The Variation of Compressional Wave Velocity with Degree of Saturation in Granites

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요 지

암석의 탄성파속도를 측정하는 방법은 암석의 공학적 특성을 나타내는 하나의 지표로서 일반적으로 인식되고 있어서 우리나라에서도 『건설 표준품셈』등의 암판정 기준으로서 보편적으로 사용되고 있다. 그러나 암석의 탄성파속도는 시료의 함수상태에 따라서 크게 변화하는 사실을 충분히 인식하지 못하고 있으므로 본 논문은 한국화강암에서 관찰된 변화특성을 설명한다. 국제 암반역학회에서 추천하고 있는 암석의 탄성파속도 측정방법도 역시 실험상의 어려움이 있는데, 예를들면 암석시료의 양쪽 끝에서 탄성파가 잘 측정되도록 하기 위하여 사용되는 바셀린이 암석 시료내로 침투하는 경우가 하나의 문제점이고, 또한 암석시료가 함수됨에 따라서 시료의 체적이 팽창하는 경우에도 해석상의 어려움이 있다. 또한 서서히 함수정도를 증가시키는 경우에 암석시료내에서 탄성파속도의 변화를 관찰하여 보면 암석시료내에 존재하는 잔류응력을 파악하는 한 방법으로서도 사용될 수도 있다는 것을 알 수 있다.

Abstract

The measurement of sonic velocities is commonly used as an index of engineering properties of rock, but it is not widely appreciated that this velocity can change markedly with the degree of saturation of the sample. This paper records the nature of this variation as seen in samples of Korean granite.

The ISRM method of testing suggested for this index can also create difficulties, especially if vaseline is used as a coupling agent, and invades the samples, and if the sample volume changes with degree of saturation. Careful measurements of the natural variation in sonic velocity that occur in a sample whose saturation is gradually increased may be a means of assessing the relic stresses within it.

Keywords : Granite, Seismic wave velocity, Rock classification, Rock mechanics

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1. Introduction

Twenty three samples of granite were collected from six granitic areas in Korea, each sample being carefully selected in the field to represent one of the following grades of weathering: fresh (F), slightly weathered(SW), moderately weathered(MW) and highly weathered(HW) (Goodman, 1993; Lee and de Freitas, 1989).

From these samples were cut cores of 3cm diameter, trimmed to right cylinders 6cm long: 18 cores each from the F and MW material and 15 cores from the SW material. The HW material could not be cored as easily and only 2 such cores were obtained. Consequently four cubes of HW granite were prepared, each with side length 6cm. A total of 53 cores and 4 cubes were therefore prepared and upon these were made the measurements of compressional wave velocity.

Each sample was oven-dried and its compressional wave velocity measured. Thereafter the moisture content of each sample was permitted to increase and the compressional wave velocity measured at a number of moisture contents, at increments of about 5 to 10% increases in the degree of saturation.

The compressional wave velocity measured in these samples varied in a consistent, non-linear and repeatable manner with increasing moisture content. This paper describes these results and proposes an explanation for the behaviour they reveal.

2. The Granites

The specimens used were taken from granites in Korea of Jurassic and Cretaceous age. Both are typical samples of the rock type, the Jurassic granites being slightly coarser grained than those of the Cretaceous.

The type of Jurassic granite tested is described petrologically as monzogranite(Streckeisen, 1976). It is mainly equigranular in texture and coarse-grained with euhedral quartz(i.e. showing its crystal faces) ranging in grain size from 0.5 to 5mm with an average size of 3.5mm. Quartz occurs both as discrete crystalsand as interstitial material between other minerals, and generally exhibits undulose extinction indicating strain within its lattice. Feldspars are euhedral to sub-hedral with crystal sizes ranging from 1 to 3.5mm and with an average size of 3mm. Alkali-feldspars are mainly perthite, microcline and orthoclase, and often show myrmekitic texture(i.e. intergrowths with quartz). Plagioclase consists dominantly of albite and oligoclase and crystals are zoned. Common ferromagnesian silicate minerals are biotite and occasionally muscovite. Biotite is sub-hedral and has a crystal size of 0.5 to 2mm. The Jurassic granites are geochemically of the alkalic calc-alkalic rock phase.

The petrological type of Cretaceous granite tested is also monzogranite(Streckeisen, 1976). It has a slightly porphyritic texture(i.e. some crystals are noticeably lager than others and called phenocrysts to distinguish them from their surrounding 'ground mass') and is medium-grained. Groundmass consists of quartz and feldspars and has a grain size ranging from 0.5 to 1.8mm with an average size of 1.5mm; some phenocrysts of feldspar have crystal sizes ranging from 2.5 to 4 mm with an average size of 3mm. Quartz is anhedral(i.e. does not exhibit its crystal faces) and shows undulose extinction like that of the Jurassic granites, indicating strain within its lattice. Feldspars are euhedral to sub-hedral. Alkali-feldspars are mainly of perthite and orthoclase, and sometimes show myrmekitic texture. Plagioclase consists dominantly of oligoclase and its crystals are zoned. Common ferromagnesian silicate minerals are hornblende and biotite. Biotite is sub-hedral and its crystal size is 0.5mm on average. The Cretaceous granites are geochemically of the calcic calc-alkalic rock phase.

The localities from which these granites were sampled are shown in Figure 1. Table 1 shows the basic mineralogy for each of the granites used in this study.

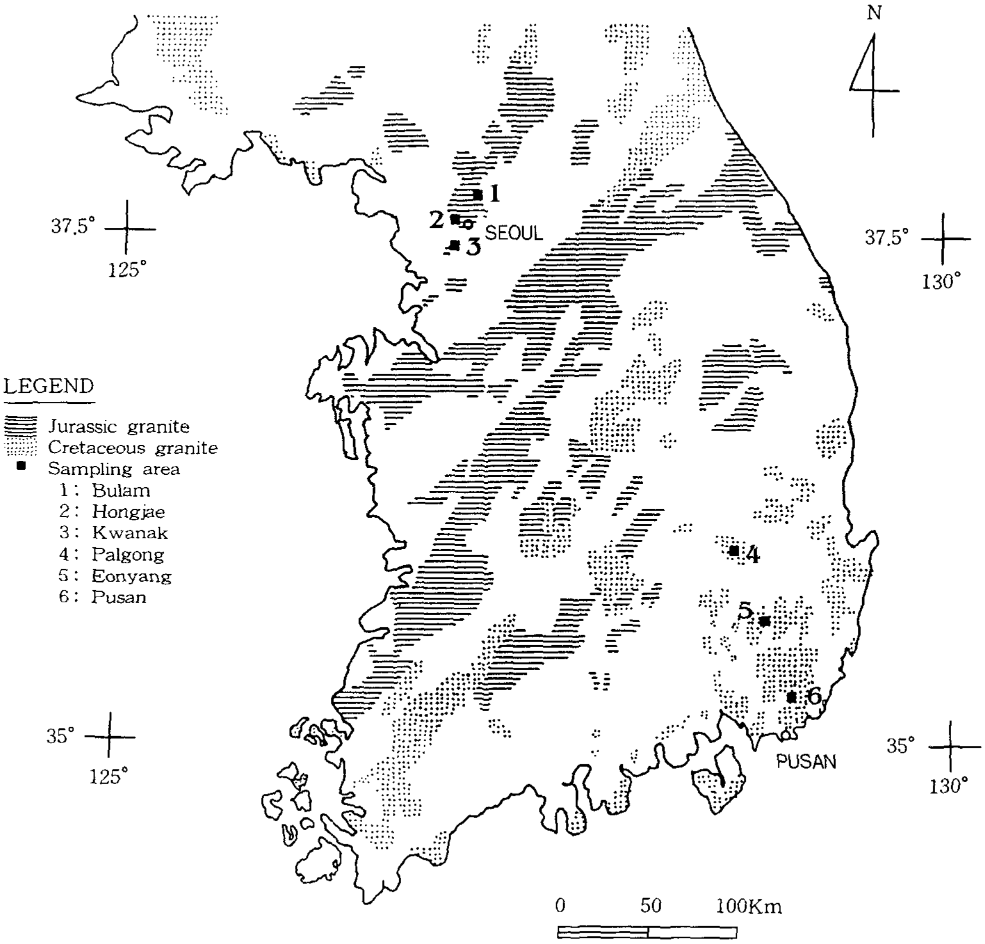


Fig 1. Sketch map of South Korea showing the distribution of granites of Jurassic and Cretaceous age and the sampling locations are indicated by numbers 1 to 5.

Table 1. The mineralogical composition of the fresh granites at Bulam, Hongjae, Kwanak, Palgong, Eonyang and Pusan areas.

Location (Fig. 1)	Quartz	Feldspars		Ferromagnesian silicate minerals			Accessory minerals**
		Alkali-feldspars*	Plagio-clase	Biotite	Muscovite	Honblend	
Bulam	35	35	25	3			< 1
Hongjae	35	30	30	2			< 1
Kwanak	30	30	35	0.5	1		< 1
Palgong	30	34	30	3		1	< 1
Eonyang	35	30	30	2.5		1	< 1.2
Pusan	30	35	30	2		0.8	< 1

* Alkali-feldspars = orthoclase, perthite, microcline.

** Accessary minerals = chlorite, sphene, zircon, apatite, magnetite, tourmaline, opaques.

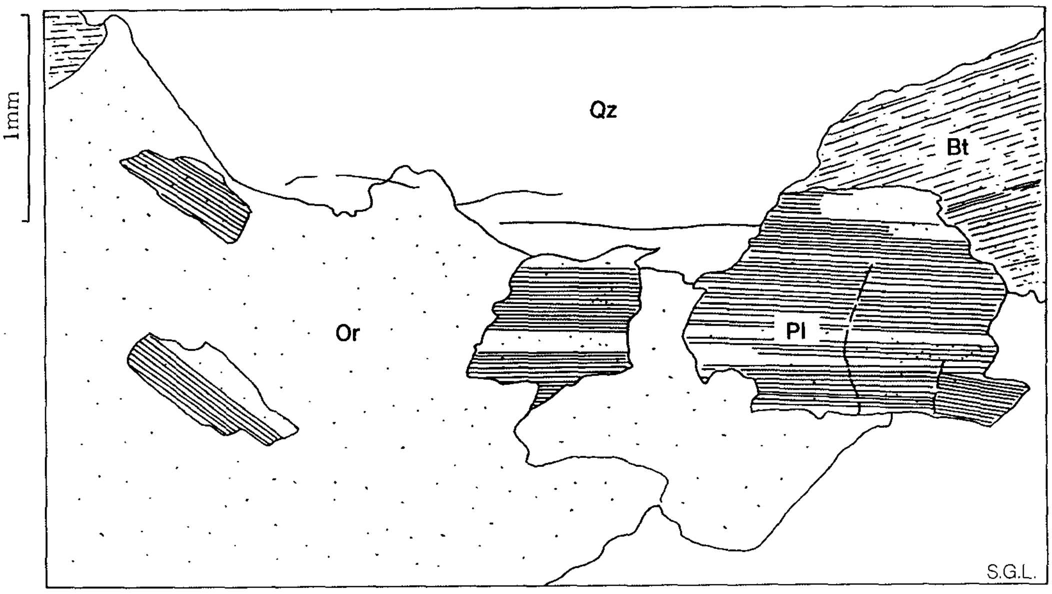
3. The Specimens

The specimens have been categorized according to the conventional scheme of weathering classification used for granitic material(Hencher and Martin, 1982; Irfan and Dearman, 1978; Lee and de Freitas, 1989). This observes 6 grades ranging from fresh(F) to residual soil(RS). Each of the specimens chosen for this study(i.e. F, SW, MW and HW) was carefully selected to be representative of the characters mid-way between the boundaries of these grades. For example the specimen representing SW granite was chosen because its character was judged to be mid-way between F granite and MW granite. It should be noted that the selection of samples was based on field observations made on hand specimens. Table 2 describes the typical mineralogical and textural characters of the granites tested and illustrates the relationship between these features and the weathering grades. Figures 2a-d illustrate typical examples of each of the grades described in Table 2.

Table 2. Typical mineralogical and textural changes associated with the weathering grades fresh (F), slightly weathered(SW), moderately weathered(MW) and highly weathered (HW) as recorded on samples collected from Kwanak, Eonyang, Bulam and Pusan, respectively. These changes were observed using a microscope of 50x magnification.

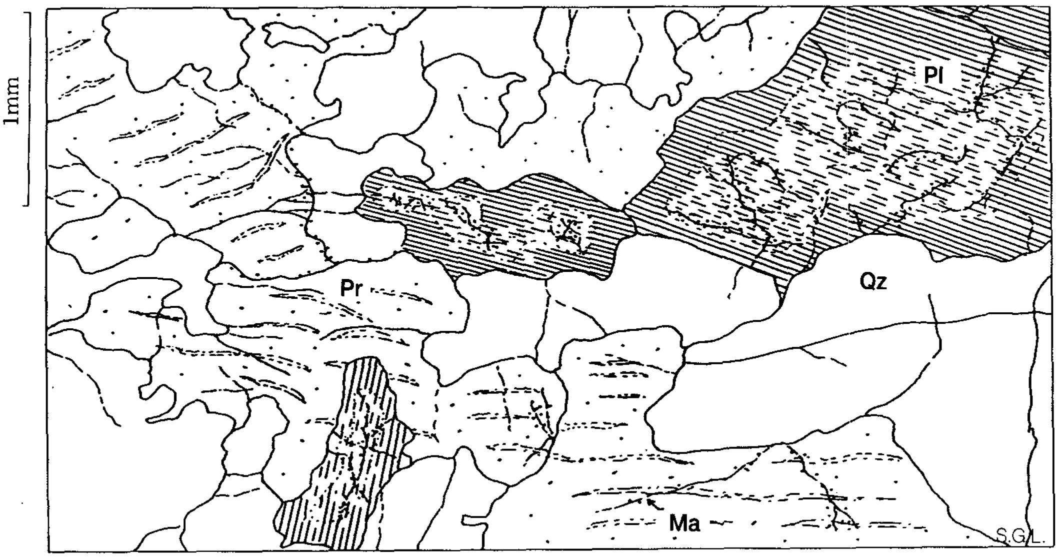
Weathering grade	Typical mineralogical	Typical textural change
F (Kwanak)	Less than 5% of alkali-feldspars, and 5% of plagioclase mainly at its centre are changed to sericite. 10~20% of biotite is changed to chlorite.	Rock is almost intact. Microcracks and grain boundaries are very tight.
SW(Eonyang)	5% of alkali-feldspars and 10~15% of plagioclase are changed to sericite. 15~25% of biotite is changed to chlorite. Some microcracks and grain boundaries are slightly iron-stained.	Rock is almost intact. Microcracks and grain boundaries are very tight.

Weathering grade	Typical mineralogical	Typical textural change
MW (Bulam)	5~10% of alkali-feldspars and 15~20% of plagioclase are changed to sericite and clay minerals. 25~30% of biotite is changed to chlorite and clay minerals. Some microcracks and grain boundaries are slighly iron-stained.	intra-granular microcracks are moderately developed(0.4~4mm spacing, 0.4~2mm length). Intra-granular microcracks and grain boundaries are relatively tight. Inter-and trans-granular microcracks are slightly developed(1.5~2.5mm spacing, 4~10mm length), and they tend to be slightly open up to 0.1mm.
HW (Pusan)	35~45% of alkali-feldspars and 55~65% of plagioclase are changed to sericite and clay minerals. 60~70% of biotite is changed to chlorite and clay minerals. Some microcracks and grain boundaries are slightly to moderately iron-stained.	Intra-granular microcracks are highly developed(0.3~0.8mm spacing, 0.3~3mm length). Intra-granular microcracks and grain boundaries tend to be slightly open up to 0.05mm. Inter- and trans- granular microcracks are moderately to hightly developed(1~3mm spacing, 3~3mm lengh), and they are generally open to 0.05~0.4mm.



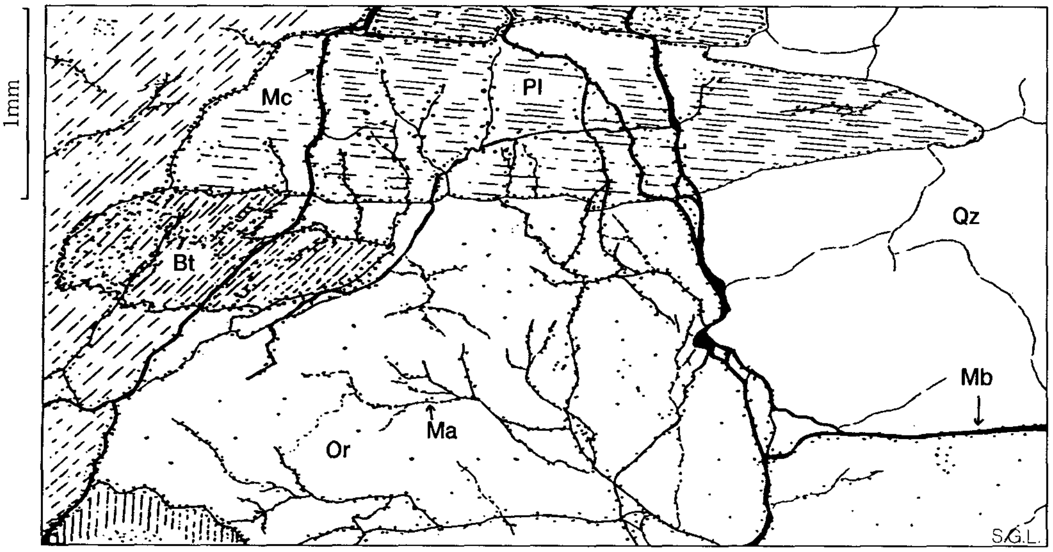
(a)

2(a) Sample of fresh(F) granite from Kwanak. Quartz(Qz), orthoclase(Or), plagioclase(Pl) and biotite(Bt) are essentially unchanged, having tight crytallographic boundaries and very few microfractures. This specimen has an air-dried uniaxial compressive strength (UCS) = 176 MPa and saturated UCS = 167MPa.



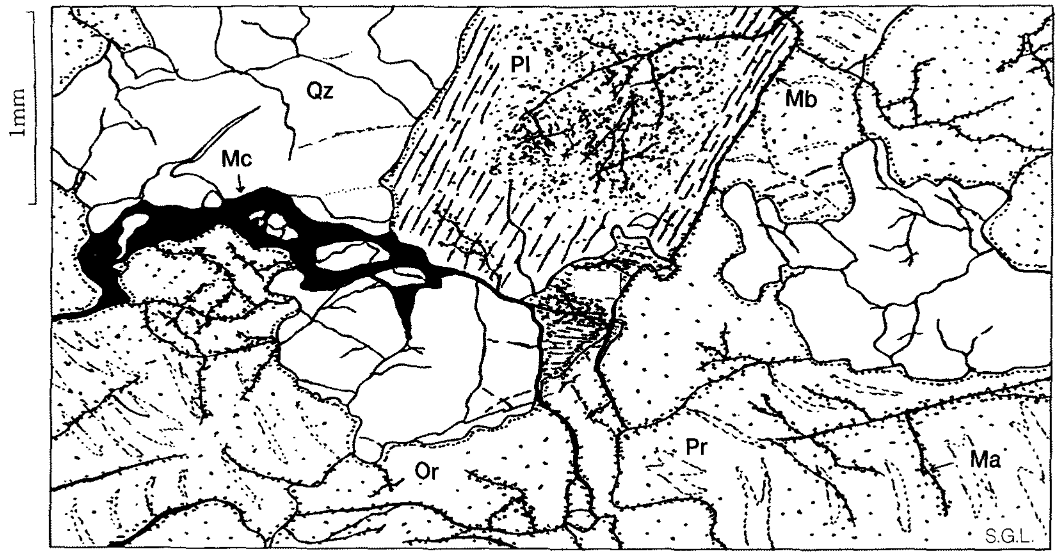
(b)

2(b) Sample of slightly weathered(SW) granite from Eonyang. The field of view is dominated by the feldspar perthite(Pr) exhibiting typical perthitic texture but traversed by a rudimentary network of tight intra-granular microcracks(Ma). These are also visible in the crystals of quartz(Qz). Plagioclase(Pl) also contains these microcracks and further, exhibits noticeable alteration at its core. This specimen has an air-dried UCS = 145 MPa and saturated UCS = 105MPa.



(c)

2(c) Sample of moderately weathered(MW) granite from Bulam. All the crystals are now invaded by a well developed and anastomosing network of intra-granular microcracks(Ma), but these are generally tight. Of greater significance are the inter-granular(Mb) and trans-granular(Mc) microcracks because they are more continuous and have a greater aperture than the intra-granular microcracks. Alteration is well established along these microcracks and the grain boundaries. Cleavage in the plagioclase(Pl) and biotite(Bt) crystals is no longer clearly visible. This specimen has an air-dried UCS = 58 MPa and saturated UCS = 33 MPa.



(d)

2(d) Sample of highly weathered(HW) granite from Pusan. Orthoclase(Or), perthite(Pr), plagioclase(Pl) and quartz(Qz) are shown and dissected by an intense network of microcracks. Intra-granular microcracks(Ma) are extensive and inter-granular microcracks(Mb) are well developed, each type also being open and providing sites for chemical alteration in the feldspars where cleavage is now indistinct. Trans-granular microcracks(Mc) assume considerable importance as they are continuous and open, often by up to 0.4mm. It is the presence of the trans-granular microcracks which frequently prevents this weathered material being from recovered as cores by conventional equipment.

Fig 2. The four weathering grades of granite recorded in Table 2. Chemical weathering is indicated by an ornament of dots, the intensity of which reflects the intensity of weathering:

4. Laboratory Testing

4.1 Equipment and Method

The compressional wave velocities through these samples were measured using a Potable Utlrasonic Non-destructive Digital Indicating Tester(PUNDIT), model Mark IV manufactured by CNS Electronics Ltd. This equipment generates high voltage(1000V) pulses of short duration(54 KHz) which cause a transmitting transducer, that is mounted at one end of the specimen to emit compressional waves. The waves travel through the sample and arrive at a receiving transducer mounted at the opposite end of the specimen to respond to their arrival. Their travel time can be measured, with an accuracy of 0.1 microseconds. The travel time is divided by the length of the specimen measured in the direction of wave propagation to obtain a value of wave velocity. Normally measurements of length are made only once because it is assumed that the volume of the specimen does not change. This is true provided the moisture content of the specimen is not changed during the test.

Many investigators have found that the velocity of propagation of compressional waves in the axial direction of a core or cubic sample, increases as the load in that direction increases(Birch, 1960; Deere and Miller, 1966; King, 1966; Ramana and Venkatanarayana, 1973; Wyllie et al, 1958; Wyllie et al, 1956). Further, care has to be taken when testing specimens with high attenuation properties, such as HW rocks, because results become unrepeatable at low axial stress. Experience has shown that the axial loads which must be applied through transducers to obtain repeatable values of velocity increase as the weathering increases. In the tests repeated here an axial load of 0.2MPa was necessary to obtain repeatable results from the specimens of HW material, and this load was used for testing all the specimens.

4.2 Control of Moisture Content

Each of the samples tested was oven-dried at 105° C for 24 hours and then individually removed from the oven and immediately weighed: this is taken as the oven-dried weight. The samples were then placed in a dessicator and permitted to cool to room temperature.

To increase their degree of saturation each sample was then submerged in distilled water for a period, being removed at intervals, dried of surface water and weighed. The moisture content was calculated from the difference in weight between the sample as measured and its oven-dried weight. From this the degree of saturation is calculated by expressing the difference in weight as a percentage of the total porosity of the specimen. Measurements of total porosity were obtained using the method prescribed by the ISRM(1979) and the following formula; Nt=(SG-Dd)/(SG) x 100%: where Nt=total porosity; SG=Specific gravity of the minerals, here calculated using the density bottle method(ISRM, 1979); Dd=dry density, based on oven-dried weights. Table 3 records the specific gravity, total porosity and dry density values of the specimens tested.

Table 3. The specific gravity, total porosity and dry density of the specimens tested.

Location & type of weathering grade	Specific gravity	Total porosity(%)	Dry density (g/cm^3)
Bulam			
F	2.648	1.51	2.608
SW	2.645	2.65	2.575
MW	2.642	3.67	2.545
HW	2.640	8.34	2.420
Honjae			
F	2.641	1.70	2.596
SW	2.640	3.37	2.551
MW	2.635	5.16	2.499
HW	2.634	9.45	2.385
Kwanak			
F	2.646	1.28	2.612
SW	2.643	1.70	2.598
MW	2.633	4.29	2.520
HW	2.634	8.27	2.416

Location & type of weathering grade	Specific gravity	Total porosity(%)	Dry density (g/cm^3)
Palgong			
F	2.673	2.06	2.618
SW	2.664	2.59	2.595
MW	2.658	3.50	2.565
HW	2.640	11.71	2.331
Eonyang			
F	2.662	1.96	2.610
SW	2.655	3.02	2.575
MW	2.647	4.87	2.518
HW	2.645	9.64	2.390
Pusan			
F	2.650	2.63	2.580
MW	2.647	5.60	2.500
HW	2.638	13.84	2.273

No difficulty was encountered in raising the degree of saturation to about 30 to 45% for F material, 40 to 62% for SW samples, 50 to 67% for MW granite and 68 to 82% for HW material, but beyond that it was necessary to apply a vacuum of 0.5 torr(70N/m^2) for up to 24 hours in order to obtain a continued increase in saturation. The maximum levels of saturation achieved were 43 to 60% for F material, 54 to 75% for SW granite, 73 to 87% for MW granite and 88 to 96% for HW granite. It is presumed that most of the water acbsorbed by the specimens travels through and is stored within the network of microfractures within them(see Fig. 2) but the exact location of the water within the specimens is not known.

4.3 Use of Vaseline

Vaseline was applied to the ends of each specimen immediately before a measurement of compressional wave velocity was made to provide a good acoustic contact between the transducers and the specimen. This is in accordance with the ISRM method suggested for compressional wave velocity measurement(1978). It was evident that this vaseline progressively invading the specimens for a dark zone could be seen extending 3mm to 10mm into the core from either end of each sample. To quantify this invasion the oven-dried weight of each specimen was remeasured after the tests for compressional wave velocity with increasing moisture content were complete: i.e. after each sample had been taken to its maximum degree of saturation. This revealed that an amount of vaseline(of unit weight 8.33 KN/m^3) had been adsorbed in accordance with a saturation by water of 2 to 3% for F specimens, 2 to 5% for SW samples and 5 to 7% for MW granite and these values reflect the accuracy with which the degree of saturation is known in the work reported here.

It is unfortunate that the ISRM method(1978) recommends the use of vaseline and other compounds of similar character in these measurements because it confuses the values of moisture content which are calculated for the specimens. This can create an error of significant proportions when seeking a correlation between compressional wave velocity and strength at low moisture contents, when a large change in strength can be expected to accompany a small change in moisture content(Colback and Wiid, 1965). Uriel and Dapena(1978) have observed the difficulties created by vaseline and have proposed the use of a rubber or similar material as a suitable substitute. The presence of vaseline also corrupts the measurement of compressional wave velocity through a specimen. The velocity of compressional wave transmission through the vaseline used in this work was 1520m/sec at 25° C, i.e. slightly higher than the velocity of distilled water(1480 m/sec). Figure 3 shows the effects of vaseline on compressional wave velocity.

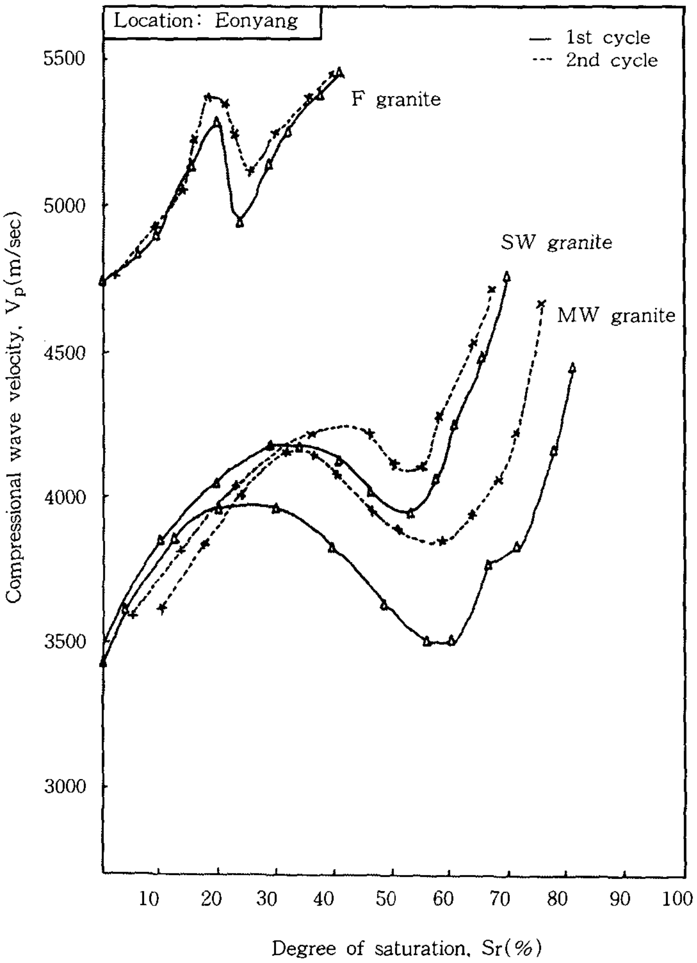


Fig 3. Variation in velocity of compressional waves in fresh(F) to moderately weathered(MW) granites from Eonyang with degree of saturation in the first and second cycles of increasing saturation with distilled water. Note how samples on their second cycle could not be returned to degrees of saturation obtained on their first cycle: i.e. they could not be 'dried-out' because vaseline had invaded and they could not be saturated to the same degree because vaseline now occupied some of the voids.

Here are shown typical results for two complete cycles of saturation on samples of F, SW and MW granite. The results for the second cycle repeat the general form of those for the first cycle, but a noticeable difference in absolute values of velocity becomes apparent in the more weathered samples. This is attributed to the presence of vaseline, its greater invasion in the more weathered material(which has greater porosities than their less weathered counterparts: Table 3) giving the samples progressively greater velocities. It is most unlikely that repeatable measurements can be obtained from porous or fractured samples when testing using vaseline.

4.4 Results

In general terms the difference in velocity measured in oven-dried samples and samples at their maximum degree of saturation increases with increasing grade of weathering. Figure 4 illustrates the velocities measured in oven-dried and air-dried samples and in samples taken to their maximum degree of saturation: note that 'air-dried' here means a sample that has been oven-dried at 105° C for 24 hours and then left to stand in free air for 72 hours.

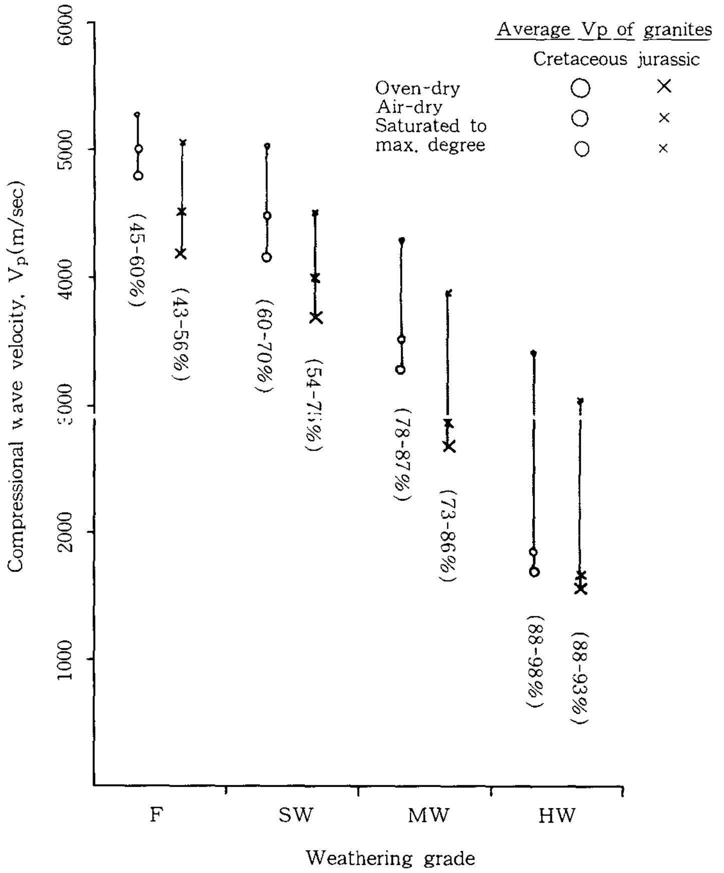


Fig 4. Variation of compressional wave velocity with weathering in oven-dry, air-dry and saturated samples of granite, the average of three measurements being shown in each case. Values in brackets indicate the maximum degree of saturation obtained in this work.

The trend shown arises from two basic causes: an increase in porosity with weathering and an increase in moisture content with saturation. The major granite forming minerals(Table 1) have compressional wave velocities in the range 5800 to 6250m/sec(Fourmaintraux, 1976), whereas air and air-filled voids have velocities of 340m/sec. Hence the attenuation of compressional wave velocities increases as the rock becomes more porous. The velocity of transmission within distilled water is 1480m/sec and hence voids filled with water support higher velocities of transmission than those filled with air. Thus velocities increase with increases in saturation, the greatest increase occurring in the most weathered material as the greatest difference in moisture content exists between oven-dried and saturated states. Note that the samples of Cretaceous granite are finer grained than those of Jurassic granite and have higher velocities at any weathering grade and degree of saturation, a character in agreement with the findings of Omi and Inoue(1975) and Lama and Vutukuri(1978).

When seen in more detail the measurements of compressional wave velocity with increased moisture content illustrate a non-linear and consistent variation: Figure 5 illustrates a typical set of results, in this case, those obtained from samples of granite collected from Eonyang.

The curves varying from about 4700 to 5400m/sec record the values from samples of F granite: those from about 3600 to 4700m/sec represent the values obtained from the SW granite: those from 3300 to 4350m/sec are typical for the MW samples, and those in the range 1450 to 3250m/sec are the values for HW samples of granite. Hence the greater the weathering the lower the velocity of wave transmission.

Therefore, it can be appreciated that it is not always easy to distinguish the weathering grade of a material from a measure of compressional wave velocities alone(e.g. SW grade from MW grade in Fig.5), and further, that if such a separation is sought it is best to use samples at their maximum degree of saturation. Under these conditions the effect of random microfractures on velocities is minimal. From them it can be seen that the weathering index provided by the ratio of velocities between fresh and weathered samples of the same material(as suggested by Illiev(1966) and given by$(V_{fresh}-V_{weathered})/V_{fresh}$) is obviously going to be very sensitive to the degree of saturation of the samples used, and very irregular in its value. All such indices should be calculated using samples taken to their maximum degree of saturation.

Another feature of considerable interest revealed by these results is the manifestation of anisotropy with increasing degrees of weathering. Figure 5 illustrates the results obtained from the four grades of weathering in the Eonyang granite. The samples of F, SW and MW material were visibly isotropic, but the samples of HW material were visibly anisotropic due to parallel microcracks of 0.5 to 2cm in spacing and 0.05 to 0.3mm in opening, as illustrated in Figure 5. The velocities of transmission differed markedly with direction of propagation but this difference decreases once the degree of saturation exceeds approximately 50%, and eventually the difference becomes negligible. Even when texture appears isotropic to the naked eye, the specimens revealed a degree of variation by their velocities of wave transmission(which is higher in oven-dried state than maximum degree of saturation), and such results serve as a warning that more than one sample should be measured of any material, even though the material may be seen isotropic before the

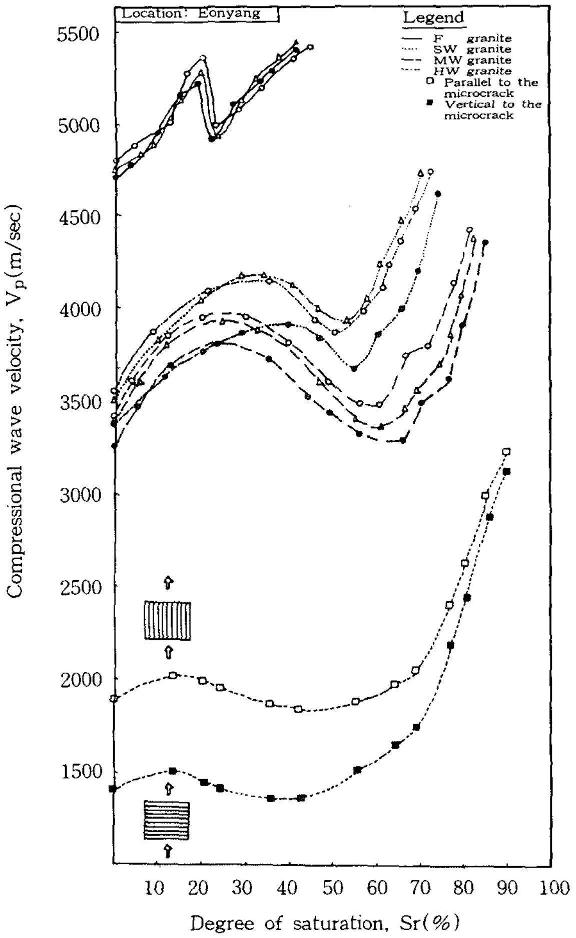


Fig 5. Variation of compressional wave velocity with degree of saturation in fresh(F) to highly weathered(HW) granites from Eonyang. Two sets of results are shown from the HW samples because in these samples microcracks were visible to the naked eye. Specimens tested with their visible sets of microcracks oriented parallel to the direction of compressional wave propagation transmitted at greater rates than those with their microcracks oriented across the propagation path. This difference in velocities reduces the more when cracks are filled with water.

range of velocities and its use as an index to design parameters such as strength and deformation can be accurately known.

Figure 5 illustrates a non-linear relationship between compressional wave velocity and degree of saturation. The majority of previous research does not report such trends(Broch, 1974; Dortman and Magid, 1969; Nur and Simmons, 1969; Ramana and Venkatanarayana, 1973; Thill and Bur, 1969; Thill et al, 1973; Wang et al, 1975) but simply record an erratic increase in velocity with increase in saturation. The relationship shown in Figure 5 appeared in all the tests completed and has been noted(always with surprise) to occur in similar measurements made by some others (Dobereiner, 1984; Omi and Inoue, 1975; Uriel and Dapena, 1978; Wyllie et al, 1956). As saturation increases, the velocity of transmission increases as well only to decrease later and increase again. It is obvious from the ubiquity of this response that these changes in velocity of transmission must reflect same fundamental character of a rock and if understood could almost certainly be utilized for a more precise characterization of rock behaviour.

4.5 A possible Explanation

It has been long established that hard rocks such as granite are capable of volumetric expansion when saturated(Duncan, 1969; Hockman and Kessler, 1950; Nascimento et al, 1968). Further, Uriel and Dapena(1978) illustrated the nature of this expansion(Fig. 6).

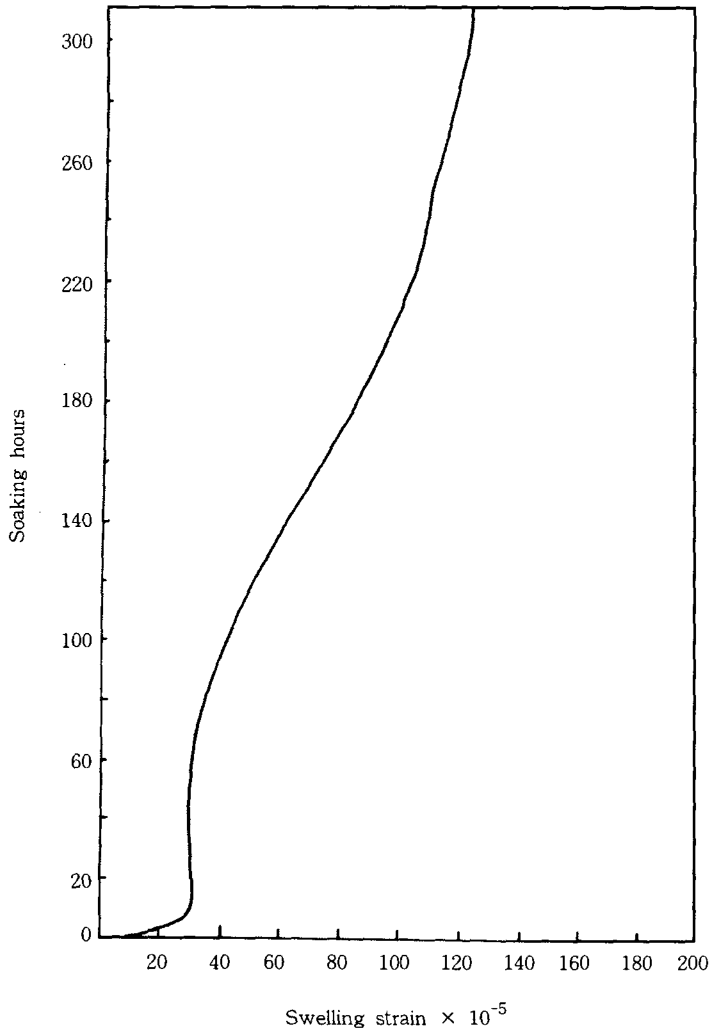


Fig 6. Variation of axial swelling strain with time in the unconfined swelling tests on a specimen of moderately weathered(MW) granite, measured by Uriel and Dapena in 1978.

An initial period of accelerated expansion is followed by a pause in expansion and a recommencement of expansion to significant degrees of volumetric strain, far more than that occurred initially. This has generally been explained by recourse to capillary water entering easily accessible pores and fissures, the subsequent hydration of minerals and the later penetration of water into the smaller voids of the sample. The results of the compressional wave velocity tests must be considered against this background.

This paper intends to introduce to this appreciation the established concepts of pendular, funicular and capillary stages used by hydrologists to describe the progressive saturation of an initially dry, porous material. The pendular stage exists when sufficient moisture enters a sample for an annulus of water to exist around all points of contact between solid surfaces, in shape rather like doughnuts. The voids within the sample remain largely full of air. The funicular stage is reached when, with continued intake of moisture, water forms a continuous film covering all surfaces. The voids still contain air but every volume of air is completely surrounded by water. The capillary stage commences when sufficient moisture enters the sample to fill the voids completely, reducing the sample to a fully saturated condition, but with pore water pressure at lower than atmospheric values. The 'suctions' within samples so wetted are accurately described by a measure of their moisture potential(pF), defined as the logarithm of the head of water(in centimetres) equivalent to the force required to draw water from a sample, (e.g. 10cm head = pF 1), and measurements of pF made on partially saturated geological materials indicate that substantial suctions can exist within them(West, 1986). The lowering of these suctions will obviously enhance any tendency which a specimen may have to expand. By combining the concepts of Versluys(1916) with the observations of Uriel and Dapena(1978) a rational explanation of the variation of compressional wave velocity with saturation may be proposed. This is illustrated in Figure 7.

Figure 7a records the typical variation in wave velocity through a sample which is receiving increasing amounts of water. Six points are noted: (1) the initial velocity; (2) the period of velocity increase; (3) the first maxima; (4) the following period of decrease; (5) the minima; and (6) the final period of velocity increase. Figure 7b schematically illustrates the possible physical meaning of these events with reference to a material whose voids are essentially microfractures.

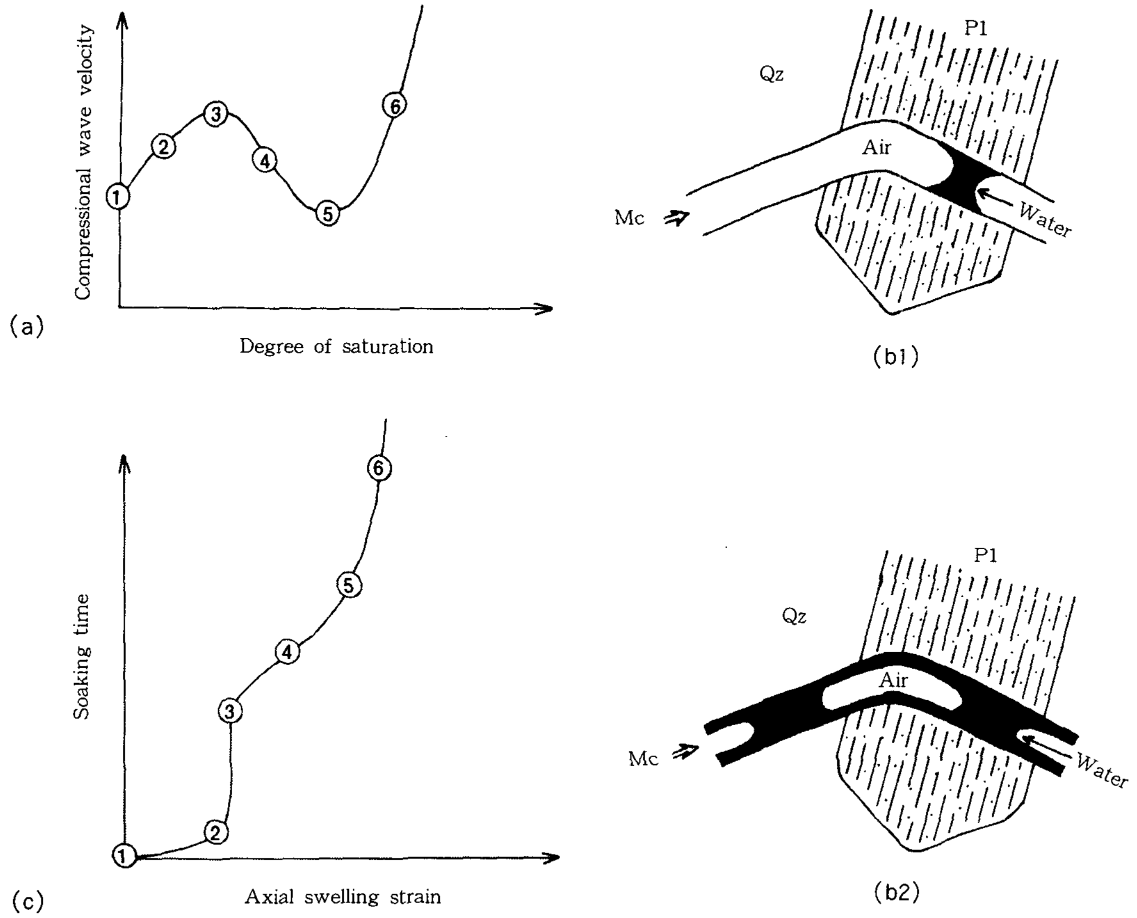
Three events will be occurring concurrently as the degree of saturation increases, viz.

(i) the load across points of contact between solid surfaces will change depending on the capillary forces around them;

(ii) hydration and expansion will occur on minerals with access to water; and

(iii) attenuation of compressional waves across voids will decrease as the voids become increasingly full of water.

The results illustrated in Figures 7a and c suggest that the relative contributions of these effects change with increasing degrees of saturation. The initial velocity(1) in Figure 7a reflects the attenuation of compressional waves through the fractured media. With the ingress of moisture, part of this fracture network is filled with water. A pendular stage must be envisaged with water around the points of contact between the solid surfaces providing an increase in the load across them(Fig. 7b1). Some hydration is probably occurring at sites where water is present and some decrease in



7(a) illustrates the general response of compressional wave velocity through a sample whose degree of saturation is gradually being increased(see Fig. 5 and Appendix B).

7(b) illustrates two stages in the general increase in saturation which occurs when the moisture content of a specimen is progressively increased. 7(b1) diagrammatically illustrates the pendular stage in a trans-granular microcrack(Mc) intersecting crystals of quartz(Qz) and plagioclase(Pl): see Figs. 2(a-d) for real textures. These sites of pendular water pull the surfaces of the crack towards each other and act as bridges for the transmission of compressional waves. 7(b2) similarly illustrates a later stage in the process of saturation when funicular water coats all surfaces but entraps air.

7(c) illustrates the axial swelling strains measured by Uriel and Dapena in 1978 and their possible relationship to the velocities measured and shown in 7(a). It is suggested that the conditions noted by numbers 1 to 6 in 7(a) and 7(c) are concurrent.

Fig 7. Four schematic diagrams to illustrate an explanation for the results obtained.

the attenuation across the fracture network occurs as water displaces air. The net result of these events is a gradual increase in velocity with increasing saturation as shown at point. (2) in Figure 7a and some swelling at point(2) in Figure 7c.

There will come a time when sufficient moisture has entered a specimen for all its fracture surfaces to be coated with water, as in the funicular stage, and as shown in Figure $7b_2$. In theory, the moisture potential reduces significantly at this stage, thus lowering the load across the points of contact between solid surfaces and likewise, reducing any internal resistance to the forces of expansion which may exist within the material. These can be expected to increase significantly now that moisture exists on all surfaces so permitting hydration to occur without restriction. Note that from Figure $7b_2$ how easily expansion can occur at this stage for compressible pockets of air surrounded by less compressible volumes of water which provide space for swelling strains to occur. All this continues as the degree of saturation continues to increase but from the results obtained (Fig. 7a) it appears that expansion eventually becomes a dominant factor(from(3) onwards) for the velocity of wave transmission decreases, stage(4), even though air is increasingly displaced by water. Unfortunately there is a degree of uncertainty in our results for these stages because degree of saturation was calculated based on the assumption that the volume of the sample does not change. Therefore, the precise nature of the relationship between wave velocity and saturation is not known. It is possible to mention that the decrease in compressional wave velocity noted as stage(4) and its associated increase in swelling may indicate the period when the degree of saturation is not increasing because the rate of swelling is keeping pace with, if not exceeding, the rate at which water is accepted by the sample.

With time, and increased acceptance of water, velocities of propagation do begin to increase in stages (5) and (6), and this is almost certainly due to the continued replacement of air by water within the sample. Swelling continues also in stage (6), owing to the presence of this water.

4.6 Potential Future Use

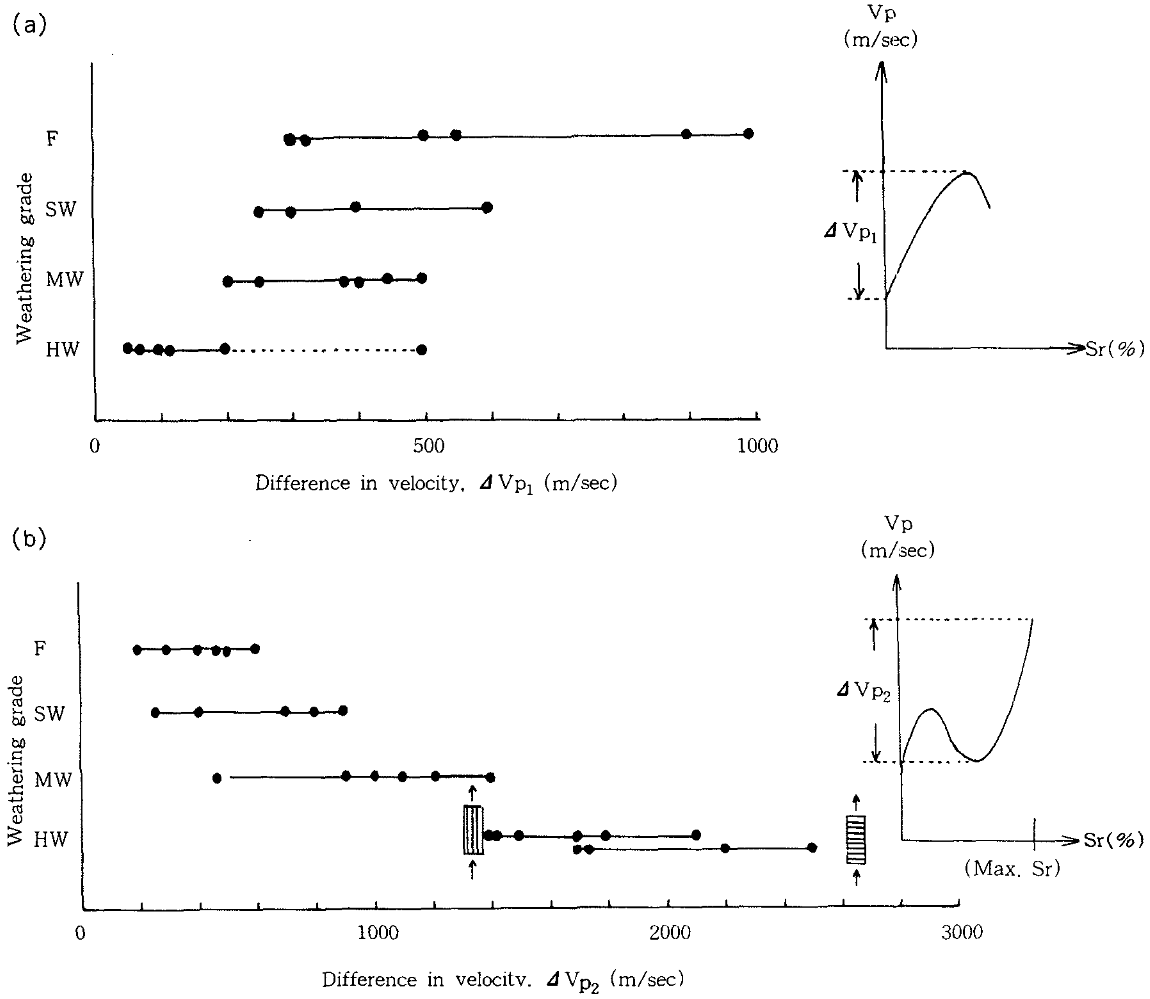
Reference to Figure 5 illustrates other features which betray the causes of the velocity variations measured and their potential use: these are listed as follows:-

(i) the sharpness of the initial rise in velocity of compressional wave propagation with increasing degree of saturation for samples ranging from F to HW grades;

(ii) the magnitude of that rise;

(iii) the magnitude of the final increase in velocity of compressional wave propagation for these samples.

The sharpness of the initial rise is generally greatest with the freshest samples indicating their immediate response to the presence of water, the more weathered samples being sluggish in this matter. The magnitude of this response is illustrated in Figure 8a where again the greater reactivity of the fresher samples can be seen.



8(a) The difference between the initial velocity and the first maxima, number 3 in Fig. 7 being greatest for the freshest materials.

8(b) The difference between the trough, number 5 in Fig. 7 and the final maxima measured at the maximum degree of saturation that could be achieved. Two ranges are shown for the highly weathered(HW) samples: one for velocities measured when visible microcracks are parallel to the direction of propagation and another with the microcracks lying across that direction.

Fig 8. The differences in velocity of compressional wave transmission(Vp) with increasing degree of saturation(Sr) for all materials tested: dots record actual results.

The degree of saturation required to reach the initial maxima is shown in Figure 9a and it is interesting to note that although the response of the HW samples stands out from that of the rest, the differences between the samples are far less noticeable when measured by their degree of saturation than by their compressional wave velocities(Figs. 4, 5, 8a). However it is apparent from Figure 9 that a much lower degree of saturation was required to bring the HW samples to a condition where expansion(as marked by the first maxima) begins to dominate their performance.

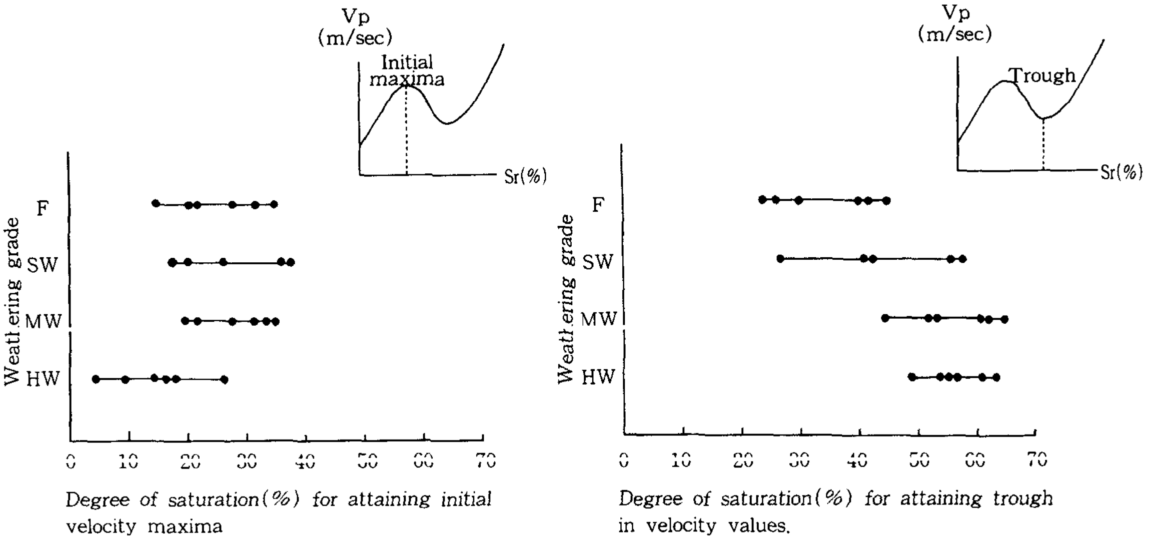


Fig 9. The difference in degree of saturation(Sr) required to achieve the first maxima (a) and the trough (b) in velocities of compressional waves for all materials tested: dots record actual results.

All these lines of evidence imply that the initial velocity maxima reflects a delicate state of balance between forces which operate to keep a rock specimen intact and those which operate to destroy it, and further suggest that the measurement of compressional wave velocities of a sample whilst its level of saturation is being increased may provide a route for obtaining an indication, if not a value, of the relic stresses within it.

The final increase in velocity is also of interest. Figure 8b illustrates the difference in the wave velocity of the samples during this phase. The most weathered samples responded with the greatest differences and this is likely to reflect the greater volumes of water which they can hold at their maximum degree of saturation. Figure 9b illustrates the degree of saturation for the onset of this phase, which generally increases as weathering increases.

5. Conclusion

The velocity of transmission of compressional waves through samples of granite varies in a non-linear and repeatable fashion with increasing degrees of sample saturation. Thus:

(i) measurements of compressional wave velocity, made as an index to correlate with other geomechanical properties, should always be accompanied by a measurement of the degree of saturation of the sample.

(ii) Further, the scatter of results obtained from such measurements is at its minimum when the samples have been taken to their maximum degree of saturation.

(iii) In addition, the velocities measured become more sensitive to the weathering state of the minerals comprising a sample, as distinct from the fractures and voids within it, as the degree of saturation increases. It is therefore recommended that velocity measurements should be undertaken on saturated samples.

In completing this work severe difficulties were created by following the ISRM methods suggested for the measurement of compressional wave velocities. It is recommended that vaseline and similar coupling materials should not be used as they invade the samples and change their properties. It is also recommended that the swelling of samples being saturated should always be measured as their dimensions change and are not constant: hence calculations of degree of saturation can be erratic.

An explanation of the variation in velocity with increase in degree of saturation has been attempted by combining these results with the observations on the swelling of granite with increasing saturation and the progressive saturation of a porous medium. From this it is suggested that a measure of the compressional wave velocity with increasing sample saturation is capable of responding to a delicate state of balance between the forces that operate to keep a rock specimen intact and those which operate to destroy it, and thus provide a route for obtaining an indication, if not a value of the relic stresses within it.

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