Effect of Pore Water on the Behavior of a Sand under High Pressures

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Abstract

A series of the results of triaxial tests on a quartz-rich sand under high pressures is presented, and the effect of pore water on the compressibility and the shear characteristics of the sand is investigated mainly from a mechano-chemical viewpoint.

It is shown that pore water increases the compressibility and decreases the shear strength of the sand under high stresses, that is, the water sensitivity of the sand has a close relationship with the surface energy change of cracks which are produced in each particle under high stresses.

Introduction

A number of studies have been made on the shear characteristics of particulate materials under high confining pressures. However, only a few studies were contributed to the effect of pore water on the high pressure behaviors of the particulate materials, and several problems which must be clarified have been still remained.

Lee et al.[1] conducted a series of drained shear tests on Antioch sand, and showed that the strength of the sand was remarkably decreased by the presence of water. It was considered that the water sensitivity of Antioch sand was mainly due to the existence of cracks which contained thin films of clay. However, Lee et al. also suggested that the presence of clay film in cracks might not be a necessary criterion for the water sensitive behavior of a granular soil, but the presence of cracks themselves might be one of causes of water sensitivity.

One possible mechanism in the effect of water on the high pressure behavior of a granular material may be that water reduces the surface energy of cracks which will be grown at the contact parts of adjacent particles under high stresses. This point of view was suggested by a number of investigations in the field of so-called "mechano-chemistry[2]."

Orowan[3] presented an equation relating the failure strength of an ideal brittle material, which contains the pre-existing cracks, to the surface energy α in the form:

$$\sigma=\sqrt{E\alpha/2c}$$

where, σ: tensile strength of a brittle material, E: Young's modulus, and c: depth of surface crack. In the right-hand side of above equation, the values of E and c are both unlikely changed with the variation of environmental conditions[2]. This equation

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suggests, therefore, that the surface energy change caused by a variation of environmental condition directly affects the failure stress of a brittle material.

In the previous paper[4)], the authors presented a set of results of high pressure triaxial test on the saturated samples of Toyoura sand, together with a limited number of test results on the dry samples. Thereafter, a number of additional experiments were performed on the dry sand, for the purpose of comparative investigation of the effect of pore water on the high pressure behavior of the sand. In this paper, various differences of mechanical properties between dry and saturated Toyoura sand will be discussed mainly from a mechano-chemical veiwpoint.

Tests

Since the detail descriptions of the physical properties of Toyoura sand and also the procedure of shear test appeared in the previous paper by the authors[4)], the explanations of them are limited, in this paper, to the necessary subjects.

Toyoura sand consists of three main mineral ingredients; quartz 79.7%, chert 3.1%, feldspar 16.7%, with a small amount of magnetite, amphibole, and pyroxene. Water senstitive minerals[5)] could not be found in the sand but very small fraction of mica of 0.03%. Each grain has an intermediate angularity, and no particles seem to be very weak.

The sand was once dried at 105°C and then cooled in a desiccator for about one day, which was used as the "dry" sand in this paper. The moisture content of the "dry" samples were scattered between 0.06% and 0.10%, when they were examined just after shear tests.

Two kinds of the samples of different densities were prepared, namely, the dense sample having an initial void ratio of $e_i \simeq 0.61$ and the loose one $e_i \simeq 0.83$. The shear test performed was so-called "CD test" in which a sample was confined at a constant hydrostatic pressure and was allowed to drain druing shear.

A typical set of the results from the compression and shear tests was tabulated in Table 1. By comparing these experimental data of dry samples with these of saturated ones (see Tables 3 and 4 in reference 4), some considerations will be made in the following sections.

Effect of Pore Water on the Mechanical Properties of Toyoura Sand under High Stresses

Compressibility

The proportion of volumetric strain of saturated sample to that of dry sample is shown in Fig. 1 which indicates the compressibility of saturated sand being higher than that of dry sand.

Each value for the volumetric strain described in Table 1 includes, to be exact, an elastic recoverable volumetric strain and also a value due to membrane penetration into the space of the sand[6)]. However, the large portion of each value given in the Table is obviously due to the non-recoverable contraction of the soil skelton, and hence it may be considered that the non-recoverable volumetric strain is mostly resulted from

Table 1. Results of drained triaxial tests at constant confining pressures on dry samples.

σ_3 (kg/cm^2)	e_i	e_c	v_c (%)	ε_c (%)	Values at the time of failure						
					$(\sigma_1-\sigma_3)$ (kg/cm^2)	ε_{if} (%)	v_f (%)	e_f	$\left(\frac{\sigma_1}{\sigma_3}\right)$	$\left(\frac{dv}{d\varepsilon_1}\right)$	ϕ_s (deg.)
500	0.61	0.43	11.0	3.6	1222	38.1	14.8	0.23	3.44	−0.03	33.4
〃	0.61	0.44	10.7	3.6	1230	37.1	15.3	0.24	3.46	−0.02	33.5
〃	0.83	0.45	20.7	6.7	1259	40.6	15.9	0.24	3.52	−0.04	33.9
〃	0.83	0.43	22.1	7.4	1259	39.3	15.2	0.23	3.52	−0.04	33.9
300	0.60	0.48	7.5	2.1	735	38.4	15.6	0.27	3.45	0.04	33.4
〃	0.83	0.53	16.5	5.0	759	43.1	19.1	0.26	3.53	0.00	33.9
200	0.59	0.54	5.0	1.3	465	37.1	12.9	0.33	3.33	0.07	32.6
〃	0.60	0.51	5.5	1.4	465	40.0	13.3	0.32	3.33	0.07	32.6
〃	0.85	0.61	12.9	3.0	497	47.0	21.0	0.31	3.48	0.04	33.7
〃	0.83	0.61	12.1	3.2	495	47.0	20.3	0.32	3.47	0.04	33.6
150	0.60	0.54	4.0	1.6	352	37.5	11.7	0.37	3.35	0.09	32.7
〃	0.60	0.54	4.0	1.1	354	35.7	11.2	0.37	3.36	0.10	3.28
〃	0.84	0.65	10.1	2.6	360	48.0	20.9	0.34	3.40	0.07	33.0
〃	0.85	0.66	10.1	2.5	363	48.9	21.0	0.35	3.42	0.08	33.2
125	0.62	0.56	3.8	1.1	290	37.5	10.7	0.40	3.32	0.10	32.5
〃	0.60	0.54	3.6	0.9	287	32.9	9.2	0.41	3.30	0.11	32.3
〃	0.86	0.69	9.1	1.7	303	51.1	20.8	0.37	3.42	0.00	33.2
〃	0.83	0.68	8.4	1.9	299	48.0	20.3	0.37	3.39	0.09	33.0
100	0.61	0.56	3.2	0.9	227	27.4	7.0	0.46	3.27	0.13	32.2
〃	0.60	0.55	3.2	0.8	230	27.4	6.4	0.46	3.30	0.13	32.3
〃	0.84	0.71	7.0	1.6	235	47.0	19.2	0.42	3.35	0.13	32.7
〃	0.83	0.70	7.2	1.5	241	47.0	19.7	0.40	3.41	0.10	33.1
75	0.62	0.57	2.9	1.1	167	22.3	4.1	0.51	3.22	0.11	31.8
〃	0.61	0.56	2.8	0.7	170	22.3	4.3	0.50	3.27	0.11	3.22
〃	0.86	0.74	6.4	1.1	173	47.0	17.2	0.46	3.31	0.11	32.4
〃	0.83	0.73	5.5	1.2	174	47.0	16.4	0.47	3.31	0.13	32.4
50	0.61	0.57	2.4	0.3	128	11.5	0.8	0.56	3.54	−0.03	34.1
〃	0.83	0.74	4.6	0.8	114	39.3	11.4	0.55	3.28	0.12	32.2
25	0.60	0.57	1.7	0.4	77	7.3	−1.2	0.59	4.08	−0.31	37.3
〃	0.61	0.58	1.7	0.3	78	7.8	−1.3	0.60	4.11	−0.34	37.5
〃	0.82	0.77	3.1	0.5	58	20.8	3.6	0.70	3.33	0.04	32.5
〃	0.84	0.78	3.1	0.4	59	20.2	3.7	0.71	3.37	0.05	32.7

Notation; e_i: initial void ratio, e_c: void ratio after compression, v_c: volumetric stain due to hydrostatic pressures, ε_c: axial strain due to hydrostatic pressures, ϕ_s: secant angle defined by $\sin^{-1}[(\sigma_1-\sigma_3)/(\sigma_1+\sigma_3)]_f$.

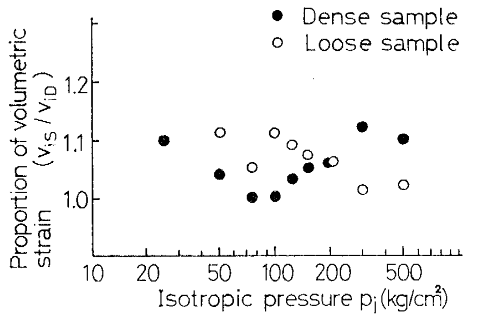

Fig. 1 Proportion of volumetric strain of saturated sample v_{iS} to that of dry sample v_{iD}.

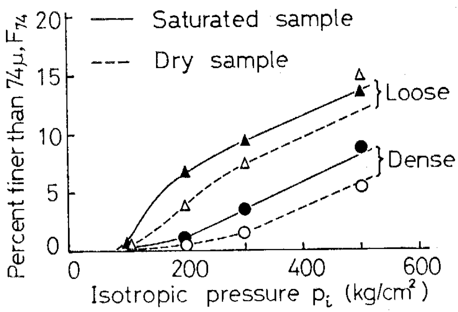

Fig. 2 Comparison of the amount of particle-crushing F_{74} between saturated sample and dry sample, under various isotropic pressuers.

the particle-crushing. Referring the results shown in Fig. 1, it was expected that the saturated sand would be crushed more strongly than the dry sand, provided that the test conditions were the same. On the basis of an assumption that the percent of the total weight of a sample passing the 74 micron sieve F_{74} indicates an amount of particle-crushing[7], a relationship was examined between the value of F_{74} and the isotropic pressure p_i. It can be seen from the results obtained, which is given in Fig. 2, that the particle-crushing was considerably facilitated by the presence of water. The relationship between the amount of particle-crushing F_{74} and the volumetric strain v_i was as shown in Fig. 3. It should be noted in this figure that $v_i \sim F_{74}$ relationship seems to be dependent of the initial density but independent of the presence of pore water. This probably indicates that pore water actually reduced the fracture strength of the sand particles. This phenomenon may be explained from a mechano-chemical viewpoint as follows; at the contact parts of adjacent particles, some cracks are induced by high stresses, and the pore water surrounding a particle penetrates into a fresh crack and reduces the surface energy of it, making ease the crack splitting.

Shear characteristics

The proportion of the maximum deviator stress of a saturated sample to that of the dry sample under the same stress condition, was as illustrated in Fig. 4, showing

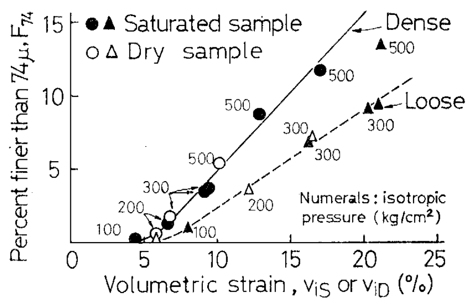

Fig. 3 Relation curves between amount of particle-crushing F_{74} and volumetric strain v_i, due to isotropic pressure.

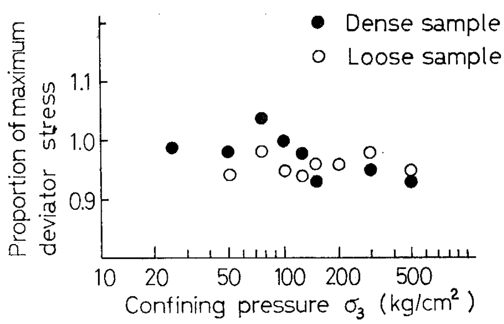

Fig. 4 Proportion of maximum deviator stress of saturated sample $(\sigma_1 - \sigma_3)_{fS}$ to that of dry sample $(\sigma_1 - \sigma_3)_{fD}$.

the former being smaller by several percent than the latter at the confining pressures tested. The difference of volume change characteristics at failure between the two kinds of samples of different moisture conditions are also shown in Fig. 5. This figure illustrates that a dry sample shows a greater tendency of dilatation than a saturated sample does, at the time of failure. For the investigation of a particle-crushing during shear, F_{74} is again adopted together with F_{10}, the weight percent finer than 10 micron. Besides, it is assumed that the amount of particle-crushing during shear can be expressed

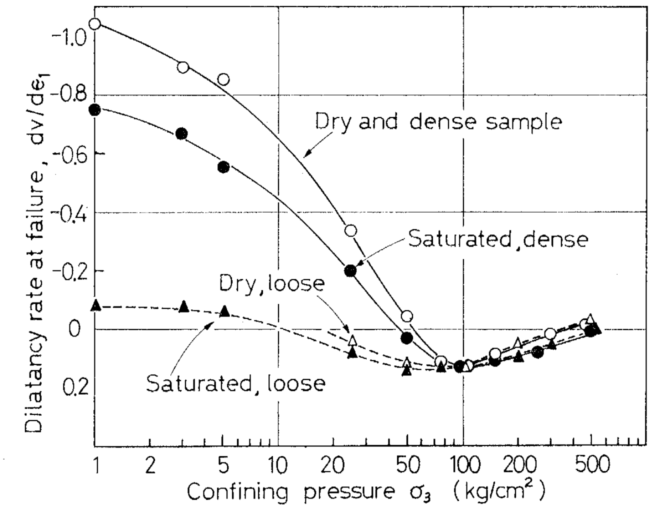

Fig. 5 Volume change characteristics of sampls at failure under various confining pressures.

by the difference of the two values of F which were measured before and after a shear test,denoting ΔF_{74} and ΔF_{10}. Relation curves between ΔF_{74} or ΔF_{10} and confining pressure are given in Fig. 6. It is seen from this figure that the difference of ΔF_{74} curves between dry samples and saturated samples is relatively small, while the values of ΔF_{10} of dry samples are remarkably larger than that of the saturated samples. Based on these results, it is suggested that the crushing mechanism of the wet particles may be different from that of the dry, that is, the wet particles tend to be carcked at the contact parts of adjacent particles and crumbled into relatively large fractions, whereas the dry particles tend to be disintegrated rather by scraping off the angular parts than by splitting. The different aspects of particle-crushing between dry particle and wet particle may be as illustrated in Fig. 7. The interpretation of particle-crushing mechanism abovementioned can be acceptable if we suppose that the surface energy of a crack is reduced by the penetration of pore water inside the crack. Thus, it may be said that the effect of pore water on the high pressure behavior of Toyoura sand can be explained by a surface energy change inside cracks which are freshly produced at each particle surface due to high pressures.

High Pressure Behavior of Toyoura Sand under Various Kinds of Fluids

In order to verify the mechano-chemical interpretation of high pressure behavior of a saturated sand, some additional shear tests were performed on dense samples

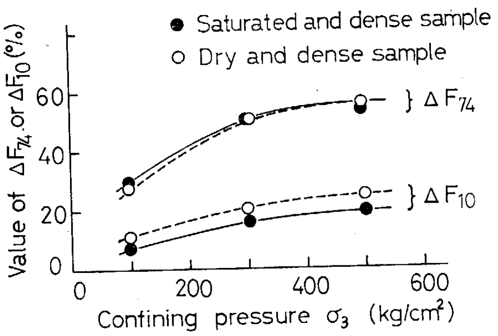

Fig. 6 Curves showing the progress of particle-crushing during shear (all samples were submitted to the same axial (natural) strain of 51%.)

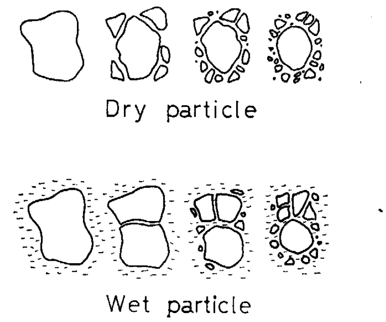

Fig. 7 Illustration of different aspects of partcile-crushing during shear between dry particle and wet particle.

which were of different pore fluid states, namely, the ethyl alcohol saturated state and the vacuum state. Ethyl alcohol is known as a liquid by which surface energy decrease of a solid being less than by water. On the other hand, in a state of sufficiently high vacuum, the surface energy dropping of a solid is virtually zero.

For the ethyl alcohol saturated samples, the test procedure was nearly the same as that of water saturated sample. The samples of a vaccum state were prepared by the following method. The sand heated up to 105°C was compacted in a mold as quickly as possible, then an oil rotary pump was connected to the sample for making a vacuum state. A vacuum of order of 10^{-3} mmHg was maintained throughout the compression and the shear tests. The confining pressure which was applied to a vacuous sample was less than each required pressure by 1 kg per sq. cm., since the atmospheric pressure worked on the specimen additionally. The volume change of a vacuous specimen could not be measured during tests because of a lack of measuring instrument.

The stress strain curves of ethyl alcohol saturated samples were compared with those of dry and saturated samples, as shown in Fig. 8, in which axial strain and volumetric strain were both expressed by natural strains. It may be seen from this figure that the alcohol saturated sample shows the intermediate strength, stiffness and dilatation at failure, between those of dry and water saturated samples.

Comparison of the strength of vacuous sample with those of the above-mentioned were listed in Table 2. Since the volume change of a vacuous sample was unknown, the conventional method of cross-sectional area correction could not be applied for the calculation of shear sterngth. Then, for the purpose of an equitable compaison between strength properties, the deviator stresses given in Table 2 were calculated by using a correction method in which only the axial strain being considered there.

It is noticed that the experimental results tabulated in Table 2 are well comparable with those presented by Hammond et al.,[8] which referred to the fracture strength of a fused silica rod in various vapors,water, ethyl alcohol, acetone and benzene, together with in a vacuum state. Hammond et al. showed that the strength of the fused silica was greatest in a vacuum state, and smallest in a water vapor. When the sample was tested in the vapor of ethyl alcohol, acetone or benzene, the strength of the fused silica

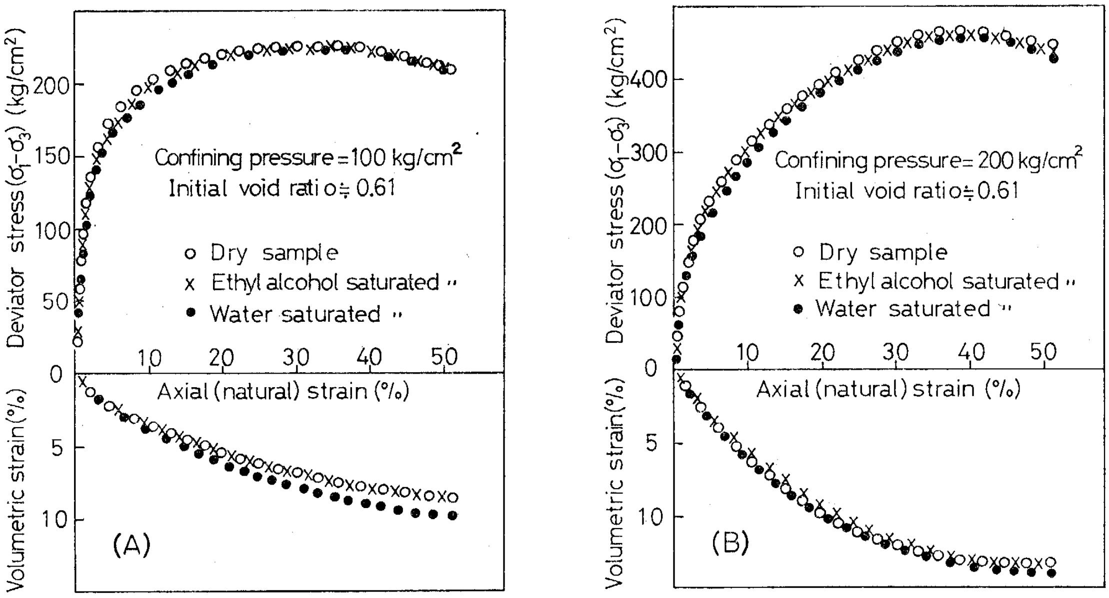

Fig. 8 Comparison of stress strain curves between different pore fluid samples.

Table 2 Maximum deviator stresses of the samples in various pore fluids.

Pore fluids	Confining pressure (kg/cm²)	Maximum deviator stress (kg/cm²)	Axial strain at failure* (%)
Water	100	207	34.2
Ethyl alcohol	100	209	32.9
Air	100	209	35.7
Vacuum state	100	220	27.4
Water	200	400	40.0
Ethyl alcohol	200	402	41.6
Air	200	407	40.0
Vacuum state	200	410	38.6

* natural strain.

was intermediate between the two extreme conditions. Furthermore, they found that there exists a consistent relationship between the lowering of the strength of fused silica and the dropping of surface energy of quartz.

In the light of the investigation above quoted, it can be said that the results shown in Table 2 also illustrate the decrease of particle strength, which implies the decrease of shear strength, due to the change of surface energy of cracks which were produced in each particle.

In order to determine how the polarity of liquid gives effect on the crushing property of Toyoura sand, simple compression tests were performed by using an instrument shown in Fig. 9. The sample used in this test had such a grading that it passed through the 210 micron sieve and left on the 149 micron sieve, which was obtained by sieving the original Toyoura sand. The heated sample of 30.0 grams was compacted in a circular ring placed on a steel plate, and was saturated with such five kinds of liquids as carbon tetrachloride,ethyl ether, ethyl alcohol, water and acetone. A constant load of 15 tons, that is 750 kg per sq. cm., was applied to each sample for 15 minutes by using a compression machine. After unloaded, the sample was put on the 74 micron sieve to be washed sufficiently by water for eliminating the liquid. The sample which was left on the sieve was submitted to a sieve analysis after dried.

The relationship between the dipole of liquid and the weight percent of the sample passing the 149 micron sieve or the 74 micron sieve, was as shown in Fig. 10. The relation curves show some different aspects from the expected linear relationship which had been suggested from an experimental results, in which Imanaka et al.[9] showed the fracture strength of an aluminum oxide being decreased with increasing of dipole of liquid. However, referring the results shown in Fig. 10, together with those shown in Table 2, it can be presumed that if a sample which is saturated by acetone or carbon tetrachloride is sheared at a high confining pressure, it will show the larger shear strength or the smaller amount of particle-crushing during shear than the sample saturated by water or ethyl alcohol will show.

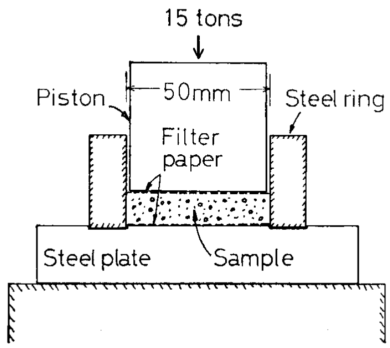

Fig. 9 Schematic diagram of the confined compression test.

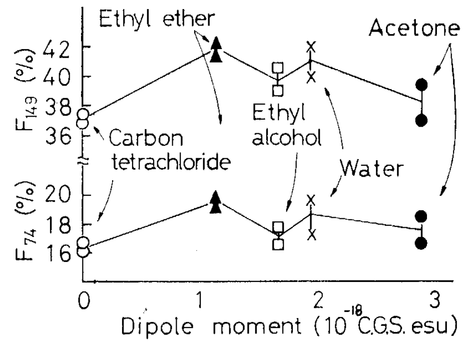

Fig. 10 Results of confined compression tests. Ordinate shows the amount of particle-crushing due to compression.

Conclusions

The effect of pore water on the high pressure behavior of Toyoura sand was investigated from a mechano-chemical viewpoint, and several findings were derived as follows.

At a high hydrostatic pressure the volumetric strain of Toyoura sand was increased several percent by the presence of pore water. In a range of volumetric strain higher than 5%, an approximately linear relationship was found between the volumetric strain and the particle-crushing, independently of the presence of pore water.

It was shown that pore water reduces the shear strength, stiffness and tendency to dilate at failure of the sand under high confining pressures. By the examination of the change of particle-crushing during shear, it was shown that the crushing mechanism of the wet particles were different from those of the dry; the dry particles tend to be crumbled into relatively large fractions, whereas the dry particles tend to be scraped off at the angular parts of them.

It was considered that the effect of pore water on such a high pressure behavior of the sand as above-mentioned, is closely related with the decrease of surface energy inside cracks which were produced in each particle under high stresses. Thus, a mechano-chemical interpretation could successfully apply to the explanation of the water sensitive behavior of Toyoura sand under high pressures.

Acknowledgement

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