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Influence of Anisotropy of Magnetic Susceptibility on Deformation and Geomechanical Response of Rocks: An Experimental Study on Carbonates of Bijawar Group

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Abstract

The present paper embodies the variability of the geomechanical properties (uniaxial compressive strength and modulus of elasticity) with respect to determined anisotropy of magnetic susceptibility for carbonate of Bijawar Group, Taura, Hirapur, Madhya Pradesh, India. For the purpose, the anisotropy of magnetic susceptibility (AMS) were measured through KLY-4S Spinner. The geomechanical properties were determined through deformation of cylindrical carbonate samples under incremental stress conditions on servo-controlled Material Testing System (MTS).

The results of investigation reveal string relationship between anisotropy of magnetic susceptibility (AMS) and geomechanical properties of carbonate. The samples from northeastern part of the area exhibit lower mean values (62.34x 10^{-6} SI to 70.28 x10^{-6} SI), compressive strength (28.12 MPa to 29.10 MPa) and modulus of elasticity (0.92GPa to 1.123 GPa). However, samples from southwestern parts of the area imparts higher values of AMS (80.12x 10^{-6} SI to 80.86 x 10^{-6} SI), compressive strength (34.12 MPa to 41.12 MPa) and modulus of elasticity (1.213 GPa to 1.687 GPa). The variation of geomechanical properties of carbonate exhibit slight differences in compressive strength and modulus of elasticity with respect to lower values of AMS. Moreover, at higher AMS values the pronounce variation in compressive strength and modulus of elasticity infers strong bearing of AMS on geomechanical response of carbonate. The study may be useful for engineering utilization of carbonate rocks as well as to develop techniques of applications on other rock types showing lack of structural anisotropy such as foliation, lineation, bedding, laminations, etc.

Introduction

Geomechanical properties of rocks are the basic requirements for planning and design of underground structures such as tunnels, caverns, underground chambers and mines. The knowledge regarding variation of geomechanical properties of rocks and rock masses is helpful for design of engineering structures as well as to estimate the self support capacity of rocks and design of suitable support system. Hence, the variation of geomechanical response of rocks is one of the important aspects of underground space technology.

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The inherent constituents and their arrangements are the fundamental frameworks of rocks resulting different kinds of fabrics and structural anisotropy. Thus, earlier, a number of studies have been carried out to quantify the influence of rock fabric on geomechanical properties (Dubey, 2002). Howarth and Rolands (1987) determined a textural coefficient (TC) comprises fabric parameters like grain size, grain shape, packing density, porosity and degree of interlocking. However, the outcome suggest that the TC is only reliable as a pre-predictive tool and unable to provide precise results (Ersoy and Waller, 1995; Azzoni et al., 1996). Gottschalk et al. (2000) observed a higher compressive strength parallel to macroscopic visible lineation. However, Brosch et al. (1988) found the maximum uniaxial compressive strength perpendicular to the foliation plane, thus perpendicular to lineation.

Layering defined by quartz and albite, epidote and chlorite also controls the geomechanical behaviour of rocks.

In addition, the layered rocks under compression impart variable deformation behaviour and geomechanical properties along orientation of structural elements with respect to stress axis. However, the rocks devoid of structural anisotropy (layered structure) also exhibit variation in geomechanical response in different directions. Some times this may create serious problems in predicted stability condition and savecability of construction based geomechanical properties of rocks as input during planning and design of engineering structures without considering the directional effects due to rocks devoid of visible structural anisotropy. Thus, the scientists and technologists have experienced that rocks showing lack of foliation and structural anisotropy are difficult in predicting the deformation pattern and geomechanical response useful for planning and design of engineering structures. Hence, the Anisotropy of Magnetic Susceptibility (AMS) may be useful for investigation of deformation pattern as well as geomechanical response for rocks showing lack of structural and depositional markers. Traditionally, the researchers are using AMS to establish the strain history of geological formations. In geomechanical aspect, Borradaile (1988) found that at room temperature, the principle direction of magnetic susceptibility of dry, synthetic, magnetic bearing sandstone rotates towards principle stress direction. Borradaile (1991) also experimentally fiund out correlation between strain and low field magnetic susceptibility (AMS) using single parameter "P′". The work of Borradaile (1991) revealed that the carbonates rocks generally show lot of geomechanical difficulties during development of geological engineering structures.

The carbonate is a non-clastic sedimentary rock formed by chemical and biochemical processes (Pettijohn, 1984). The carbonate often shows devoid of structural anisotropy due to its formation by chemical precipitation. Thus, the development of geological engineering structures involving carbonate rock types requires special attentions due to indistinct anisotropic behavior may provide unreliable geomechanical input which are unable to support the predicted serviceability and stability of engineering structures. Hence, the carbonate rocks of Middle Proterozic age located in Central India are considered for the investigations.

In view of constrains of variable deformational response and geomechanical properties in massive rocks the present study attempts to analyze the effect of indistinct and invisible fabrics on deformation and geomechanical response of rocks by introducing the concept of Anisotropy Magnetic Susceptibility (AMS). For the purpose, oriented specimens of carbonate rocks of Bijawar Group were collected from Taura, Hirapur, Bijawar area, Madhya Pradesh, India.

The Middle Proterozoinc formations deposited over Bundelkhand massif along its southeastern extremities are known as 'Bijawar Group (Kumar, 1988) The rock piles of Bijawar Group consisting of a succession of basal conglomerate and quartzite overlain by hornstone breccia, dolomitic limestone, phyllitic shales, red juspers and dioritic traps (Kumar, 1988). Lithological, association, mineralogical constituents and textural attributes of carbonate reveals that the carbonate has been formed in shallow shelf sea (Kumar, 1988).

Local litho-stratigraphy

At upper Narmada valley, the local Stratigraphy encountered during the traversing are found to be Vindhyan quartzite, Intrusive dykes, Pisolitic iron, Iron bearing shale, Dolomitic limestone, Chert and basement comprising Bundelkhand Granite Gneiss.

There is a wide composional variation found in granites, which vary from coarse gained to fine grained. Carbonates basically vary from silica bearing to calcite bearing and show distinct sets of joints. Cherts are occasionally present in the contact regions. Iron bearing shale is present widely in the area that shows presence of various sizes of gavels. Pisolitic iron generally covers hill area and are totally weathered.

Material and Methods

a) Anisotropy of magnetic susceptibility (AMS) analysis

Magnetic susceptibility is a property of solids to be magnetized under a given magnetic field. In anisotropic materials, the magnetic susceptibility (K) can be described as a second rank tensor that relates the applied magnetic field (H) to an induced magnetization (M) in a sample. The shape of the susceptibility ellipsoid is defined by three principle axes ($K_{max} = K_{int} = K_{min}$) whose orientations correspond to the Eigen vectors of the susceptibility tensors. AMS ellipsoids may be analyzed similarly to traditional fabrics or shape characteristics. For example, K_{max}/K_{int} (magnetic lineation) vs. K_{int}/K_{min} (magnetic foliation) may be plotted on Flinn-type plots to assess the shape and degree of fabric development. Another presentation for AMS measurements is the Jelýnek plot (Jelýnek, 1981; Hrouda, 1982) where Pj, the degree of anisotropy or strain is plotted directly on the X-axis with increasing fabric intensity to the right. The shape parameter (Tj) is plotted on the Y-axis with oblate fabrics having Tj values greater than zero (to a maximum of 1) and prolate fabrics less than zero (to a minimum of 1). The principal axes of the ellipsoid may also by displayed on stereonet projections to investigate geometric relationships.

Measurement of magnetic susceptibility and its anisotropy was carried out using the KLY-4S Spinner Kappabridge manufactured by AGICO (Czech Republic) (Fig. 2) at the Magnetic laboratory of the Department of Geology and Geophysics, Indian Institute of Technology, Kharagpur, India. Oriented

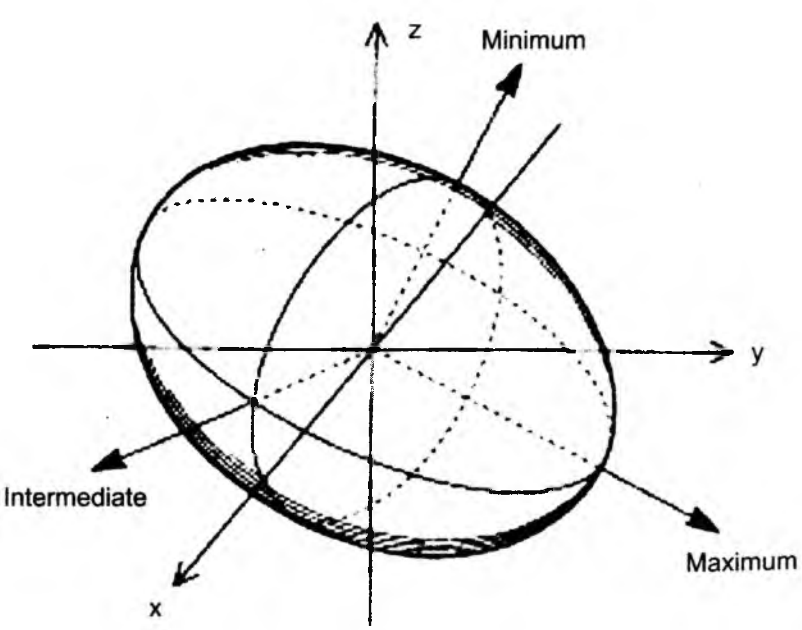

Fig. 1: The susceptibility ellipsoid (Borradaile, 1991)

cylindrical cores having 25.4 mm diameter and 22 mm height were used for measurements in the spinner mode. Measurements were made in the low magnetic field ($\pm 4\times10^{-4}$T and 920 Hz). The mean susceptibility (Km) for each core and the magnitude and orientation of the three principal axes of the magnetic susceptibility ellipsoid, were obtained along with other magnetic anisotropy parameters like anisotropy ratios, viz. magnetic foliation (F), magnetic lineation (L), corrected degree of anisotropy (P_0) and shape parameter (T). F and L are the magnitudes of the magnetic foliation and lineation, respectively.

Fig 2: The KLY-4S Kappabridge Pick up unit

b) Parameters of magnitude of anisotropy

Several parameters are present for magnetic property and petrofabric study, some of the common are :

The mean susceptibility of a single specimen is equivalent to the mean value of the integral of the directional susceptibility over the whole specimen and is given by

$$K_{mean} = (K1+K2+K3)/3$$

Where K=1 K2 =K3 are the principle susceptibility in SI units. In the studies, the magnitude of the Anisotropy is correlated with strain and the average susceptibility of an individual specimen is usually represented by the geometric mean

$$K_{geom} = (K1.K2.K3)^{1/3}$$

K_{geom} is a useful parameter as the geometric mean of the principle strain has direct physical meaning in terms of strain ellipsoid.

Magnitude of anisotropy is the ratio of the maximum and minimum susceptibility known as anisotropy degree.

Degree of Anisotropy P=K1/K2

Shape of anisotropy ellipsoid-the eccentricity of an ellipsoid can be expressed in several ways mainly in terms of the ratios or difference between the axial values. Most parameters were based on ratios like :

Lineation $L = K1\text{-}K2/K_{mean}$

Foliation $F = K1\text{-}K3/K_{mean}$

Shape parameter (T)-Shape parameter is given by

$$T = (2\ln (k2/K3)/\ln (k1/K3))-1$$

T includes all three principle susceptibilities in its calculation and is symmetrical in its distribution of values over the full range of ellipsoidal shapes.

Oblate shape: $0<T=1$

Prolate shape: $1=T<0$

Geomechanical Properties

The geomechanical properties were determined on cylindrical samples keeping length to diameter ratio as 2. The prepared samples were deformed under incremental stress condition on servo-controlled Material Testing System (MTS). The deformation and strain developed during compression were analysed by the conversion of displacement and load in stress strain. The compressive strength and modulus of elasticity were determined from the stress-strain curve.

Results and Discussion

The results of investigation exhibit that the value of AMS enhances in the carbonate samples (dolomitic limestone) collected form northeast to southwest direction in area around Taura, Hiarapur, Madhya Pradesh (T1-T5). The mean value of AMS ranges form 62.34

x 10^{-6} SI to 80.86 x 10^{-6} SI. Moreover, the majority of samples impart mean values of 80.10 to 80.90 x 10^{-6} SI (Table 1) indicate that the magnetization during compaction phase of precipitated carbonates was almost constant in magnitude and direction with minor deviation in southwestern part of the area.

Table 1: Variation of geomechanical properties with mean AMS values for carbonate of Bijawar Group, Taura, Hiarapur, M.P.

Sl. No.	Sample Code	Anisotropy of magnetic Susceptibility Km (10^{-6})	Average compressive strength (MPa)	Modulus of elasticity (GPa)
1	T1	62.34	28.12	0.92
2	T2	70.28	29.10	1.123
3	T3	80.12	34.12	1.213
4	T4	80.62	36.18	1.516
5	T5	80.86	41.12	1.687

The values of average uniaxial compressive strength of samples collected form northeast to northwest direction in the area ranges from 28.12 MPa to 41.12 MPa. The samples of northeastern part of the area exhibit lower compressive strength (28.12 MPa to 29.10 MPa) with minimum differences. However, the samples of southwestern part of the area show progressively higher (34.12 MPa to 41.12 MPa) with maximum differences in values. Similarly, the values of modulus of elasticity of samples of northeastern parts exhibit comparatively lower values (0.92 GPa to 1.123 GPa). Moreover, the southwestern part of the area shows progressive enhancement in values but confined (1.2 GPa to 1.7 GPa).

The plots between average uniaxial compressive strengths and AMS shows convex trend with respect to AMS axis (Fig. 3). Initially, the trend of change shows higher radius of curvature indicating slight variation in strength at lower values of AMS.

However, the curve shows that higher values of AMS exhibit higher compressive strength. The samples with minor increment in values of AMS at higher value levels showed higher

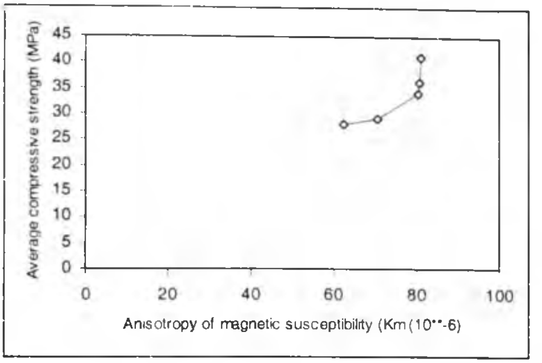

Fig. 3: Variation of average compressive strength with mean anisotropy of magnetic susceptibility in dolomitic limestone of Taura, Hiarapur, Madhya Pradesh

differences in average compressive strength suggesting pronounce control of AMS on compaction of deposited carbonates. Similarly, the plot between modulus of elasticity and AMS shows almost similar trend as observed in case of strength and AMS plot (as in Fig.3). The analysis of plot suggests that the modulus of elasticity (E) shows linear straight line with average slope of 38^0 at the lower AMS values. However, at higher AMS values the curve again shows straight and linear trend but with inclination of approximately 75^0 to 82^0 (Fig. 4).

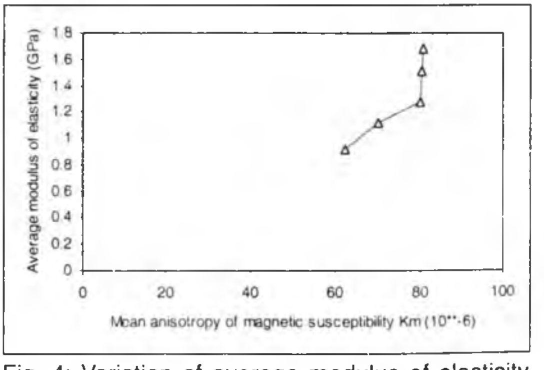

Fig. 4: Variation of average modulus of elasticity with mean anisotropy of magnetic susceptibility in dolomitic limestone of Taura, Hiarapur, Madhya Pradesh

Hence, the experimental results and their analysis reveal that the values of both average uniaxial compressive strength and modulus of elasticity varies with AMS values. The values of both these geomechanical properties increase with increase in values of AMS. This indicates that the components responsible for enhancing cohesion are responsible for strengthening the rocks and controls the deformations and have close relationship with AMS values. Therefore, these studies are useful for delineating the differential geomechanical response and deformational pattern of carbonate strata. The similar investigations will be useful for all types of rocks showing lack of structural anisotropy (foliations, bedding, laminations, etc.). Hence, the techniques of AMS may be used for analyzing geomechanical anisotropy in rocks where no visible structural anisotropy is present.

Conclusion

The present study reveals pronounce control of AMS on geomechanical variations with respect to compression directions in case of carbonate rocks of Bijawar Group. The Similar study involving more components of AMS will be more useful and may become state-of-art in field of geomechanics and engineering geology.

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