ANISOTROPY OF WADI LISB MARBLE

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الخلاصة :

أظهر وجود عدم تماثل الخواص في الصخور تأثيراً على خواصها الهندسية. ويظهر عدم التماثل هذا جَلِيّاً في الصخور المتحولة والصخور الرسوبية وذلك لوجود التورق والتطبق، وكذلك في معظم الصخور المعرضة للتجوية الميكانيكية في المناطق الجافة.

أكّدتْ الدراسات السابقة لعينات من الرخام المستخرج من وادي (لسب) في المراحل الأولى من إنتاجية المقلع أنه يحتوي على شقوق دقيقة موازية لاتجاه التورق، أما هذه الدراسة فقد أُجريت على عينات من الرخام لنفس المقلع مُستخرج من مستويات أعمق ونوعيات أفضل من عينات الدراسات السابقة.

يُعنىٰ هذا البحث – إلى حدٍّ ما – بدراسة تأثير زاوية اتجاه التورق أو الشقوق الدقيقة على الخواص الهندسية للرخام، ونتيجة لذلك – ومن خلال نوع التشوه الذي أعطىٰ الشكل (*U*) – اتضح وجود مجموعة واحدة فقط من الشقوق الدقيقة، إضافة إلى ذلك فإن منحنيات معامل المرونة أعطت نفس الشكل كذلك، كما وُجد أن قيم معامل المرونة تكون قليلة في اتجاه عمودي على اتجاه ميل الشقوق منها في اتجاه موازي لها، أما نسبة (بواسون) فلم تعطِ أي علاقة، كما أنه لم يلاحظ أي تأثير واضح للشقوق الدقيقة على الخواص الديناميكية للرخام.

ومن ذلك فإنّ سلوك رخام وادي (لسب) وتحسُّن خواصه الفيزيائية أثبتت احتوائه على شقوق بسيطة كلما استخرج من مناطق أعمق وتكون نوعيته أفضل وبالتالي يفضل قطع الكتل في اتجاه موازي للشقوق لضعفها ولضمان الحصول على كميات اقتصادية وذات نوعية جيدة.

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ABSTRACT

Anisotropy in rocks substantially affects its engineering properties. Anisotropy is more to be expected in metamorphic and sedimentary rocks due to the presence of foliation or bedding. In addition, mechanical weathering in arid areas also induces anisotropy in most types of rocks. Wadi Lisb marble has been investigated at an earlier stage of its exploitation and was found to contain microfissures parallel to the regional foliation trends. This investigation was performed on deeper levels with better quality marble.

The investigation revealed, to some extent, the effect of foliation or microfissuring orientation angle on the engineering properties of the marble. The obtained U-type deformation indicated the presence of one direction of microfissuring. The modulus of elasticity curves show the U-type form and an overall decrease in values as measured with the gauges mounted along the strike of the discontinuities. The Poisson's ratio, on the other hand, showed a highly scattered relationship. However, the overall values measured with strain gauges mounted along the line of true dip of the discontinuity planes are lower than those measured with gauges mounted along the strike. The variation in the orientation angle showed no effect on the dynamic properties of the Lisb marble.

The U-type behavior of the Lisb marble and the improvement in its physical properties indicate a simple form of discontinuity and consequently an improvement in its quality. As the marble has only one direction of weakness, the orientation of the cut blocks could be selected accordingly.

ANISOTROPY OF WADI LISB MARBLE

1. INTRODUCTION

Rock masses are generally anisotropic due to the presence of discontinuities, which have a great effect on their overall physical and mechanical properties. Intact rock material may also exist and show some degree of anisotropy in its strength and deformability. Intact sedimentary and metamorphic rock materials are more anisotropic than igneous rocks due to the presence of lamination, bedding, cleavage, or foliation. Mechanical weathering under arid conditions may also induce anisotropy in all types of rocks.

The presence of anisotropy in intact marble affects to a great extent the productivity of the quarry. Al Madrakah marble, for example, has been investigated by Tan and Lin [1] and found suitable, and was put into production. The marble productivity was drastically reduced to 15–25% due to microfissuring which forced the quarry to close down. The objective of this research is to study the type of anisotropy in Wadi Lisb intact marble and to examine its effect on the physical properties, strength, and static and dynamic elastic properties. A comparison was made a few years ago to examine the changes in the marble quality with depth of excavation. The findings may lead to some recommendations to improve the marble productivity.

2. WADI LISB MARBLE

Wadi Lisb, Wadi Lusub, and Al Madrakah are three occurrences of marble that are geologically related, in the Arabian Shield of Saudi Arabia. The presence of microfissures in Al Madrakah marble was reported and the effect of their presence on some of the marble physical and dynamic properties was investigated by Sonbul *et al.* [2]. Correlations between the dip angle of microfissures and porosity, sonic pulse velocity, and modulus of elasticity were made. No static tests were performed to investigate the effect of microfissures on the strength and deformation characteristics of the marble. Wadi Lisb marble was facing some problems during the initial stages of its quarrying [3]. Studies performed on this marble by Al-Lahyani [4] and Al-Lahyani *et al.* [5] showed the presence of microfissures within dark bands consisting of recrystallized fine-grained calcite and very fine pyrite, intercalated with white, equigranular, nonfissured calcite bands. The angle between the microfissures and the core axis (designated as orientation angle after Singh *et al.* [6]) was correlated with the physical and chemical properties. However, their findings did not clearly show the U-type anisotropy suggested by Jeager [7] as discussed by Hoek and Brown [8]. This might be due to either the sinusoidal nature of the microfissures within the dark bands or the presence of more than one direction of anisotropy.

Microfissuring in marble was also reported at other locations in Saudi Arabia. Microfissures were reported in the marble of Wadi Turabah by Badiuzaman [9] and Badiuzaman and Shehata [10] and in that in Khawar and Khanugah by El-Mukhtar and Shehata [11]. However, no detailed investigations were performed on these occurrences.

3. STRENGTH ANISOTROPY

The concept of strength anisotropy in rocks, due to the effect of a single plane of weakness, was originally developed by Jeager [7] who suggested the U-type relationship (Figure 1). Further investigations were followed on the strength behavior of shale and slates [12–17]. The behavior of gneiss and schist was investigated [18, 19]. The strength anisotropy of phyllite was also studied [6, 20–22]. Other rock types such as: sandstone [23, 24]; coal [25]; and diatomite [26] were investigated. The investigations of the strength anisotropy of marble are rather limited.

The results of all these studies showed a more or less similar behavior of strength anisotropy. The failure strength is maximum when the angle between discontinuity and core axis (β) is equal to zero or 90 degrees and it is minimum when $\beta = 45 - \varphi/2$ (where φ is the friction angle) or ranging between 20 and 40 degrees. The difference between the maximum and minimum strength varies with different rock types. A rock such as phyllite showed a medium to very high degree of anisotropy while the sandstone indicated low to very low anisotropy. In order to quantify the degree of anisotropy, the term "anisotropy ratio" which is the ratio of the maximum compressive strength obtained at $\beta = 90°$ to the minimum compressive strength was suggested by Singh [6].

4. TESTING PROGRAM

Twenty samples were collected and cored at different angles to the dark bands which were assumed to be oriented in the general direction of the microfissuring (Figure 2). The samples were collected from the same quarry that was previously investigated by Al-Lahyani [4] and Al-Lahyani *et al.* [5] although they were taken from a level at least a few tens of meters below the previously investigated level. The physical properties of the prepared samples were determined according to the methods suggested by the International Society for Rock Mechanics [27]. Both P-wave and S-wave velocities of the samples were measured and the dynamic modulus of elasticity and Poisson's ratio were calculated. The transducers used were 200 kHz and the experimental procedure followed Brown [27]. Two dual element (vertical and horizontal) resistance strain

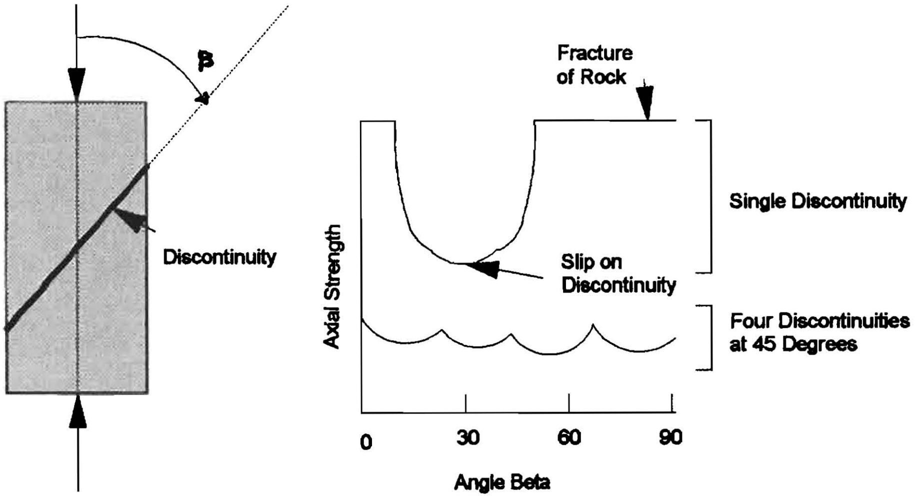

Figure 1. Strength Curves for Samples with Single Discontinuity and Four Discontinuities (Modified after Hoek and Brown, 1980).

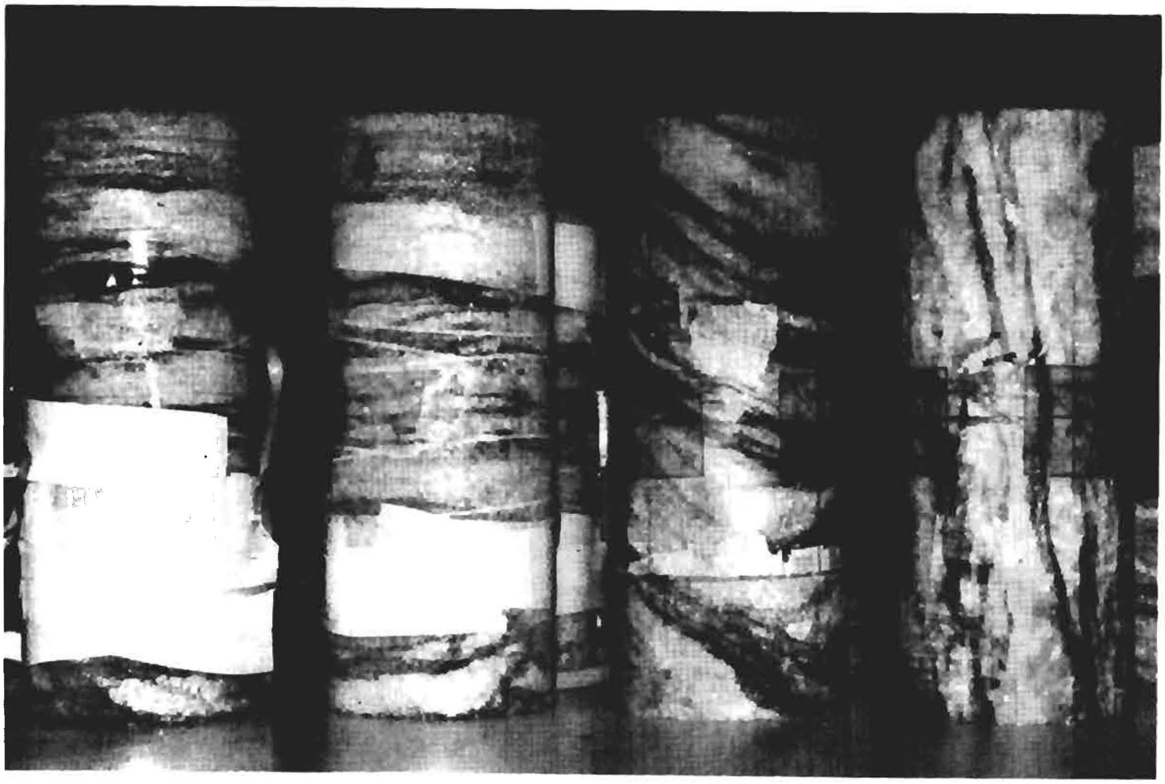

Figure 2. Some Lisb Marble Samples Cored at Different Angles to the Banding. The samples also show the location of the dual element electric resistance strain gauges.

gauges were mounted on each sample; one gauge is mounted along the strike of dark bands and the other is along the line of true dip. The tests were then subjected to axial loading until failure. The mode of failure of the different samples was observed and the compressive strength, modulus of elasticity, and Poisson's ratio were calculated.

5. MODES OF FAILURE

Three different modes of failure were observed during the uniaxial compression testing of the marble core samples. Tension failure along the planes of weakness was observed for samples having low orientation angle ($\beta < 2°$). Shear failure or sliding failure was noticed for samples having an orientation angle between 20° and 40° degrees. Samples with orientation angle ranging between 2° and 20° and those ranging between 87° and 90° show longitudinal or kink failure. Both shear failure and longitudinal failure across the weak planes were obtained for samples having orientation angle ranging between 40° and 86°.

6. PETROGRAPHY

The petrography of Wadi Lisb marble was performed by Al-Lahyani *et al.* [5]. The marble consists of white coarse equigranular calcite crystals forming with darker bands consisting of recrystallized fine grained calcite and a few very fine pyrite crystals. The dark bands represent the traces of the foliation planes in the marble which are parallel to the regional foliation in the area. Microfissuring was seldom noticed in the white equigranular calcite bands. Their presence is restricted to the darker bands as open or filled microfissures spaced at 1–2 mm apart.

7. PHYSICAL PROPERTIES

The dry density of the marble ranges between 2.71 and 2.78 g/cm^3 with an average of 2.74 g/cm^3. The porosity ranges between 0.30% and 0.33% with an average of 0.32% while the absorption ranges between 0.11% and 0.12% with an average of 0.11%.

The obtained physical property values are slightly better than those obtained and reported by Al-Lahyani [4] and Al-Lahyani *et al.* [5] (Table 1). As stated before, the present samples, although from the same quarry, but were taken from a deeper level of better rock quality. The physical properties indicate that the marble is slightly weathered to fresh. The minor variations in their values indicate that the direction of discontinuity has minor influence on the physical properties.

8. STATIC PROPERTIES

The uniaxial compressive strength of the tested samples followed the U-type strength anisotropy (Figure 3). The average maximum uniaxial compressive strength is approximately 120 MPa at $\beta = 0°$ and $\beta = 90°$ while the minimum strength is 70 MPa at $\beta = 35°$. This gives a low anisotropy ratio of 1.7 according to the classification of Singh [6].

The correlation between the static modulus of elasticity and angle β did not give a clear U-type anisotropy specially when the strain is measured along the direction of the true dip (Figure 4). The gauges along the strike of the microfissures show a minimum modulus of elasticity at $\beta = 35°$ (Figure 5). The high dispersion observed in Figures 4 and 5 is possibly due to the variation in the location of the gauges with respect to the microfissures. Gauges mounted completely on the microfissured dark bands will measure larger strain, at the same stress level, than those mounted on, or partly on, the nonfissured white bands (Figure 6).

Table 1. Comparison Between the Physical Property Values Determined in this Study and Al-Lahyani [4].

	Al-Lahyani, [4]		Present Study	
	Range	Average	Range	Average
Dry density (g/cm^3)	2.70 – 2.75	2.72	2.71 – 2.78	2.74
Porosity (%)	0.32 – 0.52	0.47	0.30 – 0.33	0.32
Absorption (%)	0.12 – 0.19	0.16	0.11 – 0.12	0.11

The correlation between the Poisson's ratio and angle β also does not give a U-type anisotropy. However, another type of anisotropy could be observed where the gauges along the dip (Figure 7) produced lower Poisson's ratio values than those along the strike (Figure 8). On the average:

μ (strike) = 1.3 μ (dip), where μ is Poisson's ratio.

Consequently, the induced lateral stresses along the true dip direction is 1.3 larger than those induced along the strike. This can be explained by the elastic slippage along the microfissures.

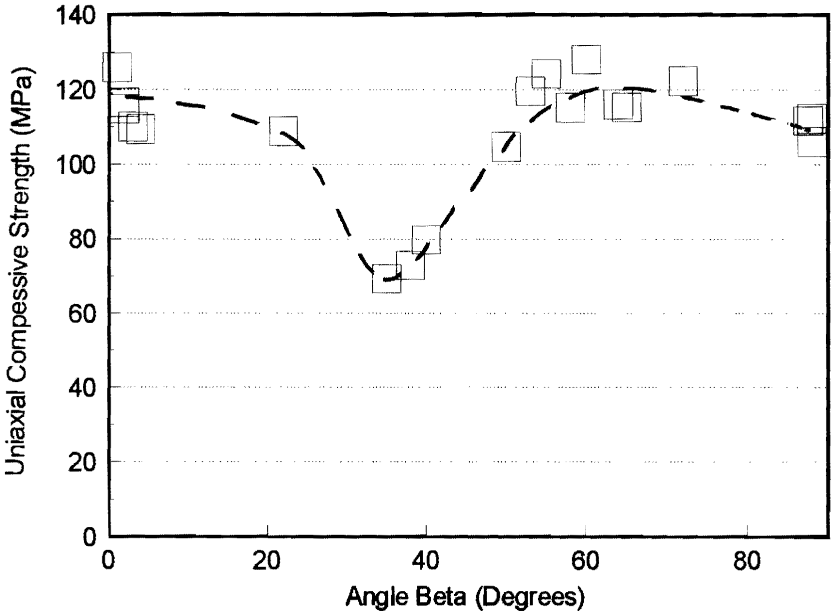

Figure 3. Correlation Between Uniaxial Compressive Strength and Orientation Angle β.

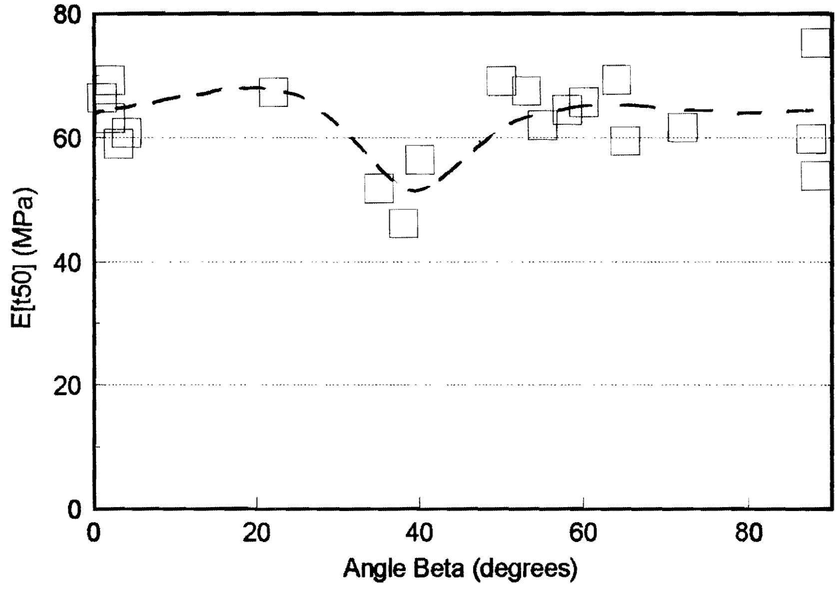

Figure 4. Correlation Between Static Modulus of Elasticity and Orientation Angle β, with Strain Gauges Mounted Along the True Dip of the Discontinuities.

9. DYNAMIC PROPERTIES

The curves of the dynamic modulus of elasticity and Poisson's ratio *versus* the orientation angle (Figures 9 and 10) also show U-type anisotropy, which has no physical meaning. Logically, if the orientation angle is equal to zero, the bands of microfissures will be oriented parallel to the core axis and consequently will record faster P-wave and S-wave velocities than in samples with β = 90°. The relationship between the dynamic modulus of elasticity and the orientation angle shows two clusters; a high modulus of elasticity cluster for orientation angles less than 20°, and a relatively lower one for orientation angles greater than 20° as reported by Al-Lahyani *et al.* [5]. They explained the clustering in terms of sample and microfissure geometry with respect to the P-wave or S-wave passes. More investigations are needed in order to outline the dynamic elastic properties anisotropy as compared to the static properties anisotropy.

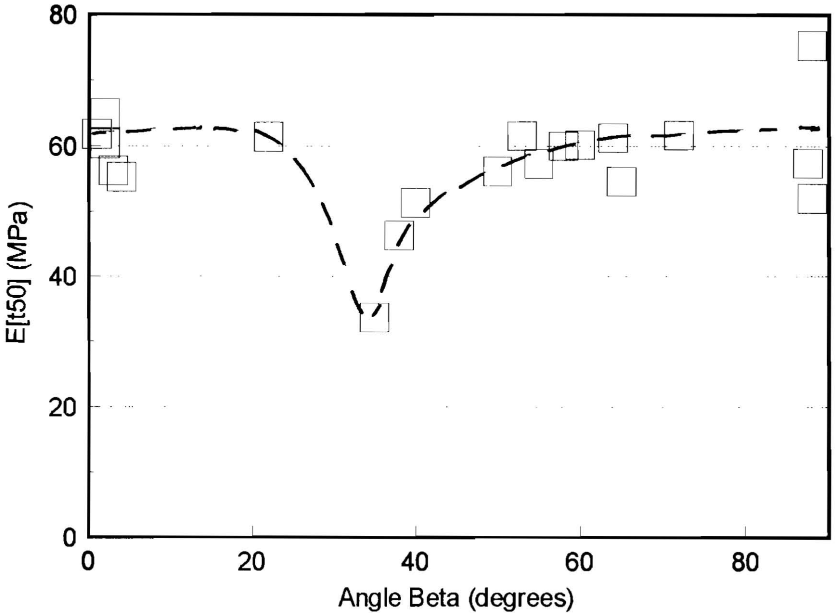

Figure 5. Correlation Between Static Modulus of Elasticity and Orientation Angle β, with Strain Gauges Mounted Along the Strike of the Discontinuities.

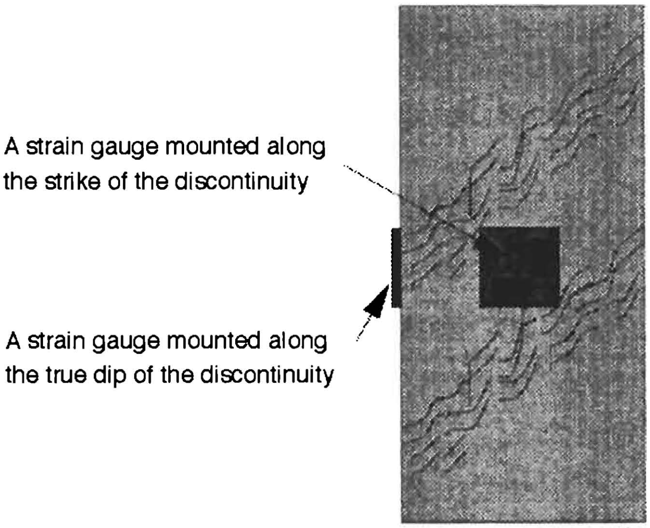

Figure 6. A Sketch of a Core Sample with a "Strike" Strain Gauge Totally Mounted on Nonfissured Marble Band and a "True Dip" Gauge Mounted on a Microfissured Band.

10. CONCLUSIONS AND RECOMMENDATIONS

The tested Wadi Lisb marble samples show anisotropy due to the presence of microfissures. However, the U-type behavior of the static properties indicate a simple type of anisotropy formed by a single set of microfissures. This was not concluded in the previous investigations performed at a shallow level of excavation. This finding combined with the improvement in the physical properties of the Lisb marble at deeper levels suggest an improvement in the rock quality.

The one set of microfissuring that exists at the deeper levels could help in orienting the cutting of the marble blocks with their longest axes parallel to the microfissuring weak plane. This orientation of the cut blocks will allow cutting larger slab sizes and prevent failure along cross fractures.

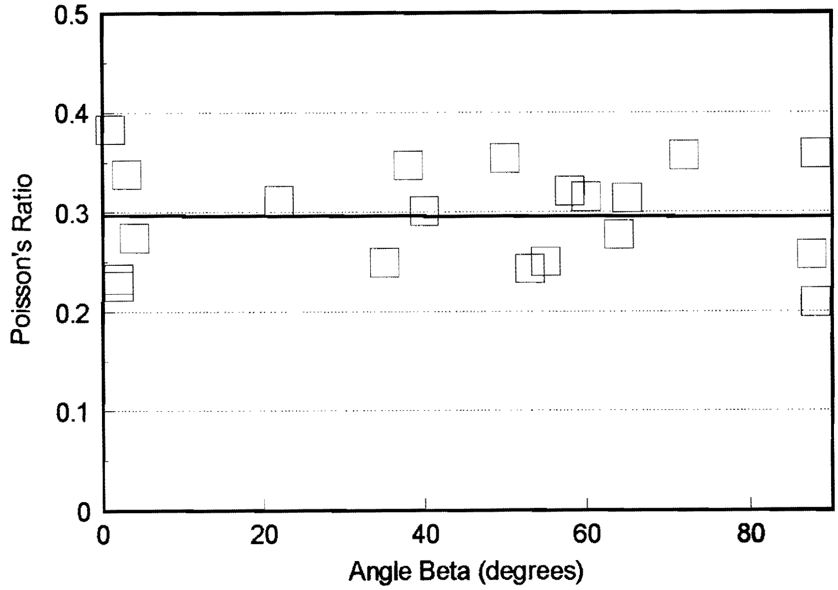

Figure 7. Correlation Between Static Poisson's Ratio and Orientation Angle β, with Strain Gauges Mounted Along the True Dip of the Discontinuities.

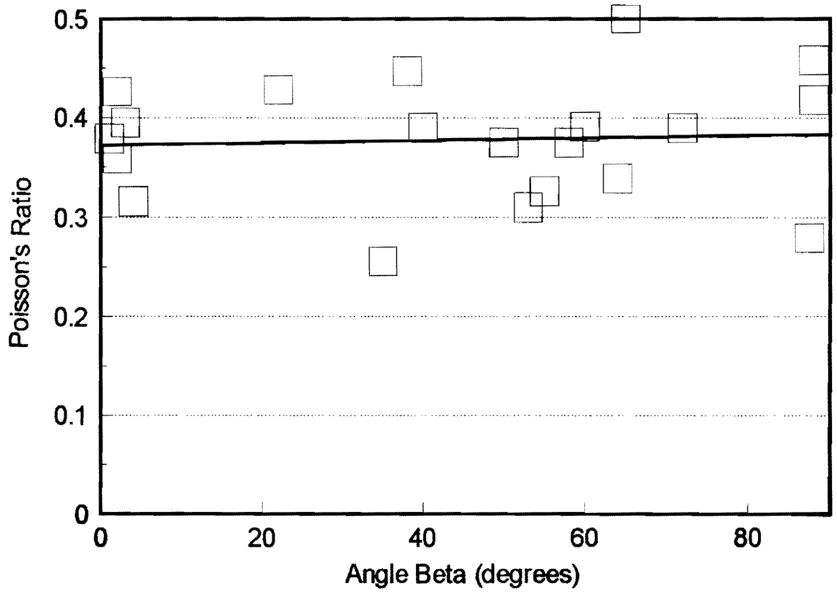

Figure 8. Correlation Between Static Poisson's Ratio and Orientation Angle β, with Strain Gauges Mounted Along the Strike of the Discontinuities.

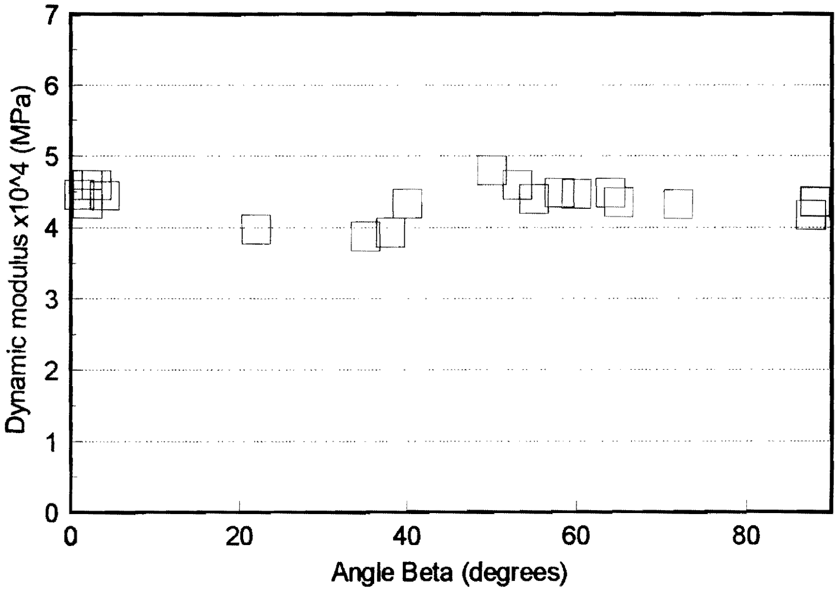

Figure 9. Correlation Between Dynamic Modulus of Elasticity and Orientation Angle β.

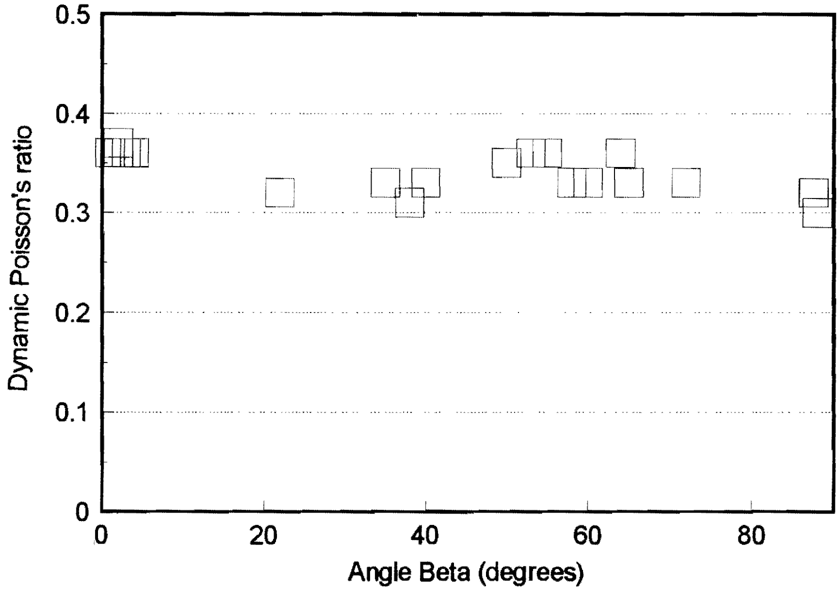

Figure 10. Correlation Between Dynamic Poisson's Ratio and Orientation Angle β.

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