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HEAT FLOW CURVE DEDUCED FROM SEISMIC WAVE ATTENUATION THROUGH CONSOLIDATED ROCK SAMPLES FROM EWEKORO, NIGERIA

[1]Deborah Oluwaseun Olorode and [2]Emmanuel O. Joshua
[1]Physics Department, University of Lagos, Nigeria
[2]Physics Department, University of Ibadan, Nigeria
E-mails: [1]dolorode@unilag.edu.ng / [2]eojoshua@yahoo.com

Abstract: In Nigeria, seismologists have embarked on the studies of the anelasticity of the interior of the Earth using various techniques and that at room temperature. This study looks into the effects of temperature on the seismic wave attenuation through three different rock samples from the Lithosphere. The rock samples are: sandstone, limestone and shale of about 2.0cm thickness from Southern part of Nigeria. Special heating chamber was fabricated to heat the samples in turn from temperature 344K to 774K, while the frequency of the seismic waves passing through the samples was over the range of 10 Hz to 1000 Hz. Each rock type attenuates differently while the oven dried samples attenuates more than in the natural state. Out of the three rock types used, sandstone attenuates most and shale has the least attenuation. Experiments revealed that the isolated pin-points in the rock matrix also unpinned when the rock samples were heated and that the samples underwent the process of annealing causing the internal constituents of the rock samples to fuse together.

Keywords: Anelasticity, Annealing, Attenuation, Isolated pin-points, rock matrix.

INTRODUCTION

Seismic waves propagated through the Earth's interior can be used to measure the travel times at boundaries within the ground. The analysis of such waves will in turn lead to the knowledge of the subsurface interfaces. Measurements of the velocity of seismic waves through many Earth layers provide major explanations to the compositions and constitution of the layers.

The earth's interior as a function of depth in km reveals that the Lithosphere extends to a depth of about 120 km and comprises of the crust that is only about 35 km deep and some part of the upper mantle. The Lithosphere is followed directly by the Asthenosphere that is a layer of the upper mantle. This extends to a depth of about 220 km. All the rock samples used in this study are from the Lithosphere.

The Earth has its internal temperature increasing from about 15 ^{0}C at the surface to about 6,000 ^{0}C at the center. At the base of the crust, the temperature could be up to about 600^{0}C.

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the internal heat of the Earth usually originates from radioactive decay of long-lived radioactive isotopes [such as U^{238} , U^{235}, Th and K^{40}], residual heat accumulation from the sun and possibly from continuous trickling of heavy metals through the mantle into the inner core.

It is a well-established fact that whenever a solid is strained mechanically, the imparted elastic energy can never be fully recovered. Some of the energy would have been converted to heat energy. This is an indication of the fact that seismic waves decay or attenuate as they propagate through the solid media. Toksoz et al (1979) have shown that several factors are responsible for the reduction (attenuation) of seismic waves through the solid (or Earth) medium either in the laboratory or on the field. Such factors include geometric spreading, scattering, dispersion, reflection, refraction, diffraction and absorption.

The effect of temperature on attenuation has not gained enough attention, as does the effect of frequency or even pressure. Very little work has been done on temperature dependence of attenuation at temperatures found in the upper crust. Volarovich and Gurevich (1957) in their investigations into the effects of temperature indicated that quality factor Q is generally temperature independent at temperatures greater than150 ^{0}C reported by Gordon and Davis (1968) which was attributed to thermal cracking. Kissell (1972) used the resonant bar technique on air-dry rock varying its temperature from -200 ^{0}C to 600 ^{0}C. He observed pronounced peak in attenuation at room temperature, which he attributed to an evidence of varying moisture content in the rock.

Spencer (1981) observed that there was a shift to high frequencies in the attenuation peak as a function of temperature for Navajo sandstone that has been water-saturated. Yu et al (1997) opined that there exist significant increases in the amplitude spectra and peak frequency of P-waves with water saturation. They showed that the peak frequency in fully and partially heavy hydrocarbon-saturated specimens is lower than that in fully water-saturated specimen. Vo-Thanh (1990) measured shear waves velocity and attenuation as a function of temperature in the kilohertz frequency range for sandstone partially saturated with glycerol. His conclusion was that the fluid viscosity plays a dominant role in shear wave attenuation and velocity of saturated sandstone. Seismologists in Nigeria have investigated the dependence of quality factor Q on frequency, resistivity, phase velocity, phase angle and depth [Umo, 1998; Salami, 2001]. Little attention has been paid to the temperature dependence of these factors on attenuation. This study is aimed at investigating the effects of temperature changes on attenuation of seismic waves and other parameters or mechanisms causing those changes. It is hoped that the study will give useful information and relevant relationships between attenuation of each rock sample and its temperature or between attenuation and frequency as temperature varies from room value to 500^0C.

EXPERIMENTAL TECHNIQUES

The experimental set-up is shown in figure 1, consisting of a sine-audio signal generator, a heating chamber, a double-beam standard oscilloscope, modular cable probes and a pair of quartz transducers. The signal generator generates the continuous sinusoidal waveforms, which propagates through the rock samples in turn while these are heated in the chamber. There is a pair of receiving and transmitting transducers fixed to either side of the rock sample. The three rock samples were in rectangular shape with thickness approximately 2 cm. The samples are:- shale, sandstone and limestone from Ewekoro cement factory, Ogun state of Nigeria, located on the Eastern Dahomey Basin.

The heating chamber, with dimensions 15cm x 18cm x 25cm, was designed and constructed specifically for this study. Proper insulation was made between its walls and the rock sample housed by it. A 0–200 mV thermoelectric transducer (thermocouple), which measures temperature of the heater in millivolts was also constructed and calibrated in degree Kelvin. Details of the experimental set-up and arrangements are well explained by Olorode (2001).

A continuous sinusoidal wave with frequency in the range 10 Hz to 1000 Hz was passed in steps of 10 Hz and 100 Hz from the sine-audio signal generator into the rock sample housed by the chamber. Records of the incident (A_i) and transmitted (A_t) waves were obtained from the double beam oscilloscope. Continuous –wave transmission and spectral amplitude wave – ratio techniques were adapted and extended for measurements of attenuation in the crustal rocks. The relation between the incident and transmitted wave has been given by White (1992) as

$$A_t(f) = A_i(f)\exp[-\pi ft/Q] \qquad \ldots\ldots(1)$$

Or

$$\ln[A_t/A_i] = -\pi ft/Q \qquad \ldots\ldots(2)$$

$$= -2kr \qquad \ldots\ldots(3)$$

from where

$$[-pft/Q] = -2kr$$

And

$$\pi f/Qv = 2k \qquad \ldots\ldots(4)$$

where v is the velocity of the wave propagated through the rock

f is the frequency of the wave

r is the thickness in meters of the rock samples

and k is the attenuation coefficient in m^{-1}.

Room temperature measurements were first taken for each rock type. The samples were then placed in turn inside the heating chamber and the temperature was varied slowly in the range 70^0C to 500^0C [i.e. 343 K to 773 K].

Attenuation coefficient, k was computed for all the rock samples using equation (4) above. The heated rocks were allowed to cool down to room temperature and attenuation coefficient was measured again to see the effect of heat on those samples. The right–hand side of equation (2) was plotted against frequency f to get a straight line graph from whose slope the value of Q was calculated. The results obtained are presented in tables 1 to 4 and figures 3 to 6.

DISCUSSION

A combination of the continuous-wave transmission and spectral amplitude wave-ratio techniques have been employed to measure seismic wave attenuation in three crustal rock samples at various frequencies ranging from 10Hz to 1000Hz. The temperature of the heating chamber was recorded by the thermoelectric thermocouple in millivolts and converted to Kelvin after being calibrated to Celsius scale.

The data obtained were analyzed on the computer. The calculated attenuation coefficients for the rock samples were plotted on graphs attached. At room temperature, sandstone attenuates most, while shale attenuates least. These agree well with experimental results of Umo [1998]. Increase in temperature of sandstone decreases its attenuation goes from positive to negative values. At temperature 630K however, there is an inversion in attenuation of sandstone as it suddenly increases from negative to positive values. Any further increase in temperature decreases attenuation of the sandstone sample. This inversion temperature is dependent on the Curie temperature [Lewowski and Wo´zniak 1997].

The overall effect of temperature on sandstone shows some picture about its internal structure. The presence of impurities and hydrocarbons may be causing the decrease in attenuation at the onset of heat. Granato and Lucke [1956]; Niblett and Wilks [1960] have observed that the presence of impurities can cause great influence on rocks. The latter increase in attenuation of sandstone at higher temperature may be due to thermal vibrations which may unpin the dislocation points in the rock matrix, or it may be due to the effect of sliding friction in the rock matrix and thermal agitation as observed by seismologists for similar rocks. Yuen and Peltier [1980]; Anderson and Archambeau [1964].

As the temperature of limestone increases, the attenuation coefficient reduces to negative values, this may be traced to the presence of organic matter, sea-shells, hydrocarbons or other impurities in the sample of limestone. Shale has negative values of attenuation coefficient also, which may be attributable to the thermal vibrations within the rock matrix which might have unpinned the dislocation points. This is revealed from the way the shale sample actually separates into thin slates after cooling. Finally, thermal agitation in the rock matrix may cause its internal constituents to fuse together in a process known as annealing.

CONCLUSIONS

This study aims at measuring in the laboratory, the variation of attenuation coefficient of consolidated crustal rocks with temperature; hence to obtain the heat flow curve for three rock samples. In this study, continuous-wave transmission and spectral amplitude wave –ratio techniques have been used to investigate the effect of temperature on seismic wave attenuation in consolidated sandstone, limestone and shale in the frequency range 10 to 1000Hz. Results have shown that rock materials react differently to heat, even when the same waves at the same frequencies were allowed to propagate through them. The fact that the rock samples attenuates more after heating reveals that if any sudden heat flow takes place underneath the Earth crust, we should expect the properties of the rock materials to change also.As soon as temperature of sandstone increases, attenuation goes from positive to negative from temperature of 334K to 555K for sandstone. At temperature 630K however, there is an inversion in attenuation of sandstone as it suddenly increases from negative to positive values. Any further increase in temperature decreases attenuation of the sandstone sample. Only sandstone exhibits this inversion.

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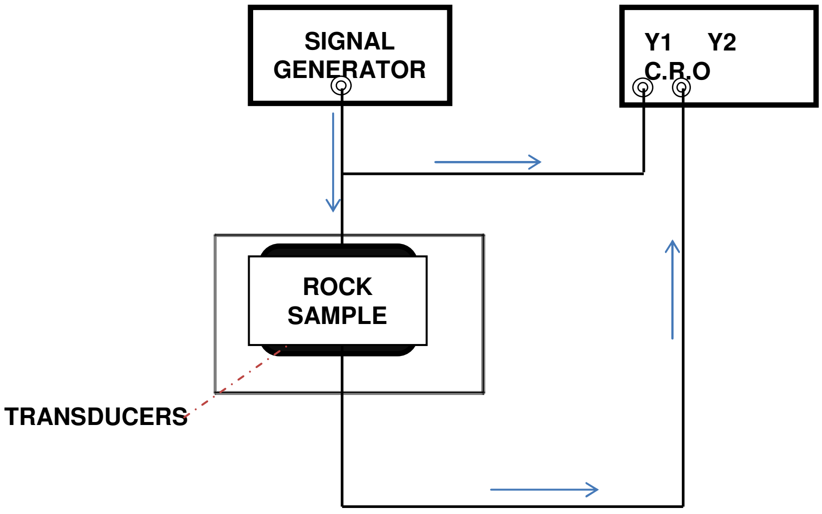

Fig 1. Experimental set-up

Table 1. Room Temperature Data of Attenuation for Rock Samples

FREQ Hz	Sandstone	Limestone	Shale
10	47.3	42.015	1.4
20	47.3	39.989	0
30	47.3	39.051	0
40	43.9	38.156	0
50	43.9	38.156	0
60	43.9	38.156	0
70	43.9	38.156	0
80	43.9	38.156	0
90	43.9	37.302	0

100	43.1	36.06	0
200	40.5	35.242	1.499
300	38.3	34.457	1.499
400	36.1	33.051	-0.74
500	33.1	32.325	-0.74
600	32.7	30.276	-1.5
700	32.7	29.624	-1.5
800	34.1	28.383	-1.5
900	34.1	28.383	-1.5
1000	34.1	28.383	-1.5

Table 2. Attenuation coef of heated shale sample at high frequencies

Freq Hz	Shale @ 380 K	452 K	523 K	595 K
100	9.2151	4.1437	-6.5382	-26.435
200	9.2151	4.1437	-6.5382	-26.435
300	9.2151	4.1437	-6.5382	-26.435
400	9.2151	4.1437	-6.5382	-26.435
500	9.2151	4.1437	-6.5382	-26.435
600	7.049	3.2523	-6.5382	-27.363
700	7.049	3.2523	-6.5382	-27.363
800	5.0714	3.2523	-6.5382	-27.363
900	5.0714	2.3946	-7.6471	-27.363
1000	5.0714	1.568	-7.6471	-27.363

Table 3. Attenuation coefficient of sandstone at high frequencies

Freq	380 K	452 K	523 K	595 K
100	-18	-18.6	0	10.14
200	-18	-18.6	0	10.14
300	-18	-18.6	0	10.14
400	-18	-18.6	0	10.14
500	-18	-18.6	0	10.14
600	-18	-18.6	0	10.14
700	-18	-18.6	0	10.14
800	-18	-18.8	0	10.14
900	-18.4	-18.8	0	10.14
1000	-18.4	-18.8	0	10.14

Table 4. Attenuation coef of heated limestone at high frequencies

Freq. Hz	Limst 380 K	452 K	523 K	595 K
100	11.61	7.049	8.106	6.039
200	11.61	7.049	8.106	6.039
300	11.61	7.049	8.106	6.039
400	10.38	7.049	8.106	5.071
500	10.38	7.049	8.106	5.071
600	10.38	7.049	8.106	5.071
700	9.215	7.049	8.106	5.071
800	9.215	7.049	8.106	5.071
900	7.049	7.049	8.106	5.071
1000	7.049	7.049	8.106	5.071

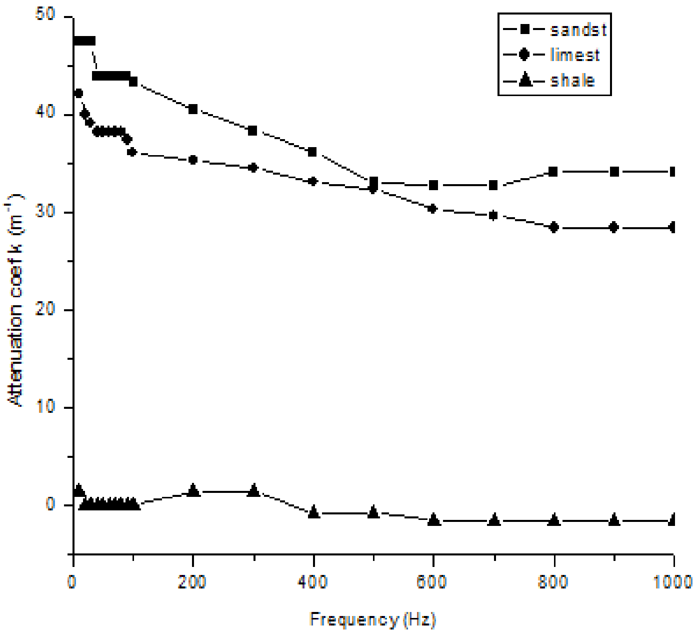

Fig 2. Attenuation coef versus frequency of natural rock samples

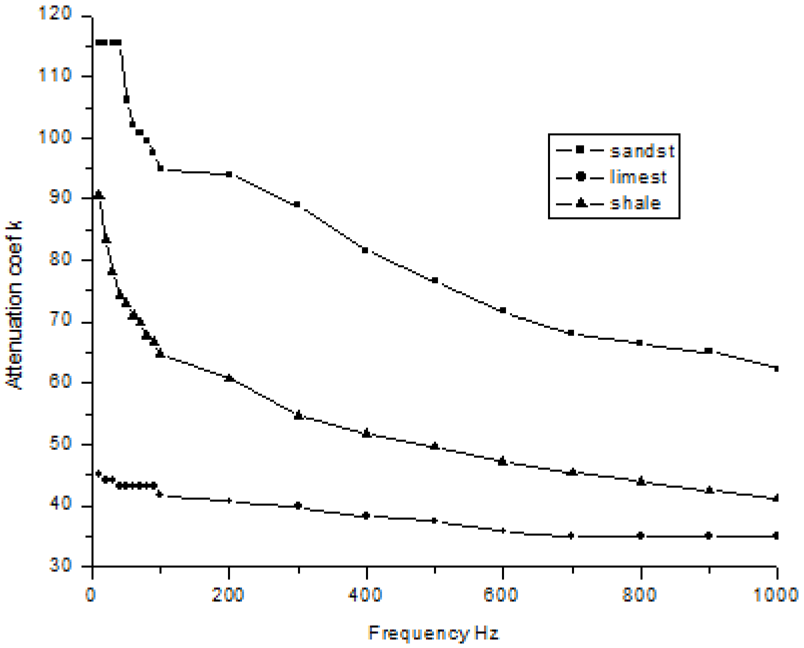

Fig 3. Attenuation coef versus frequency of oven-dried rock samples

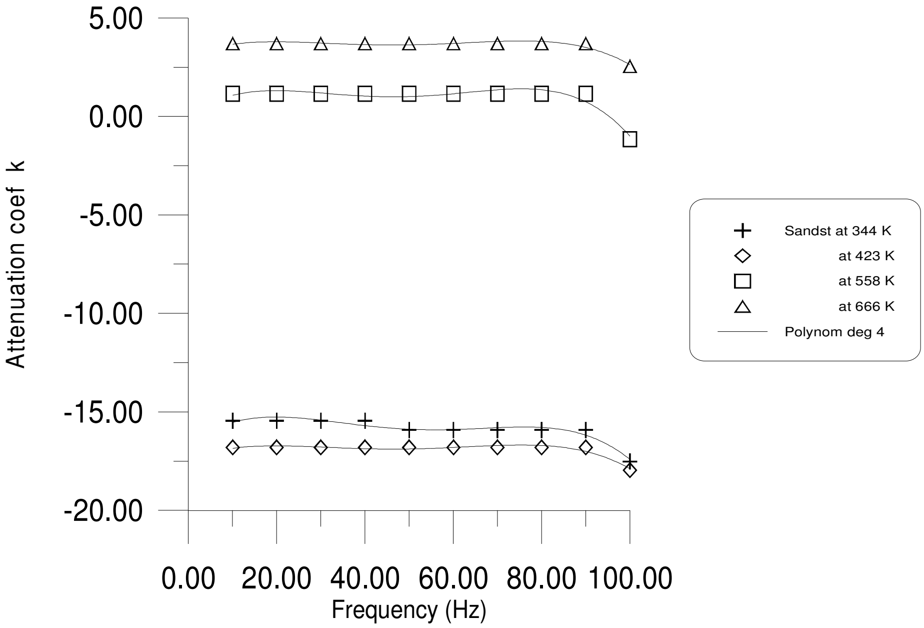

Fig 4 a. Attenuation Coefficient of sandstone at low frequencies

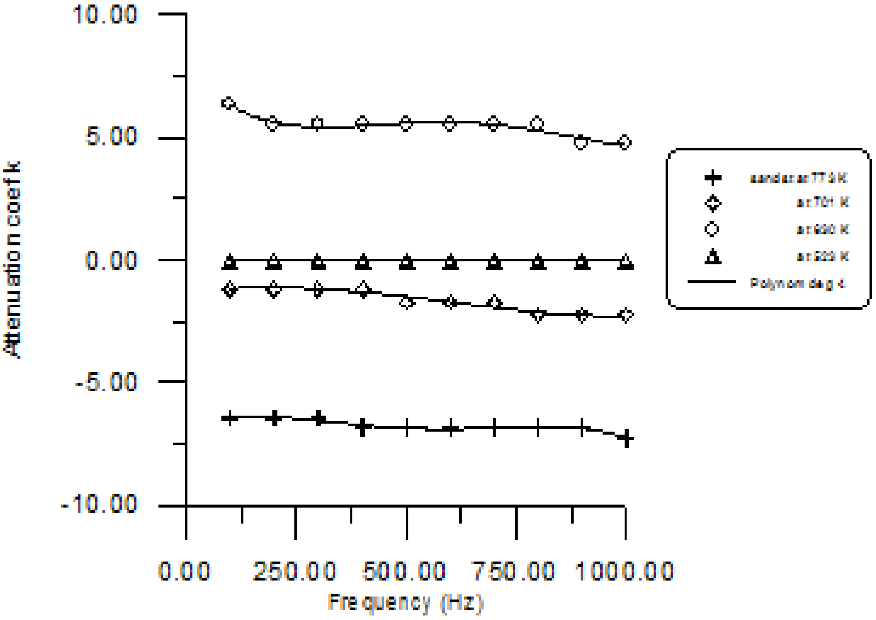

Fig 4 b. Attenuation coef of sandstone at high frequencies

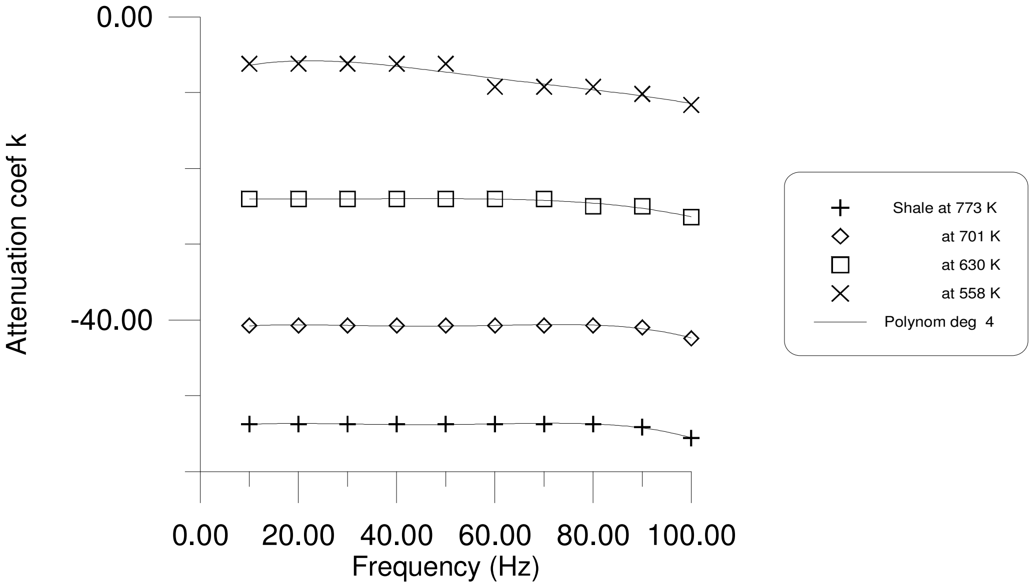

Fig 5a. Attenuation coef. of shale at low frequencies

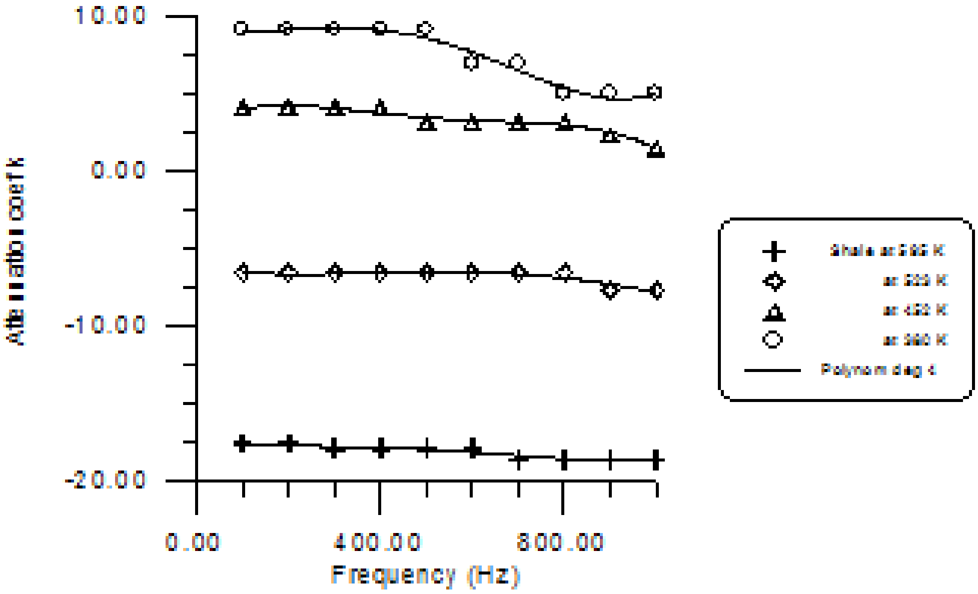

Fig 5 b. Attenuation coef. of shale at high frequencies

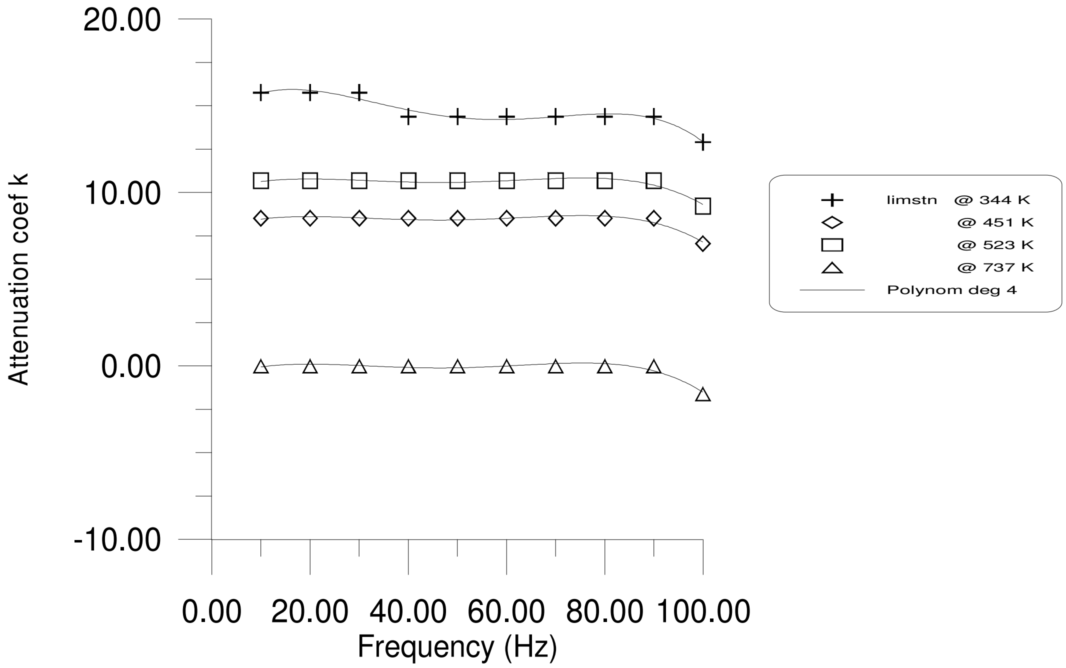

Fig 6a. Attenuation Coef of limestone at low frequencies

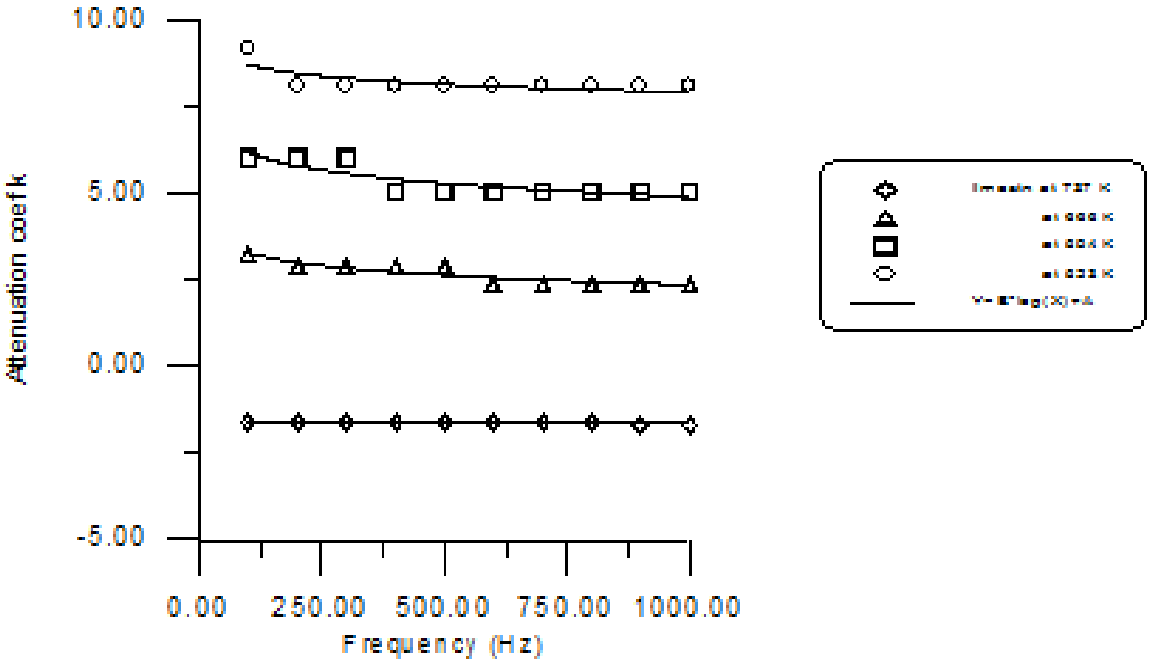

Fig 6b. Attenuation coef of limestone at high frequencies