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Spatial Variability Mapping of Soil Properties in Katsina Metropolis

Usman Abubakar Maiwada [a], Mustapha Sani [a], Nura Usman [a]

[a] *Department of Civil Engineering, College of Engineering, Hassan Usman Katsina Polytechnic, Katsina, Nigeria*
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A B S T R A C T

The index and engineering properties of soil were investigated with the aim of developing a geotechnical map of spatial variability in soil properties in Katsina metropolis. Soil samples were collected at 1.0m and 1.5m depths from 20 sample points with their respective coordinates. This study explores the application of ArcGIS software for mapping the geotechnical engineering properties of soil in Katsina metropolis with the aid of the Kriging spatial interpolation capability. Maps showing variability in soil properties such as the natural moisture content, specific gravity, consistency limits (liquid limit, plastic limit, and plasticity index), and soil bearing capacity were developed. The results provide map for preliminary design and urban planning for future development in the Katsina metropolis.

Keywords: Geotechnical properties, Variability, ArcGIS, Kriging Interpolation, Global Positioning System

1. Introduction

Soil is the consequence of rock fragments weathering due to the interaction of several environmental conditions (temperature, topography, organisms, parent material, and time). To sustain ecosystems and human civilization, soil is essential. Soil survey offers comprehensive data that is essential for soil research and development. Additionally, it provides the data required to create strategies for soil management and land use (Gunavant, et. al., 2021). The primary source of soil particles is weathering of parent rocks into rock fragments and soils. Mature soils are formed when all of the weathering agents function in harmony. The active agents that contribute to the formation of soils are climate, vegetation, and reliefs. In a dual sense, the biotic activities are likewise very active factors. The process of soil formation differs from location to location due to varying conditions. (Dasgupta, 2017, Balasubramanian, 2017; Biplap & Subhechya, 2019).

Soils vary naturally due to their mode of formation (weathering) coupled with human activities and other environmental factors (topography, vegetation cover) play a significant role in transforming their properties. Types of weathering and their agents together with continuous modification by external forces such as soil improvement, excavation, filling and chemical interaction, also influence variability in soil properties. Since soil is considered homogenous for geotechnical purposes, factors of relevance must be quantitatively valued at this level; these values should be indicative of the parameters in the soil unit (Uzielli, et. al. 2007). The investigation of both index and engineering properties guides geotechnical engineers in understanding its suitability as a foundation material, fill, and construction material or if it requires modification before being used as construction material (khatri & Suman, 2018). It is generally accepted that soils with the same index values have the same properties. Index properties of soil helps in classification as well as providing some information about the engineering properties (**Verma** et al., 2021). But there are times when this relationship between the index and engineering attributes isn't ideal (Popescu et al., 2005), soil qualities can vary both vertically and spatially within a given area (Hartemink et al., 2020).

Adebayo et al., (2022) reported that the specific gravity, natural moisture content, liquid limit, plastic limit, optimum moisture content, maximum dry density and unconfined compressive strength values do not vary significantly with horizontal locations within the same area. These variations may occur as a result of the soil type at different depths and locations. It is, therefore, imperative to carry out detailed soil investigations at any given site before construction works commence. Estimation of the index properties as done in some civilizations to give an insight into some engineering properties such as shear strength, permeability and compaction parameters (Adebayo and Balarabe, 2021).

Geotechnical maps reduce the time and cost required for the preliminary investigation of large-scale projects and serve as a ready-to-use database for low rise residential units because preliminary foundation design recommendations may be determined using these maps. The selection of suitable routes for highways by avoiding patches of poor subgrade ratings can also be performed. These maps can serve as tools for the selection of suitable borrow areas (by showing excellent to good subgrade rating) for highway embankments. This also simplifies the screening process of available sites for a particular project without requiring considerable financial implications.

GIS-based user-friendly system developed using application of Natural Neighbor Interpolation Tool can assist to easily and quickly produce the maps of different themes based on soil properties. The valuable information about soil properties obtained within any study area can be suitable for preliminary design purpose. The system can provide a means of identifying areas with suitable construction materials in the study area. Furthermore, areas with potential foundation problems within the study area can also be easily identified and avoided during the feasibility studies of future development. In this research, index and engineering properties of soil in Katsina metropolis was studied and used for the production of spatial variability map for soil properties.

2. Study location

The study was conducted in Wakilin Kudu 1 and Wakilin Kudu 2 areas of Katsina metropolitan in Katsina state, Nigeria. The GPS location of Katsina metropolitan is Latitude, 12° 59' 34.87"N ; Longitude, 7° 36' 22.19"E. Figure 1 shows the location of study area on Nigeria map.

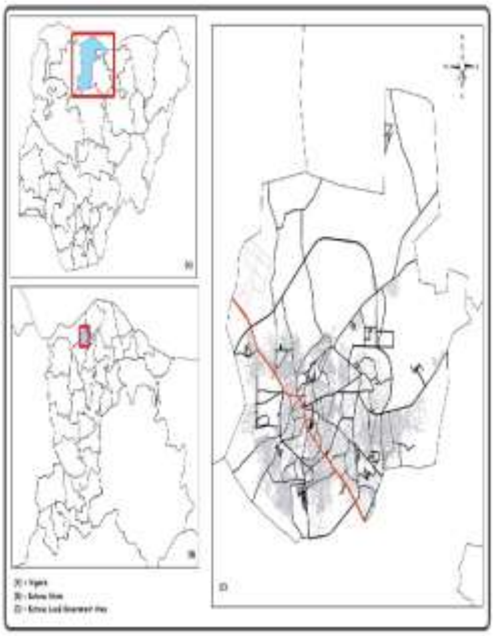


Figure 1: Map of study area

3. Materials and Method

3.1 Materials

The material used for this study is soil samples collected from 20 trial pits in the study zone, the samples were randomly selected to investigate their index and engineering properties.

3.2 Methods

The methodology adopted for this study is as follows:

3.2.1 Sample Collection

Due to the size of the study, the study area was divided into 2 zones with each zone further subdivided into 10 locations making a total of 20 locations. The trial pits were distributed randomly within the study area in order to obtain a representative cross-section of the area. A total of 20 samples were collected with their respective coordinates. Soil samples were obtained at both 1.0m and 1.5m and laboratory tests were carried out on the samples in accordance with BS 1377 (1990).

3.2.2 Sample Characterization

This is the laboratory test stage in which experiment were conducted to determine index and engineering properties of soil samples collected from the study zone. In order to classify and test the strength of the collected samples, the following tests were conducted according to the provisions of BS 1377 (1990). The natural moisture content (w), specific gravity (Gs), the consistency limits (liquid limit; LL and Plastic limit; PL), particle size distribution, soil classification (AASHTO), compaction test, and shear strength test (direct shear box).

3.3 Digitization and Development of the Study Map

Global Positioning System (GPS) map camera installed on a Samsung A21S Android mobile phone was used to obtain coordinates information of the sampled points used for this study.

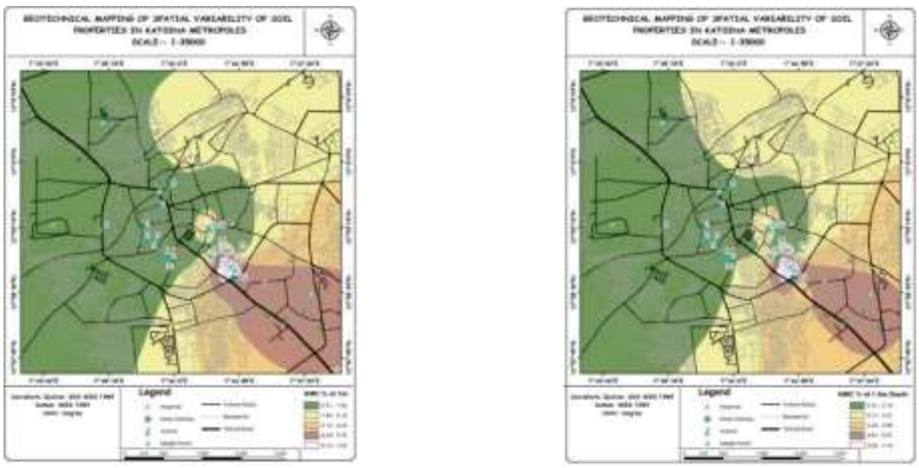
The first stage was the digitization and development of the study area map in ArcGIS. Satellite image of the area obtained from Google earth digitized and geo-referenced in Arc map. Coordinates of some control points were obtained using handheld GPS and used to geo-referenced the map. The last stage of the research was database creation and analysis of results. Map database was created using arc catalogue and uploading the tested results of the borrow pits in the database. Other spatial and non-spatial attributes of the study area also recorded, and the map was updated accordingly. Natural neighbor interpolation tool was used in performing the analyses that resulted in obtaining maps of various properties of soil. The natural neighbor interpolation tool is also called “Sibson” or “area-stealing”. The procedure of using the tool involves catching the nearby subcategory of input models to the point of enquiry and putting weights to them based on comparable areas to incorporate a value.

Spatial Interpolation is a method of estimating attributes at point locations which are not sampled or at which we do not have the data, by using the attributes at point locations for which we have the data. Geostatistical analyst extension in ArcMap is used for interpolating the Geotechnical data and predicts the data at unknown locations. Kriging is a type of spatial interpolation method that makes predictions at unsampled locations using a linear combination of observations at nearby sampled locations. The influence of each observation on the kriging prediction is based on several factors: which are, its geographical proximity to the unsampled location, the spatial arrangement of all observations (i.e., data configuration, such as clustering of observations in oversampled areas), and the pattern of spatial correlation of the data. The kriging interpolation provides us with predictions of each soil property at every location of the study area in the form of continuous maps. Thus, all the obtained test result is used in the ArcGIS software using the kriging method of spatial variation to predict accurately other areas.

4. Result and discussions

4.1 Natural moisture content

Natural moisture content test was conducted on the soil samples collected from study zone, and the spatial variation of moisture at a depth of 1m is presented in Figure 2a, while Figure 2b is the special variation of moisture content at the depth of 1.5m.



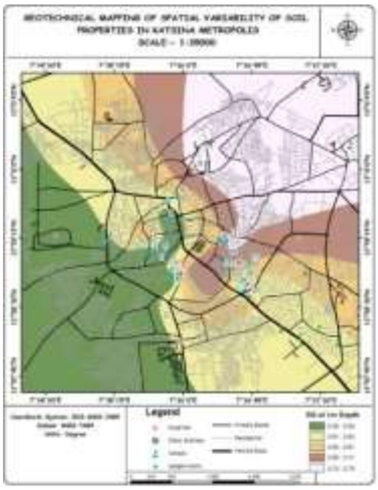
(a) (b)

Figure 2: Map of study area showing spatial variation of natural moisture content at 1m (a) and 1.5m (b)

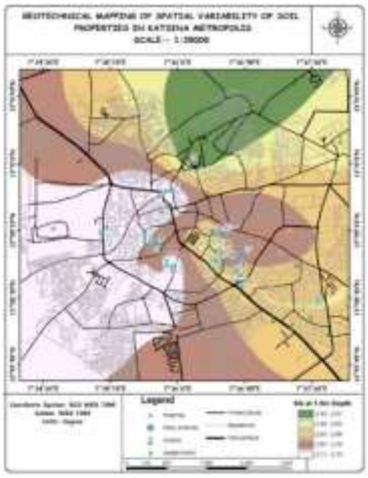
Figure 2a and 2b shows the distribution of natural moisture content over the study area at 1m and 1.5m respectively. Colour variations means different range of moisture contents; green and white colour layers denotes areas with low to high moisture content. The various colour ranges indicates the amount of moisture present, these variations are due to the soil types, proximity to ground water and the dry seasons (Wang et al., 2024).

4.2 Specific gravity

The spatial variability of soil specific gravity in the study zone is presented in Figure 3a for 1m depth and 3b for specific gravity of soil at 1.5m.



(a)



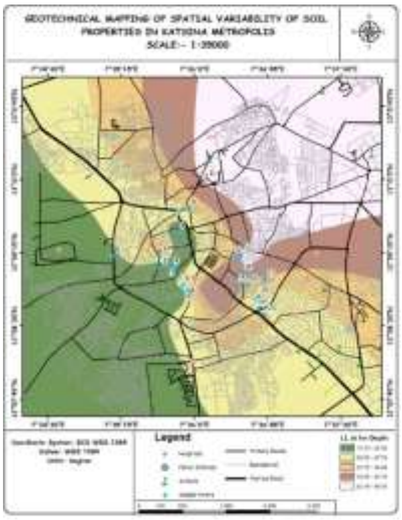
(b)

Figure 3: Map of study area showing spatial variation of specific gravity at 1m (a) and 1.5m (b)

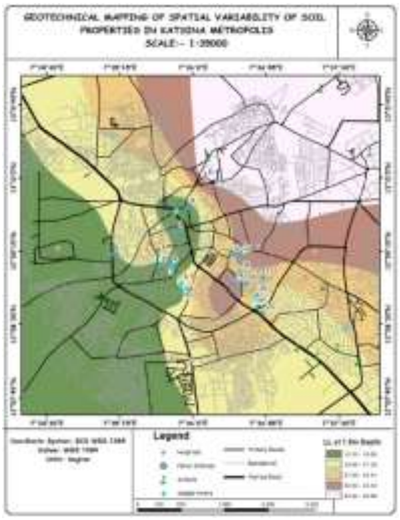
Figures 3a and 3b shows the distribution of specific gravity over the study area. Colour variations means different range of specific gravity; green and white colour layers denotes areas with high to low specific gravity. The variations seen in figure 3a and 3b are as a result of the soil composition, soil compaction, organic matter and soil structure. Soils with high organic matter have lesser specific gravity while compacted soils (densely packed) have higher specific gravity (Avci et 2024).

4.3 Atterberg limits

The spatial variation of liquid limit characteristics of soil in the study zone is presented in figures 4a and 4b. Figure 4a shows the variation of liquid limit at the depth of 1m, and figure 4b is an illustration of spatial variability of liquid limit at 1.5m.



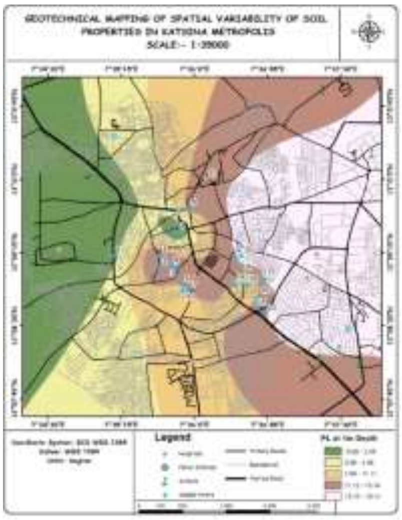
(a)



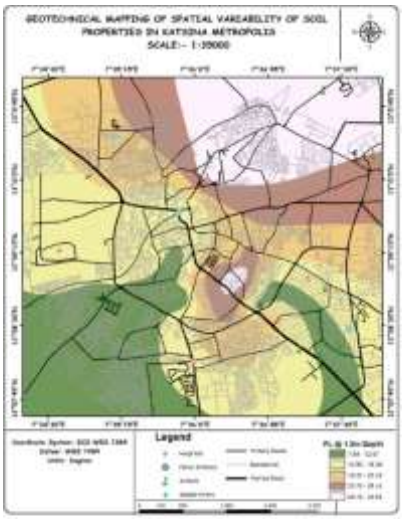
(b)

Figure 4: Map of study area showing spatial variation of liquid limit at 1m (a) and 1.5m (b)

Figure 4a and 4b shows the distribution of liquid limit over the study area at 1m and 1.5m respectively. Colour variations denote the results that; each colour layer indicates range percent of liquid limit; white and green colour layers denotes areas with high to low percent of liquid limit. The liquid limit, plastic limit and plasticity index which are the properties of fine-grained soil that depends on the moisture content are influenced by the mineralogical composition, organic matter content and environmental factors such as seasonal variation (wetting and dry cycles) (Liu et al., 2024). The location with loose soil typed have lower liquid limit than location with dense packed soil. Figures 5a and 5b shows the distribution of plastic limits for soils at 1m and 1.5m respectively.



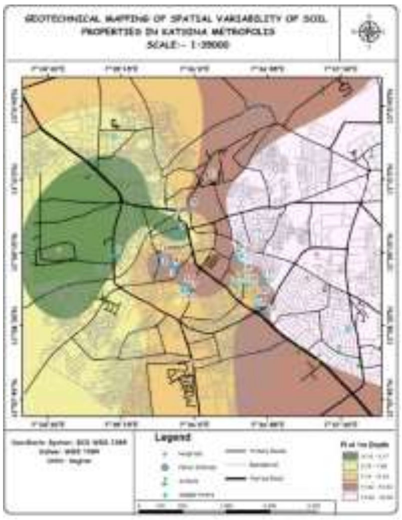
(a)



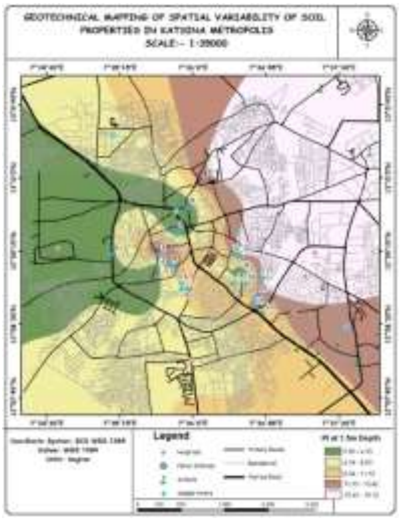
(b)

Figure 5: Map of study area showing spatial variation of plastic limit at 1m (a) and 1.5m (b)

Figure 5a and 5b shows the distribution of plastic limit over the study area, colour variations denote the results that; each colour layer indicates range percent of plastic limit; green and white colour layers denotes areas with high to low percent of plastic limit. Figure 6a is a map of plasticity index variation at 1m depth, while figure 6b is the illustration of plastic index variability at 1.5m.



(a)



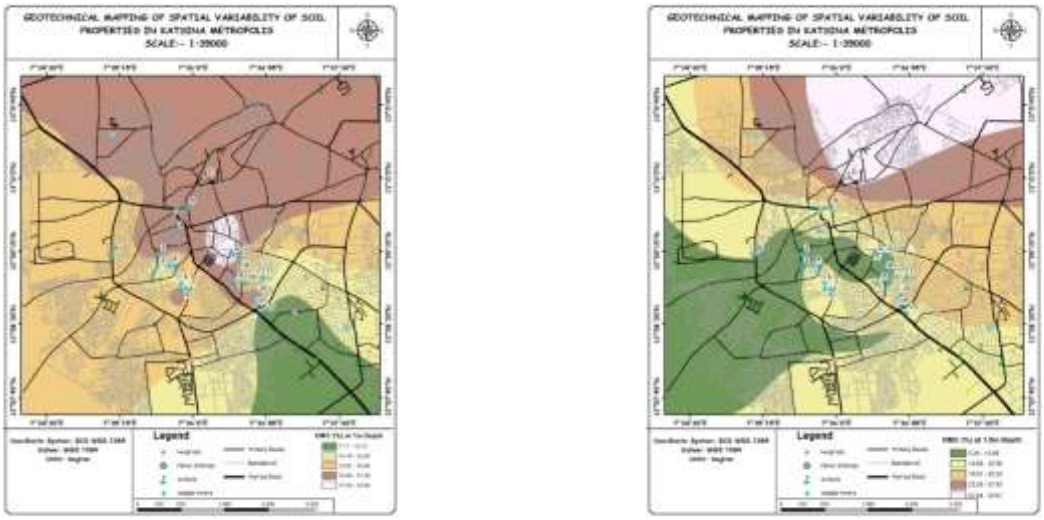
(b)

Figure 6: Map of study area showing spatial variation of plasticity index at 1m (a) and 1.5m (b)

From figures 6a and 6b, colour variations denote the results that; each colour layer indicates range percent of plasticity indices; green and white colour layers denotes areas with high to low percent of plasticity index.

4.4 Optimum moisture content

Figure 7a and 7b shows the distribution of optimum moisture content over the study area at 1m and 1.5m respectively. Colour variations denote the results that; each colour layer indicates range percent optimum moisture content.



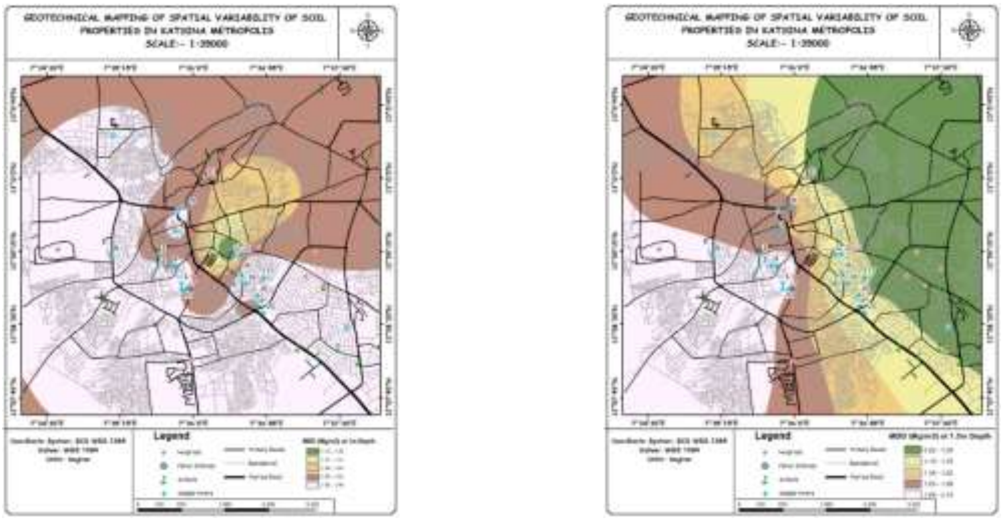
(a) **(b)**

Figure 7: Map of study area showing spatial variation of optimum moisture content at 1m (a) and 1.5m (b)

Frm figures 7a and 7b, the colour layers indicate range percent of optimum moisture content; green and white colour layers denotes areas with high to low percent of optimum moisture content. The variations in soil compositions have different water retention capacity and compaction characteristics, cohesive soil (clay) have higher OMC than granular soil (Alhakim et al., 2024).

4.5 Maximum dry density

Figures 8a and 8b shows the distribution of maximum dry density over the study area at 1m and 1.5m respectively, colour variations denote the results; each colour layer indicates ranges of maximum dry density; green and white colour layers denotes areas with low to high value of maximum dry density.



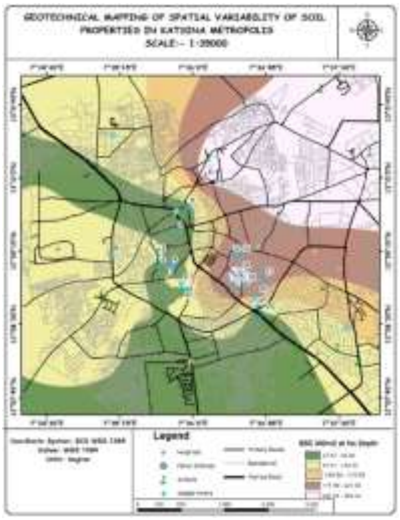
(a) **(b)**

Figure 8: Map of study area showing spatial variation of maximum dry density at 1m (a) and 1.5m (b)

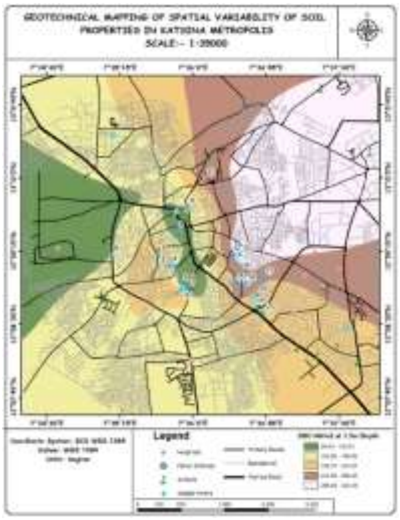
Granular soil has higher MDD than cohesive soil (clay), factors such as gradation, mineralogy, soil type and compaction effort influence the MDD property (Ali et al., 2024).

4.6 Bearing capacity

Figures 9a and 9b shows the distribution of soil bearing capacity over the study area at 1m and 1.5m respectively, colour variations denote the results; each colour layer indicates ranges of soil bearing capacity; green and white colour layers denotes areas with low to high value of soil bearing capacity.



(a)



(b)

Figure 9: Map of study area showing spatial variation of soil bearing capacity at 1m (a) and 1.5m (b)

The cohesion and angle of internal friction are one of the factors that influence the ability of a soil to resist the transfer of load. The variations in colour indicates the locations with the present of granular soils which have higher bearing capacity than regions with high percent of fines.

5. Conclusion

This study employed the use of ArcGis software for the development of geotechnical maps showing variability in soil properties of Katsina metropolis for use in preliminary design, with the aid of Kriging interpolation potential of the ArcGis. The following conclusion isdrawn.

The index (natural moisture content, specific gravity, liquid limits, plastic limits, plasticity index) and engineering properties (compaction and direct shear box test) are obtained at both 1m and 1.5m depths where a significant variation in many of the properties was observed. The geotechnical maps of the study area were developed with the aid of the ArcGis software, the soil properties results were imported to create the database. The thematic map of the study area was developed with help of the Kriging interpolation technique which provides geotechnical information of soil properties at an unsampled location.

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