Implication of Petrography and Geochemistry on Engineering Properties of Building Stones

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***Abstract*—**Granite is a common and widely occurring type of intrusive, felsic, igneous rocks. They usually have medium to coarse-grained texture. It is commonly used as dimensional stone. The quality of a dimensional stone depends of its aesthetic look, elegance and the other characteristics, like absence of closely spaced fractures, good interlocking texture, with lesser abundance of flaky minerals, absence of alterations and minerals which are susceptible to weathering and dissolution when exposed to atmospheric conditions. Six different types of rocks were collected from various quarries, and the rock specimens were prepared for laboratory testing. Important engineering properties such as abrasive resistance, water absorption, skid resistance, modulus of rupture, uniaxial compressive strength and bulk density were determined in the laboratory. Magnetic susceptibility and natural gama radiation were measured using portable field instruments. XRD and XRF studies were also carried out in the laboratory to understand the mineralogical and geochemical characteristics. Petrographical studies were also done to understand the textural characteristics of rocks. Finally all the parameters were statistically analysed in order to understand their relationship. The study concludes that ferro-magnesium minerals such as pyroxenes, magnetite and garnet are greatly responsible for high magnetic susceptibility and skid resistance. These minerals are also responsible for lower water absorption characteristics. Plagioclase feldspars are more responsible for high uniaxial compressive strength. High copper content and low silica also increase the abrasive resistance and modulus of rupture.

***Keywords*—**Building stones, Petrography, Engineering properties, South India

I. INTRODUCTION

GRANITE is a widely occurring felsic, intrusive igneous rock, exhibits medium to course grained texture. Occasionally it shows porphyritic texture where some individual minerals are larger than the ground mass. Granites can be pink to grey in colour depending on their mineralogy and chemical composition. Many different types of granite are identified based on their varied chemical and mineralogical compositions. The variation in the chemical composition depends on the depth conditions, temperature - pressure and different distributions. Hence, these rocks have economical importance and are commercially valuable. The present study is aimed to understand the mineralogy, textural characteristics, radiation property and magnetic susceptibility of commercial granites and its relation with the strength parameters.

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II. METHODOLOGY

Six different types of building stones of three different lithologies (granite, dolerite and gneiss) were collected from various quarries located in South India (Table I). In order to understand the various geological and engineering properties of rock samples, the methodology has been divided into two major parts namely field investigations and laboratory testing. Various advanced instruments such as, hand held XRF, portable magnetic susceptibility meter and Scintillometer were used to assess the chemical composition, magnetic susceptibility and radiation properties of rocks. Petrographic studies and XRD studies were carried out to understand the mineralogical characteristics. All the rock samples were prepared at suitable sizes (Fig. 1) and were tested in the laboratory for various engineering properties such as abrasion resistance, water absorption, skid resistance, modulus of rupture, uniaxial compressive strength and bulk density.

TABLE I
DETAILS OF BUILDING STONES

S.No	Geological Name	Commercial Name	Location of the Quarry (India)
1	Alaskitic Granite	G Red	Tuticorin, Tamil Nadu
2	Biotitic Granite	Himalaya Red	Kukanoor, Karnataka
3	Dolerite	Regal Black	Varathur, Andra Pradesh
4	Garnetiferous Biotitic Granite	Bash Paradiso	Varaganapalli, Karnataka
5	Garnetiferous Granite	New Colonial White	Mathangipatti, Tamil Nadu
6	Granitic Gneiss	Vizag Blue	Pattupuram, Andra Pradesh

Fig.1 Rock samples tested for various engineering properties

III. MINERALOGY AND TEXTURE

The petrographic and textural characteristics of rock samples were studied by optical microscopy. XRD studies were also carried out to understand the mineralogy of rock samples. Summary of textural and mineralogical characteristics of building stones are presented in Table II.

TABLE II
GEOLOGICAL PROPERTIES OF BUILDING STONES

Geological Name	Geological Classification	Category	Colour Index	Grain Size	Mineralogy: Essential	Mineralogy: Accessory	Texture
Alaskitic Granite	Igneous	Plutonic	Felsic	M to C	Q+F	M+Z	Meso-perthitic
Biotite Granite	Igneous	Plutonic	Felsic	Medium	Q+F	B	Hypidio-morphic
Dolerite	Igneous	Hypabyssal	Mafic	Medium	A+L	V+Q	Sub-Ophitic
Garnetiferous Biotite Granite	Igneous	Plutonic	Felsic	Coarse	Q+F	G+B	Hypidio-morphic
Garnetiferous Granite	Igneous	Plutonic	Felsic	Medium	Q+F	G+H	Hypidio-morphic
Granitic Gneiss	Metamorphic	Dynamo-thermal		M to C	Q+F	B	Grano-blastic

M to C:- Medium to Coarse; Q+F:- Q-Quartz; F-Feldspar; A-Augite; B-Biotite; G-Garnet; H-Hornblende; L-Labradorite; M-Magnetite, V-Vermiculite and Z-Zircon

A. Alaskitic granite

Alaskitic granite is leucocratic and in-equigranular in nature. It is mainly composed of quartz and feldspar, occupying 98% of the rock. Magnetite and few granules of zircon are also found as accessory minerals. Meso-perthitic texture with fine intergrowth of K– feldspar and plagioclase feldspar constitutes about 65%. They invariably contain perthitic inclusion free rim. Quartz occurs as anhedral grains and wavy extinction is not characteristically found. Predominance of mesoperthitic feldspar and quartz suggest the rock is granite and in view of the leucocratic nature it can be classified as alaskitic granite [1].

B. Biotite granite

Biotite granite exhibits hypidiomorphic texture and it is of medium to coarse grained in nature. It is essentially composed of quartz and feldspar with biotite and occasional opaques. The rock composed of 30% quartz, 65% feldspar and 5% accessories. Microcline exhibits typical cross hatch twinning and inclusion of biotite is common. In quartz, wavy extinction is typical. Biotite occurs as minute flakes and shows preferred orientation (pleochoric yellow to green). Stretching of quartz is seen, which indicates mild metamorphic imprints [2].

C. Dolerite

The rock is medium grained and it exhibits sub-ophitic texture. The rock is essentially composed of plagioclase and augite. Plagioclase is free of clouding and it occurs as laths and occupies about 60% of the rock. It exhibits polysynthetic twinning and occasional zoning. Augite is the chief mafic mineral, which occurs as anhedral prismatic grains occasionally exhibiting twinning. They are interstitial to plagioclase and hence it exhibits sub-ophitic texture. The angular inter-space between the essential minerals is filled with vermicular intergrowth of quartz and possibly K -feldspar and biotite. This represents the residual liquid, which are formed in the final stage of magma. The rock is essentially composed of plagioclase, pyroxene and in view of sub-ophitic texture, it is a dolerite. Due to the absence of clouding in plagioclase, the rock is not black in color and hence it is greenish. Opaque oxides are more than 5%.

D. Garnetiferous Biotite Granite

The rock is coarse grained, leucocratic and exhibits hypidiomorphic texture. It is essentially composed of K-feldspar and quartz with biotite as the chief accessory. K-feldspar is microcline as evidenced by the prominent grating structure and occurs as large crystals. The rock consists of 20% quartz, which occurs as anhedral grains and rounded inclusion in microcline. This exhibits wavy extinction, which is not well developed indicating moderate strain. Biotite occurs as flacks and is interstitial to microcline. It is strongly pleochroic form yellow to brownish green and frequently occurs as cluster with a habit of suggestive secondary development. Minor accessories in this rock include muscovite, which occurs as very small flacks in the margin of K-feldspar and apatite. Garnet is also found as accessory mineral in this rock.

E. Garnetiferous granite

The rock is medium grained, leucocratic, equigranular and exhibits hypidiomorphic texture. It is essentially composed of feldspars and quartz with few grains of garnet. In feldspars, K-feldspars predominate over plagioclase; both are however twinned and crosshatched. Well developed crosshatch and polysynthetic textures are seen, which are typical of K-feldspars and plagioclase respectively. The K-feldspar has irregular streaks of plagioclase inclusions and hence it is perthitic. Plagioclase exhibits faint polysynthetic twinning. Quartz is about 20% of the rock and occurs as irregular elongated grains, which are moderately developed wavy extinction. Garnet occurs as sub-rounded grains and crisscrossed by cracks, which mimic cleavage. However, the pink color and isotropic nature of the mineral indicate its identity. Garnet is specially distributed in the rock. As the rock is essentially made up of feldspar and quartz, it can be classified as granite. Due to the presence of garnet as accessory mineral the rock can be named as garnetiferous granite.

F. Granitic gneiss

The rock is fine grained due to pulverization and is leucocratic, which exhibits granuloblastic texture. The rock is essentially composed of feldspar and quartz with garnet as the chief mafic mineral with intermediate biotite and minor opaque oxides. Though the rock is leucocratic, it is dark colored due to the presence of blue colored quartz, dark colored feldspar and hypersthene. However, hypersthene of typical charnockite is absent here. Due to fine grained and pulverized nature of the rock, identification of feldspar is difficult. However, crosshatched structure and polysynthetic twinning are found frequently indicating that both microcline and plagioclase are present. Quartz occurs as minute platelets and is characterized by strong wavy extinction. It is about 30% of the rock by volume. Garnet occurs as rounded grains with tendency to be elongated and occurs as larger idioblastic grains, which are distinctly larger than the felsic minerals and garnet is also dispersed in the rock. Inclusions of opaque oxides and biotite development along the margin are also found. Biotite, which is strongly pleochroic from yellow to reddish brown, is found in the rock as small flakes and this habit suggests secondary development. They are found concentrated in places where opaque oxides occur. Opaque oxide is formed as idiomorphic granules. The rock in view of the pulverized nature can be considered as a catablastic rock and the shear has probably takes place under deep-seated condition. Hence the rock can be named as granitic gneiss.

Chemical composition of all the six rock samples was determined using handheld XRF, which works on wavelength-dispersive spectroscopic principles that are similar to an electron microprobe. It is typically used for bulk analyses of larger fractions of geological materials. The relative ease and low cost of sample preparation, and the stability and ease of use of x-ray spectrometers make this one of the most widely used methods for analysis of major and trace elements in rocks, minerals, and sediments. The major element analysis of the rock samples are given in Table III. The geochemical studies indicate except dolerite, all the rock samples are felsic in nature dominated my silica, alumina and alkalies. This is due to the presence of higher modal content quartz and feldspars in the rocks. In dolerite, the silica content is less because of its mafic nature. Ferro-magnesium content along with lime is high in this rock, which is due to the higher modal content of pyroxenes and plagioclase feldspars. The trace elements were also analysed using XRF and their concentrations are given in Table IV. The relationship between chemical characteristics and engineering properties were studied using regression analysis, which is presented in Table V. Only major oxides were correlated with the engineering properties as the trace element concentrations were insignificant, which may not alter the engineering properties.

TABLE III
CONCENTRATION OF MAJOR OXIDES (IN WT. %)

Major Oxides	1	2	3	4	5	6
SiO_2	71.45	72.11	53.05	69.31	69.94	71.49
Al_2O_3	16.23	15.24	14.52	18.21	17.99	17.65
FeO (t)	1.08	1.21	12.01	1.01	1.22	1.21
MgO	1.02	0.98	7.21	1.34	1.21	1.06
CaO	1.86	1.13	9.04	1.11	1.67	2.34
Na_2O	6.07	3.81	1.92	3.67	2.98	3.68
K_2O	1.76	4.13	0.41	3.84	3.65	2.11
TiO_2	0.06	0.09	1.12	0.06	0.21	0.09
LOI	0.41	0.6	0.62	0.54	0.51	0.6
Total	99.94	99.3	99.9	99.09	99.38	100.23

TABLE IV
CONCENTRATION OF TRACE ELEMENTS (IN PPM)

Trace Elements	1	2	3	4	5	6
Ba	BDL	0.041	0.059	0.031	0.014	0.083
Sb	0.002	0.002	BDL	BDL	BDL	BDL
Mo	0.016	0.015	0.013	0.023	0.015	0.012
Nb	0.028	0.024	0.021	0.027	0.023	0.022
Zr	0.014	0.013	0.01	0.012	0.001	0.018
Sr	0.003	0.032	0.015	0.041	0.009	0.027
Rb	0.024	0.01	0.003	0.005	0.014	0.01
Bi	0.003	0.002	0.002	BDL	BDL	0.002
Pb	0.003	0.001	BDL	BDL	0.006	0.001
Zn	0.001	0.004	0.01	0.004	BDL	0.003
Cu	0.002	0.003	0.024	BDL	0.005	0.002
Co	0.004	0.005	0.043	BDL	BDL	0.012
Mn	0.004	0.017	0.156	0.014	0.012	0.058
Cr	0.005	0.005	0.007	0.005	0.005	0.007
V	0.062	BDL	BDL	BDL	BDL	BDL
Cl	0.108	0.101	0.135	0.125	0.099	0.117
S	BDL	BDL	0.037	BDL	BDL	BDL

1.Alaskitic Granite; 2. Biotite Granite; 3. Dolerite; 4. Garnetiferous Biotite Granite; 5. Garnetiferous Granite; 6. Granitic Gneiss; BDL – Below Detection Limit.

TABLE V
CORRELATION BETWEEN CHEMICAL PARAMETERS AND ENGINEERING PROPERTIES

Engg. Properties / Chemical parameters	Abrasion resistance (mm)	Water absorption (%)	Skid resistance (BPN)	Modulus of rupture (N/mm^2)	UCS N/mm^2	Bulk density (Kg/m^3)
SiO_2	-0.90	0.99	-0.20	-0.75	-0.21	0.61
Al_2O_3	-0.79	0.99	-0.36	-0.59	-0.14	0.77
FeO (t)	0.85	-0.99	0.28	0.68	0.17	-0.69
MgO	0.87	-0.99	0.26	0.70	0.20	-0.66
CaO	0.79	-0.99	0.36	0.60	0.13	-0.77
Na_2O	-0.91	0.95	0.06	-0.82	0.17	0.70
K_2O	-0.50	0.87	-0.64	-0.25	-0.14	0.87
TiO_2	0.88	-0.99	0.19	0.72	0.07	-0.72

IV. ENGINEERING PROPERTIES

The strength of a rock is its ability to withstand an applied stress without failure. The applied stress may be compressive, tensile or shear. Hence, strength of rocks depends on the load or the force acting on it. Those forces on the rock cause deformation, which is referred as strain. The strength of rock relies on three different type of analytical method: strength, stiffness and stability, where strength refers to the load carrying capacity, stiffness refers to the deformation or elongation, and stability refers to the ability to maintain its initial configuration.

The engineering properties of an intact rock are important parameters for evaluating the engineering behavior of the rock mass during construction and they also have a significant influence on the project design and cost. They are greatly affected by the mineralogy, texture and the anisotropy of the material [3]-[10].

Uniaxial compressive strength is a crushing strength of a stone and defined as the maximum force expressed per unit area, which a stone can withstand without rupturing. Any force applied beyond the compressive strength will cause a failure or rupture of the stone. The Uniaxial compressive strength (UCS) has been determined (Fig. 2) by subjecting each rock sample to incremental loading at a nearly constant rate with the help of a Universal Testing Machine [11]. The loading is continued till the first crack appears in the test specimen indicating the beginning of the failure. Any further loading will crush the specimen. UCS is considered as one of the key properties in characterization of rock materials in engineering practice [12]. Garnetiferous biotite granite have high UCS (1856 N/mm^2) than the other rock types.

Fig. 2 Determination of Uniaxial Compressive Strength

Abrasion resistance is more a qualitative than quantitative property and may be broadly defined as the resistance, which a stone offers to rubbing action of one kind or another. This quality acquires considerable importance when a stone is intended to be used in a situation where rubbing by natural or artificial cause may become a routine. Knowledge of the abrasiveness of rock is very important when predicting the rock drillability, cuttability, borability and tunnel boring machine advance rates. This property depends to a great extent on the mineralogical composition of the rock and the type and the degree of cementation of the mineral grains [13-20]. The resistance to abrasion of rocks can be obtained using the Los Angeles abrasion testing machine [21]. Abrasion resistance is shown higher in Dolerite while lower in granitic gneiss.Modulus of rupture, water absorption and bulk densities were also determined in the laboratory for all the six rock samples. The laboratory results of engineering properties of rock samples are listed in Table VI.

TABLE VI
ENGINEERING PROPERTIES OF BUILDING STONES

Rock Samples	Abrasion resistance (mm)	Water absorption (%)	Skid resistance (BPN)	Modulus of rupture (N/mm^2)	Uniaxial Compressive strength (N/Sq mm)	Bulk density (Kg/m^3)
Alaskitic Granite	0.54	0.5	25	7.45	1516	2460
Biotitic Granite	0.68	0.55	30	6.09	1376	2520
Dolerite	0.86	0.26	40	9.48	1492	2430
Granitifeorus Biotitic Granite	0.64	0.59	32	7.45	1856	2540
Garnetifeorus Granite	0.66	0.56	20	8.12	748	2480
Granitic Gneiss	0.48	0.58	48	4.74	1352	2460

V. MAGNETIC SUSCEPTIBILITY

The magnetic susceptibility is a unitless constant that is determined by the physical properties of the magnetic material. Magnetic susceptibility is quantitative measure of the extent to which a material may be magnetized in relation to a given applied magnetic field. The KT-6 is the state-of-the-art in Magnetic Susceptibility Meters. The field geologist will normally find it an indispensable tool as it allows fast, easy and accurate analysis of rock samples. This portable, hand-held unit can be used in the field to analyze and classify rock types or core samples. The KT-6 has a maximum sensitivity of 1×10^{-5} SI units -0.8×10^{-6}cgs units. This allows the unit to accurately measure very low-level susceptibility for reliable identification of rocks and other weakly magnetized minerals. Handheld instruments are useful for rapid and sensitive measuring of magnetic susceptibility in rock exposures and hand samples or quick scanning of susceptibility of drill cores. The magnetic susceptibility of six rock samples is presented in Table VII.

TABLE VII
MAGNETIC SUSCEPTIBILITY OF BUILDING STONES

Rock Samples	Measurement of magnetic susceptibility					
	1	2	3	4	5	Average (1×10^{-5} SI unit)
Alaskitic Granite	1.57	1.69	1.55	1.06	1.90	1.554
Biotite Granite	0.92	3.33	2.04	4.10	4.13	2.904
Dolerite	33.7	36.0	37.4	35.7	36.5	35.86
Garnetiferous Biotite Granite	3.86	5.27	5.53	3.34	4.80	4.56
Garnetiferous Granite	0.76	0.47	0.51	0.50	0.58	0.564
Granitic Gneiss	0.79	0.58	0.60	0.67	0.72	0.672

VI. GAMA RADIATION

Background radiation is natural and inevitably present in the environment and varies significantly from place to place. Natural sources of radiation are the important contributors to the population exposures to ionising radiation. In particular, radon, thoron, their progenies and gamma rays are emitted by terrestrial radionuclides present in soil, rocks, building materials and in atmosphere contribute highest dose. People living in granite areas or in mineralised sands receive more terrestrial radiation than in other areas [22].

The ambient gamma radiation levels in commercial granites were measured using Scintillometer [(Type SM 141D, Electronics Corporation of India Limited (ECIL)]. The Scintillometer is a lightweight portable radiation survey meter, featuring solid-state design and ideally suited for radiometric, geophysical and environmental surveys. The detector is a thallium-activated sodium iodide crystal optically coupled to a photomultiplier. The crystal and the photomultiplier assembly are hermetically sealed. All measurements were made 1 m above the ground level. The arithmetic mean of the readings (in $\mu R\ h^{-1}$) was taken as a representative figure for each location. The natural gamma radiation is little higher in granite quarries than the normal background radiation. The effective annual dose that could arise from the samples in a closed area has been calculated and presented in Table VIII.

TABLE VIII
ANNUAL EFFECTIVE DOSES RATE

S.No	Type of rock	Annual effective dose ($mSv\ y^{-1}$)
1	Alaskitic Granite	166 ± 15
2	Biotitic Granite	170 ± 15
3	Dolerite	161 ± 20
4	Granitifeorus Biotitic Granite	186 ± 20
5	Garnetifeorus Granite	186 ± 20
6	Granitic Gneiss	161 ± 20

VII. SUMMARY OF THE RESULTS

Abrasive resistances and modulus of rupture are high in dolerite and low in granitic gneiss. However, skid resistance and water absorption properties are higher in granitic gneiss. Dolerite is having low water absorption property. High abrasive resistance, high modulus of rupture and low water absorption properties of dolerite is due to its ophitic texture. Water absorption property is high in granitic gneiss due to its pulverization nature and catablastic texture. Skid resistance and UCS are minimum in garnetiferous granite, whereas UCS and bulk density are maximum in garnetiferous biotite granite.

Among the six rocks, dolerite is having higher Ca content and lower Si and K contents. S is found only in dolerite. Abrasion resistance and modulus of rupture exhibit good positive correlation with FeO, MgO, CaO and TiO_2. These are the common constituents of pyroxenes. Hence, high abrasion resistance and high modulus of rupture in these rocks are due to the presence of pyroxenes. In the case of water absorption and bulk density, felsic components play a dominant role.

Skid resistance exhibits excellent positive correlation with Al content and Al exhibits good positive correlation with Cr. Hence, skid resistance of the rock sample is controlled by the Al content in rocks. Modulus of rupture exhibits good negative correlation with Si content of the rock samples. Modulus of rupture is high in dolerite which contains low Si and high Cu.

Magnetic susceptibility is high in dolerite and low in garnetiferous granite, which is mainly due to presence of magnetite in dolerite. Petrographic study also confirms that the rock is having more than 5% of opaque oxides. XRF studies also confirm that only dolerite is having more FeO (total) content. The other rock samples are having less concentration of FeO (total). Magnetic susceptibility exhibits excellent positive correlation with Fe content of the rock samples, and Fe exhibits positive correlation with Ca, Mn, Co, Cu and Zn.

VIII. CONCLUSIONS

Uniaxial compressive strength of the rocks mainly depends on the plagioclase feldspars. Ca and Sr are responsible for higher uniaxial compressive strength. Zn and Zr may also increase the uniaxial compressive strength of rocks considerably. Less silica and zirconium concentration, and high copper content in rocks are responsible for high abrasive resistance, high modulus of rupture, high magnetic susceptibility and low water absorption characteristics. The radioactivity is due to the presence of radioactive elements which are normally high in granitic rocks. If the rocks contain more ferro-magnesium minerals, the magnetic susceptibility and skid resistance are more. Minerals such as pyroxenes, magnetite and garnet are greatly responsible for high magnetic susceptibility and skid resistance. These minerals are also responsible for lower water absorption characteristics.

ACKNOWLEDGMENT

The first author thanks Centre for Technology Development and Transfer (CTDT), Anna University, Chennai-600025, India for the financial support to carry out this work. This article is the 63rd contribution from Earth System Science Group (ESSG), Chennai, India.

REFERENCES

[1] I. Jurkovic, "Metallogeny of Eocene syncollisional granites of motajica and prosara mountains", *Rudarsko-geološko-naftni zbornik*, Vol. 16, pp. 31- 46, 2004.

[2] S. Bhattacharya, "Eastern Ghats granulites terrain of India: an overview. Journal of Southeast", *Asian Earth Sciences,* Vol. 14, (3-4), pp.165-174. 1996.

[3] D. U. Deere and R. P. Miller, "Engineering classification and index properties for intact rock", *Tech. report, Air Force Weapon Lab.,* New Mexico, No. AFWL-TR-65-116, 1966.

[4] J. R. Mcwilliams, "The role of microstructure in the physical properties of rock", *Testing technique for rock mechanics.* ASTM STP 402, pp.175–189, 1966.

[5] R. Merriam, H. H. Rieke, and Y. C. Kim, "Tensile strength related to mineralogy and texture of some granitic rocks", *Eng Geol*, vol. 4, pp. 155–160, 1970.

[6] T. F. Onodera, and H. M. Asoka Kumara, "Relation between texture and mechanical properties of crystalline rocks", *Bull Int Assoc Eng Geol*, vol22, pp. 173–177, 1980.

[7] T. Y. Irfan, "Mineralogy, fabric properties, and classification of weathered granites in Hong Kong", *Q J Eng Geol*, vol. 29, pp. 5–35, 1996.

[8] F. S. Jeng, M. C. Weng, M. L. Lin, and T. H. Huang, "Influence of petrographic parameters on geotechnical properties of Tertiary sandstone from Taiwan", *Eng Geol*, vol. 73, pp.71–91, 2004.

[9] L. M. O. Sousa, L. M. Suraz Del Rio, L. Calleja, V. G. Ruiz De Argandona, and A. R. Rey, "Influence of microstructures and porosity on the physico-mechanical properties and weathering of ornamental granites", *Eng Geol*, vol. 77, pp. 153–168, 2005.

[10] Vikram Gupta, "Non-destructive testing of some Higher Himalayan Rocks in the Sutluj Valley", *Bull Eng Geol Environ*, vol. 68, pp. 409-416, 2009.

[11] K. B. Chary, L.P. Sharma, K. J. Prasanna Lakshmi, N.A. Vijayakumar, V. Nagalakshmi, and M.V.M.S. Rao, "Evolution of Engineering properties of Rock using Ultrasonic Pulse Velocity and Uniaxial

Compressive Strength", in *proc. of National Seminar on Non-Destructive Evaluation,* Hyderabad, 2006, pp. 1-7.
[12] A. Basu, and A. Aydin, "Predicting Uniaxial Compressive Strength by Point Load Test; Significance of Cone Penetration", *Rock Mech Engng,* vol. 39 (5), pp. 483-490, 2006.
[13] R. Selmer-Olsen, and A. Palmstrom, "Tunnel collapses in swelling clay zones", Tunnels CVEN 5768 - Lecture Notes 2, © B.Amadei & Tunnelling, pp. 49-51, 1989.
[14] D. J. Lachel, "The *Engineering geologist's role in determining the feasibility of a runneling machine for hard rock",* Engineering Geology Case Histories, No. 9. Boulder, Colo: Geological Society of America, 1970.
[15] D. E. Hansen, and D. J. Lachel, "Ore body ground conditions", in *Tunnelling Technology Newsletter,* U.S. National Committee on Tunneling Technology, No. 32, pp. 1-15, 1980.
[16] Aleman, V.P. (1983) Prediction of cutting rates for boom type road-headers, Tunnels & Tunnelling, pp. 23-25.
[17] P. P. Nelson, T. D. O'Rourke, and F. H. Kulhawy, "Factors affecting TBM penetration rates in sedimentary rocks", *Proc. 24th US Symp. Rock Mech.*, College Station, 1983, pp. 227-236,
[18] P. P. Nelson, T. D. O'Rourke, and F. H. Kulhawy, "Cutter wear and its influence on tunnel boring machine performance", *Proc. Int. Conf. on Design and Performance of Underground Excavations,* Cambridge, England, 1984, pp. 239-246,
[19] D. F. Howarth, W. R. Adamson, and J. R. Berndt, "Correlation of model tunnel boring and drilling machine performances with rock properties", *Int J Rock Mech Min Sci & Geomech Abstr.,* Vol. 23, No.2, pp. 171-175, 1986.
[20] G. West, "Rock abrasiveness testing for tunnelling", *Int J Rock Mech Min Sci & Geomech Abstr.,* Vol. 26, No.2, pp. 151-160, 1989.
[21] R. H. Atkinson, "Hardness tests for rock characteristics", in: *Rock testing and site characterization— compressive rock engineering*, vol 3. J.A. Hudson, Ed. Oxford: Pergamon Press, 1993, pp. 105-117.
[22] C. Ningappa, J. Sannappa, and N. Karunakara, "Study on Radionuclides in granite quarries of Bangalore Rural District, Karnataka, India", *Radiation Protection Dosimetry*, vol. 131 (4), pp. 495-502, 2008.

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