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ANISOTROPY EFFECTS ON THE ELASTIC PARAMETERS OF ROCKS; DETERMINATION USING ULTRASONIC TECHNIQUES

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ABSTRACT

In the present investigation anisotropy of rocks is determined using ultrasonic techniques, in relation to the deformation parameters. For this purpose, P and S wave velocities (V_p, V_s) were measured along the main axis of cylindric specimens of dolerite (Vandée), rhyolite (Vandée, France) and marble (Carrara, Italy) oriented along the three axes of rock-fabric, by turning the specimens every 20 Gra (grades) Furthermore radial measurements of P-wave velocities ($V_{p(rad)}$) were made in every 20 Gra around the cylindric surface of the specimens, at every 1 cm of length. Anisotropy was expressed by means of V_p/V_s and $V_p/V_{p(rad)}$ ratios, confirming that the two above non destructive methods can be used for anisotropy determination.

INTRODUCTION

Stones do not behave mechanically in the same way along different directions. Orientation of minerals in rocks cause anisotropic phenomena, referred to the physical and mechanical properties. Deformation is one of the more important properties related to the rock fabric. This property is expressed by Elastic moduli, such as Young's modulus and Poisson's ratio, obtained either statically using loading techniques, or dynamically using ultrasonic and resonance frequency techniques. Weathering is also related to the rock fabric, causing different phenomena in different directions.

Anisotropy measurements are given in terms of a system of anisotropic axes. Most often, these axes cannot coincide with the system of the so-called global reference axes, corresponding usually to the microfabric orientation.

The easier non-destructive method for determining anisotropy in a rock is using P and S wave ultrasonic velocity techniques, with dynamic elastic moduli determination along x,y,z directions in the space.

This paper is a preliminary approach for determining anisotropic deformation and weathering results obtained in rocks.

DETERMINATION OF THE ELASTIC MODULI OF ROCKS

Elastic moduli, used to express the deformation ability of rocks, may be obtained by dynamic methods in addition to static compression or shear tests. Dynamic elastic moduli are obtained by rapid application of stress to the sample.

Two different dynamic methods can be proposed for this purpose. The first is referred to the P & S wave ultrasonic velocity measurements, along core specimens, while the second is referred to the excitation and detection of mechanical resonance frequencies in small cylindric rods and prismatic bars.

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The static method is referred to a direct compressional technique. For this purpose, small deformation gauges, attached both horizontally and vertically to the specimen axe, provided deformation data.

Test results compared statistically each other, determine regressions for an accurate expression of the static elastic moduli using dynamic, non-destructive techniques.

The use of the above dynamic methods, instead of the direct static ones, is related obviously to the simplicity of these methods and the preservation of the specimens.

Static Elastic Moduli of rocks

Deformation data may be obtained from compression tests and used to calculate the static elastic moduli of intact rock. The modulus of elasticity (E), or Young's modulus and the Poisson's ratio (n) are the most common used. The modulus of elasticity, which is a form of Hooke's law, is derived from applied axial compressive stresses and resulting axial strains. Poisson's ratio is calculated from axial and diametral strains resulting from applied axial compressive stresses.

The above parameters are useful in estimating elastic response of intact rock to compression from *in situ,* construction and post-construction stresses. Abutment stresses in a dam or those exerted against the rock by water-pressure tunnel are examples of post-construction stresses. The values for E-modulus may be obtained from stress-strain diagrams. Between the average modulus, tangent modulus and secant modulus, referred in the literature, the last one is the more common used, predicting the maximum elastic deformation that would occur at the 50 % of ultimate strength (Johnson & De Graff, 1988).

Dynamic elastic moduli

Ultrasonic velocity tests (PUNDIT): Modulus of elasticity (E_d), and Poisson's ratio (n_d) may be obtained by dynamic methods. One common dynamic method for elastic moduli determination is to subject the rock sample to compression and shear wave pulses. Compression and shear wave transducers are attached to the ends of the core specimen, for this purpose. Wave velocity is calculated from the travel time of the pulse through the specimen. Samples may be loaded to approximately field conditions because both P & S wave responses increase with compression. Typically the dynamic modulus of elasticity is greater than the static one, because the response of the specimen to very short duration strain and low stress level is essentially purely elastic (Clark, 1966).

Ultrasonic velocity is not only related to the elastic moduli but it is a very good index for rock quality classification and weathering determination (Christaras, 1991).

Mechanical resonance frequencies (GRINDO-SONIC): The procedure consists of exciting a specimen by means of a light external mechanical impulse and of the analysis of the transient natural vibration during the subsequent free relaxation. This excitation is given in such a way as to favour the desired vibration mode. A pinpoint transducer is used to pick up the mechanical vibration (Mosse, 1990). Tests are carried out on thin cylindric rods or prismatic bars..

Specimens can easily be excited into flexural or torsional modes in order to obtain the E-modulus and the Poisson's ratio (Spinner & Tefft, 1961, Glandus, 1981). To excite a response, a light and elastic tap is given, in the centre or on the side of the specimen, depending on our decision to obtain a longitudinal, flexural or torsional vibration. To detect the resulting vibration and to convert it into electrical signals, a hand-held piezo-electric vibration

Table I: Regressions between the methods used. Correlation Coefficients (r) and Standard Deviations (SD) are also given (Christaras et al. 1994)

X / Y	Regression	r	SD of Y
PUNDIT dynamic / Static Elasticity Modulus	$E_{st}-3.16+1.05E_d$	0.994	38.02
GRINDO-SONIC dynamic / Static Elasticity Modulus	$E_{st}=-3.12+1.05E_{dg}$	0.997	38.02
PUNDIT dynamic / Static Poisson's Ratio	$n_{st}+0.063+0.71n_d$	0.737	0.057
GRINDO-SONIC dynamic / Static Poisson's Ratio	$n_{st}=0.029+0.85n_{dg}$	0.962	0.057
PUNDIT / GRINDO-SONIC P-wave velocities	$V_{pg}=-270.85+1.05V_p$	0.988	1334
PUNDIT / GRINDO-SONIC S-wave velocities	$V_{sg}=45.72+1.01V_s$	0.982	801.9
GRINDO-SONIC / PUNDIT Elasticity Modulus	$E_d=0.83+0.98E_{dg}$	0.992	35.79
PUNDIT P-wave / Static Elasticity Modulus	$E_{st}=3.02e^{0.00055Vp}$	0.970	38.02

detector is used, in contact with the test sample.

For E-modulus (E_{dg}) and Poisson's ratio (n_{dg}) determination, flexural and torsional vibration frequencies are measured. Torsional measurements are made in two directions and a mean value is used for the calculation of the elastic moduli.

Velocity values (V_{pg}, V_{sg}), are calculated from the above elastic moduli.

Experimental results: Eight different rock types from Central and Western France were studied regarding their elasticity moduli, determined both by static and dynamic methods.

Two dynamic methods were used for this investigation. The first is referred to the P & S wave ultrasonic velocity determination while the second is referred to mechanical resonance frequency detection. Both of them provided data comparable to those that had been obtained by the static method.

According to our statistical interpretation the two methods provided results that were significantely comparable between them as well as with those obtained by the static method. A consistent difference noted between the static and dynamic values underlines our observation.

ANISOTROPY OF ROCKS AND ULTRASONIC TECHNIQUES

Ultrasonic velocity measured along different directions can provide data concerning the anisotropic physico-mechanical behaviour of rocks. Data obtained, using a provisional system of x,y,z axes, can determine the global reference ellipsoid of anisotropy in the space.

In our investigation the dolerite of Bouzantese (Bou, Massif Central, France), the rhyolite (roches bleues) of Mareuil (Rb, Vandée, France) and the marble of Carrara (Ca, Italy) were studied in order to determine their anisotropy using ultrasonic techniques Tables 2, 3, 4). For this purpose, P and S wave velocities (V_p, V_s) were measured along the main axis of cylindric specimens oriented along the three perpendicular principal axes of rock-fabric. The

Table 2: Mean values of the radial P & S waves velocities and dynamic elastic moduli, around the specimens from Bouzantese (Bou). Axes X, Y, Z

Angle ;	Axis: X, Axial-Vp: 4747				Axis: Y, Axial-Vp: 4978				Axis: Z, Axial-Vp:4919			
in Gra.;	P-wave ;	S-wave ;	Ed ;	vd ;	P-wave ;	S-wave ;	Ed ;	vd ;	P-wave ;	S-wave ;	Ed ;	vd ;
0	4943	2898	55,16	0,203	4832	2965	58,8	0,225	4652	2874	55,76	0,241
20	4937	2936	56,02	0,19	4764	2948	58,37	0,23	4674	2882	55,97	0,239
40	4914	2953	56,39	0,184	4734	2935	58,03	0,233	4725	2890	56,18	0,236
60	4928	2954	56,41	0,184	4690	2918	57,58	0,236	4767	2902	56,49	0,233
80	4944	2954	56,41	0,184	4649	2874	56,37	0,25	4817	2906	56,6	0,232
100	4962	2950	56,33	0,185	4672	2850	55,72	0,256	4848	2927	57,14	0,226
120	4959	2903	55,28	0,201	4691	2858	55,93	0,254	4844	2919	56,93	0,228
140	4958	2903	55,28	0,201	4731	2874	56,37	0,25	4801	2919	56,7	0,231
160	4950	2882	54,79	0,208	4820	2906	57,26	0,241	4724	2902	56,49	0,233
180	4935	2892	55,02	0,205	4847	2927	57,81	0,236	4682	2890	56,18	0,236

Table 3: Mean values of the radial P & S waves velocities and dynamic elastic moduli around the specimens from Carrara (Ca). Axes X, Y, Z

Angle ;	Axis: X, Axial-Vp: 4271				Axis: Y, Axial-Vp: 4738				Axis: Z, Axial-Vp:4919			
in Gra.;	P-wave ;	S-wave ;	Ed ;	vd ;	P-wave ;	S-wave ;	Ed ;	vd ;	P-wave ;	S-wave ;	Ed ;	vd ;
0	4747	2746	46,39	0,148	4356	2698	49,16	0,26	4450	2733	47,2	0,175
20	4785	2750	46,45	0,146	4368	2734	50,05	0,251	4510	2748	47,48	0,169
40	4755	2724	46,02	0,157	4387	2735	50,12	0,25	4585	2759	47,68	0,164
60	4666	2707	45,73	0,164	4432	2737	50,17	0,25	4678	2769	47,86	0,16
80	4533	2677	45,19	0,176	4485	2747	50,38	0,247	4772	2777	48	0,157
100	4429	2651	44,7	0,187	4522	2754	50,61	0,245	4815	2771	47,89	0,159
120	4371	2634	44,37	0,193	4529	2748	50,46	0,247	4739	2761	47,72	0,163
140	4388	2652	44,72	0,186	4477	2738	50,2	0,249	4657	2748	47,48	0,169
160	4472	2678	45,21	0,176	4428	2723	49,81	0,253	4554	2741	47,35	0,172
180	4613	2719	45,94	0,159	4380	2719	49,71	0,254	4466	2736	47,26	0,173

Table 4: Mean values of the radial P & S waves velocities and dynamic elastic moduli around the specimens from Vandée (Rb). Axes X,Y,Z

Angle ;	Axis: X, Axial-Vp: 6051				Axis: Y, Axial-Vp: 5802				Axis: Z, Axial-Vp:4353			
in Gra.;	P-wave ;	S-wave ;	Ed ;	vd ;	P-wave ;	S-wave ;	Ed ;	vd ;	P-wave ;	S-wave ;	Ed ;	vd ;
0	5754	3379	75,9	0,273	5189	3310	71,99	0,259	5975	3304	64,83	0,142
20	5619	3365	75,43	0,276	5305	3331	72,64	0,254	5944	3291	64,59	0,147
40	5266	3358	75,19	0,277	5508	3344	73,04	0,251	5893	3285	64,47	0,149
60	4942	3351	74,96	0,279	5727	3351	73,25	0,25	5843	3285	64,47	0,149
80	4795	3337	74,49	0,281	5881	3365	73,68	0,247	5814	3277	64,32	0,152
100	4744	3331	74,29	0,283	6000	3371	73,86	0,245	5843	3271	64,21	0,154
120	4945	3337	74,49	0,281	5851	3358	73,47	0,248	5823	3271	64,21	0,154
140	5286	3344	74,72	0,28	5602	3344	73,04	0,251	5903	3277	64,32	0,152
160	5593	3365	75,43	0,276	5378	3324	72,45	0,255	5893	3277	64,32	0,152
180	5742	3372	75,66	0,275	5230	3317	72,2	0,257	5903	3297	64,7	0,145

cylindric specimens were placed between the 300 KHz P & orthogonal S1, S2 wave transducers of the PUNDIT velocimeter. Measurements, for both P & S waves, were taken, in every 20 Gra, rotating the specimens around their main axis. Furthermore measurements of radial P wave velocities ($V_{p(rad)}$) were made in every 20 Gra (grades), around the cylindric surface of the specimens, at every 1 cm of length. The specimens were of dia. 5 cm x 10 cm length. The tests were performed in the "Laboratoire de Construction Civile et Maritime, Université de La Rochelle, France".

Test results of the above ultrasonic measurements were given by regression diagrams showing the linear relationship observed between anisotropy and modulus of elasticity (Figures 1-6). The anisotropy was expressed by the ratio of

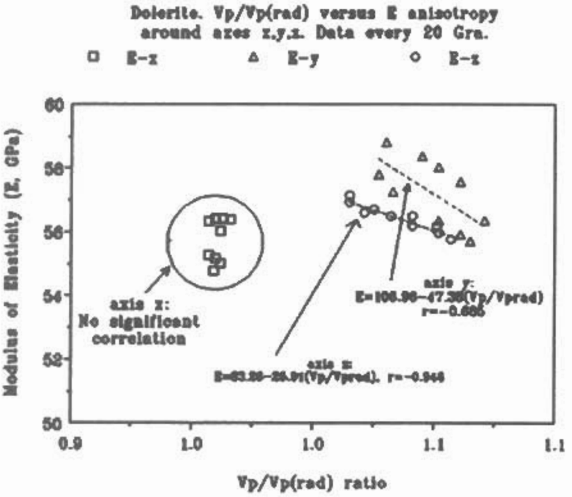

Fig. 1: Dolerite from Bouzantese (France). Correlation diagram between the ratio of the axial and radial P-waves (every 20 Gra) and the modulus of Elasticity. Measurements were performed along the three axes.

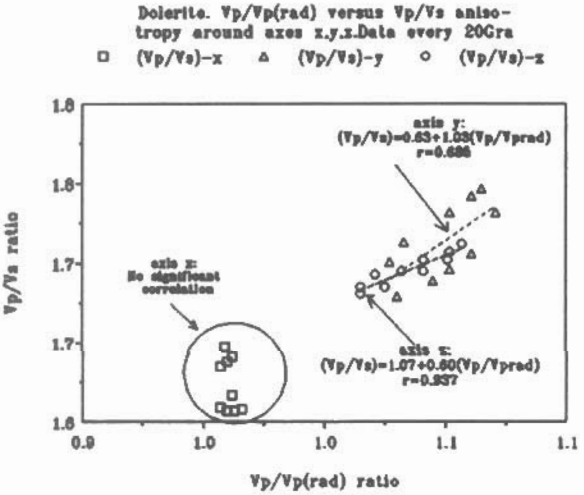

Fig. 2: Dolerite from Bouzantese (France). Correlation diagram between the ratio of the axial and radial P-waves (expression of anisotropy) and the ratio of P & S waves for every 20 Gra (expression of anisotropy). Measurements were performed along the three axes.

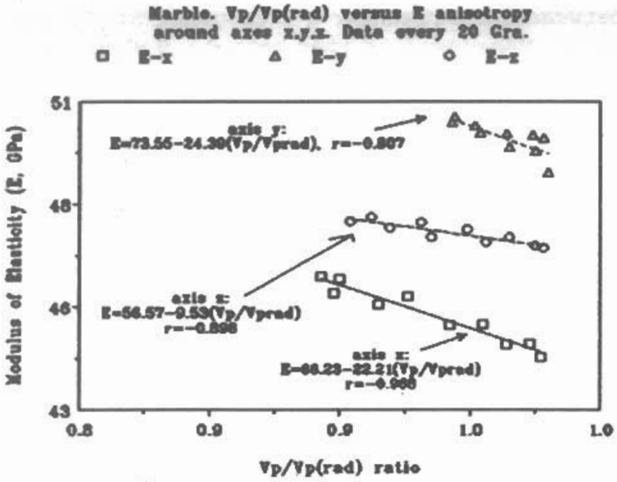

Fig. 3: Marble from Carrara (Italy). Correlation diagram between the ratio of the axial and radial P-waves (every 20 Gra, expression of anisotropy) and the modulus of Elasticity. Measurements were performed along the three axes.

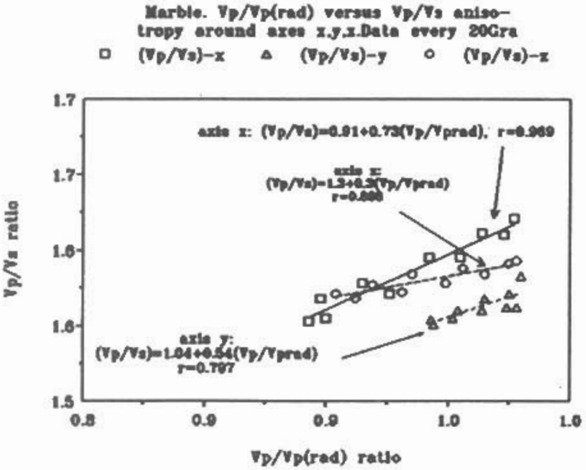

Fig. 4: Marble from Carrara (Italy). Correlation diagram between the ratio of the axial and radial P-waves (expression of anisotropy) and the ratio of P & S waves for every 20 Gra (expression of anisotropy). Measurements were performed along the three axes.

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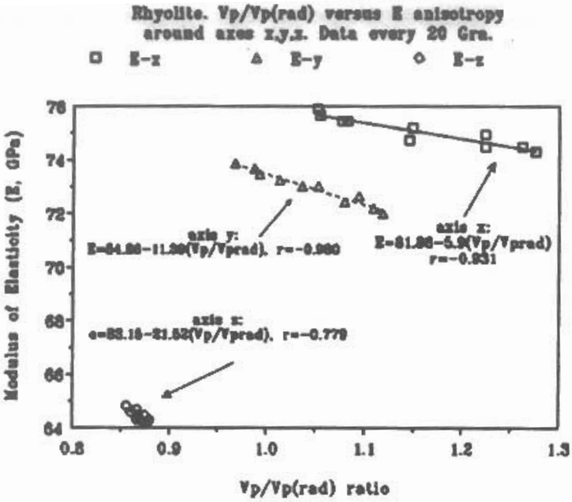

Fig. 5: Rhyolite from Vandée (France). Correlation diagram between the ratio of the axial and radial P-waves (every 20 Gra, expression of anisotropy) and the modulus of Elasticity. Measurements were performed along the three axes.

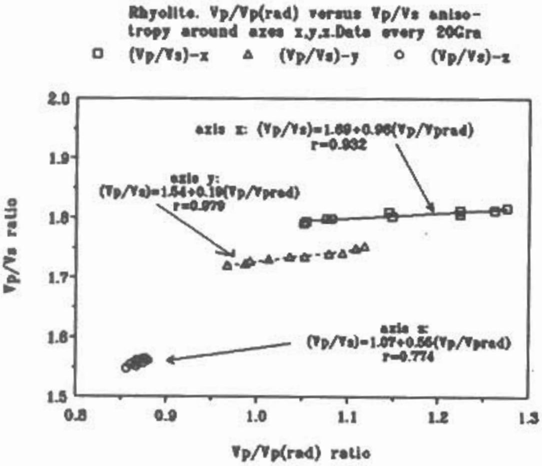

Fig. 6: Rhyolite from Vandée (France)). Correlation diagram between the ratio of the axial and radial P-waves (expression of anisotropy) and the ratio of P & S waves for every 20 Gra (expression of anisotropy). Measurements were performed along the three axes.

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