Massif. By integrating scientific rigor with practical considerations, this study provides a valuable contribution to the ongoing efforts towards achieving a balance between economic development and environmental stewardship.

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