

Mechanical behaviour of Basalts from Central India

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ABSTRACT: Five variants of Massive basalt and three variants of Vesicular basalt from Central India have been investigated in the laboratory for understanding the mechanical behaviour of rock. These basalts were obtained from different locations of Betwa river basin. The mineralogical compositions of these basalts were quantified through X-ray diffraction method (XRD). These basalts have been investigated for uniaxial compressive strength, indirect tensile strength, Tangent Modulus (E_{50}), Poisson's ratio (μ) and shear strength parameters (cohesion and angle of internal friction). In addition to above, physical, durability and wave velocities (compressive, shear) characteristics have been measured for holistic study. And, the propagation of failure of these basalts has been discussed. As the amount of vesicles and foreign materials in basalt decreases, the responses of vesicular basalt approach that of massive basalt. Irrespective of location, massive basalts are found to be superior compared to vesicular basalts. The failure propagated along chain of vesicles in vesicular basalts, acting as stress concentrators.

KEYWORDS: basalt, laboratory study, engineering behaviour, mineralogical composition

I. INTRODUCTION

Basalt is an igneous rock (extrusive type, on or above the earth's surface), which is formed due to solidification of magma, and in which plagioclase feldspars and mafic mineral occur in almost equal proportion. Basalt has 45-55% SiO_2 ; it has high content of Fe, Mg, Ca and less of K and Na. It is generally formed as massive, under volcanic conditions.

Due to rapid cooling under atmospheric conditions, basalt typically shows a very fine grained texture. Texture depends mainly on crystallinity, granularity, shape of minerals and mutual relations of mineral grains. In some variants, small cavities are formed by the expansion of bubbles of gas or steam during solidification of the volcanic rock. Several researchers have observed that the strength of vesicles in basaltic flows is considerably effected by their porosity [1,2]. These vesicles are sometimes filled by secondary minerals like calcite, quartz, or olivine depending on ground water chemistry and underground physical conditions [3].

The knowledge of basalts including its strength, deformation behaviour and their failure characteristics is important in geotechnical engineering. Uniaxial compression and Brazilian strength tests are conventional methods that are often used to investigate the strength and failure characteristics of rocks. The presence of non-connected vesicles in basaltic flows greatly affects their engineering properties such as compressive strength, modulus of elasticity, Poisson's ratio and sonic velocities [4]. However, the deformation behaviour of saturated basalts in conjunction with texture has further scope for investigations by researchers. Hence, an attempt is made in the present study to understand strength and deformation behaviour of two texturally varied basalts namely massive basalt (of fine grained texture) and vesicular basalt (having open cavities) along with their failure characteristics.

For the present study, five variants of massive basalt (M1, M2, M3, M4 and M5) and three variants of vesicular basalt (V1, V3 and V5) were obtained from Central India. And, all the variants are selected from different locations of Betwa river basin (Fig.1). The basaltic flows of these locations belongs to Malwa group of the Deccan Trap complex comprising low lying hills, hill clusters, valleys and extensive plains.

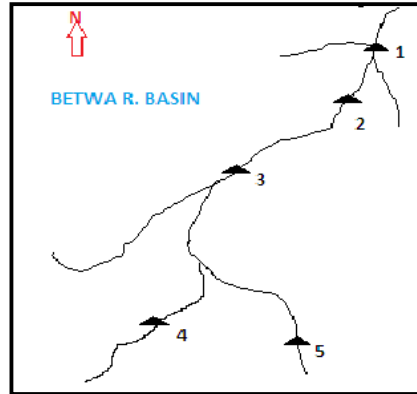


Fig. 1 Map showing locations in Betwa river basin

II. MINERALOGICAL COMPOSITION

The mineralogical composition of massive basalt and vesicular basalt is quantified through X-ray diffraction method to delineate the influence of intrinsic properties on strength and deformation behaviour of basalt. Using $CuK\alpha$ radiation ($\lambda = 1.5404\text{\AA}$), the representative powdered sample of rock is used for quantification of minerals. Figure 2 shows the diffraction patterns of vesicular basalt and massive basalt (relative intensity v/s 2 THETA). Table 1 shows average mineral compositions of both variants of basalt.

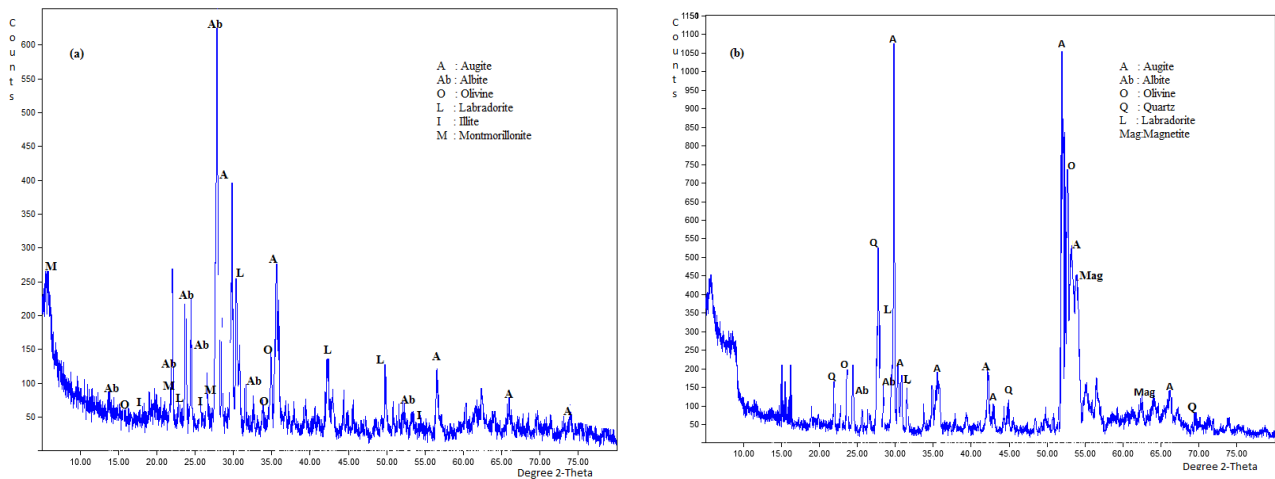


Fig. 2. X-ray diffraction patterns for (a) vesicular basalt (b) massive basalt

Table 1 Chemical composition of Basalts

Mineral	Augite	Albite	Olivine	Labradorite	Quartz	Magnetite	Illite	Montmorillonite
Vesicular basalt (%)	27.1	38.4	2.0	23.6	Not detected	Not detected	6.5	2.4
Massive basalt (%)	40.5	18.8	22.7	8.5	6.2	3.3	Not detected	Not detected

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III. EXPERIMENTAL WORK

In accordance with the above objective, five variants of massive basalt collected from 1 to 5 locations (denoted as M1, M2, M3, M4 and M5) and three variants of vesicular basalt collected from 1, 3, 5 locations (denoted as V1, V3 and V5) of Betwa river basin have been investigated for different properties and parameters in saturated condition. The tests have been conducted as per ISRM suggested methods [5]. The results are discussed under the following major categories: i) strengths, (ii) deformability characteristics with their failure patterns. For holistic analysis, physical, durability and wave velocity characteristics were also evaluated.

For uniaxial compressive strength (UCS), NX size cylindrical cores with length to diameter ratio of 2.5, were loaded until failure under static loading. The longitudinal and lateral strains were measured with the help of electrical resistance strain gauges. In the first instance, the samples were subjected to load up to half of anticipated strength, and unloaded (to the value seating load) to know permanent set. In the second cycle, samples were loaded until failure. Tangent modulus and Poisson's ratio are measured at 50% of failure stress. The Indirect Tensile Strength is assessed employing Brazilian test, the NX size saturated specimens, with length to diameter ratio of 0.5, were tested under static loading. The justification of the test is based on the experimental fact that most of rocks in biaxial stress fields fail in tension at their uniaxial tensile strength when one principal stress is tensile and the other finite principal stress is compressive with a magnitude not exceeding three times that of the tensile principal stress.

Using NX size cylindrical samples, $I_{s(50)}$, is evaluated in saturated state, under diametral and axial, both, types of loading. The test is considered valid only if the failure plane passes through both the loading points. As per standard, size correction is subsequently applied to make it correspond to 50 mm size sample. The Anisotropy Index, I_a , which is ratio of ' $I_{s(50)}$ under axial loading to $I_{s(50)}$ under diametral loading', also presented.

For triaxial compression test, Hoek cell was employed, and saturated specimens, with length to diameter ratio of 2, were tested over the desired range of confining pressure. For each of variants at each location, the whole data, does not lend itself to draw classical straight line Mohr-Coulomb failure envelop for the scattered triaxial test data. Hence, triaxial test data for massive basalts from five locations (M1, M2, M3, M4 and M5) and vesicular basalts from three locations (V1, V3 and V5) clubbed; tangents drawn to their upper and lower bound envelops; and the range of shear strength parameters (i.e., c and ϕ) as a whole, for both variants, were evaluated.

The evaluation of waves' velocities - compressive and shear both, and in dry and saturated states, both- are evaluated employing two piezoelectric crystals of 200 kHz and 33kHz frequency for compression and shear wave respectively. These velocities help in understanding scatter in the data and arriving at a representative value of parameters. Hence, velocities are evaluated for the samples subjected to uniaxial strength test. The dynamic deformability characteristics were also calculated from waves' velocities data, using basic equations [6].

IV. RESULTS AND DISCUSSION

1. Strengths:

Table 2 shows the strength parameters namely uniaxial compressive strength (UCS_{sat}), indirect tensile strength ($\sigma_{t(sat)}$), point load strength ($I_{s(50)}$), both in axial and diametral conditions, cohesion (c), and angle of internal friction (Φ) for massive and vesicular basalts.

Table 2 Strengths of Basalts (in saturated condition)

Parameters	Massive basalts					Vesicular basalts		
	M1	M2	M3	M4	M5	V1	V3	V5
UCS_{sat} (MPa)	70	70	100	80	95	15	30	18
ISRM Class	H*	H*	H*	H*	H*	L*	M*	L*
$E_{50(sat)}$ (GPa)	80	50	65	65	65	30	45	15
μ_{sat}	0.29	0.25	0.28	0.29	0.29	0.20	0.29	0.29
$\sigma_{t(sat)}$ (MPa)	13	11	11	15	15	3.5	7.5	4
$I_{s(50) sat-Dia}$ (MPa)	7	6.5	9.5	6	6	3.5	3.5	1.9
$I_{s(50) sat-Axial}$ (MPa)	7	6.5	9.5	6	6	3	3	1.9
I_a (sat)	1	1	1	1	1	0.9	0.9	1
c (MPa)	-----		4-5.5	-----		-----		2.5-4 -----
Φ (degrees)	-----		50-55	-----		-----		45-50 -----

*H-High; M-Moderate; L-low

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 3, March 2016

1.1. Uniaxial Compressive Strength:

It is observed that vesicular basalts were failed much lower strengths than massive basalts possibly because of vesicular texture. Most of the samples failed along the periphery of vesicles and propagation of failure is along chain of the vesicles. Figure 3 shows the failure pattern of vesicular basalts under uniaxial compression. Unlike vesicular basalts, most of massive basalts failed in multi axial splitting, developing tensile cracks. The variation of UCS_{sat} for massive and vesicular basalts of different locations can be observed in Figs. 4(a), 4(b).



Fig. 3 Failure pattern of vesicular basalt under uniaxial compression

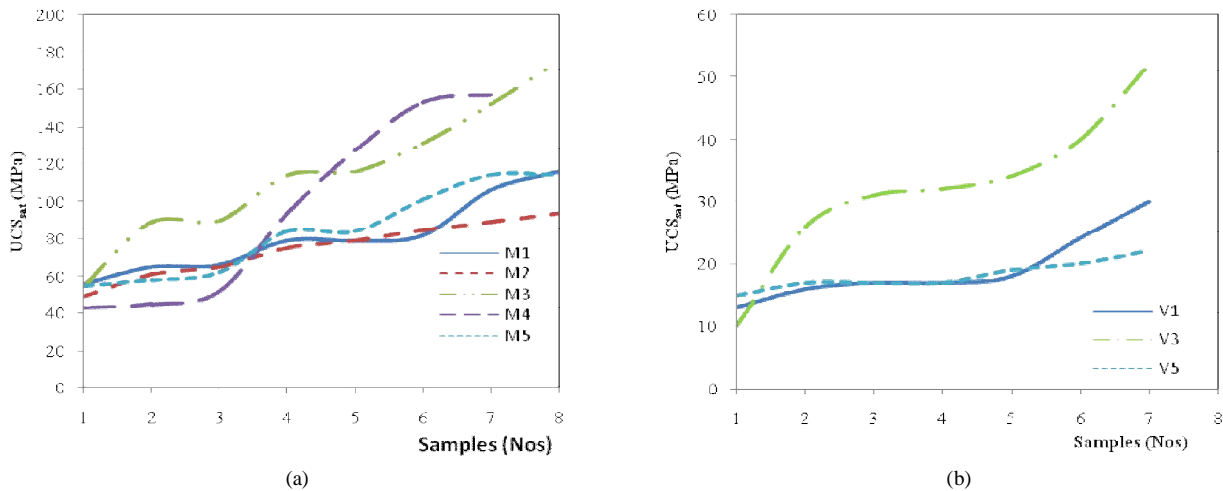


Fig. 4 (a) UCS_{sat} variation of massive basalts, (b) UCS_{sat} variation of vesicular basalts

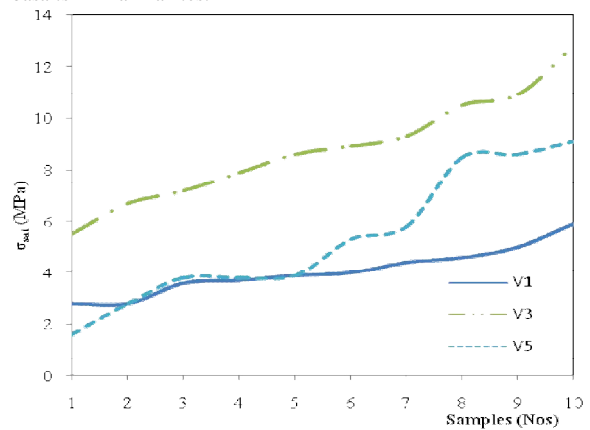
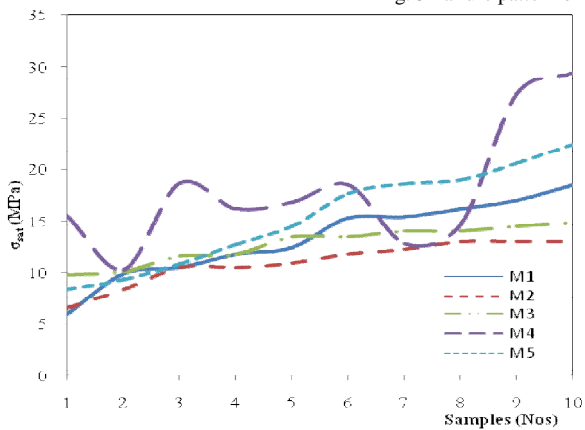
Among the variants, in location 3, the percentage of variation of UCS_{sat} data is higher. It is inferred that in massive basalts, the presence of harder minerals such as augite and olivine in higher proportion has also contributed higher UCS than the vesicular basalts.

1.2 Indirect Tensile Strength:

Table 2 shows that vesicular basalts failed at very low strengths compared to massive basalts (less than 50%). In addition to the existence of vesicles over the surface area of rock cores, the clay minerals played greater role in reducing bond between rock's constituents. This resulted in greater decrease in strength of vesicular basalts on saturation. Figure 5 shows the mode of failure of vesicular basalts in Brazilian test. The variation of $\sigma_{t(sat)}$ for both massive basalts and vesicular basalts of different locations can be observed in Figs. 6 (a), 6(b).



Fig. 5 Failure pattern of vesicular basalts in Brazilian test



(a) $\sigma_{t(sat)}$ variation of massive basalts, (b) $\sigma_{t(sat)}$ variation of vesicular basalts

Similar to UCS, in Brazilian test also, vesicular basalts have failed along periphery of vesicles. Moreover, the variation of data is substantial compared to other variants of vesicular basalts. However, the detrimental effect of strength on saturation due to existence of clay minerals in vesicular basalts cannot be ignored in the present case also. Point load strength ($I_{s(50)sat}$) evaluated in saturated state, under diametral and axial, both, types of loading, samples having vesicular texture have shown least values compared to fine grained texture. It is also noted that samples from both variants of basalt are of quasi-isotropic in nature [7] (as anisotropy index, I_a is less than or equal to 1).

1.3 Shear strength parameters:



Fig.7 Typical failure of vesicular basalt in triaxial compression

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 3, March 2016

Figure 7 shows failure of vesicle samples in triaxial compression test. And, figures 8(a), 8(b) shows the variation of triaxial data for massive and vesicular variants respectively. In view of scatter in triaxial test data, for both variants of basalt, upper and lower bound curves are plotted; and, the tangents drawn to these curves are considered as classical strength envelopes that yield lower and upper bound values for the respective shear strength parameters. In the literature, it is shown [8], that for true pattern of inherent variability to emerge, at least 40 samples are required to be tested. Accordingly, for a scattered triaxial data, range of shear strength parameters (i.e., cohesion, c and angle of internal friction, ϕ) was presented in the table 2.

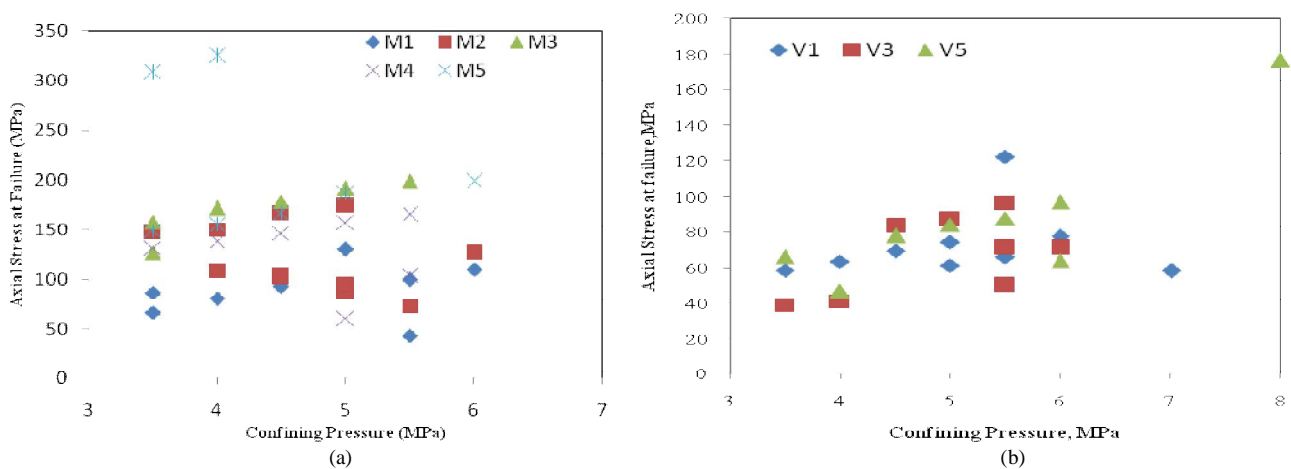


Fig.8 (a) Triaxial data variation of massive basalts, (b) Triaxial data variation of vesicular basalts

2. Deformability Characteristics:

The deformability behaviour is addressed for both variants of basalt through uniaxial compression test under static loading and by measurement of dynamic waves' velocities through ultrasonic pulse technique in the laboratory.

2.1 Static Tangent Modulus (E_{50sat}) and Static Poisson's ratio (μ_{sat}):

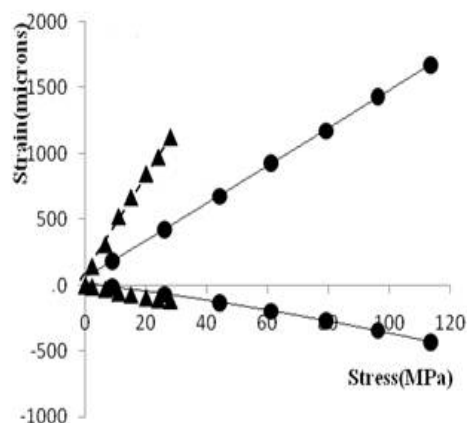


Fig.9. Typical stress-strain plot of both, variants of basalt

Figure 9 shows typical stress –strain plot for both massive and vesicular variants of basalt. It shows for vesicular basalts have failed at low strains than massive basalts. The E_{50sat} and μ_{sat} values of both variants of basalt are presented in table 2. Generally, it is observed for rocks, Tangent modulus (in GPa) is less than UCS (in MPa); whereas for vesicular basalts, the representative values reveal reverse correlation. Here, the stress obtained for vesicular basalts is

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 3, March 2016

less than actual due to, i) effective area is less than the notional computed cross-sectional area; and ii) stress concentration at openings /cracks/vesicles. As such, E_{50sat} is possibly increased on consideration of low compressive stress than the actual. However, there is not much variation observed in μ_{sat} even the variants are texturally different.

2.2 Dynamic Modulus (E_{dyn}):

The dynamic modulus calculated from waves' velocities data [Fig.10] using basic equations [6] is usually higher than obtained elastic modulus under static loading conditions. Figure 11 shows the variation of ratio of dynamic elastic modulus to static elastic modulus of vesicular basalt samples. The ratio varies for these vesicular basalt samples about 0.2 to 1.6. The assumptions involved in computation of E_{dyn} not being cordial in a rock [8], the present ratio at best taken as a qualitative indicator.

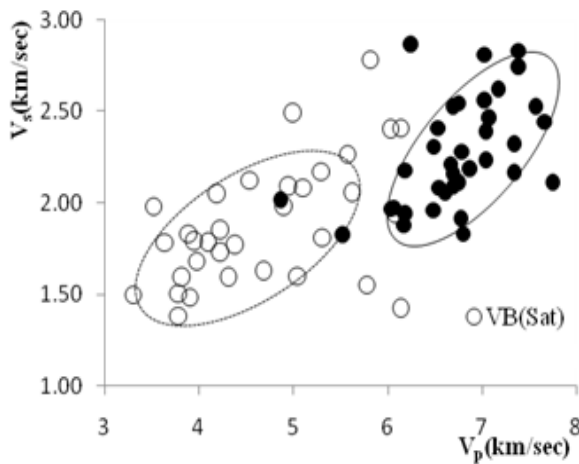


Fig.10 Variation of Compressive v/s Shear waves' velocities

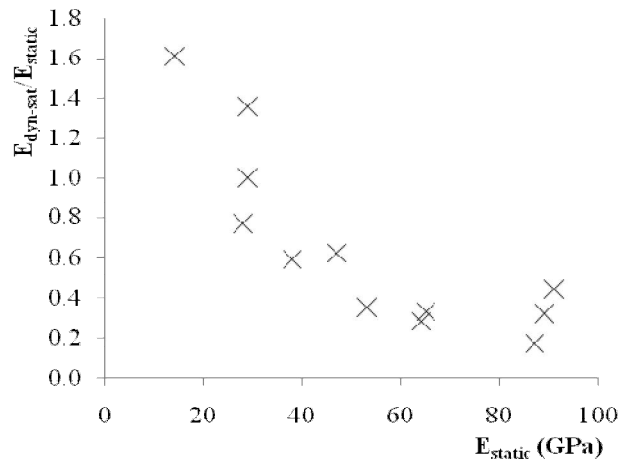


Fig.11 Comparison of E_{dyn} and E_{static} for vesicular basalt

For holistic analysis, physical and durability characteristics were computed, it is observed that vesicular basalts are less dense and medium porosity rocks compared to massive basalts. On saturation, the reduction in waves' velocities is observed in some of vesicular basalt samples, possibly due to alteration of clay fillings with water.

V. CONCLUSIONS

The presence of vesicles has drastically reduced the strengths- UCS, $\sigma_{t(sat)}$, $I_{s(50)sat}$, deformability values (E_{50sat} and μ_{sat}) of saturated vesicular basalts. Most of vesicular basalt samples failed along periphery of vesicles and propagation of failure is along chain of vesicles. An usual increase of E than its UCS is observed in vesicular basalts. This is possibly due to computation of stress corresponding to notional cross sectional area than its effective area on deduction of vesicles/openings; and secondly, due to stress concentration at the periphery of vesicles/cracks. On saturation, reduction in waves' velocities is observed in vesicular basalts possibly due to alteration of clay fillings with water.

VI. ACKNOWLEDGEMENT

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