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# Effect of grains roughness on waves velocities in granular packings

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**Abstract :** The effect of particles roughness on wave velocities is investigated in granular materials using bender-extender elements. The roughness of the particles was modified by a chemical degradation process of initially smooth beads. Wave velocities were calculated along isotropic stress paths from 100 to 500 kN/m<sup>2</sup> in order to compare these experimental results to theoretical predictions by Hertz or previous results presented in the literature. Our results show a little effect of the surface roughness on the longitudinal wave velocities but a notable effect on the shear wave velocities.

**Keywords:** elastic properties, glass beads, bender-extender elements, wave propagation, grains roughness, Hertz's theory

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## 1 INTRODUCTION

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Bender elements have become a very popular experimental tool in the geotechnical community to assess the shear modulus of soils in the very small strain domain through the measurement of shear wave velocities (Dyvik and Madhus, 1986 ; Brignoli *et al.*, 1996). Recently, Lings and Greening (2001) presented a new type of piezo-ceramics transducers called bender – extender elements. Such elements present the great advantage of generating both compression waves (or P-waves) and shear waves (or S-waves). Therefore, not only the shear modulus but also the Young's modulus and therefore the Poisson's ratio characterizing the Hooke's law can be determined.

Although the bender – extender elements proved their efficiency for the identification of elastic properties of many soils (sands, clays, mixtures of sand and clay ...), the accuracy of the calculated values is still debated. This is mainly due to a lack of agreement between the users as for the interpretation of the electric signals recorded during a pulse test. To partially circumvent this shortcoming, experiments were carried out on a reference granular material in which wave velocities have been already measured using different experimental methods.

The experimental results were also compared to theoretical predictions assuming the Hertz's micro-mechanical theory. The effect of the particle roughness at the grain level was more especially investigated.

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## 2 THEORETICAL CONSIDERATIONS

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Wave velocities in granular materials depend on many factors related to the individual grain properties (elastic characteristics, surface characteristics, geometry: shape and dimensions ...) and to the fabric, mainly through the density of the granular skeleton and the degree of disorder in the contact between the grains. Theoretical predictions by Hertz establish that in a 1D chain of elastic spherical beads of equal diameter, the wave velocity formally depends on the applied stress as a power law :

$$V_w \propto k \times \sigma^{1/6} \quad (1)$$

where  $k$  is a constant depending on the grain properties and the density of the granular assembly,  $\sigma$  the normal stress applied to the grains (Duffy and Mindlin, 1957). The validity of the Hertz's theory was experimentally examined by many authors (Duffy and Mindlin, 1957; Warren and Anderson, 1973; Pilbeam and Vaisnys, 1973; Goddard, 1990; Jia *et al.*, 1999; Coste, 2001). In disordered

assemblies of beads, the power law exponent usually falls in the range  $[1/4 ; 1/3]$  rather than the theoretical value  $1/6$ .

Various reasons were highlighted to justify the gap between experimental data and Hertz's theory predictions. Three of them can be emphasised. The first one, proposed by De Gennes (1996), stated that the superficial envelope of the beads is softer and therefore more compressible than the core because of oxidation for instance. The second one suggests that the imperfections at the particle surface induce conical contacts and plasticity responsible for the  $1/4$  value of the exponent (Goddard, 1990; Coste and Gilles, 1999). The third reason put forward the disorder of the contacts between the grains (Coste and Gilles, 1999; Anfosso, 2003) which can be due to a slight dispersion in the diameter of the particles.

### 3 EXPERIMENTAL PROCEDURE

The glass beads Vattac Sig10-12 used in this study have a diameter ranging from 1 to 1.2 mm. The specific weight of the beads made of silica, determined by the pycnometer method, is  $25.5 \pm 0.2 \text{ kN/m}^3$ .

Photos of the original glass beads were taken using a scanning electron microscope (Fig. 1). These photos show that the glass beads present a spherical shape and a smooth surface, even if some defects are visible. Isotropic compression tests on these intact glass beads were conducted to assess the evolution of the wave velocities as a function of the mean effective stress. The results will be subsequently described.

The glass beads were then corroded by attack of hydrofluoric acid with a molarity of 22.6 mol/l. The degradation process is the following :

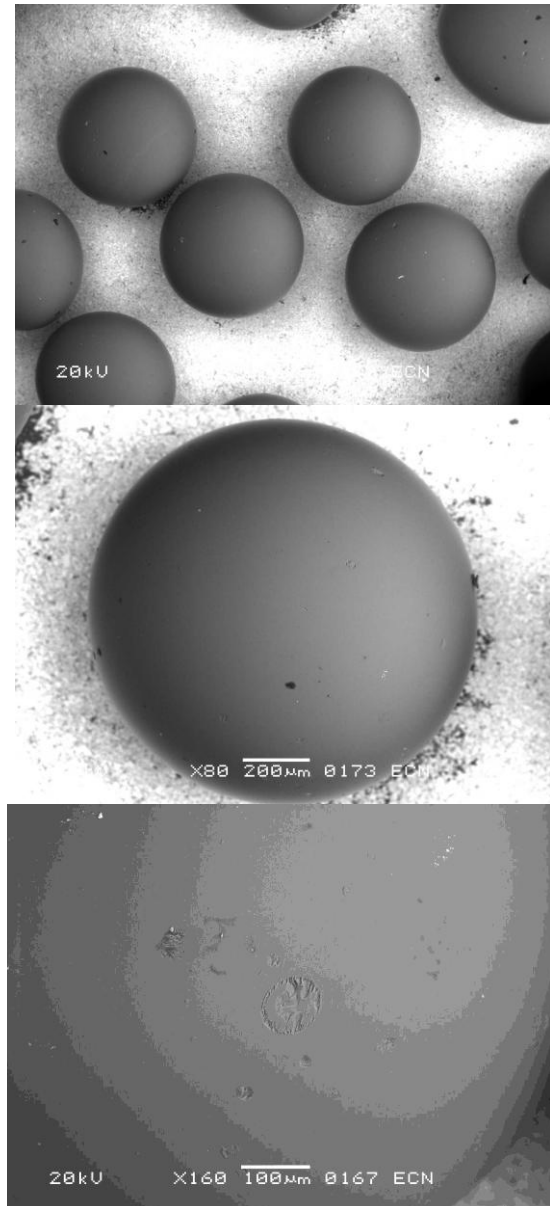
- The glass beads were plunged in water to humidify them;
- The mixture of water and hydrofluoric acid diluted at 50% was prepared in a plastic container;
- The wet glass beads were deposited in the mixture during 20 minutes;
- The acid was removed and the glass beads were cleaned under a running water flow;
- The glass beads were finally dried.

The degraded glass beads were also observed using a scanning electron microscope (Fig. 2). The irregularity of the surface and the apparition of facets are clear. However, the diameter of the particle remains greater than 1 mm. Isotropic compression tests on these degraded glass beads were also carried out to assess the effect of the degradation process on the wave velocities.

The cylindrical specimens of dry glass beads, 100 mm in diameter and about 200 mm in height, were prepared by a raining method to obtain a homogeneous and relatively dense granular material. Different settings of the raining tool enable to prepare samples at different initial void ratios (Table 1). Tests No. 1 and 4, respectively on intact beads

and degraded beads, present the same initial void ratio: they are therefore used for the comparison of the wave velocities.

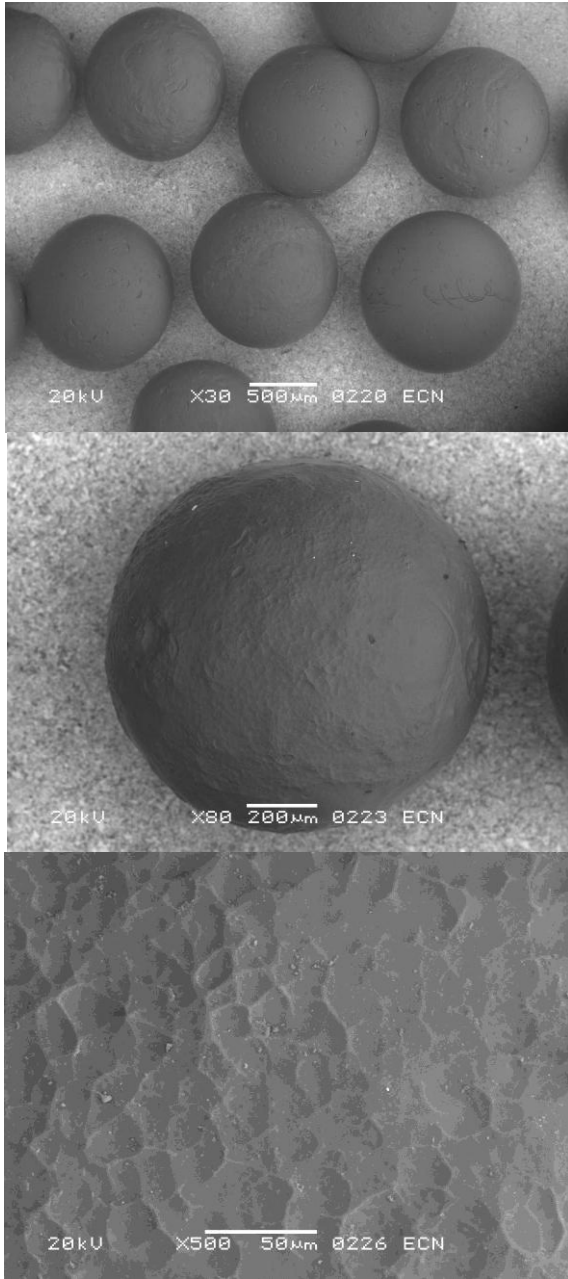
The bender – extender elements were set up in the lower and upper pedestal of the triaxial cell. They are also in direct contact with the tested material through the active part, 10 mm large, 2.5 mm high (length of penetration of the elements into the sample) and 0.5 mm wide. Bender-extender elements were also carefully aligned because of polarization and possible subsequent boundary effects.



**Figure 1** Pre-degradation scanning electron microscope imaging

Finally, the specimens were protected from the confining fluid by a thin latex membrane of 0.5 mm thickness, adding an excess stress of 0,3 kPa. The cell pressure was controlled by a Standard GDS pressure - volume controller. The beads were tested in a dry state, under drained conditions. Isotropic compression tests were carried out from 100 to 500  $\text{kN/m}^2$ . For each stress level, different wave shapes (pseudo-square or pseudo-sinus input signal) and different

frequencies (from 5 to 10 kHz) of the pulse were transmitted through the granular material. Only pseudo-sinus signals of 10 kHz in frequency and an amplitude of  $\pm 5$  V that provide the clearest output signals are presented in this paper.



**Figure 2** Post-degradation scanning electron microscope imaging

#### 4 INTERPRETATION OF PULSE TESTS

As previously mentioned, the interpretation of bender-extender elements tests is not an easy task since the physical phenomena induced by the propagation of a wave into a soil are complex. In the literature, three kinds of interpretation method can be found (Sharifipour *et al.*, 2004).

Table 1. Characteristics of the tests.

Test No.	Beads	$\gamma_d$	$e_0$	D	H
		$\text{kN/m}^3$		mm	mm
1	smooth	15.43	0.653	97.1	198.1
2		15.52	0.643	96.5	197.9
3		16.57	0.539	97.6	197.8
4	rough	15.42	0.653	99.1	197.7
5		15.37	0.658	97.46	197.6
6		16.32	0.562	98.25	198.4

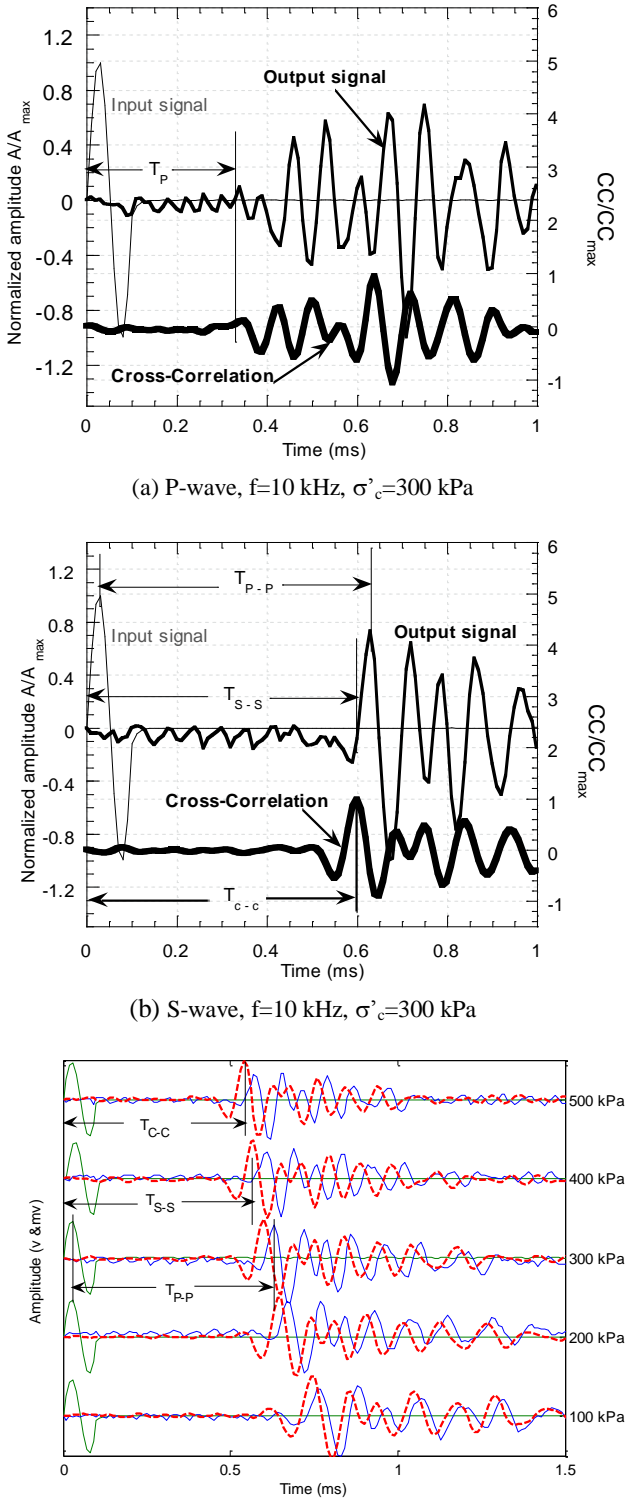
$\gamma_d$ : initial dry weight of the sample;  $e_0$ : initial void ratio, D: mean diameter of the sample; H: mean height of the sample.

The most often used and most robust method (time analysis) consists in identifying the travel time of the wave from the recorded electric signals. For a P-wave, the first deflection of the output signal corresponds to the arrival of the wave on the receiver (Fig. 3a). For a S-wave, near-field effects and distortion of the signal occur and make the determination of the travel time difficult (Jovicic *et al.*, 1996; Brignoli *et al.*, 1996). Practically, two travel times can be defined. The peak-to-peak travel time  $T_{P-P}$  is the delay between the first peaks of the input signal and the output signal as shown in Fig. 3b and 3c (denoted  $T_{P-P}$  for glass bead under a pressure of 300 kPa). That value has to be considered as a reliable estimate of the travel time under certain circumstances. The start-to-start travel time  $T_{S-S}$  is the delay between the beginning of the input signal and the time that corresponds to the arrival of the S-wave on the receiver (Fig. 3b and 3c).

The second method consists in comparing the input and the output signals by cross-correlation (Viggiani and Atkinson, 1995; Mohsin and Airey, 2003). The travel time  $T_{C-C}$  corresponds then to the time that fits at best the two signals. Examples are shown in Fig. 3b and 3c under pressure of 500 kPa.

The third interpretation method (frequency analysis) is based on Discrete Fourier Transformations in order to analyze the frequency spectrum of the signals (Mancuso *et al.*, 1989; Theron *et al.*, 2003). Group velocity and phase velocity can be then determined.

In this study, cross-correlation was used to give a first indication of the possible travel time of the shear wave. The peak-to-peak travel time was also considered as an indicator. The travel time used for the calculations of the wave velocities is therefore the start-to-start time as currently done in the literature. Moreover, the travel length is the tip-to-tip distance between the tips of the two transducers (total length of the sample minus the length of penetration of the bender – extender elements into the sample) ((Viggiani and Atkinson, 1995; Jovicic *et al.*, 1996; Brignoli *et al.*, 1996). Therefore, the velocity is calculated as the ratio between the travel length and the travel time.



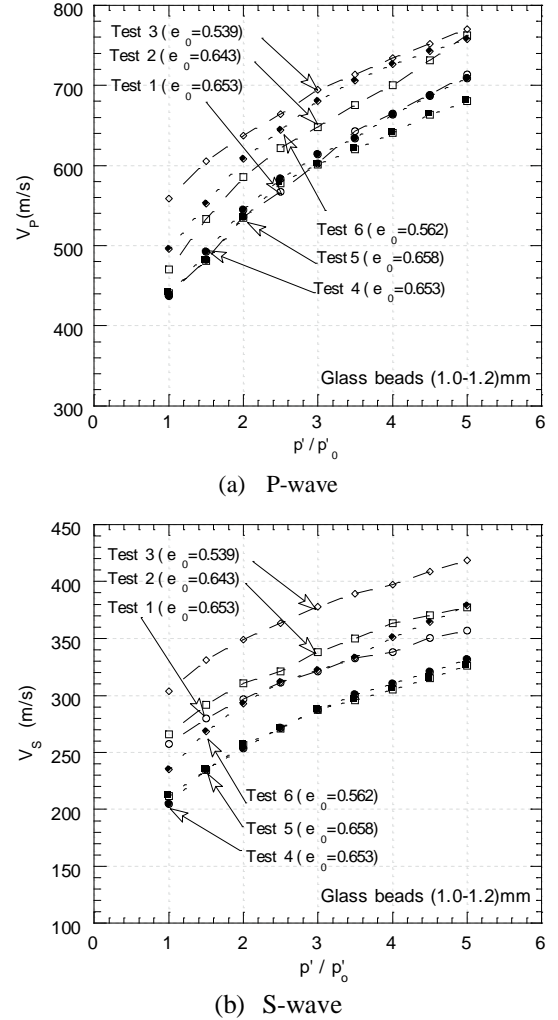
(c) Evaluation of arrival time in function of pressure for S-wave

**Figure 3** Examples and interpretation of signals during Test No. 1

## 5 EXPERIMENTAL RESULTS

The isotropic compression tests (Fig. 4) clearly show the effect of the void ratio: the denser the granular skeleton is,

the greater the velocities. The effect of the grain surface characteristics on the wave velocities is also obvious, in particular for the tests No. 1 and 4 carried out at the same void ratio. The degradation of the grain surface induces a significant decrease of the velocities of the shear waves whereas the effect seems to be minor for the velocities of the compression waves.



**Figure 4** Comparison of wave velocities

Those experimental data were fitted by a power law defined by two parameters  $k$  and  $n$  as following:

$$\left( \frac{V}{V_{ref}} \right) = k \times \left( \frac{p'}{p'_{ref}} \right)^n \quad (2)$$

where  $V_{ref}$  is the velocity of the wave at the effective pressure  $p'_{ref}$  (here  $p'_{ref} = 100$  kPa). That formula is suitable for both P-waves and S-waves. The values of the exponent are collected in Table 2. While the exponent for the P-waves is not very affected by the chemical degradation, a clear increase of the exponent characterizing the shear waves is noted.

Table 2. Values of the exponent n.

Test No.	Beads	P-wave	S-wave
1	smooth	n = 0,31	n = 0,20
2		n = 0,29	n = 0,22
3		n = 0,20	n = 0,20
4	rough	n = 0,30	n = 0,30
5		n = 0,28	n = 0,27
6		n = 0,27	n = 0,28

## 6 COMMENTS

The decrease of the shear wave velocities while the grain surface is rougher is not a new fact. It was previously observed by Santamarina and Cascante (1998) on high-tolerance steel spheres, about 3.2 mm in diameter, by resonant column tests: the shear wave velocities were divided by a factor close to 2 between clean spheres and corroded spheres. They also showed that the velocities were the same on loading stages and unloading stages during isotropic compression tests for clean spheres. On the contrary, the corroded spheres exhibit a different behavior during a loading stage and an unloading stage for which the velocities are lower. Nevertheless, Santamarina and Cascante (1998) presented relatively low values of the velocity – stress exponent n (Eq. 2). The value of n was 0.14 to 0.15 for clean spheres on both loading and unloading stress paths, which was lower than the theoretical value  $n = 1/6 (\approx 0.167)$  predicted by the Hertz's theory. For corroded steel balls, the exponent was 0.16 on a loading stress path and 0.22 on an unloading stress path. The difference is therefore less obvious than in the experiments presented in this paper. However, the results obtained by Santamarina and Cascante (1998) could be explained by the preparation of the tested samples. Indeed, gypsum was used to improve the coupling between the device and the sample: it probably gave a small cohesion at the ends of the sample that could induce a decrease of the exponent value n.

Jia and Mills (2001) performed acoustic tests on similar glass beads than those used in this study. They prepared their samples in dense states by layer wise deposition and tapping of dry beads, or sometimes by compaction with a very small amount of a solid lubricant. They compared the velocities of P-waves and S-waves of intact dry glass beads and intact lubricated glass beads. They showed that the lubrication induces a slight increase of the velocities and the P-waves velocities are more affected by the lubrication than the S-waves velocities. Their experimental data are fitted by power laws (Roux, 2004): the exponent value was close to 1/6 for shear waves and close to 0.25 for P-waves.

The coefficients found in this study are slightly greater but the order of magnitude is relevant. The discrepancy between the theoretical value of the power law exponent and the fitted experimental data could be due either to the nature of the contacts (from a spherical contact to a conical contact respectively from the intact glass beads to the degraded

glass beads) or to the disorder of the contacts favored by the occurrence of facets on the grains surface and by the slight scattering in the grain size distribution of the glass beads (between 1 and 1.2 mm).

The different exponents for the compression waves and the shear waves also mean that the Poisson's ratio does not remain constant along an isotropic stress paths. The Poisson's ratio can be determined from the velocities of both P-waves and S-waves:

$$\nu = \frac{1}{2} \times \frac{V_P^2 - 2V_S^2}{V_P^2 - V_S^2} \quad (3)$$

The evolution of the Poisson's ratio for the intact and degraded glass beads is plotted in Fig. 5. For the intact glass beads, the dependence of the Poisson's ratio with the mean effective stress is gradually reduced while the granular skeleton is denser.

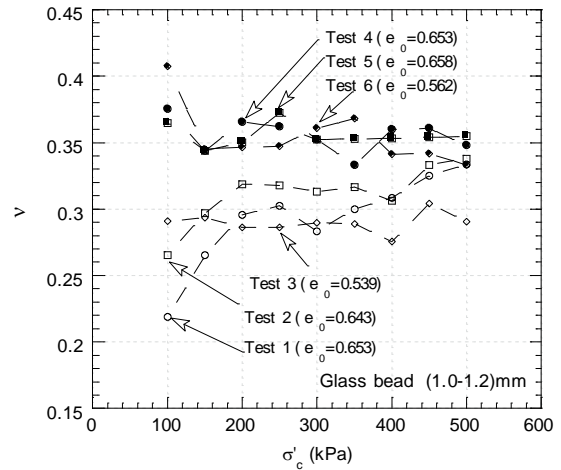


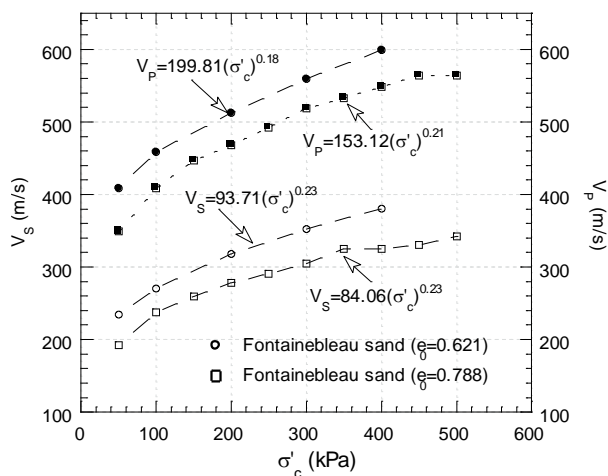
Figure 5 Evolution of the Poisson's ratio in glass beads

The trend was in accordance with previous experimental results by Aubry *et al.* (1982) for which the Poisson's ratio can increase with the stress level. However, that dependence should be related to the density of the granular packing and the ability for the grains to move: here, for the densest packing, the value of the Poisson's ratio is almost constant. For the degraded beads for which the main part of contacts should be conical contacts, the movement should be also limited: therefore, the value of the Poisson's ratio is greater (less compressible material) and remains constant or even slightly decreases. In any case, it is worth noting that the Poisson's ratio tends to a similar value for the greatest stress levels.

The roughness of the particles is a key parameter for the wave velocities. However, some other parameters could mainly affect these velocities : grain size distribution, quantity of fine particles, mineralogy and angularity of the particles, soil history and stress path ... The figure 6 shows the results obtained in a sample of purely siliceous Fontainebleau sand composed of sub-angular grains (mean diameter: 210 μm, Hazen's coefficient: 1.4). The value of the velocity – stress exponent is between 0.18 and 0.23,



very close to the values obtained in the case of the intact spherical glass beads. It means that the velocities have to be related to the ability for the granular packing to create or cancel grain contacts during loading.



**Figure 6** P-waves and S-waves velocities in Fontainebleau Sand

## 6 CONCLUSION AND FUTURE WORK

Those results reveal that the surface characteristics of the grains in a packing of beads do have a significant effect on the shear wave velocities but a negligible effect on the compression wave velocities. This effect is sensitive on the absolute value of the velocities but also on the evolution of the velocities with the mean effective pressure.

Any process that could change the grain surface (either degradation or lubrication) probably induces a change in the contacts between the grains and also modify the grain ability to slide or roll on the neighboring particles. Plane-to-plane contacts oppose against the movement of the grains whereas lubricated spherical contacts favors that movement.

In any case, it is worth noting that the Poisson's ratio tends to a similar value for the greatest stress levels.

The velocities have to be related to the ability for the granular packing to create or cancel grain contacts during loading.

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