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Geological, Engineering Geological and Hydrogeological Characteristics of the Knowledge Economic City, Al Madinah Al Munawwarah, KSA

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Abstract

The Knowledge Economic City (KEC) of Al Madinah Al Munawwarah is one of the major projects and represents the cornerstone for the new development activities for Al Madinah. The study area contains different geological units dominated by basalt and overlain by surface deposits. The surface soils vary in thickness and can be classified into well-graded SAND with silt and gravel (SW-SM), silty SAND with gravel (SM), silty GRAVEL with sand (GM), and sandy SILTY clay (CL-ML). The subsurface soil obtained from the drilled boreholes can be classified into poorly graded GRAVEL (GP), well-graded GRAVEL with sand (GW), poorly graded GRAVEL with silt (GP-GM), silty CLAYEY gravel with sand (GC-GM), silty SAND with gravel (SM), silt with SAND (ML), and silty CLAY with sand (CL-ML), sandy lean CLAY (CL), and lean CLAY (CL). The relative density of the deposit and the different gravel sizes intercalated with the soil influenced the Standard Penetration Test (SPT) values. The SPT N values are high and approach refusal even at shallow depths. The shallow refusal depth (0.10 to 0.90 m) of the Dynamic Cone Penetration Test (DCPT) was observed. Generally, the soil can be described as inactive with low plasticity and dense to very dense consistency. The basalt of the KEC site is characterized by slightly (W2) to highly (W4) weathering, their strength ranges from moderate (S4) to very strong (S2), and the Rock Quality Designation (RQD) ranges from very poor (R5) to excellent (R1). The engineering geological map of the KEC characterized the geoengineering properties of the soil and rock materials and classified them into many zones. The high sulphate (SO_4^{2-}) and chloride (Cl^-) contents in groundwater call for protective measures for foundation concrete. The current study revealed that geohazard(s) mitigation measures concerning floods, volcanic eruptions, and earthquakes should be considered.

Keywords

Engineering Geology, Knowledge Economic City, Petrographic Description, Rock and Soil Investigations

1. Introduction

Geological, engineering geological, and hydrogeological investigations are important in understanding the interrelationships between the geological environment and the engineering situation. The nature and relationships between the geological components, the active geodynamic processes, and the prognosis of processes likely to result from the changes being made and the final character of rocks, soils and hydrogeological conditions. Characterization of the engineering geological properties of earth materials (soils and rocks) is essential to help in analysis, land-use planning and design, construction, and maintenance as applied to civil and mining engineering [1]. In addition, evaluating the different or unexpected geological hazards helps prevent any negative impact on the future structures constructed in the area, especially the effect of groundwater level rise.

Soil and rocks are formed by different processes. They are notoriously variable and often have properties that are undesirable from the point of view of a proposed structure. Unfortunately, the decision to develop a particular site can not usually be taken based on its complete suitability from the engineering viewpoint; engineering geological problems, therefore, occur and require geoengineering parameters for their solution. However, properly designed and built engineering structures bring a dynamic equilibrium with the geological conditions of the site. For these reasons, evaluating the engineering geological properties of the surface and subsurface earth materials is essential to give more information relevant to the needs of engineers and planners and evaluate different geological hazards to mitigate any threats in the future.

Al Madinah Al Munawwarah is situated in the northwestern part of the Kingdom, within the western part of the Arabian Shield and on a nearly flat basin surrounded by mountains and plateaus. It is far by about 250 km east of the Red Sea coast and 340 km north of Makkah and surrounded by several mountains: Al Hujaj to the West, Salaa to the northwest, Al E'er to the south, and Uhad to the north; its elevation is around 600 - 610 m above mean sea level (m.s.l.). Geomorphologically, the Al Madinah Al Munawwarah gently dips from the east to the west and the northwest, and it is characterized by numerous topographic features of lowlands, highlands, and hilly areas with various elevations. It has a hot desert climate; the summer is extremely hot, with an average temperature of about 43˚C and above 45˚C, which is not uncommon between June and September. Winter is milder, with average temperatures of 12˚C. The rainfall reaches up to 17 mm, which falls almost in winter.

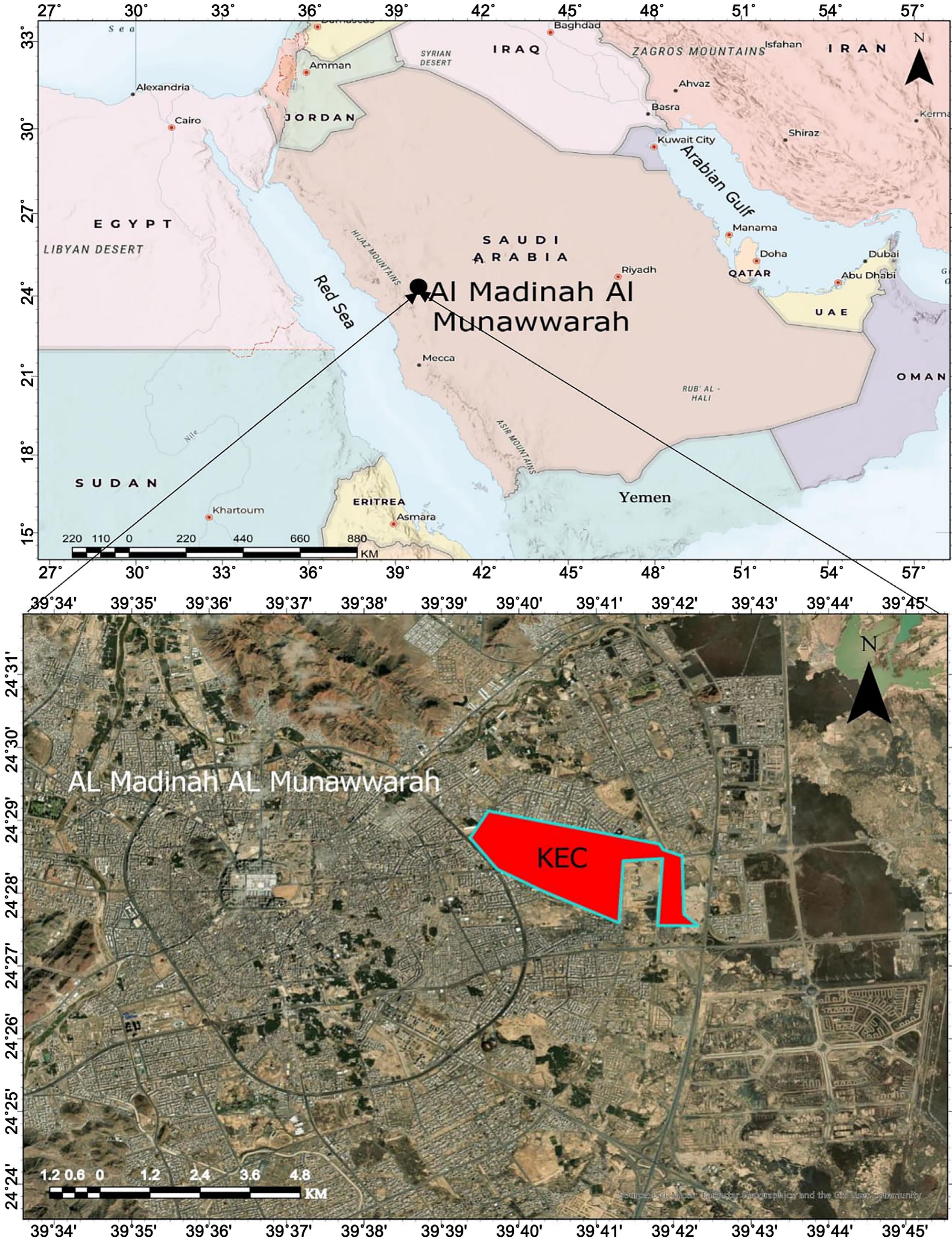

Figure 1. Location of Al Madinah Al Munawarah and the KEC boundaries.

Volcanic rocks played a potential role in developing surface runoff of the city, in response to the hard bedrock and high, rugged topography, leading to the development of good surfaces for drainage networks. Two major wadis, Al Aqiq and Qana, joined north of Al Madinah Al Munawwarah, ran northwest, and discharged into the Red Sea.

The city has been witnessing accelerated urban development, as indicated by the significant increase in the population. This went hand in hand with urbanization and the expansion of residential areas and large infrastructures. Therefore, a decision has been made to establish a new economic city known as "Knowledge Economic City (KEC)", which is situated about 6 km east of the Prophet's Mosque and 8 kilometres south of the Prince Mohammad bin Abdulaziz International Airport (**Figure 1**). It is easily accessible from the Haramain high-speed railway station. The purpose of the city is to attract investors, developers, and knowledge seekers to become a major focus in the fields of information technology, education, health, and other vital city services complementary to economic development. The KEC has an area estimated to be 6.8 million square meters and is connected via five main roads. Generally, the KEC provides for those settling and working in a suitable living environment, life, education, medical services, residential, commercial, mixed development, entertainment, communication networks, water and electricity networks, water treatment plants, and other activities related to the development of economic cities [2] [3].

This manuscript aims to study and characterize the geology, engineering geology, and hydrogeology aspects of the Knowledge Economic City (KEC) site and delineate unexpected geological hazards. Such information is required for engineers and constructors to recommend the most appropriate type of foundations and methods of construction and ensure the stability of the structures in their natural setting.

2. Methods of Investigation

A detailed geology and topography desk study was undertaken using geological and topographic maps and satellite images. A walkover survey was also conducted to study the geology and geological structures and measure rock strikes, dips, and fractures.

The surface and subsurface investigations of the soil, rocks, and groundwater of the proposed KEC site have been carried out. During the investigation, the location of the weathered and fresh rocks was verified. Nine boreholes have been drilled to explore the subsurface and collect rock and soil samples for identification and classification purposes (**Figure 2**), conduction of the SPT, DCPT, calculation of the RQD, and measure groundwater level. Rock and soil samples were collected from the surface and subsurface for laboratory tests to assess their variability, obtain parameters for particular geoengineering calculations, and verify their physical and mechanical properties, texture, colours, and mineral composition. Representative thin-sections have been studied petrographically in order to know rocks' mineral composition, microstructural features, and degree of weathering. The *in-situ* soil density using a sand cone density apparatus is determined. Water samples have been collected for hydrochemical analysis.

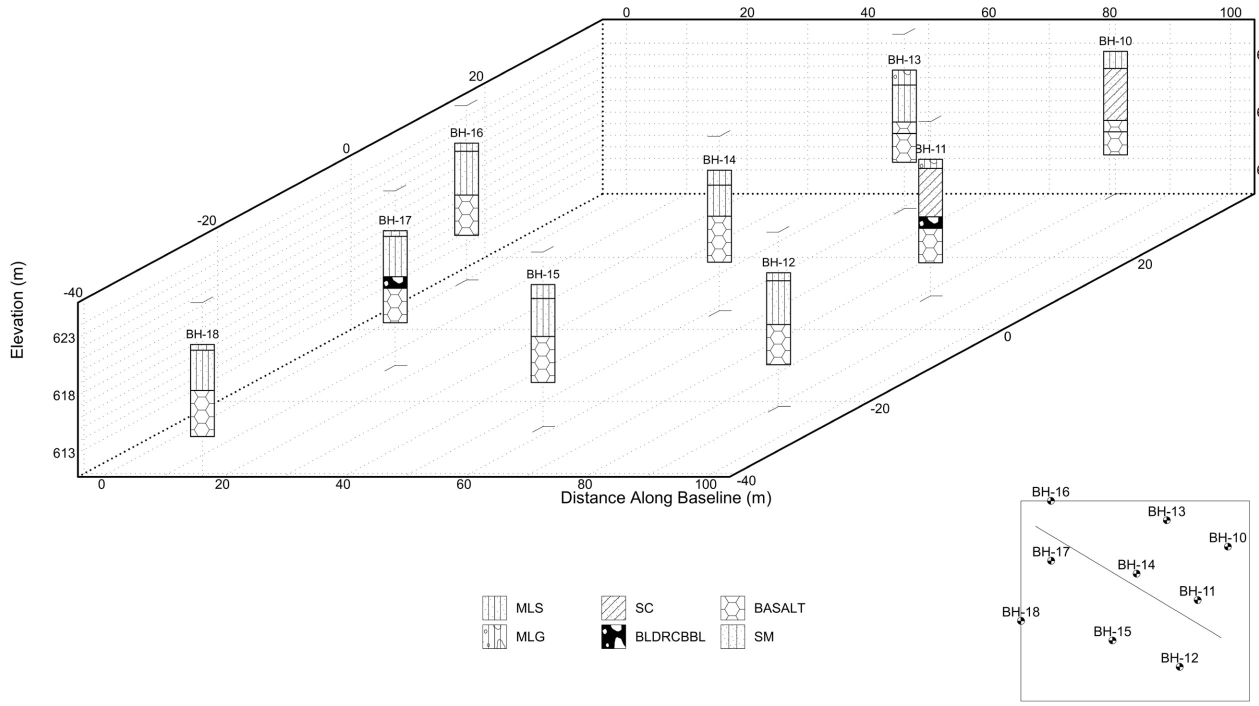

Figure 2. Boreholes distribution and subsurface lithology.

3. Geology of Al Madinah Al Munawwarah

In terms of geology, the Kingdom of Saudi Arabia is classified into four vast terrains: 1) Precambrian Arabian shield, 2) Phanerozoic Arabian Platform, which contains clastic, carbonates, anhydrite and evaporitic rocks, 3) Tertiary to Quaternary volcanic (harrats) (extensive basalt plateaus) and 4) Narrow Red Sea coastal plain [4]. The western half of Saudi Arabia belongs to the Arabian Shield, where diverse igneous and metamorphic rocks are exposed and, in places, are overlain by lava flows (**Figure 3**).

The geology of Al Madinah Al Munawwarah is part of the Arabian Shield, composed of Precambrian metasedimentary, metavolcanic, and igneous rocks that passed through different tectonic events before the Cambrian [6]-[8]. It is nearly covered by about 75% basalt of Harrat Rahat and 25% of the Precambrian basement rocks that occupy the west edge and northeast part of the study area and are represented by distinct units [9] [10]. The Upper Proterozoic of the Precambrian age is divided into Hulayfah, Al Ays, and Furayh Groups [11]; the latter unconformably overlain the Al Ays Group. Cambrian-Ordovician strata of variable thicknesses overlain the Precambrian rocks and cover extensive and vast areas northeast of the quadrangle. The strata were deposited on a faulted topography and dipped gently to the north at 10˚ to 20˚. The outcrops, however, are

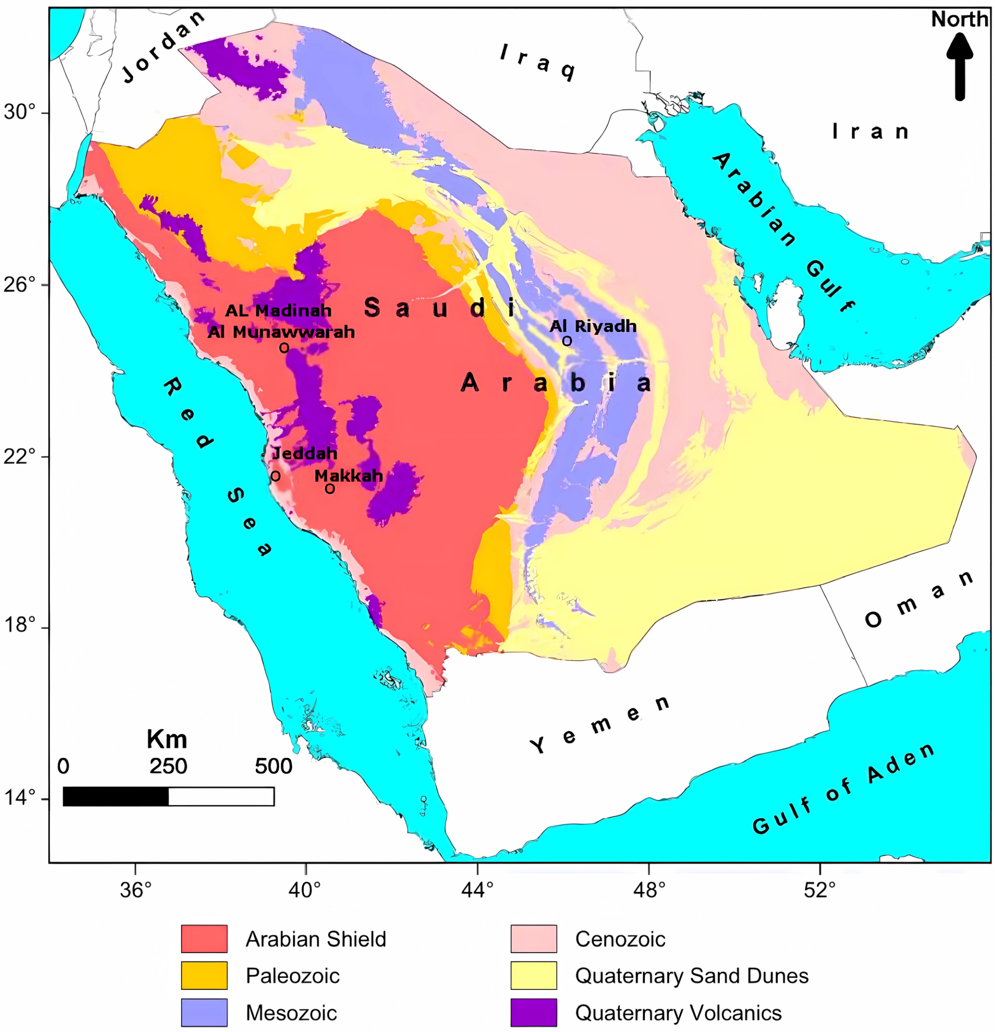

Figure 3. The main geological units of the Kingdom of Saudi Arabia (Modified from USGS and MP&MR, 1963 [5]).

restricted to small buttes that have resisted erosion, elsewhere, the rocks are covered by alluvial sand and gravel deposits. Cenozoic Tertiary and Quaternary basaltic flows and trachy-phonolitic volcanic rocks exist in the study area and overlain the Cambrian-Ordovician strata. It is part of a huge terrane of N-S alignment basalt plateau (harrats). The basalt occurs either as large fissured; porous and fractured flows only slightly affected by erosion or as erosional remnants perched on top of prominent buttes. Three rock types were mapped in Al Madinah Al Mnawarah, namely Tertiary basalts (b2), Trachy-phonolitic volcanic rocks (b4), and Quaternary basalt (b5) (**Figure 4**). Lava and pyroclastic flows are abundant in the study area, they form thick layers and have been severely affected by erosion. The Quaternary Holocene deposits are intermixed fluvial, eolian and lacustrine in origin. Wadi alluvium (gravel, sand, and clay) and sabkhah or khabrah deposits (sand and clay with or without saline deposits in closed or semi-closed depressions) are commonly associated with Tertiary and Quaternary Basalt Flows. Sand accumulations and sand dunes also exist. Alluvial fans dissected by recent erosion and terraces are abundant in the plain to the north of the Al Madinah airport, and elsewhere, they are covered by recent basalt flows.

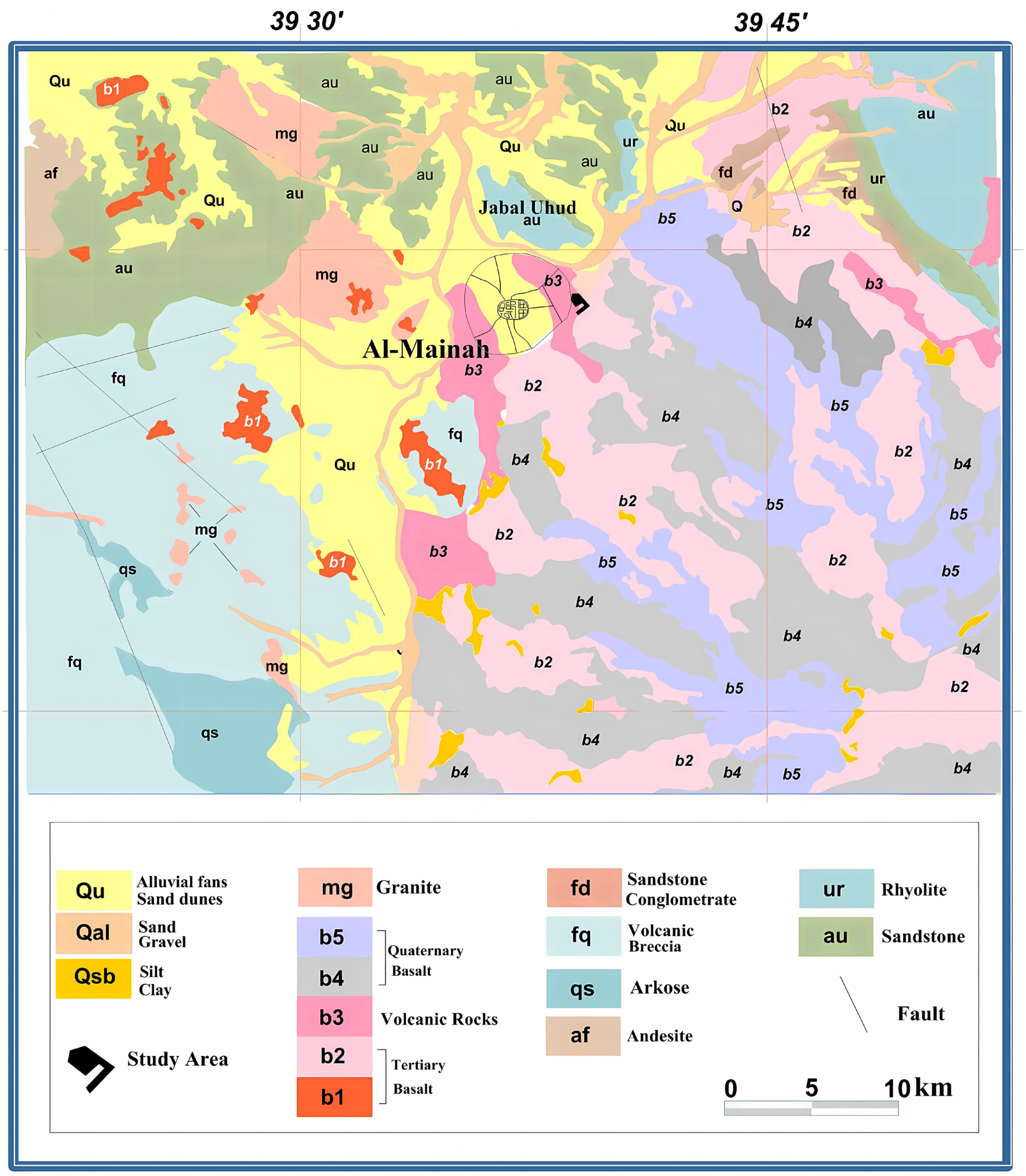

Figure 4. Geological map of Al Madinah Al Munawwarah area.

4. Petrographic Description of Rock Samples

The petrographic characters of the collected rock samples were studied under the microscope in Plane-Polarized Light (PPL) and cross-polarized light (XPL). The study explains that most of the basalt in the study area is fine-grained, vesicular, with intergranular or inequigranular texture, sub-trachytic, and porphyritic texture. It is essentially composed of a rock matrix and phenocrysts (**Figure 5**). The rock matrix is microcrystalline with intergranular and sub-trachytic fabric, fine-grained and comprised of microlites of plagioclase, pyroxene, and accessory olivine and opaques. Plagioclase microlites are fine-grained and occur as slender laths with random orientation. Their intergranular spaces are filled by pale brownish pyroxene or pale purplish brown clinopyroxene, accessory olivine, and opaques. In some samples, the plagioclase microlites display subophitic to intergranular interrelationship with clinopyroxene. Phenocrysts are dominantly represented by plagioclase and olivine ± pyroxene. Plagioclase phenocrysts are subhedral to anhedral, platy to tabular in habit, and range in size from less than 0.10 mm to over 2.5 mm in length. Olivine phenocrysts are subordinate when compared to plagioclase phenocrysts. It is fine to medium-grained, subhedral to anhedral in form, and ranges in dimension from 0.10 mm to about 2.5 mm in length. In general, rocks are fresh except olivine, which is oxidized and partially altered to reddish-brown. In some samples, particular alteration is observed. Very fine-grained opaque minor minerals occur as tiny granules or aggregates associated with rock matrix were detected. There are random (photomicrographs in PPL) and good orientations (photomicrographs in XPL) for the tiny laths of plagioclase feldspar, and some clear cavities are also detected.

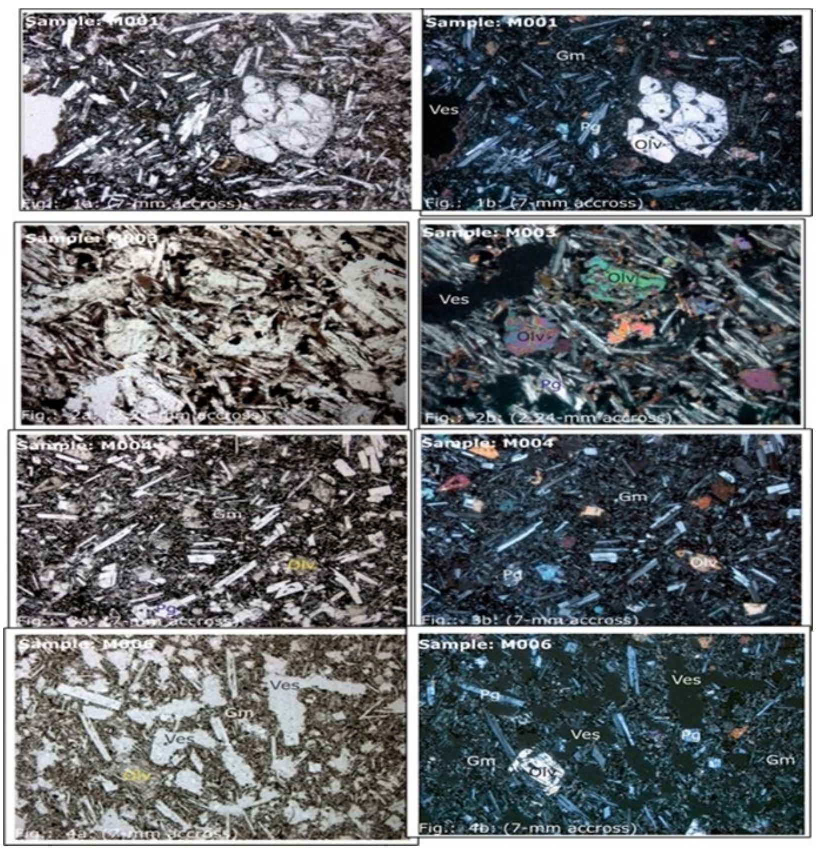

Figure 5. Thin-section photomicrographs (1a, 2a, 3a, and 4a) in PPL and (1b, 2b, 3b, and 4b) XPL, displaying the texture and mineral composition of four basaltic rock samples (M001, M003, M004, and M006); the photomicrographs display microcrystalline intergranular groundmass (Gm) enclosing tiny phenocrysts of plagioclase (Pg) and locally subhedral phenocrysts of olivine and vesicular cavity (Ves).

5. Geological Structures

The area has a long history of tectonics and geologic events that produce complex lithological and structural settings. Most of the rocks in the study area are folded with the axial planes generally trending N-S. Dips in some places are steep and overturned, but generally between 30˚ and 40˚. Most faults in the Al Madinah quadrangle appear to belong to the Najd fault system: they are numerous and generally strike NW-SE, NE-SW, and N-S (**Figure 6**). Several E-W fractures belonging to another fault system [12], probably later than the Najd, occur in Jabal Al Arajib and Al Baydã granites.

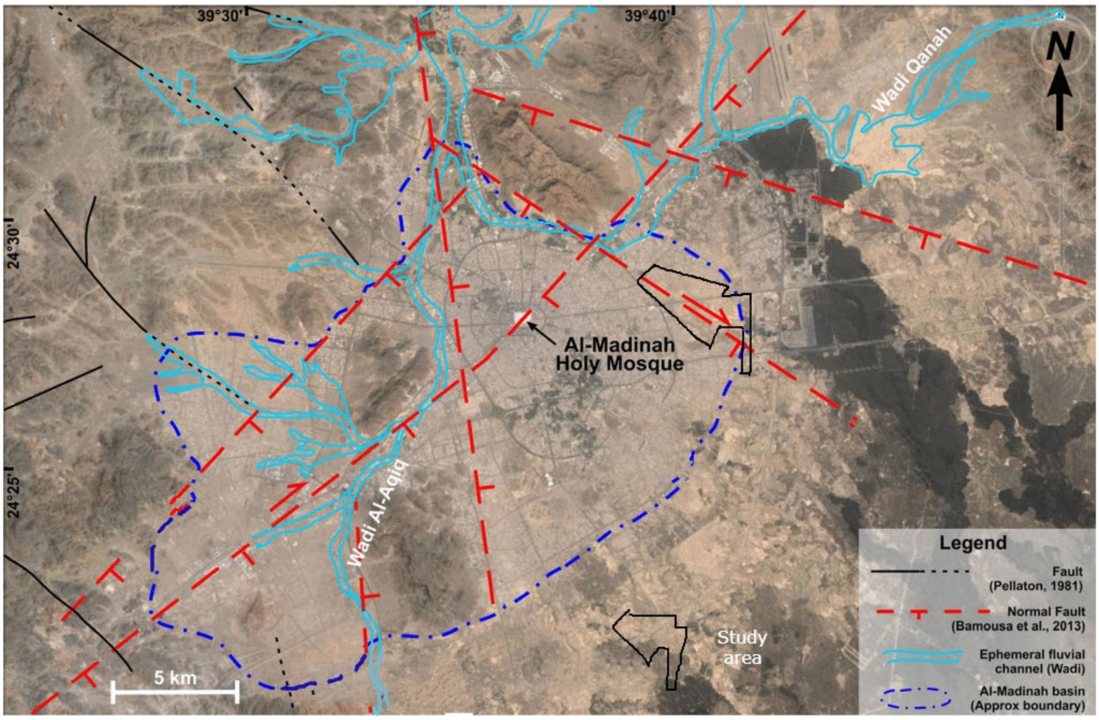

Figure 6. Structural and hydrological map of the Al Madinah Al Munawwarah basin (after Murcia *et al.*, 2015 [12]).

6. Hydrogeology

Tectonic development in the Late Precambrian and during the Tertiary to the Quaternary period influences the drainage system and hydrogeology of Al Madinah Al Munwwarah. This long history of developments produced Tertiary basalt relief inversion geomorphology and formed a deltaic-shaped basin of Al Madinah (**Figure 6**) [12] [13]. The centre of the city has experienced a shallow groundwater rise, where the problem was first observed. A short-term remedial solution was implemented to pump groundwater through a good network to lower the water table to acceptable levels [14]. The groundwater aquifer under the city consists of nearly two distinct layers: the old basaltic lava flows (known as Harrat Rahat) and the sub-basaltic alluvial deposits [15] [16]. Wadi Qanat, Wadi Al Aqiq, and Wadi Al Hamd systems greatly influence the recharge. Therefore, the hydrogeology of the Al Madinah aquifer occurs mainly along the Wadi systems. The weathered basalt unit represents a secondary unit of the aquifer, which is hydrologically connected with the main aquifer.

The chemical facies of the water in the city are not typical of the lithologies in which they occur, except those found in the basalt flows with some high sulfate and magnesium contents. The most noticeable feature is a downstream increase in TDS, sodium, chloride, nitrate, and sulfate contents; the groundwater in the upstream zone contains low TDS and predominant bicarbonate facies, and those with the highest TDS values in the downstream zone, show chlorides predominant over sulfates.

7. Results

The surface and subsurface rocks and soil properties at the KEC site were investigated through a series of field investigations and laboratory tests. The surface soil varies in thickness and can be characterized into four soil units: well-graded SAND with silt and gravel (SW-SM), silty SAND with gravel (SM), silty GRAVEL with sand (GM), and sandy SILTY clay (CL-ML). The thickness of the soil overlaying the basalt, as revealed from the drilled boreholes, represents about 25.5% of the total of the subsurface materials, and the maximum thickness ranges from 0.5 m to 4.8 m. The soil of the site contains 63% coarse and 37% fine-grained materials; it ranges from poorly/well-graded GRAVEL to lean CLAY. The subsurface soil obtained from the drilled boreholes can be classified as poorly graded GRAVEL (GP)/well-graded GRAVEL with sand (GW)/poorly graded GRAVEL with silt (GP-GM)/silty CLAYEY gravel with sand (GC-GM), silty SAND with gravel (SM), silt with SAND (ML) and silty CLAY with sand (CL-ML)/sandy LEAN CLAY (CL)/lean CLAY (CL).

The natural moisture contents of the soil samples range from 0.85% to 3.8%. The maximum values of plastic and liquid limits are 24% and 29%, respectively, and the maximum plasticity index is 8%. The plasticity ranges from non-plastic to low plasticity. Generally, the soil can be described as inactive with low plasticity.

During the conduction of the SPT, refusal was encountered at different depths in the different boreholes, and it could be near the surface where the soil layer was thin (0.5 m) and the SPT N values were high. Low "N" resistances were found in locations with poorly graded gravel or well-graded gravel with sand. Generally, the relative density of the deposit and variation in gravel sizes influence the SPT values. The DCPT refusals were encountered, and they are relatively shallow; they vary from 0.10 m to 0.90 m. Generally, the soil is described as dense to very dense.

The rocks' thickness revealed from the drilled boreholes represents about 74.5% of the total drilled lithology. The physical properties of the basalt collected from the drilled cores were tested to obtain their geoengineering properties. The specific gravity, porosity, and water absorption of the basalt samples ranges from 2.24 g/cm^3 to 2.84 g/cm^3, 1.22% to 16.70%, and 0.43% to 7.75%, respectively (**Figure 7**). The basalt samples collected from the cores and outcrops at the KEC site are classified according to their degree of weathering to grade from II to III corresponding to slightly (W2) to moderately (W3) weathered, and highly weathered basalt (W4) corresponding to grade IV is not uncommon [17]. RQD values range from 0% to 97%, and 100% RQD also exists. Generally, it can be described as very poor (R5) to excellent (R1).

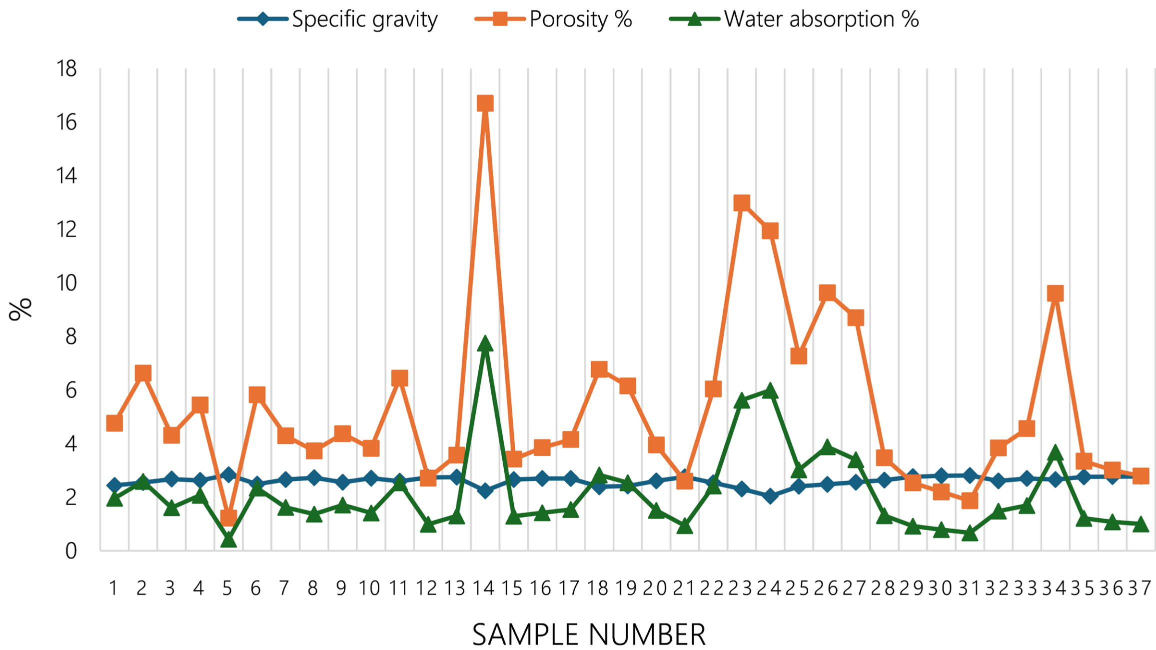

Figure 7. Specific gravity, porosity, and water absorption of Al Madinah Al Munwarah basalts.

Uniaxial Compression Strength (UCS) and Point Load Tests (PLTs) were carried out to determine the strength of the basalt cores. The UCS strength ranges from 37 MPa to 146 MPa, while the PLT ranges from 59 MPa to 182 MPa. Both are classified as moderate (S4) to very strong (S2).

8. Engineering Geological Map of the Knowledge Economic City

As stated by the IAEG, an engineering geological map is defined as a type of geologic map that provides a generalized representation of all the components of a geological environment and geotechnical information of significance in land use planning and in the design, construction, and maintenance of engineering structures as applied to civil and mining engineering.

Taking the geological and geotechnical properties of the soils and rocks as determined in this study, a zonation map is produced (**Figure 8**). The KEC area is described, classified and categorized into different zones based on the engineering geological properties of soil and rocks, in its present state depending on the combined effects of the mode of origin (**Figure 8**).

1) Rocks zonation in the KEC

Zone I: Olivine basalt—dark grey, slightly weathered, strong, fair rock mass quality with widely spaced joints. Zone II: Less vesicular olivine-rich basalt—light to dark grey, slightly to moderately weathered, moderately strong, fair to poor rock mass quality and moderately wide to closely spaced joints. Zone III: Moderately to highly vesicular olivine basalt—light to dark grey, moderately to highly weathered, moderately weak, poor to very poor rock mass quality and characterized by having closely spaced joints (**Figure 8**).

2) Soils zonation in the Knowledge Economic City

From field and laboratory tests, eight zones of the surface soils were determined, and these are as follows:

Zone I: Sandy SILT, Zone II: Silty SAND, Zone III: Silty SAND with gravel, Zone IV: Silty GRAVEL with sand, Zone V: Poorly graded GRAVEL, Zone VI: Silty CLAY with sand, Zone VII: Sandy LEAN CLAY, and Zone VIII: Sandy SILT with gravel (**Figure 8**).

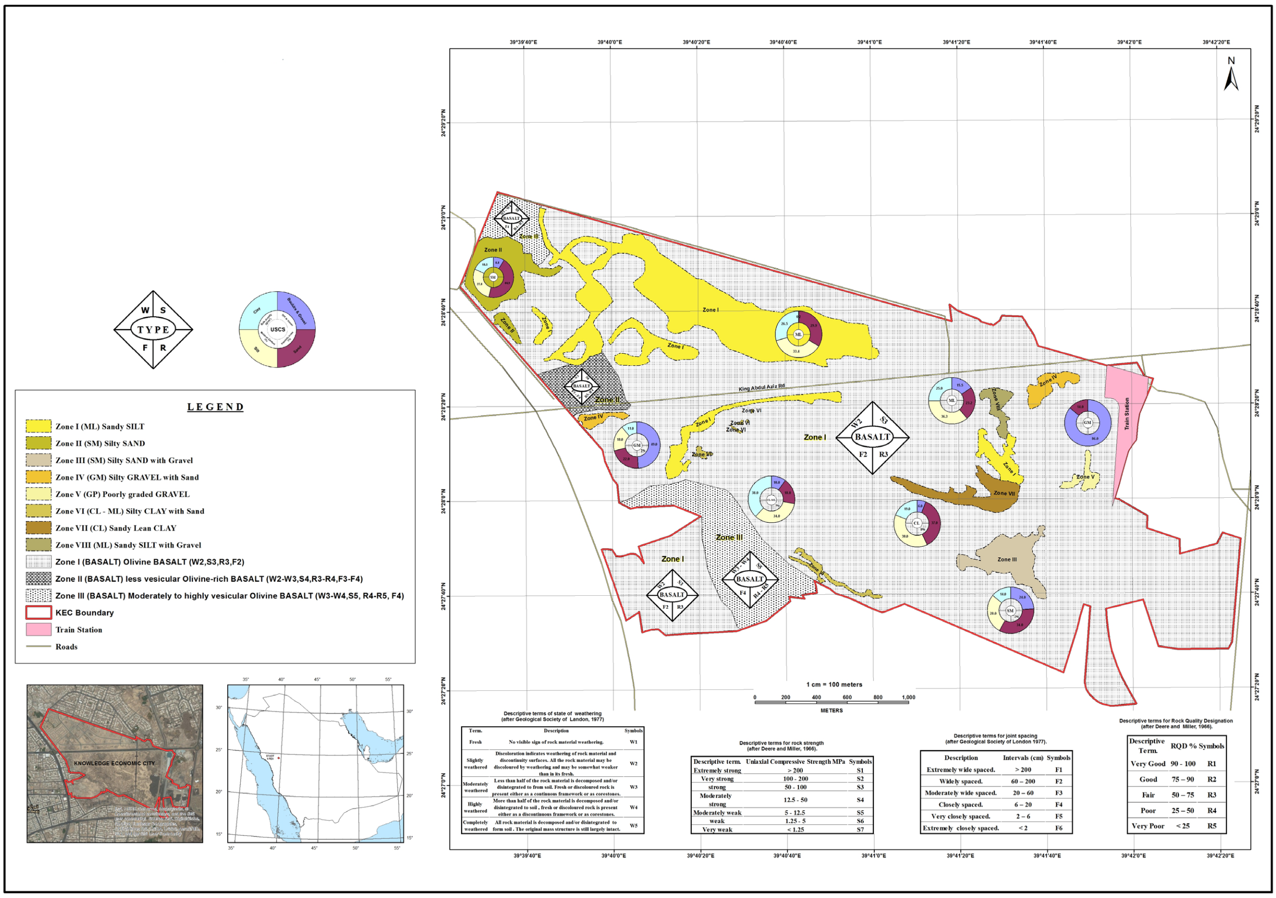

Figure 8. The engineering geological map of the Knowledge Economic City (KEC).

9. Discussion

The KEC is a relatively flat area surrounded by mountains and dominated by basaltic flows. The soil in the central area is largely coarse-grained, resulting from the basalt's disintegration and decomposition of the basalt. The thin to medium clay layers may have originated from the basalt weathering.

The lower moisture contents are due to soil dryness caused by dry weather and high temperatures. The low N values are due to the presence of gravel mixed with coarse-grained materials transported from the surrounding mountains and deposited near the surface. The *in-situ* tests revealed that the soil density increases with depth.

The porosity of the basalt in the research area is generally low because the vesicular cavities are filled with secondary minerals, but higher values are not uncommon. The weathering of the basalt started from the discontinuities, with highly weathered ones easily broken during sampling, and often, a complete sequence is found.

The moderately to highly weathered basalt (W3 - W4) zones are confined to the northwest and south of the study area. The high degree of weathering is likely due to the vesicular nature of the basalt, which retains rainwater for an extended period. The slightly weathered basalt (W2) is located in the southwest and center of the study area, where fewer or no vesicular cavities exist. Positive relationships exist between the degree of weathering, rock quality and strength of the basalt in the study area, which decreases with an increase in the degree of weathering.

The moderately to highly weathered basalts (W3 - W4) correspond to poor and very poor (R4 - R5), and fair to poor basalt (R3 - R4) qualities, respectively. The slightly weathered basalt (W2) correlates with fair (R3) and excellent basalt (R1) rock quality.

Additionally, the strength of the basalt varies considerably depending on rock quality and the degree of weathering. The moderately weak basalt (S5) corresponds to (R4 - R5), while the moderately strong (S4) and strong (S3) basalts refer to (R3 - R4) and (R3), respectively.

Variation in UCS and PLT strength values is probably due to the different degrees of basalt weathering, presence of vesicular cavities, increase of porosity, and mineral alteration. Some porous rocks exhibit a low strength compared to other rocks that are characterised by a low percentage of porosity, which shows high strength. The percentage of water absorption of the KEC basalt is relatively high (0.43% - 7.75%) compared to the normal content (0.1% to 1.0%). The specific gravity of the basalt (2.44 g/cm^3 - 2.84 g/cm^3) is less than the standard (2.7 g/cm^3 - 2.9 g/cm^3); this is probably due to the medium to high porosity, weathering, alteration of the minerals and the presence of vesicular cavities as revealed from the inspection and petrographic study. There is a direct relation between porosity and water absorption and an inverse relation between specific gravity and porosity. From field and laboratory tests, the dark grey colour vesicular basalt with variable degrees of weathering has been classified into three zones and the surface soil into eight zones.

Engineering structures often interfere with the dynamic equilibrium of a geological environment, and the geological and engineering geological maps provide more information about the subsurface materials (soil and rocks) that allow them to maintain stability while subjected to external loads. The engineering properties (physical and mechanical) of the subsurface materials and conduction of the groundwater, excluding the total amount of solids dissolved in the water (TDS), indicate that the area of the KEC is suitable as a construction site. In this state, if the internal forces and reactions within the structure encounter changes caused by the applied loads or changes in subsurface conditions, the structure will remain stable.

By far, the most critical effect of groundwater in a rock mass is the reduction in stability resulting from water pressures within the discontinuities and corrosiveness. Hydrochemistry of groundwater from some wells showed the effect of cyclic salting and water-rock interaction. The high TDS values of the groundwater are due to the discharged water containing many dissolved salts, which precipitated in the soil zone due to extremely high evaporation rate and cycling salting [18]. In addition, groundwater reflected high sulfate and nitrate concentrations, which exceeded the drinking water standards, as proven by [19] [20]. Pro corrosion risk might occur in cement affected by soluble salts. The content of dissolved sulphate and chloride in groundwater affects concrete strength.

10. Conclusion

The study area has ground elevations varying between 600 m and 610 m above mean sea level (m.s.l.). It is situated on a flat mountain plateau surrounded by some mountains. The relative density of the deposit and the presence of gravel of different sizes influence the SPT values. DCPT refusals were encountered, and they are relatively shallow; they vary between 0.10 to 0.90 m. Basalt in the study area is slightly to moderately weathered and strong, and it can serve as a reliable foundation and building material. Faults, fractures, and weathering happen in the basalt masses, reducing the bearing strength of the rock. High sulphate and chloride content in groundwater calls for protective measures for foundation concrete. The natural hazards that may be expected in the area are reflected in the geomorphological units, such as flash flood potential in the low ground area, volcanic flow from the harrat, and earthquakes should be taken into consideration.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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