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Geotechnical Evaluation of Basalt Rocks: A Review in the Context of the Construction of Civil Engineering Structures

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Abstract: Basalt rocks are a common geological formation that plays a crucial role in various engineering applications, such as construction, infrastructure development, and geotechnical engineering. Understanding the physical and geotechnical properties of basalt rocks is essential for ensuring the stability and safety of structures built on or within these formations. It is crucial to understand how basalt rocks deform and fail under applied loads for geotechnical assessments. Deformation and failure mechanisms are influenced by factors such as jointing, weathering, and stress conditions. Therefore, a comprehensive analysis is necessary to ensure reliable engineering designs. Proper site investigations and geotechnical assessments are essential to address these challenges effectively and ensure reliable engineering designs.
This paper provides a comprehensive review of the geotechnical properties of basalt rocks, including their origin, mineralogy, physical characteristics, and engineering behavior. The paper also includes case studies of the Sardar Sarovar (Narmada) dam Project and Karjan dam, Gujarat, India, highlighting the successful utilization of basalt rocks in the construction of major dams and underground powerhouse. These case studies provide insights into potential challenges posed by basalt rocks and associated features in the construction of structures and their adequate solutions.

Keywords: Physical Characteristics, Engineering behavior, Red bole, Weathered Rock Seams, Weathering, Narmada Dam, Karjan Dam.

1. Introduction

Basalt is an extrusive igneous rock that forms from the rapid cooling of lava flows. It is characterized by its fine-grained texture and mineral composition, primarily consisting of plagioclase feldspar, pyroxene, and olivine. The engineering behavior of basalt rocks is a complex interplay of their mineralogical composition and the external conditions they are subjected to. Understanding these factors is crucial for their effective use in various engineering applications. The widespread occurrence of basalt makes it an important geological formation with diverse applications in civil engineering.

1.1. Origin and Formation

Understanding the geological processes that lead to the formation of basalt rocks is crucial for assessing their geotechnical properties. Basalt is primarily formed through volcanic activity, where molten lava solidifies upon exposure to the Earth's surface [1]. Sometimes, in one flow, different types of basalt can be formed due to variations in the cooling rate of the lava. For example, fine-grained basalt can form on the surface of the flow where the lava cools quickly, while medium-grained basalt can form deeper within the flow where the lava cools more slowly. Amygdaloidal basalt can form in areas where gas bubbles are trapped in the lava and minerals are deposited over time.

Basalt dykes are formed when magma flows into a crack in the pre-existing rock and then solidifies as a sheet intrusion, either cutting across layers of rock or through a contiguous mass of rock. These dykes are generally more resistant to weathering than the surrounding rock, so that erosion exposes the dyke as a natural wall or ridge.

In some basalt terrain lava tubes are formed in two ways: 1) During an eruption, a crust forms on the surface of the slowly flowing lava in flatter terrain. The lava can continue to flow hot under this crust, creating a tunnel. The tunnel created in this way empties at the end of the volcanic activity, when no more new lava comes. 2) Highly fluid, super-hot magma flows from its source into, or under, a layer of cooling, slowly flowing lava.

1.2. Engineering Behavior

The engineering behavior of basalt rocks, suitable for various applications, is influenced by factors such as moisture content, temperature, and stress conditions. These rocks exhibit notable mechanical properties including high compressive strength, favorable shear strength, and stiffness, making them ideal for load-bearing applications. However, their tensile strength is relatively lower, and the presence of anisotropy necessitates careful consideration in design and construction processes. Thus, a comprehensive understanding of these factors is crucial for effective utilization of basalt in engineering applications.

1.3. Geotechnical Challenges and Considerations

Generally basalt rocks are considered good foundation for the construction of civil engineering structures and also as construction material [2]. Despite their favorable engineering properties, basalt rocks present certain challenges in geotechnical applications. These challenges include susceptibility to weathering, potential for jointing and fracturing, and variations in rock quality. These factors, along with stress conditions, contribute to how basalt rocks deform and ultimately fail under applied loads. Therefore, understanding these aspects is essential for geotechnical assessments. Proper site investigations and comprehensive geotechnical assessments are crucial to effectively address these challenges and ensure reliable engineering designs.

2. Characteristics of Basalt Rocks

2.1. Mineralogy and Composition

The geotechnical and geo-mechanical properties of basalt rocks are influenced by their mineralogical composition, which primarily consists of plagioclase feldspar, pyroxene, and olivine [3]. Variations in the proportions of these key minerals can significantly impact the rock's strength, durability, weathering resistance, and response to stress [3],[4].

Plagioclase feldspar, a series of tectosilicate minerals within the feldspar group, is a crucial mineral in determining the hardness and resistance of basalt [4]. Pyroxene, a group of important rock-forming inosilicate minerals found in many igneous and metamorphic rocks, is essential in assessing the wear resistance of the rock. Olivine, another high-temperature mineral, contributes to the overall strength of the basalt rock. The proportions of these minerals can vary in different basalt formations, leading to significant changes in the rock's properties. For instance, a higher concentration of hard minerals like feldspar and pyroxene would generally increase the rock's strength and durability. On the other hand, if the rock has a higher proportion of softer minerals, it could be more vulnerable to weathering and less resistant to stress.

The chemical composition of basalt typically includes silica (SiO_2), aluminum oxide (Al_2O_3), iron oxide (FeO/Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), sodium oxide (Na_2O), and potassium oxide (K_2O) [3],[4]. The exact percentages of these elements can vary based on the specific geological source and type of basalt.

2.2. Physical Characteristics and Geotechnical Properties

Basalt rocks, known for their unique physical characteristics, are significant in geotechnical assessments. These characteristics, including density, porosity, permeability, and thermal conductivity, play a crucial role in determining the geo-mechanical behavior of basalt rocks. They influence the rock's ability to withstand loads, transmit stresses, and interact with fluids. Understanding these properties is not only crucial for designing foundations, tunnels, and other engineering structures, but also for predicting how these structures will interact with the geological environment. Therefore, a comprehensive understanding of these physical characteristics and Geotechnical properties is essential for the effective use of basalt in various engineering projects [5],[6],[7],[8],[9],[10].

Density: Basalt is a heavy and dense rock, with an average density ranging from 2.7 to 3.0 grams per cubic centimeter, which is higher than many other rocks [7]. This makes it a heavy and dense rock, which can have implications for its use in construction and other applications.

Porosity: The porosity of basaltic rocks is highly variable. The porosity of a rock, which is the measure of void spaces within it, can vary from 1.311% to 7.809% [7]. The porosity affects the rock's capacity to absorb water and other fluids.

Permeability: Permeability is the property that quantifies the ease with which fluids can flow through the rock's pores. It's a key factor in oil and gas reservoir studies, groundwater flow modeling, and in the assessment of seepage problems in dams and levees. The permeability of basaltic rocks is highly variable and depends largely on the primary and secondary causes. Primary causes are cooling rate of the basaltic lava flow, the number and character of interflow zones, joints and the thickness of the flow. Whereas, secondary causes include tectonic forces causing shearing, jointing and faulting of basalt rocks.

Thermal Conductivity: The thermal conductivity of basalt samples can vary between 2.003 and 3.060 W/m·K [7]. Thermal conductivity, the measure of the rock's ability to conduct heat, is crucial in geothermal energy studies and in the design of structures where temperature changes could impact the rock's stability.

Moisture Content: The presence of water in basalt rocks can alter their physical properties. When water enters the tiny crevices and pores in rocks, it can weaken the rock's structure. Additionally, when water freezes, it expands and exerts pressure on the rock, which can cause it to crack.

Temperature: Basalt rocks can undergo expansion and contraction due to temperature changes, which can lead to the development of stress within the rock. Additionally, high temperatures can cause chemical changes in the minerals present in the rock, thereby altering its mechanical properties.

Stress Conditions: Basalt rocks can undergo deformation when subjected to stress, whether it is compressive (squeezing) or tensile (pulling apart). The rock's response to stress is a crucial factor in determining its mechanical properties.

Compressive, Tensile and Shear Strength: Basalt rocks are known for their high compressive strength, which makes them ideal for load-bearing applications. The compressive strength of basalt is 100-300 MPa, whereas tensile strength is relatively lower, ranging from 10-30

MPa, necessitating careful consideration in design and construction processes. Shear strength of fresh basalt rocks is 20-60 MPa [7],[11].

Anisotropy: An important factor to consider when dealing with basalt rocks is their anisotropy, which refers to the property of being directionally dependent. In the context of rocks, this means that their mechanical properties can vary depending on the direction of the applied force. This is often due to the alignment of minerals within the rock or the presence of fractures or bedding planes. For instance, the theory suggests that under an anisotropic load, the anisotropy parameters of basalt rocks are linear functions of the stress exponentials.

Variations in Rock Quality: Variations in the quality of basalt rocks depend on factors such as its mineral composition, texture, degree of weathering, and the presence of discontinuity planes such as joints and fractures. These variations can affect the rock's strength, durability, and resistance to weathering and erosion [11].

Weathering: Weathering is a process involving disintegration and decomposition of rocks in-situ in nature [12]. The process of weathering in basalt rocks is intricate and involves changes in the rock's mineralogy and chemistry. The mineral composition, joints, and fractures of basalt rocks play a significant role in the weathering process. The presence of joints and fractures in basalt rocks can create a 3-dimensional network that can cause the rock to break into different sizes pieces separated by the fractures. Water can penetrate more easily along these fractures, and each of the rock pieces will begin to weather inward. Moreover, along flow contacts weathered zones, sometimes pinching and swelling, can be formed associated with clay minerals. Basalt rocks that contain minerals such as olivine and pyroxene can weather faster. Weathering affects strength and durability of rocks. Weathered rocks in the foundation can cause settlement and sliding of the structures.

Red Bole layers:

Red bole layers are commonly found in continental flood basalt (CFB) provinces such as the Deccan Traps as weathered clay horizons between basalt flows. These layers are formed due to the weathering of flow-top and flow-bottom breccias, which are highly prone to weathering [12]. These boles not only signify considerable gaps in basalt flow placement but also, in some instances, bear a resemblance to the initial stages of palaeosol deposits. The chemical properties of red bole are characterized by a higher cation exchange capacity (CEC) and lower sodium adsorption ratio (SAR) and organic carbon (OC) as compared to the weathered basalts. The bole layers are present as weathered clay horizons between basalt flows, and exhibit a range of colors from red to green,. These boles are composed of fine-grained clayey material and are found between traps, particularly within the Deccan traps. Geochemical analysis suggests that they originated from basalts due to weathering processes. These bole layers pose foundation problems of seepage and sliding.

Weathered rock seams:

Weathered rock seams are formed between basalt flows following the cooling of layered basalts along the contacts of the flow [13]. This process is facilitated by the percolation of water through open or sheared contacts. The key distinction between a weathered rock seam and a red or green bole is that the seam does not indicate a hiatus. However, both weathered rock seams and bole layers present similar geotechnical challenges.

Jointing and Fracturing: Jointing and fracturing are two important geological processes that can affect the stability and strength of rock masses. Joints and fractures are the weak planes in the rock mass, which can significantly affect its stability and strength. The presence of these weak planes in the rock mass can create problem of seepage and stability of foundations and slopes [14].

Deformation properties of basalt rocks: The deformation properties of basalt rocks are influenced by factors such as jointing, weathering, and stress conditions [15]. In general, the deformation modulus of a jointed basaltic rock mass ranges from 10-40 GPa with a Poisson's ratio of 0.3. The tensile strength of a basaltic rock mass ranges from -0.1 to -2.5 MPa, while its uniaxial compressive strength ranges from 10-90 MPa. Cohesion of a basaltic rock mass ranges from 0.6-6 MPa [15]. However, these properties can vary depending on the site conditions.

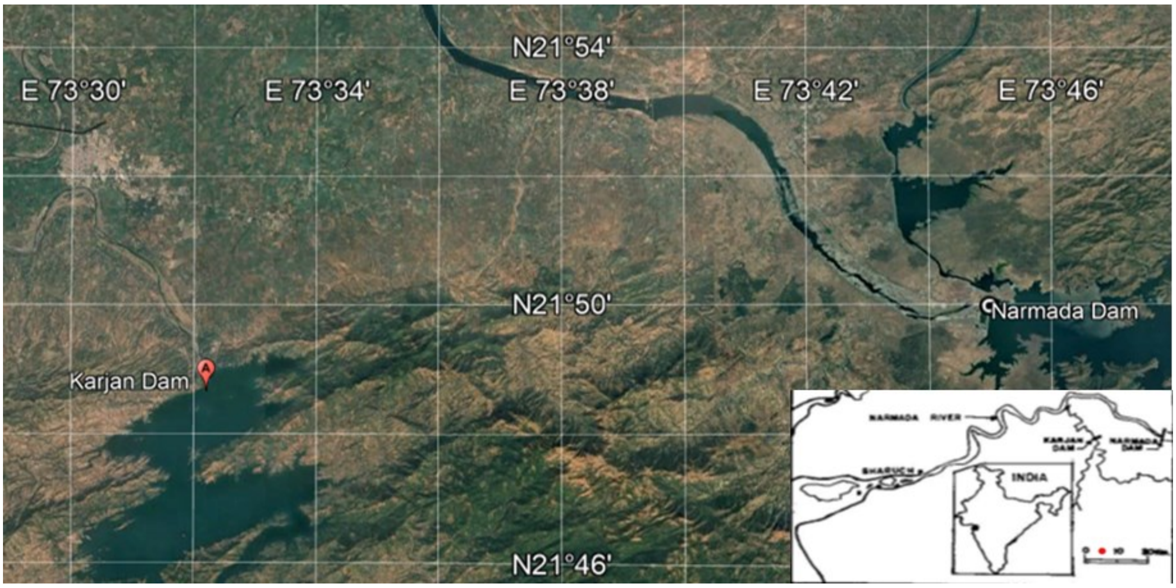

Fig. 1. Location Map of Narmada Dam and Karjan Dam, Gujarat, India

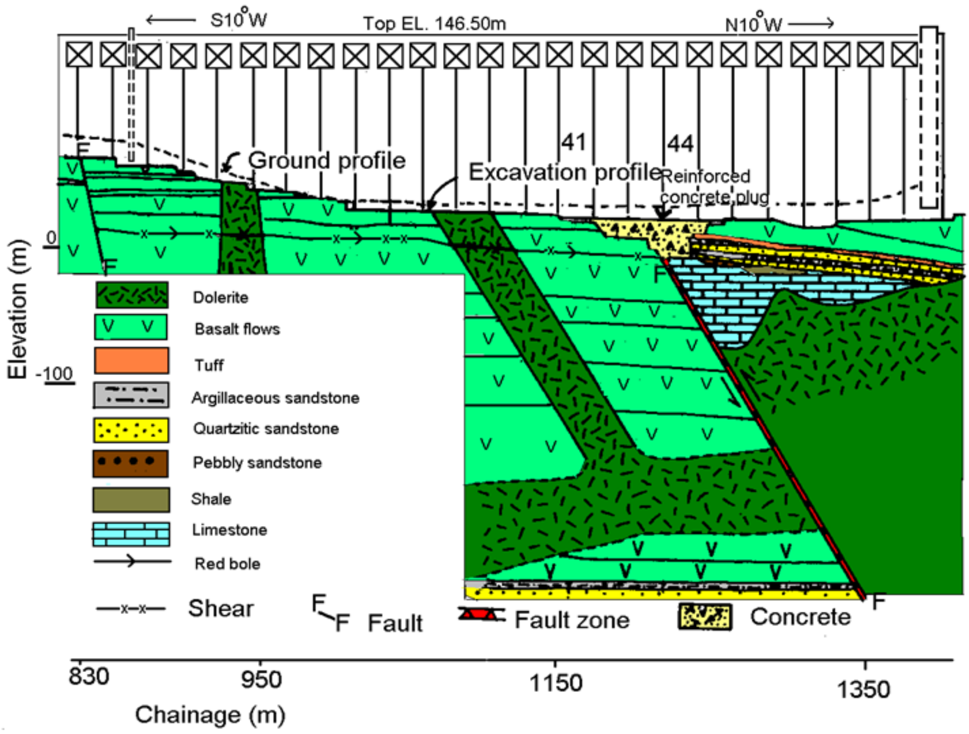

Fig. 2. Geological longitudinal section of Narmada dam spillway blocks [14]

3. Case Studies

Case studies of two major dams (Narmada and Karjan dams) located in the Narmada Valley in Gujarat, India have been discussed to understand geotechnical problems posed by basalt rocks and remedial measures adopted for the successful construction of structures [16],[17],[18],[19],[20],[21],[22]. The Narmada Dam is multi-purpose concrete gravity dam constructed to create a terminal reservoir on the Narmada River. The main structure of the dam measures 1227m in length and stands 162m high from the deepest foundation level, or 129m from the river bed level. The Narmada project site also includes a 1200 MW underground powerhouse, a 250MW surface powerhouse, and four rock fill dams. Approximately 25km downstream of the Narmada Dam, on the left bank of the Narmada River, is the Karjan Dam. This dam, primarily built for irrigation purposes, is a masonry-cum-concrete gravity dam situated across the Karjan River, a tributary of the Narmada. The Karjan Dam is 911m long and 100m high from the deepest foundation level.

Weak geological layers/ features identified in the Deccan basalt flows included tuff, agglomerate, red bole, highly jointed zones, shears and faults. Weak sheared argillaceous sandstone layers (Infra-trappean Bagh beds) also occur in juxtaposition with basalt at shallow depth in the foundations of Narmada dam [23] (Fig. 2).

3.1. Sardar Sarovar (Narmada) Project

The Narmada dam (21.8305° N, 73.7485° E) site is occupied by the "Aa" type Deccan basalt flows underlain by sedimentary rocks of Bagh beds (infra-trappeans) [14] (Fig. 1). A typical "Aa" flow of Hawaii type is tripartite with a basal clinkery zone, thick and massive middle part exhibiting columnar joints, and upper tuff or agglomerate or clinkery fragment zone. In this area, the basal zone is almost absent, and the top of the flows is marked by agglomerate or tuff.

On the left bank, eight flows of dense and porphyritic basalt varieties and on the Right Bank, five flows of dense, porphyritic, and amygdaloidal varieties have been delineated in the foundation area above the riverbed level. The thickness of the individual lava flows varies from 7 to 56m. The attitude of basalt flows varies from near horizontal to low dips (up to 25°). Basalt flows are displaced along a steeply dipping fault. A red bole layer separating amygdaloidal basalt flows was exposed in the riverbed on the left bank and in the foundation of the left divide wall between the lower chute and stilling basin. The continuity of the red bole layer towards the Right Bank is cut by a River Channel (bed) Fault [23],[24].

The underground powerhouse is situated within the basalt flows, sandwiched between two dolerite dykes, each 40 to 45 meters thick. Bottom of the Turbo generation units are founded on the dolerite sill. The surface powerhouse is located on the basalt flows.

The area is marked by a number of ENE-WSW trending basic dykes. The thickness of the dykes varies from 1-2m to 20-25m. These dykes in the foundation area are displaced along low dipping shears/ faults [14]

The physico-engineering (geomechanical) properties of the foundation rocks were determined, including specific gravity, water absorption, compressive strength, ultrasonic velocity, modulus of elasticity, and modulus of deformation [25].

Physical Properties of Rocks

The foundation rocks are generally moderately strong. Test results indicate that the compressive strength of rocks is mostly higher than 34.08 MPa (348 kg/cm²), except for fault breccia (34 kg/cm²), and ultrasonic velocity varies from 4395 to 5670 m/sec. The specific gravity of the foundation rocks varies from 2.64 to 2.94, and the percentage water absorption ranges from 0.52 to 4.94. The high percentage of water absorption (4.94) has been noticed only for the fault breccia, which also shows low values of compressive strength 3.4 MPa (34 kg/cm²) [14] (Fig. 3).

Rock Mass Rating (RMR) Values

The Rock Mass Rating (RMR) values of the foundation rocks were compared with the physical properties. In general, RMR values of the foundation rocks are directly related to the Rock

Quality Designation (RQD)% and Unconfined Compressive Strength (UCS) values [26],[27],[28],[29],[30],[31] (Fig. 4).

Shear Strength of Foundation Rocks

The shear strength of the foundation rocks was determined by laboratory tests and in-situ tests. Design parameters of the foundation rocks were evaluated based on these tests. Shear strength parameters of Cohesion 'C' varies from 0 to 0.25 MPa and angle of internal friction 'ϕ' varies from 11 to 39 degree. Interflow layer (red bole) 'C' value is 0.08 MPa and 'ϕ' value 17 degree.

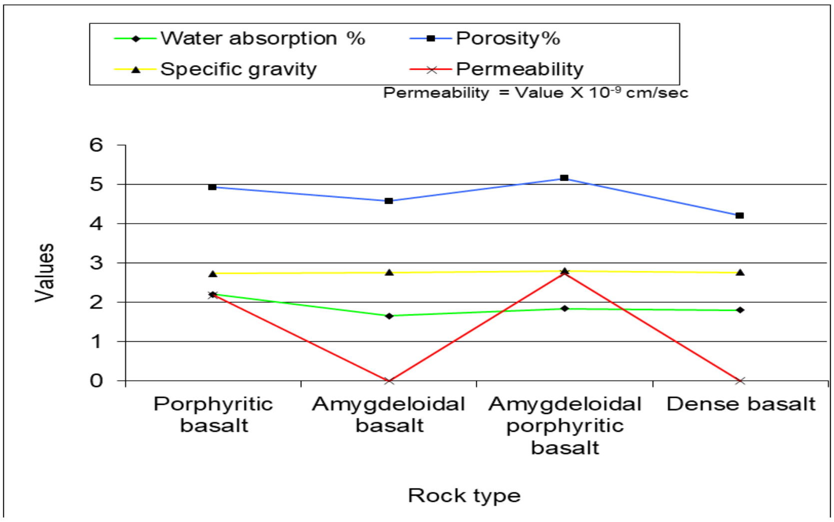

Fig. 3. Water absorption %, Porosity %, Permeability and Specific Gravity values of basalt rocks, Narmada dam

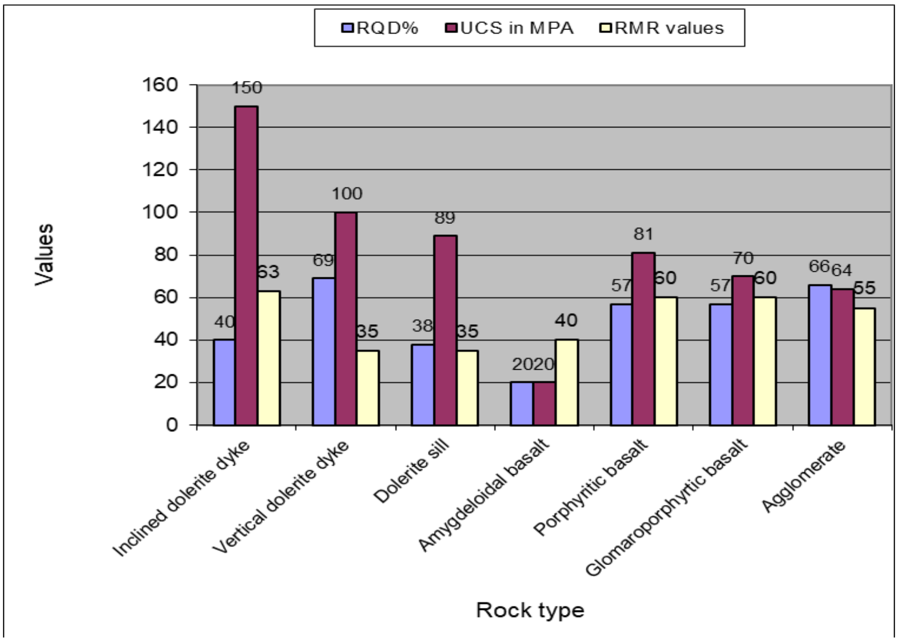

Fig. 4. RQD, UCS and RMR values of basalt rocks, Underground power house, Narmada Project

Modulus of Deformation Values of Fault Zone and Foundation Rocks

In-situ test results indicated low values of modulus of deformation for the fault zone (0.04 x 10^5 kg/cm²). High values of modulus of deformation were obtained for the basalt (0.14 to 0.653 x 10^5 kg/cm²) and sandstone (0.55 x 10^5 kg/cm²). The ratio of average values of the modulus of elasticity and modulus of deformation of the basalt adjacent to the fault zone varies from 1.87 to 2.4. This indicates the weathered and/or jointed nature of the rock mass. Sedimentary rocks adjacent to the fault zone are also highly jointed, as indicated by the high ratio of two moduli (2 to 4). In view of the low modulus of deformation of the fault zone and high modulus ratio of the abutment rocks of varying physico-engineering properties (Fig. 5), the problem of differential settlement in the foundations of riverbed blocks 41 to 44 was apprehended [14],[23]

Petrographic analysis of slaked dolerite shows alteration of feldspar to sericite and augite/olivine to chlorite [32]. A few cracks observed in these rocks are of branching type infilled with chloritic material. X-ray analysis revealed the presence of saponite (Smectite group) as a major constituent in the slaked dolerite rock and chlorite as a minor constituent along joints.

Based on the engineering geological investigations following geotechnical problems were identified at Narmada dam site [14] (Table 1).

Stability analysis indicated that the Narmada dam does not satisfy criteria for design of solid gravity dams for factor of safety against sliding as per IS specification (6512) [33]. Therefore, to achieve the desired factor of safety against sliding concrete shear keys were provided for the treatment of argillaceous sandstone layers and red bole layer (Fig. 6). Treatment was on the similar line of treatment provided for the Itaipu dam (Brazil) [34]. Itaipu dam was having identical foundation problems of sub-horizontal weak layers associated with basalt flows

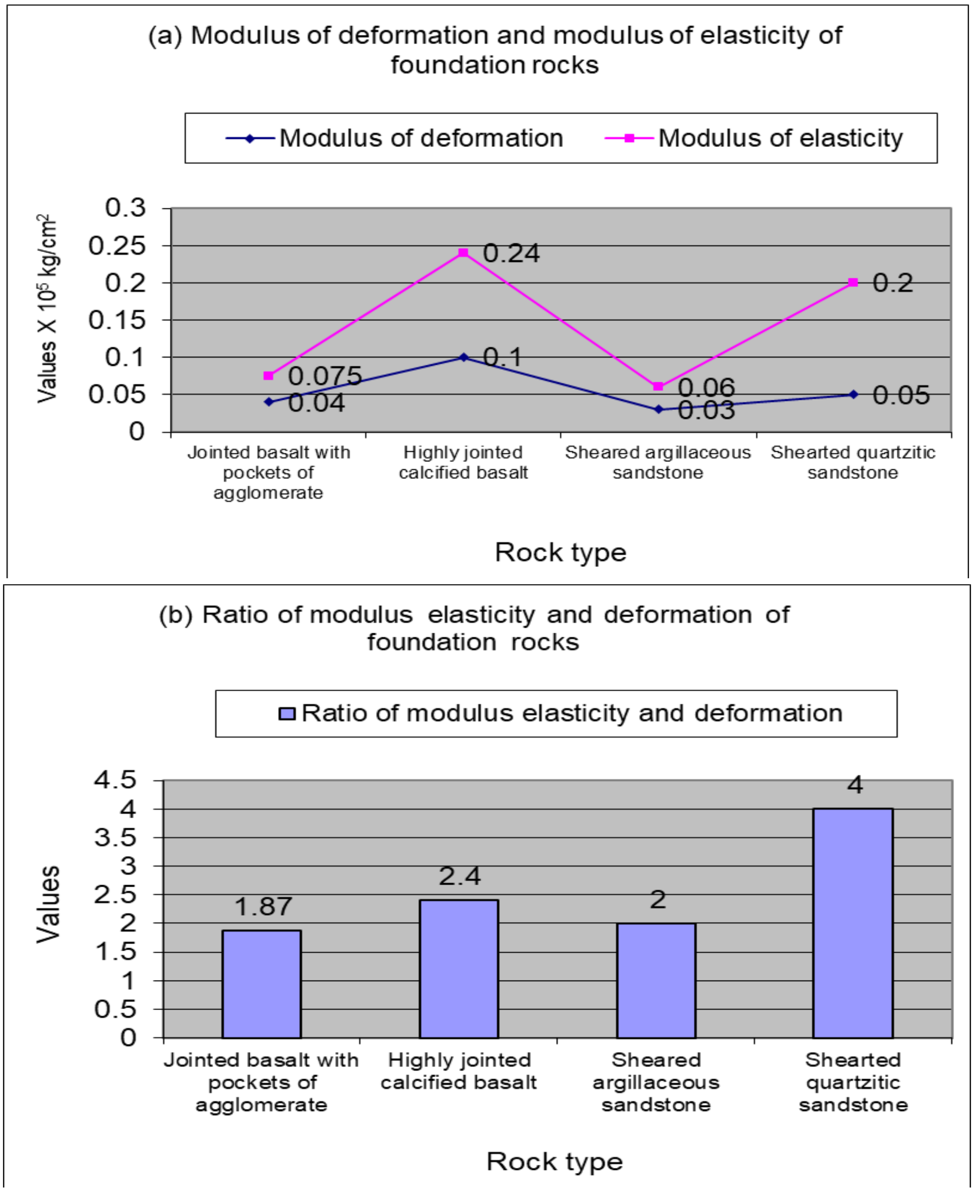

Fig. 5. In-situ deformability of sheared and jointed foundation rocks, Narmada Project

Table 1. Geotechnical problems observed at Narmada Dam site

Geotechnical Problems	**Main geological features responsible for the problems**
Sliding	Red bole, tuff layer, argillaceous sandstone layers and sub-horizontal to low dipping shears
Settlement	River channel fault, minor faults and jointed weathered rocks
Seepage	Sub-horizontal Shears, basalt flow contacts, fault, fractured limestone rock
Seismicity	Major Faults and shears

Fig. 6. Treatment of intra-formational shear associated with red bole layer in the spillway foundation of Narmada Dam [14]

3.2. Karjan Dam Project

The Karjan Dam (21.7834° N, 73.5329° E) is located on the Deccan basalt flows, which are of two types: “Aa” and “Pahoehoe”. The “Aa” flows are characterized by a fine-grained or porphyritic dense basalt at the base, which transitions to an amygdular or tuffaceous composition at the top. These flows are exposed on the abutments at higher levels. In contrast, the river section reveals the “Pahoehoe” type of basalt. This type is recognized by its wrinkled (ropy) and vesicular top, along with pipe amygdales at the base. The thickness of each individual flow unit ranges from 4 to 40 meters. A unique feature of the rocks in this area is the presence of weathered rock seams (Fig. 7) at the interfaces of many flows posing the problem of seepage and sliding of dam blocks [13]

Physico-engineering Properties of the Karjan Dam Foundation Rocks

The physico-engineering properties of the foundation rocks were determined, including specific gravity, water absorption, porosity, permeability, unconfined compressive strength, and tensile strength (Fig. 8). The average values of water absorption percentage vary from 1.60 to 2.20, porosity from 4.20 to 5.15, specific gravity from 2.58 to 2.70, unconfined compressive strength from 62 to 79 MPa, tensile strength from 10 to 12.50 MPa, and permeability from 0 to 2.73×10^{-9} cm/sec. These values are within the normal limit of fresh, moderate to good values of basalt [14]

In-situ shear tests carried out on weathered rock seams in the foundations of overflow blocks indicated a value of cohesion 'C' = 0 kg/cm² (low values of cohesion were neglected in the design hence stated as zero) and the value of angle of internal friction 'ϕ' = 22° to 26°. Low values of shear parameters have necessitated the provision of concrete shear keys along the weak layers in the foundation of dam blocks to resist the sliding forces.

Foundation treatment of sub-horizontal geological weak features at Narmada and Karjan dams, inter-alia, includes excavation of the drifts or open shear keys in the grid pattern along weak layers and back filling them with concrete to provide adequate resistance against sliding. As an alternative modifications adopted in the design include Mild curvature in the axis of dam, Flattening of upstream batter in the spillway blocks (Karjan dam) and Stilling basin type of Energy Dissipater [14].

Treatment of weathered rock mass in the foundation of dam blocks was done by providing single layer or two-tier reinforced concrete mat depending on the nature of weathering and foundation topography. Reinforced concrete plug was provided in the foundation of three dam blocks to treat main river channel fault. Seepage through jointed/ sheared/ faulted basalt rocks, red bole and weathered rock seams was controlled by curtain grouting in the entire length of both the dams' foundation (Fig. 9). Shear keys provided to treat sub-horizontal features also intercepted the seepage path at the dam base in the upstream [13]

Power house:

Major problem associated with excavation of the 58m high powerhouse cavern of Narmada Project was development of cracks in the basalt rocks. Rock mass was stabilized by providing longer rock bolts and pre-stressed cables.

Underground power house and tunnels are located in basalt rocks intruded by dolerite dykes and sills. Problems of rock falls and roof falls were experienced during the excavation of Exit tunnels through dolerite rocks dissected by chlorite-coated joints, shears and slaked zones. Rib supports were provided to stabilize the rock mass [35],[36],[37].

Fig. 7. Weathered rock seam developed at the contact of basalt flows in the foundation of Karjan dam [14]

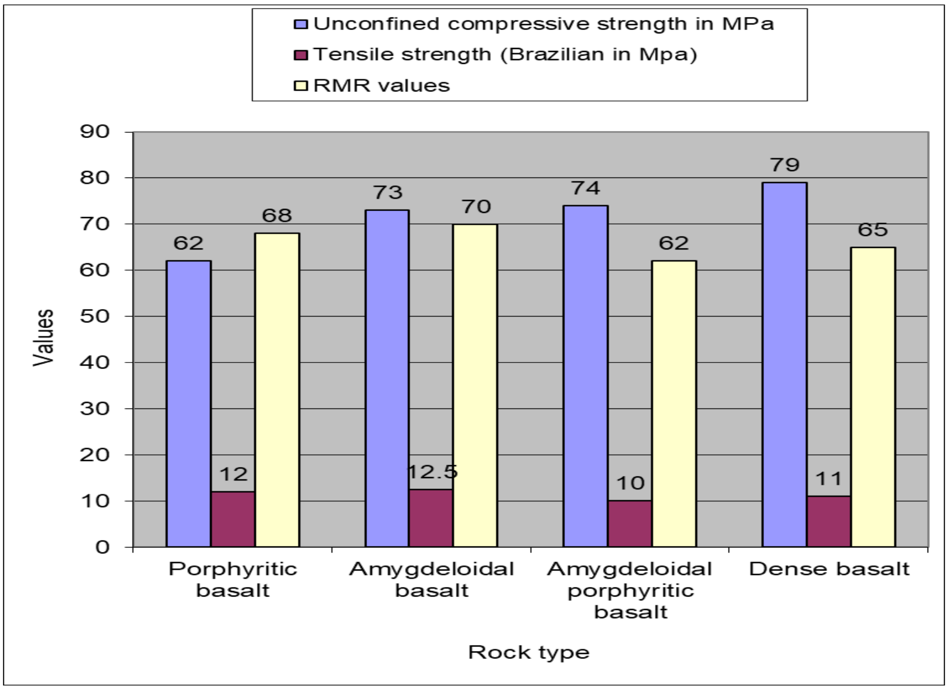

Fig. 8. Compressive, Tensile strength and RMR values of foundation rocks, Karjan dam

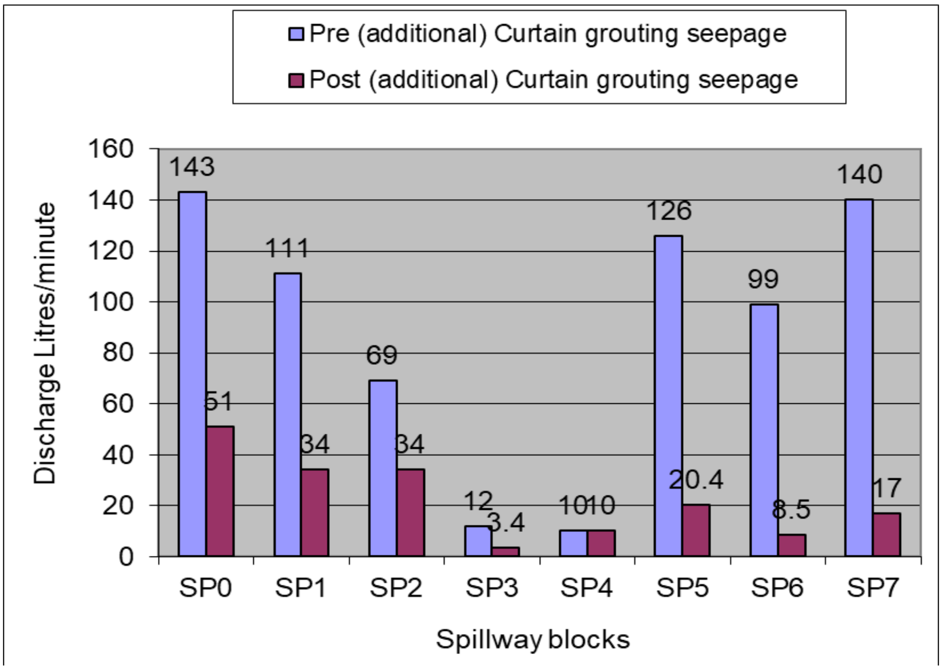

Fig. 9. Pre and Post curtain grouting results of the Karjan dam spillway blocks foundations

4. Discussions

The paper discusses thoroughly geotechnical and geo-mechanical properties of basalt rocks, with a specific focus on mineralogy, composition, physical characteristics, and geotechnical attributes [3],[4],[10],[14]. Understanding the implications of these characteristics is crucial for effective evaluation of basalt rocks and their engineering applications. The discussion unfolds in two main sections: Characteristics of Basalt Rocks and Case Studies.

The geotechnical properties of basalt rocks are intricately linked to their mineralogical composition, dominated by plagioclase feldspar, pyroxene, and olivine. The proportions of these minerals significantly influence the rock's strength, durability, weathering resistance, and response to stress. Plagioclase feldspar determines hardness and resistance, pyroxene assesses wear resistance, and olivine contributes to overall strength. Variations in mineral concentrations lead to diverse properties; a higher proportion of hard minerals enhances strength and durability, while a prevalence of softer minerals increases vulnerability to weathering [12],[13].

Basalt rocks possess distinct physical characteristics crucial for geotechnical assessments. Density, porosity, permeability, thermal conductivity, moisture content, temperature response, and stress conditions are key parameters. The understanding of these properties is vital for designing structures and predicting their interaction with the geological environment [14]. Basalt's high density impacts its use in construction, variable porosity influences water absorption, and permeability is vital for oil and gas studies and dam seepage assessments. Thermal conductivity is critical for geothermal energy studies, and moisture content and temperature changes affect stability. Basalt's response to stress, with high compressive strength but lower tensile strength, underscores the need for careful consideration in design and construction.

The stress and strength characteristics of basalt rocks are outlined, emphasizing their high compressive strength (100-300 MPa) but relatively lower tensile strength (10-30 MPa). Anisotropy, shear strength, and variations in rock quality are also considered, recognizing their significance in engineering applications [9],[25].

Anisotropy, variations in rock quality, and the intricate process of weathering are additional factors discussed. Anisotropy, influenced by mineral alignment or fractures, affects mechanical properties. Variations in rock quality depend on mineral composition, texture, weathering degree, and discontinuity planes, impacting strength, durability, and resistance to weathering. The paper underscores the role of weathering in affecting the strength and durability of basalt rocks, potentially causing settlement and sliding in structures [14].

The Sardar Sarovar (Narmada) Project and the Karjan Dam Project serve as practical illustrations of the geotechnical challenges associated with basalt rocks [14]. The Sardar Sarovar Project, situated on Deccan basalt flows underlain by sedimentary rocks, faces challenges such as red bole layers and sheared contacts. Physico-engineering properties, shear strength, and modulus of deformation are evaluated to assess foundation stability. The presence of sheared dolerite dykes, weathered rocks, red bole layer and a fault zone necessitates a detailed geomechanical analysis [13],[21],[23].

The Karjan Dam Project, located on Deccan basalt flows of "Aa" and "Pahoehoe" types, deals with seepage and sliding challenges due to weathered rock seams [14]. Physico-engineering properties and shear tests are conducted to evaluate foundation suitability. In-situ shear tests on weathered rock seams indicate low cohesion, prompting the provision of concrete shear keys to resist sliding forces [13].

The present case studies also underscore the importance of thorough geotechnical investigation and evaluation in the construction of large dams, even on weak foundations [14]. The engineering geological studies of the Narmada and Karjan dams founded on basalt rocks and associated weak features serve as compelling evidence of this. These dams demonstrate that with meticulous geotechnical evaluation, it is indeed possible to successfully construct large dams on less than ideal foundations. This finding will open up new possibilities for dam construction in geologically challenging areas, thereby contributing significantly to the field of geotechnical engineering. It is hoped that this comprehensive review will inspire further research and innovation in this critical area of study.

5. Conclusions

This review synthesizes existing knowledge on the geo-mechanical properties of basalt rocks.

The origin, mineralogy, physical characteristics, and mechanical behavior of basalt rocks are explored in depth, highlighting their significant geotechnical properties that make them indispensable in engineering applications.

The paper serves as an all-encompassing resource for researchers, engineers, and geologists, providing a thorough examination of basalt rock characteristics and their geotechnical implications. The integration of case studies further augments the practical understanding, offering invaluable insights for professionals involved in projects related to basalt formations.

However, it is important to note that geology is inherently complex and varies significantly across different locations. Therefore, site-specific geotechnical investigations and evaluations of foundation rocks are essential for the safe and economical construction of civil engineering structures. This ensures that the unique geological characteristics of each site are taken into account, leading to more accurate and reliable project outcomes.

The review extensively covers the geotechnical properties of basalt, emphasizing its crucial role in engineering projects and the necessity of site-specific evaluations for reliable outcomes. To advance this research domain, future endeavors could focus on employing advanced testing techniques and modeling methodologies to deepen the understanding of basalt behavior under diverse stress conditions and long-term loading scenarios. Concurrently, extended monitoring and observational studies of structures built on basalt formations would offer insights into their durability, performance, and potential deterioration mechanisms over time. Investigating the influence of environmental factors, such as climate variations and seismic activity, could also contribute significantly to predicting basalt stability accurately. Moreover, conducting detailed geological mapping and site-specific investigations across various regions would facilitate a more comprehensive understanding of regional variations in basalt properties, aiding in tailored engineering designs and construction practices.

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