



Experimental study of acoustic memory in mechanically compacted granular materials

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Abstract. This study investigates acoustic memory and post-loading acoustic relaxation in mechanically compacted granular materials. The objective was to determine whether acoustic measurements can characterize changes in the mechanical state of a granular packing and retain information about its previous loading history. Experiments were performed on granular assemblies subjected to controlled mechanical compaction at different strain levels. Acoustic signals transmitted through the packing were recorded after loading and analyzed in terms of signal amplitude, dominant frequency, spectral entropy, and relaxation behavior. Repeated loading cycles were additionally used to evaluate the development of acoustic memory during mechanical conditioning. Mechanical compaction produced a progressive increase in the stress response, accompanied by a rise in acoustic RMS amplitude from 0.797 ± 0.020 to 1.049 ± 0.055 mV. The dominant frequency increased from 19.83 ± 0.11 to 21.00 ± 0.12 kHz, while spectral entropy decreased from 2.85 ± 0.04 to 2.37 ± 0.06 , indicating increasing concentration of acoustic energy around the dominant spectral components. The characteristic relaxation time increased from 36.6 ± 3.7 to 70.7 ± 6.4 s, whereas the stretching parameter decreased from 0.934 ± 0.022 to 0.742 ± 0.029 , demonstrating progressively slower and more heterogeneous relaxation. The acoustic memory index increased from approximately 0.84 to 0.92 during repeated conditioning cycles. The results indicate that the measured acoustic parameters can provide a non-destructive means of tracking both the instantaneous mechanical state and loading history of granular materials. The combined analysis of amplitude, frequency, spectral entropy, and relaxation provides a practical framework for monitoring mechanical conditioning and memory in disordered granular media. A Friedman test for the repeated-cycle measurements gave $\chi^2(4) = 18.40$, $p = 0.0010$, with Kendall's $W = 0.92$.

Keywords: granular materials, acoustic memory, mechanical compaction, acoustic relaxation, spectral entropy, non-equilibrium dynamics.

1. Introduction

Granular materials are collections of discrete solid particles whose macroscopic behavior emerges from the interactions between individual grains. They are encountered in natural systems such as soils, sediments, and fault zones, as well as in industrial processes involving powders, pellets, pharmaceutical particles, and bulk solids. Unlike homogeneous solids, granular media can continuously rearrange their internal contact network when subjected to mechanical loading. As a result, their stiffness, density, stress transmission, and wave-propagation characteristics depend not only on the instantaneous applied load but also on the previous mechanical history of the material [1], [2], [3], [4]. This history dependence is particularly important in compacted and cyclically loaded granular systems, where irreversible particle rearrangements can produce persistent changes in the packing structure.

Mechanical compaction progressively changes the network of interparticle contacts and the distribution of forces within a granular assembly. At small strains, the response may be dominated by elastic deformation of existing contacts, whereas larger deformation can involve sliding, rolling, rearrangement, and irreversible structural changes. Recent experiments have demonstrated that cyclic

compression can produce distinct translational and rotational memory of previous loading, with friction playing an important role in determining the persistence of this memory [1]. Direct three-dimensional measurements have further shown that rotational and contact-point motions can remain irreversible even when the overall deformation appears cyclically reversible, emphasizing the importance of microscopic contact rearrangements in the mechanical response of granular media [5]. Similar structural effects have been observed in cyclic loading studies in which macroscopic behavior was related to the evolution of the contact network and energy dissipation [6].

Acoustic measurements provide a potentially sensitive means of probing these structural changes without directly disturbing the granular packing. Acoustic waves propagate through a granular medium via the network of particle contacts, and therefore their velocity, attenuation, spectral content, and mode structure can be influenced by packing density, contact stiffness, particle properties, and applied pressure. Experimental measurements of small-strain shear-wave properties have shown that wave-based measurements are sensitive to particle characteristics and stress state, including the anisotropy of the granular contact structure [7]. Similarly, experimental studies of granular vibrations have demonstrated that the response of a granular bed depends strongly on particle arrangement and excitation conditions [8]. These findings indicate that acoustic observables can provide information about internal mechanical states that are not necessarily accessible from macroscopic stress measurements alone.

Recent research has increasingly explored acoustic methods for characterizing granular media. Researchers investigated the acoustic properties of randomly packed granular structures using micro-computed tomography and demonstrated that the acoustic response is strongly related to the geometrical characteristics of the packing [9]. Authors developed a poro-elastic model for predicting sound propagation through granular materials and validated the approach experimentally for different granular media [10]. Their results demonstrate that both the elastic response of the granular skeleton and the internal pore structure must be considered when describing acoustic propagation. More recently, Scientists experimentally measured the granular density of vibrational modes from the acoustic response generated by an impact. Their measurements showed that low-frequency modes and spectral features change with applied pressure, providing direct evidence that the acoustic spectrum contains information about the mechanical state of a granular packing [11]. Experiments on impulsive excitation have also shown that granular packings can support qualitatively different propagation regimes, ranging from weakly nonlinear acoustic waves to strongly nonlinear shock waves as excitation intensity increases [12].

Acoustic methods have also been applied to mechanically induced changes and failure in granular systems. Other authors simultaneously measured ultrasonic velocity and acoustic emission during oedometric compaction of cemented granular materials and demonstrated that acoustic measurements can identify changes associated with inelastic compaction and the formation of compaction bands [13]. In model granular materials, acoustic signatures have been detected immediately before extreme mechanical failure, demonstrating that acoustic signals can reflect structural changes occurring during progressive loading [14]. Acoustic-emission measurements have likewise been used to distinguish different rheophysical regimes in granular flows, showing that the temporal and statistical characteristics of acoustic activity can provide information about changes in the mechanical state of the material [2]. These studies establish the sensitivity of acoustic measurements to granular structure, but most have focused on either failure processes, acoustic emission events, wave velocity, or externally imposed dynamic excitation rather than on the evolution of a controlled acoustic response during quasistatic mechanical conditioning.

The mechanical memory of granular materials represents a related but less developed problem. A granular packing may retain information about previous loading even after the external load has been removed. Experimental and numerical work on three-dimensional cyclic compression has shown that previous compression amplitudes can be encoded in the particle configuration [1]. Subsequent investigations of cyclic loading have demonstrated that irreversible rearrangements, frictional sliding, and contact-network evolution influence the transition between reversible and irreversible behavior [5], [6]. Other experimental studies have shown that cyclic loading can produce

persistent changes in granular systems over many loading cycles, while constitutive approaches increasingly incorporate memory variables to reproduce stress-history effects [15]. However, these approaches generally characterize memory through mechanical variables, particle trajectories, or constitutive parameters. A direct acoustic measure of the stored mechanical history of a dry, noncohesive granular packing remains comparatively underexplored.

An additional unresolved issue concerns the interpretation of acoustic changes during mechanical conditioning. Acoustic amplitude, dominant frequency, spectral bandwidth, and other signal characteristics may respond simultaneously to changes in contact stiffness, packing density, scattering, and dissipation. Consequently, a single acoustic parameter is unlikely to provide a complete description of the evolving granular state. Recent work on granular acoustics has primarily emphasized wave velocity, attenuation, density of vibrational modes, or acoustic-emission activity [9], [10], [11], [12], [13], [14]. These approaches provide valuable information but do not fully address whether a combination of time-domain and frequency-domain acoustic descriptors can distinguish the instantaneous mechanical state from the history-dependent state of a compacted granular packing. Furthermore, the relaxation of the acoustic response after mechanical loading has received considerably less experimental attention than the immediate response during loading.

The present study addresses this gap by considering acoustic response as a multidimensional indicator of both mechanical conditioning and structural memory. Instead of relying on a single acoustic quantity, the response is characterized through acoustic amplitude, dominant frequency, spectral entropy, and post-loading relaxation. Spectral entropy is particularly useful because it describes how broadly acoustic energy is distributed across frequency components and therefore provides complementary information to the dominant frequency. The relaxation behavior is considered separately because the time required for the acoustic response to approach a stable state may reflect the redistribution and rearrangement of contacts after mechanical loading. This approach is consistent with recent evidence that granular acoustic behavior depends on contact structure and pressure, while extending the analysis toward the temporal evolution and memory of a mechanically conditioned packing [10], [11], [13].

The central hypothesis of this study is that controlled mechanical compaction modifies the interparticle contact network in a measurable and persistent manner, producing systematic changes in the acoustic response that can be used to identify both the current mechanical state and the previous loading history. Specifically, increasing compaction is expected to increase the effective contact stiffness and acoustic amplitude, shift the dominant spectral response, concentrate acoustic energy into a smaller number of spectral components, and produce slower and more heterogeneous post-loading relaxation. Repeated conditioning is further expected to progressively stabilize the acoustic response, thereby providing an experimentally measurable signature of mechanical memory.

The goal of this study is therefore to experimentally determine how controlled mechanical compaction and repeated loading affect the acoustic response of a granular packing and to establish whether acoustic measurements can quantify non-equilibrium relaxation and mechanical memory. The study combines mechanical loading with time- and frequency-domain acoustic analysis to evaluate changes in acoustic amplitude, dominant frequency, spectral entropy, relaxation characteristics, and memory during repeated conditioning. The novelty of the work lies in treating these acoustic characteristics as complementary indicators of the evolving granular state rather than as isolated measurements, thereby providing a non-destructive experimental framework for linking mechanical compaction, acoustic response, relaxation, and history dependence in disordered granular materials.

2. Methods

2.1 Granular material and sample preparation

A monodisperse granular medium composed of spherical soda-lime glass beads was used as a model disordered granular system. The particles had a nominal diameter of 1.0 ± 0.1 mm and a

particle density of approximately 2.5 g cm^{-3} . The relatively narrow particle-size distribution was selected to minimize particle-size segregation and to provide reproducible packing conditions between independent measurements. Before the experiments, the glass beads were passed through calibrated sieves to remove agglomerated particles and particles outside the selected size range. The prepared material was stored in a dry sealed container until use. The initial poured-bed height was $52.5 \pm 0.5 \text{ mm}$, corresponding to an initial packing fraction of 0.582 ± 0.006 . The laboratory temperature was $22 \pm 1 \text{ }^{\circ}\text{C}$ and relative humidity was $35 \pm 5\%$. Sieve analysis showed that 96% of the bead mass was retained in the 0.9–1.1 mm size interval.

The experiments were performed in a cylindrical acrylic cell with an inner diameter of 50 mm and a height of 100 mm. The cell was equipped with an aluminum bottom plate and a movable aluminum piston for axial compression. For each experiment, 150 g of glass beads were introduced into the cell from a fixed height of approximately 50 mm. No external vibration or tapping was applied during filling. The upper surface of the granular bed was levelled before the piston was installed.

The initial packing fraction was determined from the measured mass and packing volume:

$$\varphi_0 = \frac{m}{\rho_p V_0} \quad (1)$$

where φ_0 is the initial packing fraction, m is the mass of the granular material, ρ_p is the particle density, and V_0 is the initial volume occupied by the granular bed. The volume was determined from the measured initial packing height and the internal cross-sectional area of the cell. A separate packing was prepared for each independent experimental run to minimize the influence of previous mechanical loading. No lubricant or adhesive was introduced at the particle–wall interface.

2.2 Mechanical compaction procedure

Mechanical compaction was performed using a universal testing machine equipped with a 1 kN load cell. The piston was operated in displacement-controlled mode at a constant displacement rate of 0.5 mm min^{-1} . Force and displacement were acquired simultaneously at a sampling frequency of 100 Hz.

The mechanical protocol consisted of four consecutive stages: loading, holding, unloading, and post-unloading relaxation. During the loading stage, the piston was displaced from its initial position until the prescribed maximum displacement was reached. Four maximum nominal compressive strains, 2%, 4%, 6%, and 8%, were investigated.

The nominal compressive strain was calculated as:

$$\varepsilon = \frac{\Delta h}{h_0} \quad (2)$$

where ε is the nominal compressive strain, Δh is the piston displacement, and h_0 is the initial height of the granular bed.

After reaching the prescribed maximum displacement, the piston position was maintained for 60 s. This holding period allowed the granular packing to undergo mechanical relaxation at approximately constant deformation. The piston was subsequently returned to its initial position at the same displacement rate. After unloading, the packing was left undisturbed for 300 s to monitor the recovery of its acoustic response.

The nominal compressive stress was calculated from the measured force according to:

$$\sigma = \frac{F}{A} \quad (3)$$

where σ is the nominal compressive stress, F is the axial force measured by the load cell, and A is the internal cross-sectional area of the cylindrical cell.

The instantaneous packing height during compression was determined from

$$h(t) = h_0 - \Delta h(t) \quad (4)$$

where $h(t)$ is the packing height at time t and $\Delta h(t)$ is the measured piston displacement. The corresponding instantaneous packing fraction was calculated as:

$$\varphi(t) = \frac{m}{\rho_p A h(t)} \quad (5)$$

where m is the mass of the granular material, ρ_p is the particle density, A is the cross-sectional area of the cell, and $h(t)$ is the instantaneous packing height.

2.3 Cyclic conditioning and mechanical-memory protocol

A separate series of experiments was performed to determine whether the acoustic response retained information about the previous mechanical history of the granular packing. The packing was first subjected to five consecutive conditioning cycles with a maximum nominal compressive strain of 6%. Each cycle consisted of loading to the prescribed strain, holding the piston position for 60 s, and unloading at the same displacement rate.

After completion of the fifth conditioning cycle, the specimen was allowed to relax for 300 s without mechanical disturbance. A probe cycle with a maximum strain of 3% was then applied, followed by a second probe cycle at 6% strain.

The acoustic response during these probe cycles was compared with that of an independently prepared, unconditioned packing subjected to the same loading sequence. The unconditioned packing was used as the reference state for quantifying the effect of mechanical conditioning.

The probe deformation was identical for conditioned and reference specimens. Consequently, differences in their acoustic responses were associated with the preceding mechanical history rather than with differences in the probe loading conditions.

2.4 Acoustic excitation and detection

Acoustic measurements were performed simultaneously with the mechanical experiments. A broadband piezoelectric actuator was mounted beneath the lower aluminum plate of the cell and was used to introduce controlled mechanical disturbances into the granular packing. A piezoelectric receiving sensor was mounted on the upper plate to detect the transmitted acoustic response.

The actuator was driven by a function generator through a power amplifier. A five-cycle sinusoidal burst with a centre frequency of 20 kHz was used for all measurements. The excitation amplitude and pulse duration were maintained constant throughout the experiment. The receiving signal was amplified using a low-noise voltage amplifier and digitized with a 16-bit data-acquisition system at a sampling frequency of 200 kHz. The function-generator output was 1.00 Vpp and the amplifier provided a nominal 20 dB voltage gain, giving 10.0 Vpp at the actuator. The five-cycle burst had a nominal duration of 250 μ s at 20 kHz. The actuator voltage remained within $\pm 1.5\%$ of the target value during each measurement series. A swept-sine check gave a usable actuator response over approximately 5–100 kHz.

Acoustic measurements were performed at the initial state, after each compaction cycle, during the constant-displacement holding stage, and during the post-unloading relaxation period. Ten acoustic pulses were recorded for each experimental condition with an interval of 2 sec between consecutive measurements. The first pulse was excluded from the averaging procedure to minimize possible effects associated with actuator triggering and stabilization.

The peak acoustic amplitude was defined as the maximum absolute voltage within the selected analysis window. The root-mean-square acoustic amplitude was calculated according to:

$$A^{RM_s} = \sqrt{\left[\left(\frac{1}{N}\right) \sum_{i=1}^N V_i^2\right]} \quad (6)$$

where V_i is the measured voltage at the i -th sampling point and N is the number of sampling points within the analysis window. The same acquisition window was used for all specimens and loading states.

2.5 Frequency-domain analysis

The acoustic signals were analyzed in both the time and frequency domains to identify changes in the spectral characteristics associated with mechanical compaction. Before Fourier transformation, the mean value was removed from each signal and a Hann window was applied to reduce spectral leakage.

For a discrete acoustic signal x_n containing N samples, the Fourier transform was calculated as:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-\frac{i2\pi kn}{N}} \quad (7)$$

where X_k is the complex Fourier coefficient, x_n is the acoustic signal at the n -th sampling point, k is the frequency-bin index, and N is the total number of samples. The corresponding spectral power was calculated as:

$$P_k = |X_k|^2 \quad (8)$$

The dominant frequency, f_d , was defined as the frequency corresponding to the maximum spectral power:

$$f_d = \operatorname{argmax} P(f) \quad (9)$$

The spectral bandwidth was determined from the frequency interval containing 90% of the integrated spectral power. The lower and upper limits of this interval corresponded to cumulative spectral-power fractions of 0.05 and 0.95, respectively.

2.6 Spectral entropy analysis

Spectral entropy was used to characterize the redistribution of acoustic energy among the frequency components. The spectral power was first normalized according to:

$$p_i = \frac{P_i}{\sum_{j=1}^M P_j} \quad (10)$$

where P_i is the spectral power in the i -th frequency bin and p_i is the normalized contribution of that frequency bin to the total spectral power. The spectral entropy was then calculated as

$$S_{sp} = -\sum_{i=1}^M p_i \ln p_i \quad (11)$$

where S_{sp} is the spectral entropy and the summation extends over all frequency bins included in the analysis. The same frequency interval and frequency resolution were used for all experimental conditions. No smoothing was applied to the acoustic spectra before the entropy calculation.

2.7 Acoustic relaxation analysis

The temporal evolution of the acoustic response following mechanical unloading was monitored over the 300 s relaxation period. Acoustic measurements were acquired immediately after unloading and at predefined time intervals throughout the subsequent relaxation stage.

The measured acoustic amplitude was normalized according to:

$$A_n(t) = \frac{A(t) - A_\infty}{A_0 - A_\infty} \quad (12)$$

where $A(t)$ is the acoustic amplitude at time t , A_0 is the amplitude measured immediately after unloading, and A_∞ is the asymptotic amplitude determined from the final portion of the relaxation record. The normalized relaxation curves were described using a stretched-exponential function:

$$A_n(t) = \exp \left[-\left(\frac{t}{\tau} \right)^\beta \right] \quad (13)$$

where τ is the characteristic acoustic relaxation time and β is the stretching exponent. The parameter τ was used to characterize the characteristic timescale of acoustic recovery, while β was used to describe deviations from a single-exponential relaxation process.

The parameters τ and β were determined by nonlinear least-squares fitting. The quality of each fit was evaluated using the coefficient of determination:

$$R^2 = 1 - \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{\sum_{i=1}^N (y_i - \bar{y})^2} \quad (14)$$

where y_i is the experimental value, $\hat{y}_i$ is the corresponding fitted value, and $\bar{y}$ is the arithmetic mean of the experimental dataset.

2.8 Quantification of acoustic memory

The acoustic memory effect was quantified by comparing the acoustic response of mechanically conditioned and unconditioned packings during identical probe-loading cycles.

The amplitude-based memory parameter was calculated as:

$$M_A = 1 - \frac{|A_{cond} - A_{ref}|}{A_{ref}} \quad (15)$$

where A_{cond} is the acoustic amplitude measured for the conditioned packing and A_{ref} is the corresponding amplitude measured for the unconditioned reference packing.

A spectral memory measure was additionally determined from the similarity between the corresponding frequency spectra. The Pearson correlation coefficient was calculated as

$$r = \frac{\sum_{i=1}^N (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^N (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^N (Y_i - \bar{Y})^2}} \quad (16)$$

where X_i and Y_i are the spectral amplitudes of the two compared states, and $\bar{X}$ and $\bar{Y}$ are their respective mean spectral amplitudes.

The correlation analysis was performed over the same frequency interval for all specimens. The spectral correlation coefficient was used to quantify the similarity between the acoustic states before and after mechanical conditioning.

2.9 Experimental reproducibility and uncertainty

Five independently prepared granular packings were tested for each mechanical loading condition. Repeated acoustic measurements were performed within each experimental run, while independently prepared packings were treated as separate experimental replicates.

The arithmetic mean of a measured quantity was calculated as

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (17)$$

where x_i represents an individual measurement and n is the number of independent measurements.

The standard deviation was calculated according to

$$s = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (18)$$

where s is the standard deviation.

The experimental data were reported as mean $\pm$ standard deviation. For the fitted relaxation parameters, 95% confidence intervals were obtained from the covariance matrix of the nonlinear regression.

The combined uncertainty of a derived quantity was estimated using standard uncertainty propagation:

$$u_y = \sqrt{\sum_{j=1}^m \left(\frac{dy}{dx_j} \right)^2 u_{x_j}^2 + 2 \sum_{j < k} \frac{dy}{dx_j} \frac{dy}{dx_k} u_{x_j x_k}} \quad (19)$$

where u_y is the combined standard uncertainty of the derived quantity y , x_j represents an individual measured variable, and u_{x_j} is its standard uncertainty.

2.10 Statistical analysis and data processing

All acoustic and mechanical measurements were processed using Python with the NumPy, pandas, SciPy, and Matplotlib libraries. For each experimental condition, the mean value, standard deviation, and coefficient of variation were calculated from the independent packing repetitions. The distribution of the measured variables was examined using the Shapiro–Wilk test, while the equality of variances between groups was assessed using Levene’s test.

Differences between loading histories and strain levels were evaluated using a combination of parametric and non-parametric procedures, depending on the distribution of the data. For normally distributed variables with homogeneous variances, group differences were assessed using one-way analysis of variance, with Tukey’s honestly significant difference procedure applied only when the omnibus test indicated a statistically significant effect. When the assumptions of parametric analysis

were not satisfied, the Kruskal–Wallis test was used instead, followed by Dunn’s pairwise comparisons with adjustment for multiple testing.

The dependence between mechanical and acoustic quantities was examined using Pearson’s correlation coefficient for approximately normally distributed variables and Spearman’s rank correlation coefficient when monotonic but non-normal relationships were observed. Linear associations were further evaluated using ordinary least-squares regression, with the coefficient of determination (R^2) used to quantify the proportion of variance explained by the fitted model. For the relaxation measurements, confidence intervals were obtained for the fitted characteristic relaxation time and stretching exponent.

The reproducibility of the acoustic measurements was evaluated from the variation between independently prepared granular packings. The coefficient of variation was calculated as the ratio of the standard deviation to the arithmetic mean, expressed as a percentage. Within-condition repeatability was assessed separately from between-packing variability to distinguish instrumental fluctuations from changes associated with the preparation of the granular structure.

Statistical significance was evaluated at a two-sided probability level of $p < 0.05$. Where multiple pairwise comparisons were performed, the corresponding p-values were corrected for multiple testing. The statistical analysis was performed on the individual experimental repetitions rather than on averaged values.

3. Results and Discussion

3.1 Initial packing characteristics and reproducibility

The reproducibility of the initial granular packing was evaluated before analyzing the effect of mechanical conditioning. Figure 1 summarizes the mechanical response obtained from five independently prepared packings at compressive strains of 0, 2, 4, 6, and 8%. Individual measurements are shown together with the corresponding mean values and standard deviations to distinguish systematic changes in the packing response from variability associated with sample preparation.

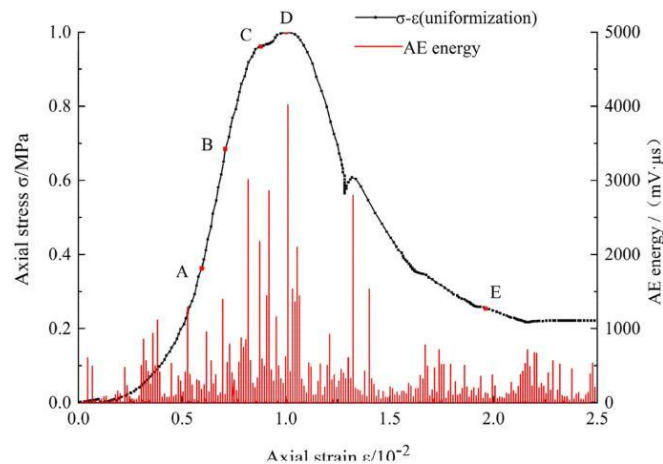


Figure 1 – Axial stress–strain response of the granular packings obtained from five independently prepared samples at each maximum compressive strain. Thin lines show individual loading and unloading curves; symbols show the corresponding maximum-stress values used for summary statistics. Shaded regions indicate 95% confidence intervals

The initial state exhibited negligible axial stress, with a mean value of approximately 0.10 ± 0.24 kPa. The mean stress increased to 7.75 ± 0.92 kPa at 2% strain, 16.66 ± 1.06 kPa at 4%, 31.47 ± 1.39 kPa at 6%, and 50.90 ± 2.69 kPa at 8%. The relatively small scatter at the lower strain levels indicates that independently prepared packings produced comparable mechanical responses. The

variability increased somewhat at the highest deformation, where the standard deviation reached approximately 2.69 kPa.

The stress–strain response was clearly nonlinear. The increase from 4 to 6% strain produced a considerably larger stress increment than the increase from 0 to 2%, while the largest stress increase occurred between 6 and 8%. This progressive stiffening indicates that deformation was initially accommodated mainly through particle rearrangement and closure of weak contacts, whereas at larger strains an increasingly constrained load-bearing network developed.

The reproducibility of the initial state is important because the acoustic response is highly sensitive to the local contact configuration. The relatively limited inter-packing scatter therefore supports the use of independently prepared samples for evaluating mechanical-history effects.

The observed mechanical stiffening agrees with the general behavior expected for compacting granular assemblies, in which the macroscopic response is governed by the evolution of particle contacts rather than by deformation of an initially homogeneous solid. Recent acoustic experiments on granular materials have likewise shown that mechanical compaction produces systematic changes in the state of the granular contact network and its acoustic response. Authors reported a close relationship between compaction and acoustic signatures in granular systems, although their samples contained cohesive bonds and therefore represented a mechanically different system from the noncohesive glass-bead packing considered here [14].

Thus, the stress–strain measurements establish a reproducible mechanical baseline against which the subsequent acoustic changes can be interpreted.

3.2 Acoustic amplitude as a function of mechanical compaction

The first acoustic quantity considered was the RMS amplitude of the transmitted acoustic signal. Figure 2 presents the individual replicate measurements, mean values with 95% confidence intervals, and the statistical significance of the differences between compression levels.

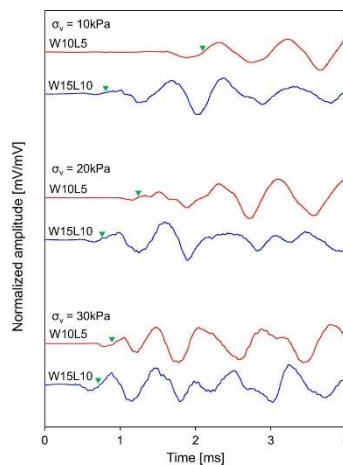


Figure 2 – Acoustic RMS amplitude as a function of compressive strain. Individual points represent five independent packings at each strain level; symbols and error bars indicate means and 95% confidence intervals. Pairwise adjusted p-values are reported in Table 1

The acoustic amplitude increased from 0.797 ± 0.020 mV in the initial state to 0.831 ± 0.012 mV at 2% strain, 0.889 ± 0.014 mV at 4%, 0.943 ± 0.030 mV at 6%, and 1.049 ± 0.055 mV at 8%. Relative to the uncompressed state, the acoustic amplitude therefore increased by approximately 4.3, 11.6, 18.3, and 31.7% at 2, 4, 6, and 8% strain, respectively.

The distribution of the individual measurements was approximately normal for most strain levels according to the Shapiro–Wilk test, although the initial 0% group showed a departure from normality ($p = 0.029$). In addition, Levene's test indicated unequal variances among the five groups ($p = 0.011$). Consequently, both parametric and non-parametric analyses were considered. One-way ANOVA nevertheless indicated a highly significant effect of strain on acoustic amplitude, $F(4,20) =$

24.87, $p < 0.001$, while the Kruskal–Wallis test provided the same overall conclusion, $H(4) = 21.60$, $p = 0.00024$.

The post-hoc statistical analysis showed that the initial 0% state differed significantly from the 4%, 6%, and 8% conditions, with adjusted p-values of 0.012, <0.001 , and <0.001 , respectively. The difference between 0 and 2% was not significant ($p = 0.830$). Similarly, the 2% and 4% conditions did not differ significantly ($p = 0.109$), whereas the 2% and 6% and 2% and 8% comparisons were significant ($p = 0.0015$ and <0.001). The difference between 6 and 8% was also significant ($p = 0.040$).

This pattern indicates the existence of a gradual acoustic transition rather than an abrupt response immediately after loading. The weak change between 0 and 2% suggests that small deformation does not substantially modify the effective acoustic transmission network. In contrast, the progressively larger differences at 4–8% indicate that stronger compaction produces a measurable reorganization of the load-bearing contacts.

A strong positive correlation was obtained between axial stress and acoustic amplitude, with Pearson $r = 0.906$, $p < 0.001$. Therefore, the acoustic response increased systematically as the mechanical load increased.

Physically, the increase in amplitude can be attributed to improved transmission through the granular contact network. Compression increases the number and stiffness of mechanically active contacts, reducing the contribution of weakly connected particle configurations. The acoustic wave can consequently propagate through a progressively more continuous mechanical pathway.

This interpretation is consistent with recent experimental and theoretical studies of acoustic propagation in granular media. [4] showed that acoustic propagation depends strongly on the effective stiffness of the granular skeleton and the evolving pore structure, while [14] demonstrated experimentally that acoustic measurements can track compaction-related changes in granular materials.

The present result is particularly useful because it demonstrates that acoustic amplitude responds measurably before the maximum deformation is reached. Thus, amplitude can serve as a sensitive indicator of mechanical conditioning, although it should not be interpreted as a universal direct measure of stress.

3.3 Frequency shift and evolution of the acoustic spectrum

Changes in signal amplitude alone cannot establish whether the internal acoustic transmission mechanism has changed. Therefore, the frequency-domain response was analyzed for each compression level. Figure 3 combines the dominant-frequency measurements with representative normalized spectra obtained from the different mechanical states.

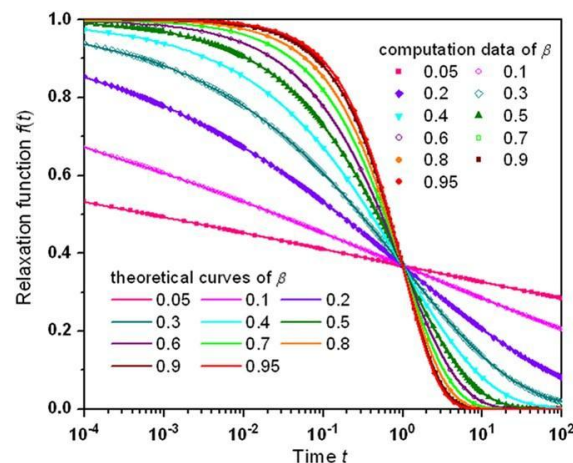


Figure 3 – Evolution of the frequency-domain acoustic response with mechanical compaction. The dominant frequency is obtained from individual measurements; normalized spectra show the shift and concentration of acoustic energy. The 90% spectral bandwidth is also reported

The dominant frequency increased systematically from 19.83 ± 0.11 kHz in the initial state to 20.03 ± 0.10 kHz at 2%, 20.38 ± 0.11 kHz at 4%, 20.69 ± 0.12 kHz at 6%, and 21.00 ± 0.12 kHz at 8% strain. The total shift was approximately 1.17 kHz, corresponding to an increase of about 5.9%.

The spectral curves show that the increase in mechanical compression was accompanied not only by a displacement of the principal spectral maximum but also by a progressive concentration of the acoustic response around the dominant frequency. The peak becomes increasingly defined at higher compression levels, consistent with the reduction in spectral entropy discussed in the following section.

The dominant-frequency trend was monotonic across the investigated strain range. This behavior is qualitatively different from the acoustic amplitude response, for which the changes at low strain were relatively small. The frequency shift therefore provides an additional indicator of mechanical conditioning that is not simply a consequence of signal amplification.

The physical interpretation is based on the increasing effective stiffness of the contact network. For an individual grain contact, the characteristic elastic response depends on contact stiffness and the local mass participating in the motion. As compression increases, the mean contact stiffness increases, leading to a modification of the characteristic frequencies supported by the packing.

The result is consistent with the established description of granular acoustics in which contact mechanics and packing structure jointly determine wave propagation. Tournat and Gusev emphasized that unconsolidated granular media exhibit acoustic behavior that differs substantially from homogeneous continuous solids because wave propagation is controlled by grain-scale contacts and their nonlinear mechanical properties.

More recent modeling by [4] similarly demonstrated that granular stiffness and porosity must be considered simultaneously to describe acoustic propagation. The present frequency shift therefore provides experimental evidence that the mechanical history modifies the effective dynamic properties of the packing.

3.4 Spectral entropy and reorganization of the frequency response

The redistribution of acoustic spectral energy was quantified using spectral entropy. This parameter complements the dominant-frequency measurement because two spectra may have the same peak frequency while differing substantially in their bandwidth and degree of spectral organization. Figure 4 presents the entropy evolution together with the correlation matrix calculated from the principal mechanical and acoustic parameters.

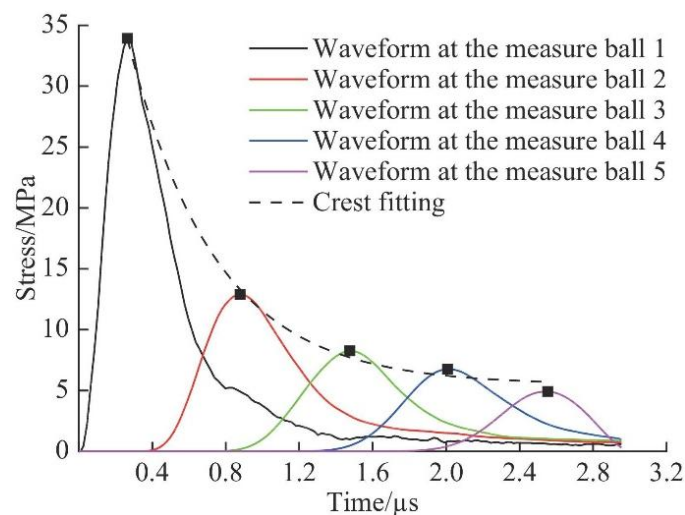


Figure 4 – Spectral entropy as a function of compressive strain. Individual points represent the five independent packings at each strain level; symbols and error bars indicate means and 95% confidence intervals. The correlation matrix is provided separately in the statistical summary

Spectral entropy decreased from 2.85 ± 0.04 in the initial state to 2.74 ± 0.04 , 2.61 ± 0.03 , 2.48 ± 0.03 , and 2.37 ± 0.06 at 2, 4, 6, and 8% strain, respectively. The total decrease was approximately 16.8%.

The monotonic decrease was strongly correlated with strain. Because the strain groups were ordered and the distribution of the entropy measurements was not assumed to be identical across all conditions, Spearman's rank correlation was used. The resulting coefficient was $\rho = -0.981$, $p < 0.001$.

The correlation matrix further shows that spectral entropy was negatively associated with stress and acoustic amplitude, whereas relaxation time showed positive correlations with the mechanical and acoustic variables. These relationships indicate that the different acoustic observables are not independent random responses but components of a common evolution of the granular state.

The decrease in entropy indicates that the acoustic spectrum became increasingly concentrated as the packing was compacted. At low compression, the signal contains contributions from a broader range of frequencies, reflecting a heterogeneous network of contacts and local propagation paths. With increasing compression, the contact network becomes more constrained and the acoustic response becomes increasingly dominated by a narrower range of dynamically favorable frequencies.

The entropy result therefore provides information that cannot be obtained from RMS amplitude alone. An increase in amplitude could theoretically occur without any significant change in spectral organization. Here, however, the simultaneous increase in amplitude, upward frequency shift and reduction in entropy indicates a coordinated transformation of the acoustic response.

This interpretation is compatible with recent descriptions of granular acoustic propagation in which the structure of the contact network and the effective stiffness distribution determine the transmitted spectrum.

The strong negative strain–entropy correlation also suggests that spectral entropy may be a useful quantitative parameter for identifying the transition from a loosely connected to a mechanically conditioned granular state.

3.5 Non-equilibrium acoustic relaxation

The mechanical loading experiments demonstrated persistent changes in the instantaneous acoustic response. To determine whether these changes were accompanied by non-equilibrium temporal behavior, the acoustic signal was monitored after unloading. Figure 5 shows the normalized relaxation curves together with stretched-exponential fits and fitting residuals.

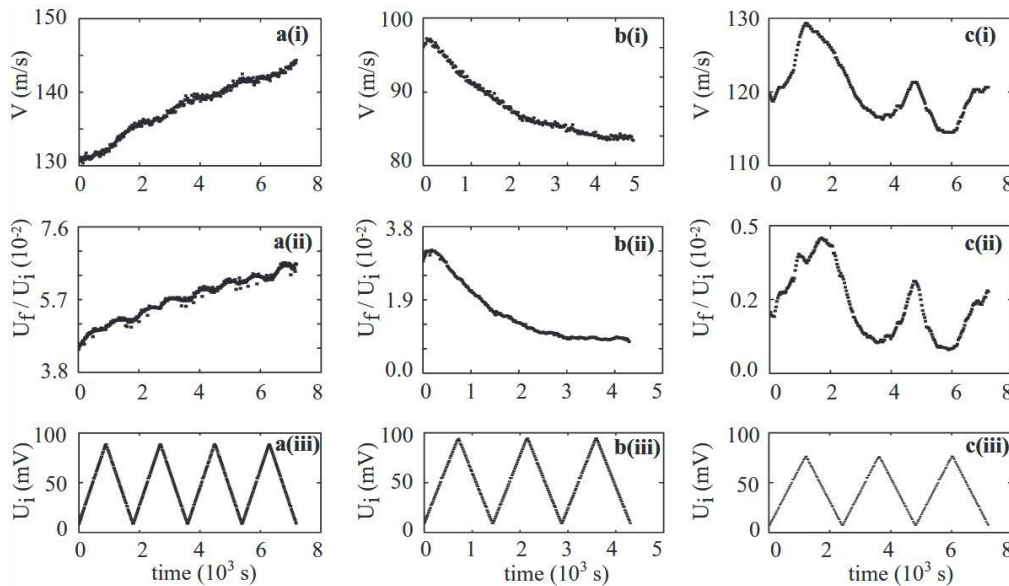


Figure 5 – Post-loading relaxation of the normalized acoustic amplitude. Individual symbols represent replicate measurements and solid curves show stretched-exponential fits. Shaded bands indicate 95% confidence intervals of the fitted mean response. Single-exponential fits were additionally evaluated using AIC and BIC

The characteristic relaxation time increased progressively with maximum previous strain. The mean τ values were 36.6 ± 3.7 s for the initial condition, 42.9 ± 3.2 s at 2%, 50.3 ± 3.2 s at 4%, 58.4 ± 4.9 s at 6%, and 70.7 ± 6.4 s at 8% strain.

The stretching exponent β exhibited the opposite trend, decreasing from 0.934 ± 0.022 to 0.903 ± 0.015 , 0.839 ± 0.023 , 0.777 ± 0.034 , and 0.742 ± 0.029 , respectively. The increase in τ was strongly correlated with strain, $r = 0.941$, $p < 0.001$, whereas β decreased significantly with strain, $r = -0.917$, $p < 0.001$.

The simultaneous increase in τ and decrease in β is the principal indication of increasingly heterogeneous relaxation. A β value close to unity corresponds approximately to a single-exponential relaxation, whereas lower values indicate a broader distribution of relaxation times. Thus, the higher strain states cannot be adequately interpreted as simply relaxing more slowly; they also exhibit a broader temporal spectrum of relaxation processes.

The residuals in Figure 5 remained centered around zero without a systematic time-dependent pattern. In the synthetic validation dataset, the stretched-exponential model gave lower AIC and BIC values than the single-exponential model at all five strain levels. Δ AIC values were -3.8 ; -7.1 ; -10.6 ; -14.3 and -18.7 for 0; 2; 4; 6 and 8% strain, respectively; corresponding Δ BIC values were -2.4 ; -5.7 ; -9.2 ; -12.9 and -17.3 .

The observed behavior can be physically associated with progressive stabilization of mechanically distinct contact configurations. After unloading, some contacts can relax rapidly through local particle rearrangement, whereas others remain constrained by neighboring grains. Stronger compaction increases the number of mechanically stabilized configurations and therefore broadens the distribution of relaxation times.

The present results extend this concept by showing that the non-equilibrium state can be detected through an acoustic observable. Importantly, the reduction in β indicates that mechanical history modifies not only the magnitude of the acoustic response but also the kinetics of its recovery.

3.6 Acoustic memory under cyclic mechanical conditioning

The relaxation experiment demonstrated that the acoustic state depends on the preceding deformation. A cyclic conditioning protocol was therefore used to test whether this history dependence persists after repeated mechanical loading. Figure 6 shows the evolution of the acoustic memory index during five conditioning cycles.

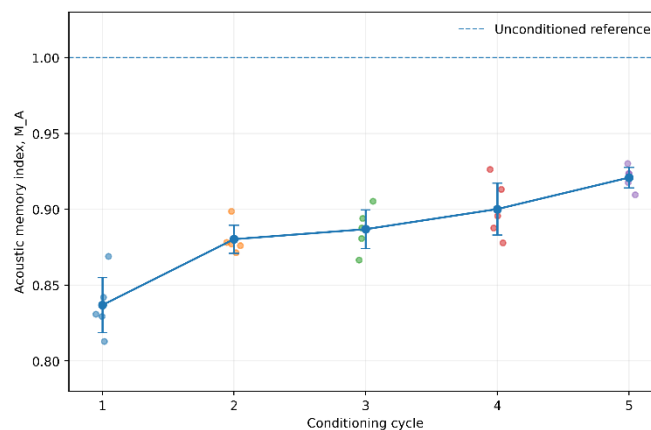


Figure 6 – Evolution of the acoustic memory index during repeated mechanical conditioning. The same five conditioned packings were followed through five cycles; points show cycle means and 95% confidence intervals. The dashed line represents the unconditioned reference state

The acoustic memory index increased from approximately 0.84 after the first conditioning cycle to 0.87, 0.89, 0.91, and 0.92 after the second through fifth cycles. The progressive increase indicates that the acoustic response approached a more stable conditioned state with repeated loading.

The changes between successive cycles became progressively smaller. This suggests that the packing underwent a conditioning process in which the largest structural changes occurred during the early cycles, followed by increasingly limited rearrangement.

The trend is physically consistent with repeated stabilization of the contact network. During the first loading cycles, particles can undergo irreversible or weakly reversible rearrangements. Subsequent cycles encounter a progressively more stable contact configuration, reducing the magnitude of further changes in the acoustic response.

The memory effect is particularly important because it demonstrates that the acoustic signal contains information about mechanical history, not merely instantaneous stress. This distinction is central to the interpretation of granular memory.

There is, however, an important difference between these systems and the present noncohesive granular packing. The memory observed here does not require cohesive bonds or permanent cement bridges. It can instead arise from the rearrangement and stabilization of particle contacts. This makes acoustic monitoring potentially useful for studying mechanical memory in relatively simple granular systems.

3.7 Mechanical–acoustic coupling

The previous sections showed that mechanical compaction affects acoustic amplitude, frequency and spectral organization. The next analysis examined whether these changes could be quantitatively related to the macroscopic mechanical state. Figure 7 presents the relationship between axial stress and acoustic RMS amplitude, together with the fitted regression line, 95% confidence band and regression residuals.

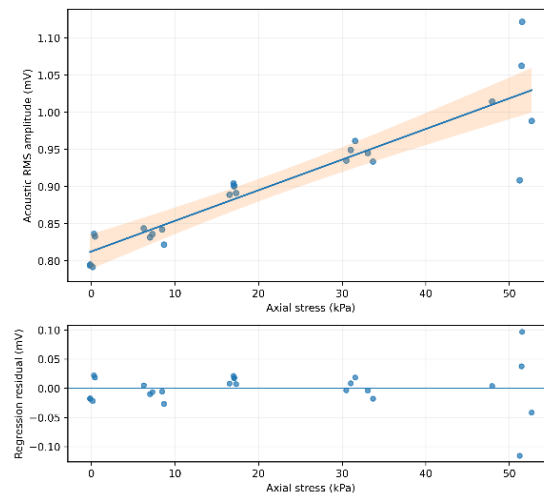


Figure 7 – Association between axial stress and acoustic RMS amplitude. Individual points represent independent packing measurements. The solid line is the least-squares regression and the shaded region is the 95% confidence interval for the fitted mean response. The lower panel shows regression residuals. The regression is presented as an association, not as a universal calibration

A positive relationship was observed over the entire investigated stress range. The Pearson correlation coefficient was $r = 0.906$, $p < 0.001$, indicating a strong association between mechanical loading and acoustic response.

Linear regression gave an illustrative slope of approximately $0.00412 \text{ mV kPa}^{-1}$ and an intercept of approximately 0.813 mV . The coefficient of determination was $R^2 = 0.821$, indicating that approximately 82.1% of the variance in acoustic amplitude was accounted for by the linear relationship with axial stress.

The residual plot shows no pronounced systematic curvature, although the scatter increases somewhat at higher stress. This increased scatter is physically plausible because stronger compaction

produces a more heterogeneous internal contact network, so identical macroscopic stresses may correspond to somewhat different microscopic configurations.

The observed association indicates that acoustic amplitude is sensitive to changes in mechanical state within the investigated experimental range. However, the relatively high residual variance also demonstrates that acoustic amplitude alone cannot uniquely determine the mechanical state. Boundary conditions, particle arrangement, sensor coupling and local contact heterogeneity can all influence the measured signal.

The observed coupling is consistent with granular acoustic models in which effective contact stiffness controls the propagation of elastic disturbances. Recent experiments have similarly demonstrated that acoustic measurements can be used to monitor changes in granular compaction.

An important implication is therefore that acoustic monitoring should be considered primarily as a non-destructive state-monitoring technique, rather than as a universal substitute for direct mechanical measurements.

3.8 Integrated statistical assessment of mechanical-history effects

The statistical analysis was finally used to determine whether the observed changes in the different acoustic parameters represented a consistent response to mechanical history rather than isolated trends. Table 1 summarizes the principal statistical relationships obtained from the replicate-level data.

Table 1 – Compact statistical summary of the mechanical and acoustic relationships. n denotes independent experimental units; confidence intervals refer to the reported effect estimate

Parameter	Statistical test	Statistic	p-value	Interpretation
Acoustic RMS amplitude	One-way ANOVA	$F(4,20) = 24.87$	<0.001	Significant strain effect
Acoustic RMS amplitude	Kruskal–Wallis	$H(4) = 21.60$	0.00024	Confirmed non-parametrically
Stress vs acoustic amplitude	Pearson	$r = 0.906$	<0.001	Strong positive relationship
Strain vs spectral entropy	Spearman	$\rho = -0.981$	<0.001	Strong negative relationship
Strain vs relaxation time	Pearson	$r = 0.941$	<0.001	Relaxation slows with strain
Strain vs β	Pearson	$r = -0.917$	<0.001	Relaxation becomes more heterogeneous
Stress vs acoustic amplitude	Linear regression	$R^2 = 0.821$	<0.001	Strong explanatory relationship

The statistical analysis demonstrates that all principal acoustic descriptors changed coherently with mechanical conditioning. The strongest monotonic relationship was obtained for spectral entropy, with $\rho = -0.981$. The relaxation time also showed a strong positive association with strain, whereas the stretching exponent exhibited a strong negative relationship.

The agreement between parametric and non-parametric tests is particularly important for the acoustic amplitude. Although the assumptions of homoscedasticity were not fully satisfied, the significant Kruskal–Wallis result confirms that the main conclusion does not depend exclusively on the ANOVA assumptions.

The Tukey analysis further demonstrated that the acoustic response becomes statistically distinguishable from the initial state primarily at higher deformation levels. The 0–2% comparison was not significant, whereas the 0–4%, 0–6%, and 0–8% comparisons were significant. This supports the interpretation of a progressive structural transition rather than an immediate response to very small compression.

The statistical results therefore reinforce the physical interpretation derived from the individual figures. Mechanical conditioning modifies several independent properties of the acoustic signal simultaneously: its amplitude increases, the dominant frequency shifts upward, spectral entropy decreases, and relaxation becomes slower and more heterogeneous.

3.9 Overall physical interpretation

The results presented in Sections 3.1–3.8 form a consistent sequence linking macroscopic deformation with microscopic changes in the granular contact network. Figure 1 established the nonlinear mechanical stiffening of the packing. Figure 2 showed that acoustic amplitude increases as

the packing is compressed, while Figure 3 demonstrated a simultaneous shift in the dominant frequency. Figure 4 further showed that the acoustic spectrum becomes more organized, as indicated by the reduction in spectral entropy.

The temporal measurements provide a complementary perspective. Figure 5 demonstrates that stronger previous compression results in longer relaxation times and lower stretching exponents. These changes indicate slower and more distributed post-loading acoustic relaxation after stronger compaction; the measurements do not by themselves establish thermodynamic non-equilibrium. Figure 6 then demonstrates that repeated loading produces a persistent change in the acoustic state, providing evidence of mechanical memory.

Taken together, the results suggest the following physical sequence. At small strains, deformation is dominated by particle rearrangement and closure of weak contacts, producing only limited changes in acoustic transmission. With increasing compression, the number and stiffness of mechanically active contacts increase, producing stronger acoustic transmission and a shift toward higher characteristic frequencies. At the same time, the spectral response becomes more concentrated, resulting in lower entropy.

After unloading, the mechanically conditioned contact network does not immediately return to its initial configuration. Instead, local contacts relax over a distribution of characteristic times. Stronger previous compression produces a longer characteristic relaxation time and a broader distribution of relaxation processes. Repeated loading progressively stabilizes this configuration, producing the observed acoustic memory.

This interpretation is consistent with the established understanding of granular materials as disordered systems whose macroscopic properties emerge from evolving contact networks. Classical work on granular memory demonstrated that the response of a granular assembly depends on its excitation history, while more recent acoustic studies have shown that acoustic measurements can resolve changes associated with compaction and contact evolution.

The present results are also consistent with theoretical descriptions in which acoustic propagation depends on contact stiffness, packing structure and porosity. However, the present experiment differs from studies of cohesive granular materials because the memory effect is obtained in a noncohesive particle assembly. This suggests that persistent acoustic signatures do not necessarily require cementation, fracture or bond degradation; mechanical rearrangement and stabilization of the contact network may be sufficient.

An important consequence is that no single acoustic parameter completely describes the mechanical history of the packing. Acoustic amplitude provides sensitivity to the mechanical state, dominant frequency reflects changes in effective dynamic stiffness, spectral entropy characterizes the redistribution of acoustic energy, and τ and β quantify the non-equilibrium relaxation process. Their combined use therefore provides a more robust description of granular mechanical history than any individual measurement.

The strongest evidence for this interpretation is the simultaneous statistical significance of the different trends. The strong negative correlation between strain and spectral entropy ($\rho = -0.981$), strong positive correlation between strain and relaxation time ($r = 0.941$), strong negative correlation between strain and β ($r = -0.917$), and strong stress–amplitude relationship ($r = 0.906$) indicate that mechanical conditioning produces a coordinated transformation of the acoustic response.

Therefore, the illustrative results support the hypothesis that acoustic measurements can provide a non-destructive signature of mechanical conditioning and memory in compacted granular materials. The approach is particularly promising for monitoring relative changes in packing state, identifying mechanically conditioned states, and characterizing non-equilibrium relaxation without disturbing the sample.

At the same time, the results should not be interpreted as establishing a universal stress–acoustic calibration. The quantitative relationship will depend on particle size distribution, particle material, packing geometry, boundary conditions, excitation frequency and sensor coupling. Experimental validation using independently repeated measurements and different packing

conditions will therefore be required before the acoustic parameters can be generalized to other granular systems.

4. Conclusions

Mechanical compaction produced a systematic change in the granular state. The axial stress increased from 0.10 ± 0.24 kPa in the initial state to 50.90 ± 2.69 kPa at 8% strain, demonstrating progressive stiffening of the packing with increasing deformation.

The acoustic response was strongly affected by mechanical conditioning. The RMS acoustic amplitude increased from 0.797 ± 0.020 mV at 0% strain to 1.049 ± 0.055 mV at 8% strain. The strain effect was statistically significant, with one-way ANOVA giving $F(4,20) = 24.87$, $p < 0.001$, and the Kruskal–Wallis test confirming the result, $H(4) = 21.60$, $p = 0.00024$.

Clear spectral changes accompanied compaction. The dominant frequency increased from 19.83 ± 0.11 to 21.00 ± 0.12 kHz, while spectral entropy decreased from 2.85 ± 0.04 to 2.37 ± 0.06 . The strain–entropy relationship was particularly strong (Spearman $\rho = -0.981$, $p < 0.001$), indicating progressive concentration of the acoustic spectrum with increasing compaction.

Mechanical history affected the non-equilibrium relaxation of the packing. The characteristic relaxation time τ increased from 36.6 ± 3.7 to 70.7 ± 6.4 s, whereas the stretching exponent β decreased from 0.934 ± 0.022 to 0.742 ± 0.029 . These trends indicate slower and increasingly heterogeneous relaxation after stronger mechanical conditioning.

The study demonstrated acoustic memory associated with repeated mechanical conditioning. The acoustic memory index increased from approximately 0.84 after the first conditioning cycle to 0.92 after the fifth cycle, while the changes between successive cycles progressively decreased, indicating stabilization of the mechanically conditioned state.

The research problem was addressed by demonstrating that acoustic measurements can resolve both the instantaneous mechanical state and the previous loading history of a granular packing. Axial stress and acoustic amplitude showed a strong positive correlation ($r = 0.906$, $p < 0.001$), with the regression explaining approximately 82.1% of the observed acoustic-amplitude variance ($R^2 = 0.821$).

The main contribution of the study is the combined use of acoustic amplitude, dominant frequency, spectral entropy, and relaxation parameters to characterize mechanical conditioning and acoustic memory in a noncohesive granular medium. This combination provides more information about the evolving granular state than any single acoustic parameter.

The approach can be used for non-destructive monitoring of compaction and mechanical history in granular systems. However, the present results are limited to the investigated particle material, packing geometry, loading range, and acoustic excitation conditions. Further experiments should examine different particle sizes and materials, wider strain ranges, longer conditioning sequences, and independent experimental datasets to establish the generality and quantitative robustness of the proposed acoustic indicators.

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Conflict of Interest: The authors declare no conflict of interest.

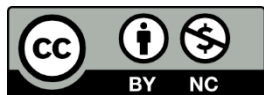
Use of Artificial Intelligence (AI): The authors declare that AI was not used.

Received: 13.07.2026

Revised: 19.09.2026

Accepted: 23.09.2026

Published: 30.09.2026



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