Sources and Measurement of Velocity Anisotropy of Cambay Shale, Cambay Basin, India

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***Abstract* - Velocity anisotropy is the variation of wave velocity along different directions in a material. Preferential orientation of clay mineral alignment, layering, microcracks, low aspect ratio pores and fracturing all causes velocity anisotropy observed in many sedimentary rocks. Our purpose is to find the variation of wave velocity in a different direction as a function of confining pressure in dry saturated samples Shales are the richest lithology in a sedimentary basin and exhibit a relatively large degree of anisotropy. Ultrasonic measurements are carried out on Cambay shale samples to study its anisotropy. The elastic stiffness constants and Thomsen's parameters are calculated and plotted against the Confining pressure on a suite of two core plugs of the Cambay shale. The variation of velocities on different core plugs of the same suite indicates that the Cambay shale is anisotropic. Rocks mechanical properties like Young's modulus and Poisson's ratio are also play an important role in describing the anisotropy in the rocks. Here we determine these two parameters with the help of P and S wave velocity and plot against confining pressure and Thomson parameters. That shows the variation in magnitude of these two parameters higher in the vertical plane of bedding because of the presence of microcracks, fractures and low aspect ratio pores along the vertical plane cause anisotropy in shales.**

Key words - Shale, Ultrasonic velocity, Velocity Anisotropy, Microcracks, Fractures, Young's modulus, Poisson's ratio

1. INTRODUCTION

Shales mudstones and silts comprise a large proportion of the rocks in most sedimentary basins and also the most important overlying rocks of sedimentary basins bearing hydrocarbon [7]. In reservoir shales, the shale acts as both the source rock and reservoir and there is currently great interest in resource shale plays [14]. Because of their low permeability, for economic production from reservoir shales, well is required stimulated by a large hydraulic fracture treatment, a horizontal wellbore or multilateral wellbores [12]. All sedimentary rocks are anisotropic in nature. Anisotropy is defined as the rock properties changes with the direction in which it are measured. Velocity anisotropy is the variation of wave velocity on the measurement direction in a material [4]. There are two types of anisotropy present in the rocks, intrinsic and induced. The intrinsic anisotropy is caused by the preferential orientation of clay platelets [15], sediment grains, microcracks, fractures and pores. Intrinsic anisotropy in sedimentary rocks is normally in the form of transverse isotropy [13]. The induced anisotropy is developing after the deposition of rocks due to the overburden pressure axis of minerals and sediment changes. And it is also caused by the strain associated with applied stress, microcracks and fractures [16]. Rock mechanical properties like Young's modulus and Poisson's ratio are also playing an important role in describing anisotropic behavior. Young's modulus parallel to bedding always greater than the young's modulus perpendicular to bedding but poisson's ratio may greater equal or lesser [12].

2. WHAT IS ANISOTROPY AND VELOCITY ANISOTROPY

Anisotropy is defined as the variation in the physical properties of a rock fluid system with respect to direction [4]. Anisotropy differs from the rock property called heterogeneity in the sense that anisotropy is the variation in vectorial values with direction at a point while heterogeneity is the variation in scalar or vectorial values between two or more points. Velocity anisotropy is the defined as the variation of rock properties along the direction of wave propagation in a homogenous material or matter [2].

3. SOURCES OF ANISOTROPY, TYPE AND SYMMETRY OF ANISOTROPY MEDIUM

The origin of anisotropy takes place in the rocks during and after deposition. Seismic anisotropy is a range of phenomena that may cause rock materials to display seismic anisotropy. All sedimentary rocks are generally anisotropic [1]. In sedimentary rocks there are many sources of velocity anisotropy, some of them are preferred orientation of clay minerals, Presence of aligned fractures, cracks and pores and Fine layering [15]**.** Anisotropy is defined as the variation of rock properties by the direction in the material. There are two types of anisotropy present in the rocks intrinsic and induced. Intrinsic anisotropy develops during deposition of rocks which results of preferred orientation of minerals [15]. The preferential orientation of clay platelets, low aspect ratio pores, microcracks and fractures [12]. But induced anisotropy in the rocks develops after deposition due to the overburden pressure changes the axis of sediments and grains and fine layering. There are two types of alignment present in earth materials, horizontal and vertical and they give rise to two types of anisotropy [1]. The elastic properties may vary vertically, such as from layer to layer, but not horizontally such a material is called transversely isotropic with a vertical axis of symmetry or vertically transverse isotropy (VIT).The waves generally travel faster horizontally, along layers, than vertically. The horizontal transverse anisotropy corresponds to material with aligned vertical weaknesses due to presence of cracks or fractures, or with unequal horizontal stresses. There is a change in the elastic properties in the direction normal to the fractures, but it does not change along the plane of the fractures [1].Such a material is called transversely isotropic with the horizontal axis of symmetry or horizontal transverse isotropy (HIT) as shown in the figure (1) [16].

4. METHODOLOGY

4.1 Experiments for the Velocity Measurement

The experiments were conducted under the maximum confining pressure up to 600 Mpa and compressional or primary and Shear or secondary wave velocities were measured in rock samples using the ultrasonic pulse transmission technique. Velocity measurements were made at 30 Mpa at starting of Experiment and maximum of 600 Mpa.

4.2 Ultrasonic Pulse Transmission Technique

An ultrasonic pulse transmission technique was used to determine the P- and S-wave velocities in the samples. Elastic constants of geologic materials can be determined by the pulse transmission method. In this method, measurement the travel time of an ultrasonic wave is propagating through a rock sample. Velocities are found from the travel times and elastic constants are then calculated from the velocities. The experiment is performed on the two core plug samples that are belong to the (Sanand-East) one of the field situated in the Ahmedabad-Mehsana sub block of Cambay basin. Sanand-East field lying in the northwest of Ahmedabad is located on the southern part of Mehsana-South Kadi-Jhalora-Sanand high trend in the north Cambay Basin. It is an elongated doubly plunging anticline trending NNW-SSE direction [9]. Shale presents in our study area of Late Paleocene to Early Eocene and distributed in 81.36 km^2 of area [5]. According to wave propagation and polarization directions with respect to bedding-parallel splitting six velocities canbe measured (Fig. 2) for the wave propagation parallel to the axis of symmetry (Normal to bedding), there are a compressional wave (V_{pv}) propagates vertically and two vertically propagating Shear waves (V_{sv1} and V_{sv2}). For a propagation parallel to bedding (Normal to the axis of symmetry), there are a horizontally propagating compressional wave (V_{ph}), a Shear wave (V_{sv}) with horizontal propagation and vertical polarization, and a Shear wave (V_{sh}) with horizontal propagation and polarization direction. At the start, ultrasonic measurements are carried out on dry plugs following the above procedure. The results are shown in the tables below. Table (I) shows velocities of P and S and waves Partitioned into V_{pv} and V_{sv} defined as Pressure and Shear wave for (Vertical core plug), V_{ph} and V_{sh} for (horizontal plug). Table (II) shows the Thompsen parameters derived from P and S wave velocities given in equation (1 and 2). Table (III, IV) displays young's modulus and poisson's ratio and stiffness constant derived from P and S wave velocity equation (7, 8 and 3, 4, 5, 6) gives the relationship.

5. MATHEMATICAL ANALYSIS

5.1 Thomsen's Parameter

Thomsen parameters are plays an important role for the measure of velocity anisotropy. Thompsen parameters are dimensionless combinations of the elastic moduli which characterize materials having transverse isotropy [6]. Thomsen parameters are the terms of the elastic constant, and P and S wave velocities. These parameters are given as,

$$\epsilon = \frac{C_{11} - C_{33}}{2C_{33}} = \frac{V_{ph}^2 - V_{pv}^2}{V_{pv}^2} \quad (1)$$

$$\Upsilon = \frac{C_{66} - C_{44}}{2C_{44}} = \frac{V_{sh}^2 - V_{sv}^2}{V_{sv}^2} \quad (2)$$

Where ϵ and Υ represent measurements of anisotropy of P-wave velocity and S-wave velocity respectively [7].

5.2 Stiffness Study

The stiffnessof a body is a measure of the resistance offered by an elastic body to deformation. Stiffness of rocks, plays an important for the applications [12].Such as hydraulic fracture design, analysis of wellbore stability, completion interval and rock failure determination [14].

$C_{11} = \rho V_{ph}^2$ (3)

$C_{33} = \rho V_{pv}^2$ (4)

$C_{44} = \rho V_{sv}^2$ (5)

$C_{66} = \rho V_{sh}^2$ (6)

[16].

Density (ρ) of shale in Cambay Basin varies 1.8 to2.9 g/cc for we take the average value of density 2.3g/c [11].

Where C_{11} C_{33} C_{44} and C_{66} are elastic stiffness constants which denote elastic properties of transversely isotropic medium

5.3 Poisson's Ratio

It is an elastic constant that measures the compressibility of the material perpendicular to the applied stress, or it can be also defined as the ratio of latitudinal to longitudinal strain [10].Poisson's ratio in terms of velocities of P-waves and S waves as shown below [8].

$$\vartheta = \frac{(V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)} \quad (7)$$

5.4 Young's Modulus

The modulus of elasticity (Young's modulus) is a material property, that describes its strength or stiffness and is therefore one of the most important properties of solid materials.Young's modulus in terms of velocities of P-waves and S waves as shown below [8].

$$E = \frac{\rho V_s^2 \left(3V_p^2 - 4V_s^2\right)}{\left(V_p^2 - V_s^2\right)} (8)$$

Density (ρ) of shale in Cambay Basin varies 1.8 to2.9 g/cc for we take the average value of density 2.3g/c [11].

6. RESULTS AND DISCUSSIONS

6.1 Effects of Confining Pressure on P and S wave Velocities of Experiment Samples

Our experimental study shows that microcracks, low aspect ratio pores and fractures close gradually with increasing Confining pressure, fig. (3, 4) displays the relationship between confining pressure and wave velocity, with an increase in confining pressure, which results in the increase of P-and S-wave velocities for different propagation directions, but the rates of increase are different for the velocities measured in different directions. P and S-wave propagating perpendicular to bedding (vertical plane) has the largest velocity change, and P and S-wave propagating parallel to bedding (horizontal plane) has the least velocity change. These differences are mainly due to the existing of microcracks, low aspect ratio pores and fractures along the bedding which closes more easily under pressure perpendicular to bedding. As a result largest velocity change in vertical plane shows the presence of fractures, microcracks and low aspect ratio pores in the vertical plane of bedding.

6.2 Effect of confining Pressure on Thompsen Parameter and Stiffness Constant of Experiment Samples

The fig. (5), displays the relationship between anisotropy parameter(Thompsen's parameter) Epsilon (Є) and Gamma (ϒ) of samples as a function of Confining pressure. Epsilon (Є) reflects the degree of anisotropy for P-wave and Gamma (ϒ) reflects the degree of anisotropy for S-wave. Both the anisotropy factor decreases with increasing Confining pressure because an increasing Confining pressure microcracks and fractures close progressively, at higher pressure Thompsen's parameter shows no any change because microcracks and fractures are completely closes. And the fig. (6), shows the relationship between P and S wave stiffness constant ($C_{11,}C_{33,}C_{44}$ and C_{66}) and confining pressure. Fig. (6), displays that with increase in confining pressure, stiffness constant increases gradually, which results the progressively closer of microcracks and fractures present in the rocks. Due to which the strength, rigidity and stiffness of rocks increases with increase in confining pressure [3].

6.3 Effects of Confining Pressure and Thompsen parameters on Young's modulus and Poisson's ratio

Our experimental study exhibits the relationship between young's modulus and Poisson's ratio with Confining Pressure. Fig. (7, 8) displays the relationship between confining pressure and (Young's modulus and Poisson's ratio). Fig. (7), displays that the poisons ratio having scattering behavior in horizontal and vertical plane, which shows the heterogeneity present in the rocks. But having higher values in the vertical plane which indicates the presence of microcracks andfractures in the vertical plane. Figure (8) displays that with increase in confining both the young's modulus (horizontal and vertical) increases. The largest change in the Young's modulus is in the vertical direction and least change is in the horizontal direction of bedding. These differences are mainly due to the existing of microcracks and fractures along the bedding. That closes more easily under pressure vertical to bedding. Fig. (9, 10) displays relationship between Thompsen parameter's (Epsilon and Gamma) and Poisson's ratio (horizontal and vertical plane) and displays a scattering behaviour, shows the heterogeneity present in the rock. That is mainly because of the presence of microcracks and fractures. Fig.(11, 12) displays the relationship between Thompsen parameter and young's modulus and which shows the inverse relationship. An increase in Thompsen parameter young's modulus decreases,

7. CONCLUSIONS

Our experimental study indicates that shale exhibit elastic anisotropy in the study area of the Cambay basin (Sanand-East field). Under dry saturated conditions, velocities of shale samples for all propagation directions increase with increasing confining pressure, but anisotropic parameters

Epsilon (Є) and Gamma (ϒ) which denotes P- and S wave anisotropy show a reverse tendency of decrease. We find that the alignment of clay mineral, microcracks and fractures and low aspect ratio pores are the main factors to cause samples exhibiting anisotropy under low confining pressure. Microcracks, low aspect ratio pores and fractures are gradually closed, with an increasing confining pressure, which decreases the anisotropy.

Measurements were made on two cores parallel (Horizontal core), andperpendicular (Vertical core)to bedding plane. Values of anisotropy were up to 16% for Compressional or primary and 23% for Shear or secondary wave velocity, and were found that the anisotropy decreases with increasing confining pressure. Because of increasing Confining pressure, microcracks, low aspect ratio pores and fractures close gradually. At low pressure in the shale formation, the preferred orientation of not completely closed fractures contributes strongly to the velocity anisotropies. In the lower part of the formation, where fractures and microcracks closes because of the higher pressures, the fine layering typical of shales mainly causes the anisotropy. Our experimental study also exhibits the relationship between Poisson's ratio and young's modulus and Anisotropy factor (Thompsen parameter). Poisson's ratio and Thompsen's parameter shows scattering behavior which shows the heterogeity present in the rock.Thompsen's parameter and young's modulus shows the inverse relationship between each other. With increase in Thompsen parameters both young's modulus and poisson's ratio decreases.

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Abbreviations

TI = Transverse Isotropy

HTI = Horizontal Transverse Isotropy

VTI = Vertical Transverse Isotropy

E = Young's Modulus

E_1 = Young's Modulus Parallel (Horizontal) to bedding

E_3= Young's Modulus Perpendicular (Vertical) to bedding

ϑ = Poisson's ratio

ϑ_1 = Poisson's ratio, Parallel (Horizontal) to bedding

ϑ_3 =Poisson's ratio Perpendicular (Vertical) to bedding

Є = P-wave Anisotropy factor

ϒ = S-wave Anisotropy factor

Table I: Experimental Results of Ultrasonic Measurements of Velocities on the two core plugs (dry)

Confining Pressure (Mpa)	Vertical Core Plug		Horizontal Core plug	
	V_{pv} (km/s)	V_{sv} (km/s)	V_{ph} (km/s)	V_{sh} (km/s)
20	5.1	2.51	5.81	2.92
50	5.42	2.72	6.22	3.28
100	5.78	2.82	6.31	3.34
200	6.01	2.91	6.41	3.4
250	6.23	3.12	6.52	3.41
300	6.33	3.14	6.67	3.42
400	6.41	3.26	6.81	3.43
450	6.52	3.29	6.88	3.46
500	6.67	3.31	6.91	3.47
550	6.86	3.32	6.92	3.48
600	6.91	3.33	7	3.5

Table II: Confining Pressure and Thompsen Parameter

Confining Pressure (Mpa)	Є	ϒ
20	0.15	0.18
50	0.16	0.23
100	0.10	0.20
200	0.07	0.18
250	0.05	0.10
300	0.06	0.09
400	0.06	0.05
450	0.06	0.05
500	0.04	0.05
550	0.01	0.05
600	0.01	0.05

Table III: Confining Pressure, Poisson's Ratio and Young's Modulus

Confining Pressure (Mpa)	ϑ_1	ϑ_3	E_1 (Gpa)	E_3 (Gpa)
20	0.33	0.34	52.20	38.84
50	0.31	0.33	64.70	45.32
100	0.31	0.34	66.99	49.16
200	0.30	0.35	69.36	52.47
250	0.31	0.33	70.16	59.67
300	0.32	0.34	71.11	60.63
400	0.33	0.33	71.98	64.80
450	0.33	0.33	73.28	66.18
500	0.33	0.34	73.74	67.36
550	0.33	0.35	74.13	68.30
600	0.33	0.35	75.13	68.80

Table IV: Confining Pressure and Stiffness Constants

Confining Pressure (Mpa)	C_{11} (Gpa)	C_{33} (Gpa)	C_{44} (Gpa)	C_{66} (Gpa)
20	77.64	59.82	14.49	19.61
50	88.98	67.57	17.02	24.74
100	91.58	76.84	18.29	25.66
200	94.50	83.08	19.48	26.59
250	97.77	89.27	22.39	26.74
300	102.32	92.16	22.68	26.90
400	106.67	94.50	24.44	27.06
450	108.87	97.77	24.90	27.53
500	109.82	102.32	25.20	27.69
550	110.14	108.24	25.35	27.85
600	112.70	109.82	25.50	28.18

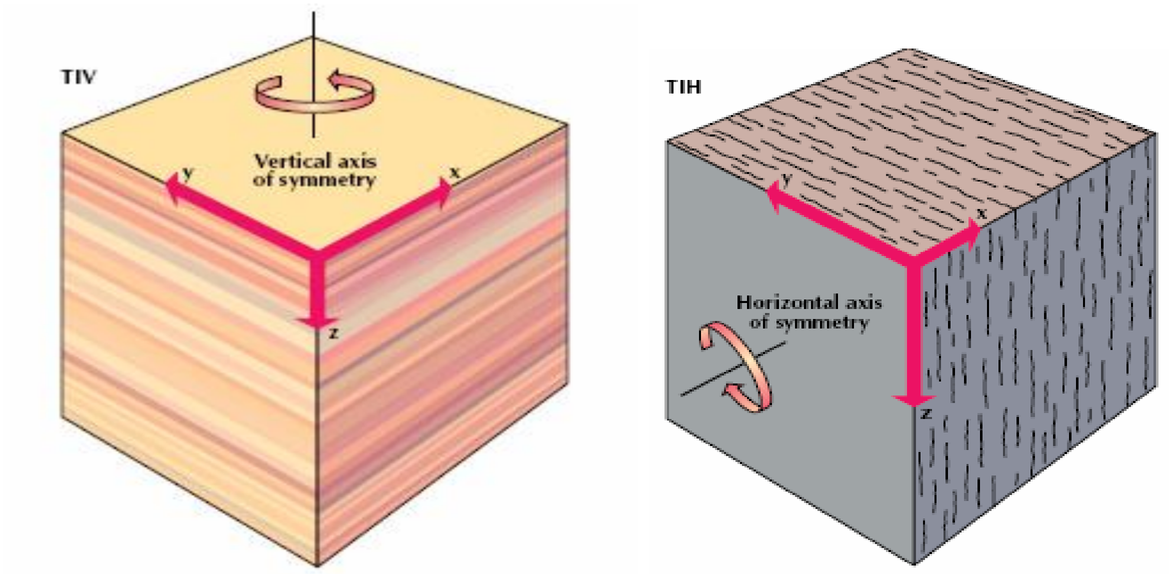


Fig.1: Two types of Anisotropy TIV and TIH [1].

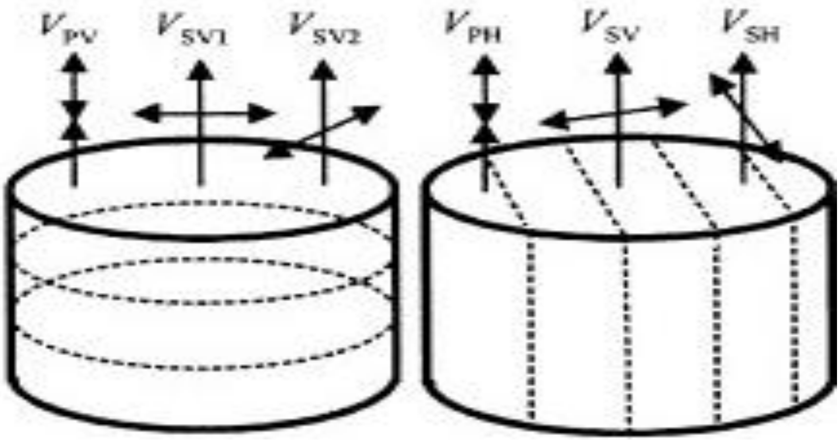
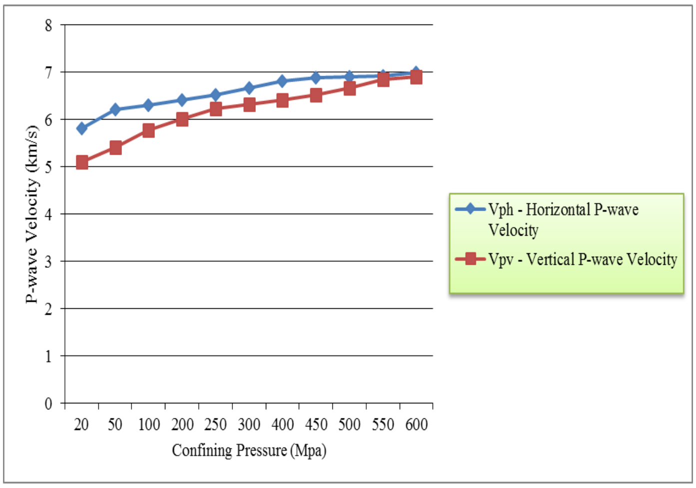


Fig.2: Schematic diagrams of the samples plug and velocities measured in the experiment. Single arrows represent directions of wave propagation; double arrows represent directions of particle motion, and dashed line in the sample represent bedding planes [7].



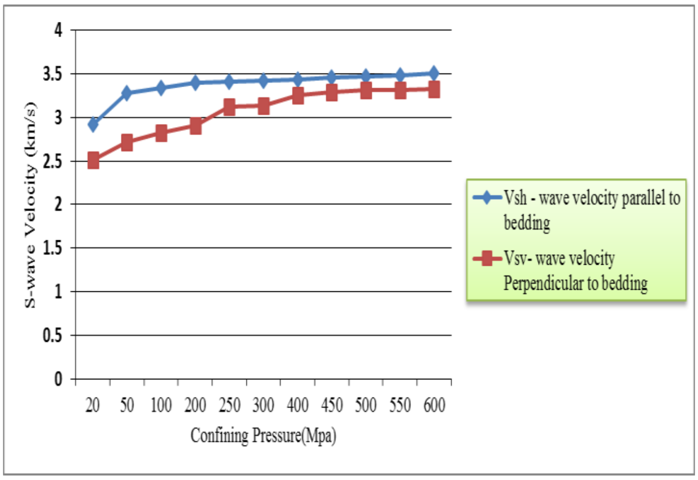
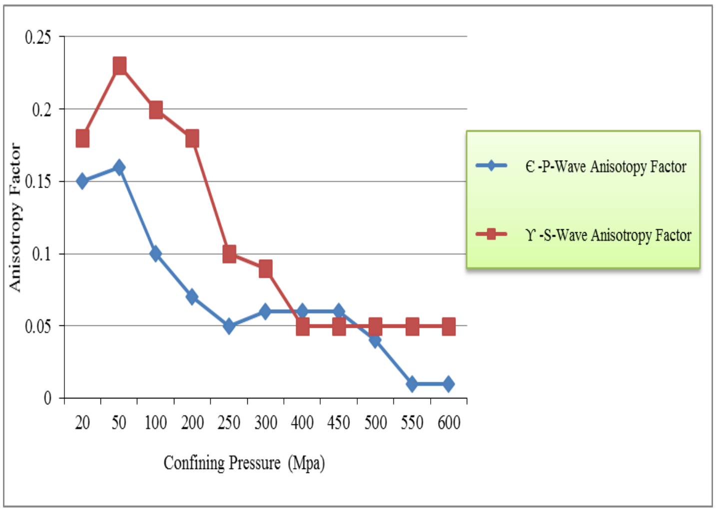


Fig. 3: Confining Pressure Versus P-Wave VelocityFig. 4: Confining Pressure Versus S-Wave Velocity



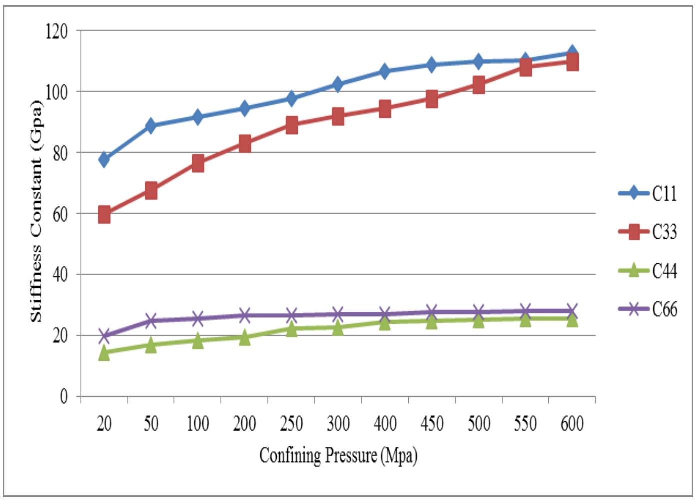
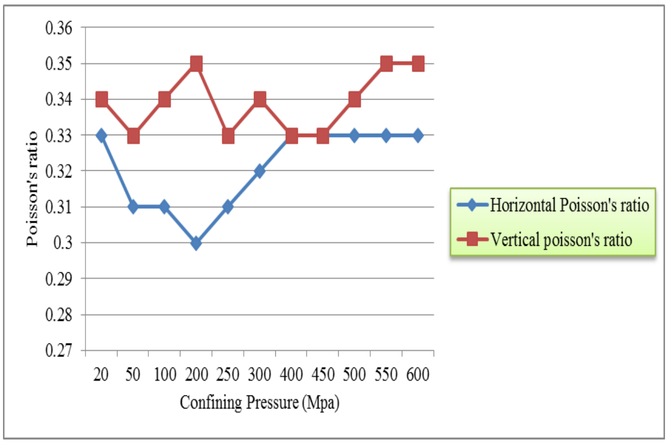


Fig.5: Confining Pressure Versus Anisotropy FactorFig. 6: Confining Pressure Versus Stiffness Constant



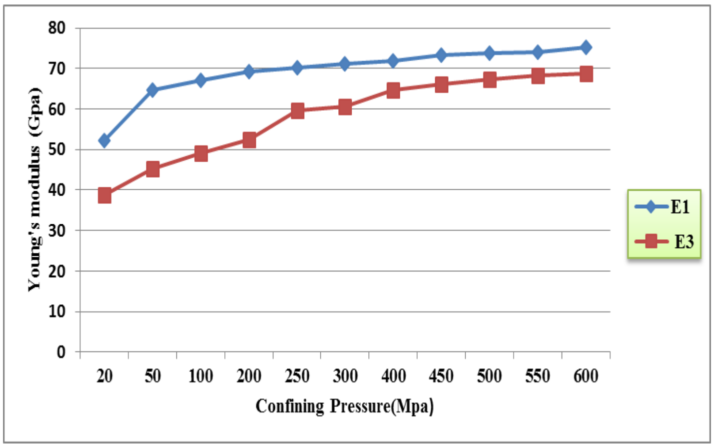


Fig.7: Confining Pressure versus Poisson's ratio Fig. 8: Confining Pressure versus Young's Modulus

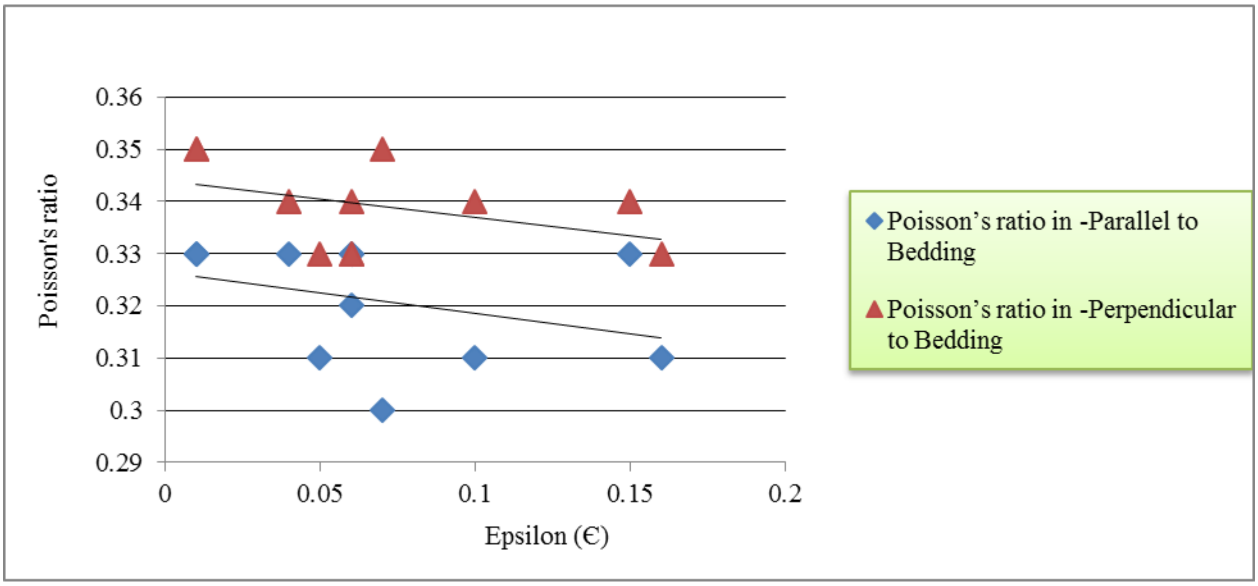


Fig. 9: Epsilon(€) Versus Poisson’s ratio

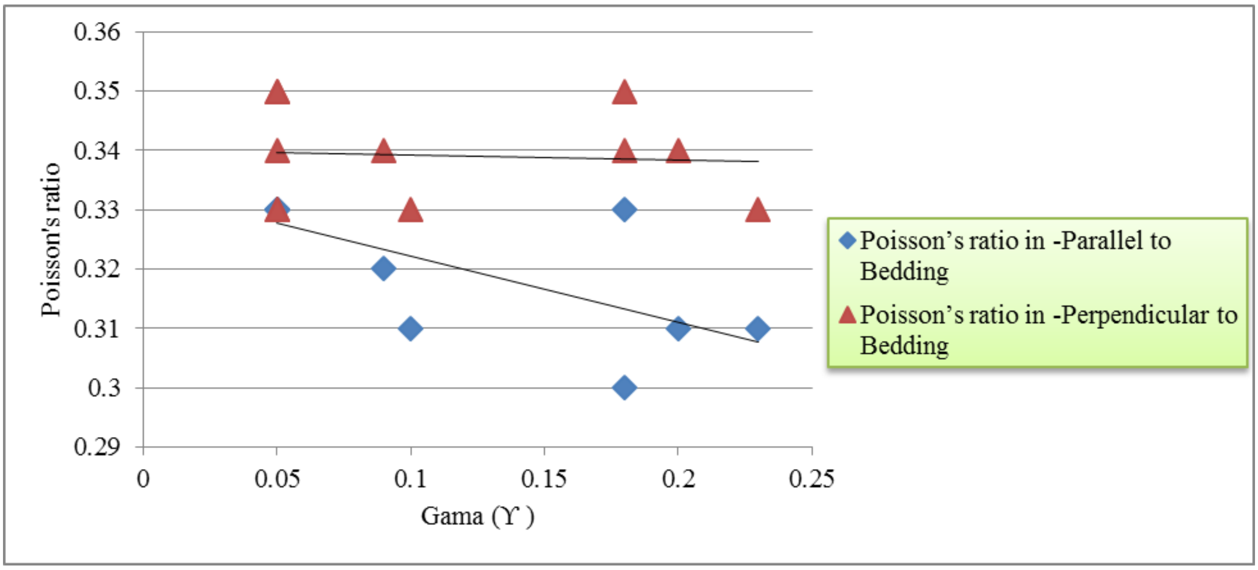


Fig. 10: Gamma (ϒ)Versus Poisson’s ratio

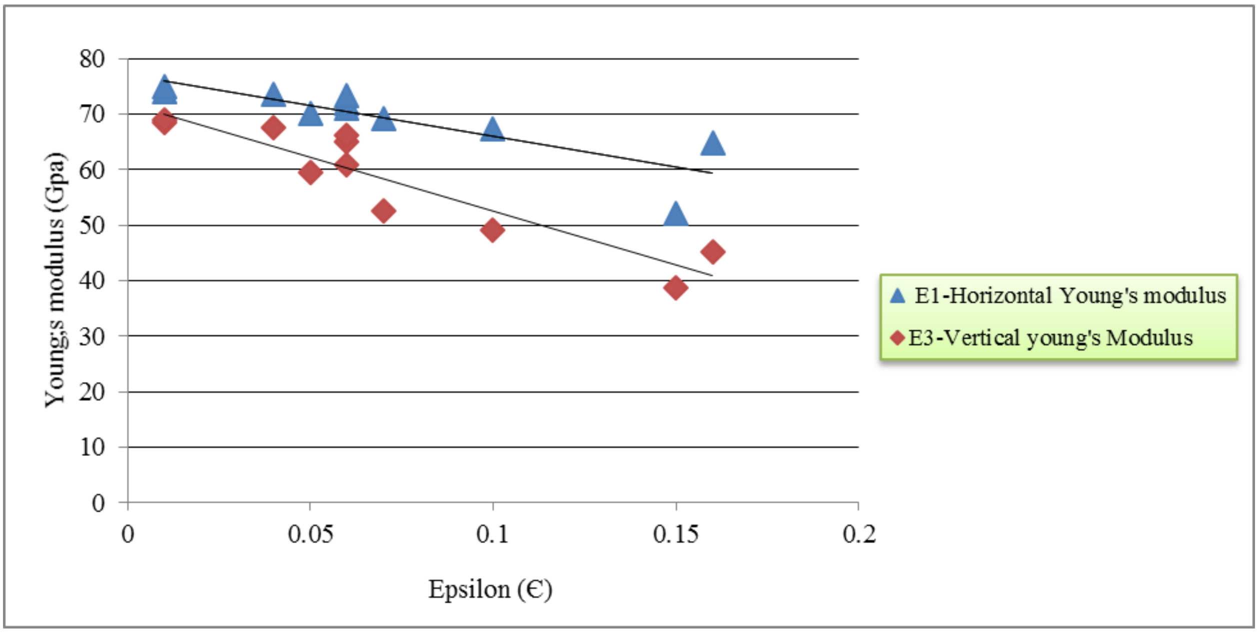


Fig. 11: Epsilon(€) Versus Young's Modulus

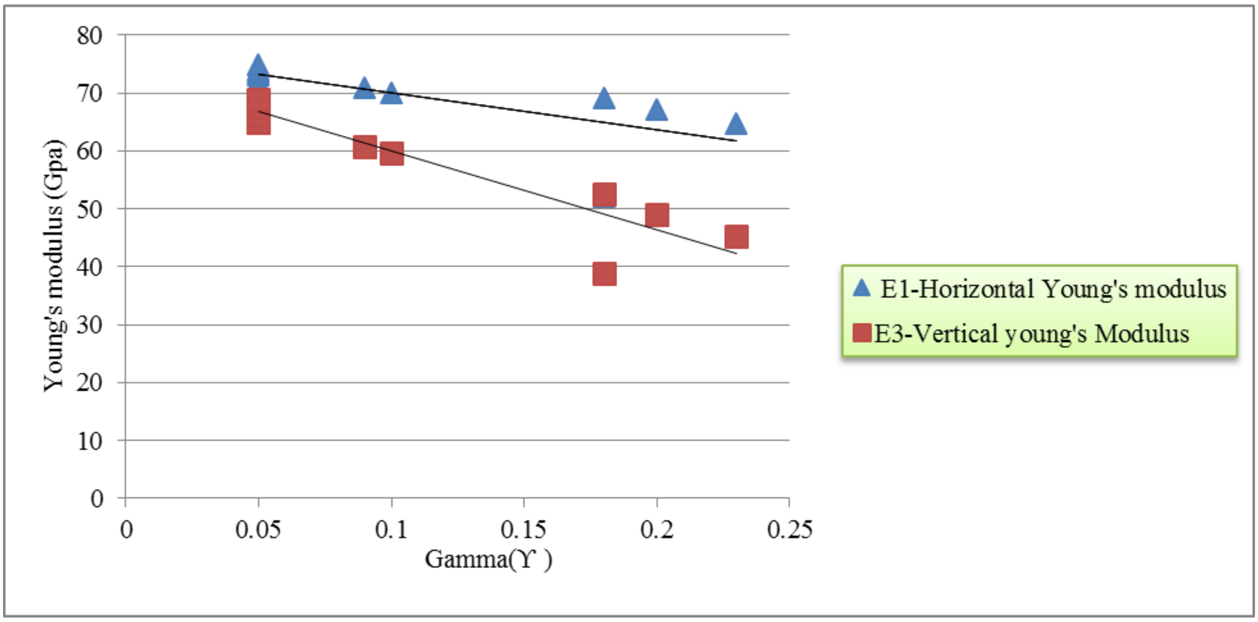


Fig.12: Gamma(ϒ) Versus Young's Modulus