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# Investigation of the effect of frequency on shear strength and damping of pure sand and sand stabilised with rice husk ash using cyclic triaxial tests

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**Abstract:**
Rice husk ash (RHA), owing to its pozzolanic properties and wide abundance, is an additive that can be used as an alternative to cement to improve a variety of soils. Damping and shear modulus are two important soil dynamic parameters used to predict soil behaviour under dynamic loading. Therefore, in this study, materials were prepared and their specifications were determined. A cyclic triaxial device was used to determine the dynamic parameters (stress control). Subsequently, the results related to shear modulus and damping calculated for pure sand before and after stabilisation were analysed according to different percentages of stabilisers for two frequencies of 0.5 and 1 Hz. The results revealed the effect of different frequencies on the damping of pure sand, which differed for stabilised sand. In all stabilised specimens, the shear modulus decreased with increasing frequency. Additionally, the damping decreased with increasing frequency in the stabilised samples. The shear modulus increases with the increase in the amount of stabilisers. The results also showed the positive effect of partially replacing cement with RHA.

**Keywords:**
Damping; Shear modulus; Cyclic triaxial test; Frequency; Sand

## 1 Introduction

Currently, chemical stabilisation methods are widely used to improve and stabilise problematic soils, or even many soils that encounter the problem of bearing capacity or subsidence. Therefore, based on the type of project and its purpose, the geotechnical characteristic that should be optimised is identified through which the type of stabilisation additive is determined. These additives include lime, cement, rice husk ash (RHA), pozzolans, micro-silica, aluminium sulfate, and fly ash. The technique of reinforcing soil with lime has been used since ancient times, and soil remediation with hydrated lime has been used in the United States since 1945 [1]. The most important reactions that occur in soil additives are the ion exchange, pozzolanic, and hydration reactions, the most important of which is the pozzolanic reaction. This reaction, which increases the shear strength of soil by creating cementitious materials, occurs between lime and water and siliceous and aluminous soil materials, and is a function of time and stops in the absence of moisture [2]. The use of pozzolanic materials such as fly ash increases and accelerates the effect of additives (lime). Lime improves the behavioural properties of fine-grained clay soils, such as swelling, shear strength, water uptake, and plastic characteristics (Atterberg limits) [3]. Fly ash is primarily composed of oxides of silicon, aluminium, iron, and calcium. The addition of fly ash significantly increases the pH value. As the pH increases, soil silica is released from its quadrilateral sheet structure, and soil alumina is released from its octagonal sheet structure, which accelerates pozzolanic reactions [4, 5]. RHA contains a large amount of silica with a high specific surface area, which is suitable for activating soil reactions with lime. Residual RHA is the result of controlled burning rice husks at 600 °C [6], and approximately 20 % of ash is produced from rice husks [7]. RHA, which is a combination of silica and alumina, is in the pozzolanic category (ASTM-C618-2012a). Rice husks are abundant in countries such as China and India [8]. They are also light, and because of their low density, they are dispersed in air. In addition, RHA can be used as a pozzolanic grade material with a high specific surface area [9] in combination with lime to reduce the amount of Portland cement required [10-13]. Rice husks are a waste product of rice production. As approximately 500 million tons of rice is produced annually in the world, of which 20 % is the weight of the husk, it is an important material. Research on the pozzolanic properties and application of RHA in concrete began in the late 1960s, and today, with the development and existence of suitable furnaces for controlled combustion and the possibility of removing ash impurities using chemical methods, this research continues [14]. RHA has the highest amount of silica [15]. In 2006, Nair studied the pozzolanic reactions of RHA to investigate the possibility of replacing RHA with cement in rural buildings. The results showed that when RHA with a higher specific surface area was used, greater resistance was observed in the sample [16]. In 2004, Feng studied the pozzolanic properties of RHA and improved its properties using hydrochloric acid. The results showed that RHA previously fortified with hydrochloric acid had a more pozzolanic reaction than a normally burned sample [17]. Owing to its pozzolanic properties, abundance, ease of preparation, and low price in Guilan province, RHA is an additive that can be used as a complete alternative to or partial replacement of cement to improve various soils. Thus, in recent years, RHA has been used to improve the static bearing capacity of various soils, particularly clay soils, and insufficient research has been conducted on the behaviour of sandy soils stabilised with this additive. In 2012, Sarkar, et al. investigated the effects of RHA on cohesive soils [18]. In 2013, Tripati and Yadou conducted a study on the bearing capacity of foundations in soil modified with RHA. The optimum amount of RHA for soil stabilisation was 12 % [19]. In 2002, Mantohar conducted a study on the use of RHA as a pozzolanic material to improve the soil characteristics of Indonesia. The results of this study indicated a decrease in soil swelling and an increase in soil strength and bearing capacity [20]. In 2011, Fattah studied the improvement of clay properties using RHA [21]. In 2009, Salas compared the production of high-performance concrete using two different methods of RHA production [22]. The advantages of using RHA in concrete include increasing the flexural and compressive strengths of concrete, reducing permeability, increasing resistance to chemical attacks, increasing durability, reducing the effects of alkali–silica reactivity, reducing shrinkage and creating denser concrete, increasing concrete efficiency, reducing heat transfer through a building wall, reducing the amount of super plasticisers, and reducing the salting potential owing to the reduction of calcium hydroxide [22]. Nair et al. conducted structural research on the pozzolanic activity of RHA. Preliminary observations show that the highest amount of amorphous silica is present in samples burned at 500 to 700 °C. Therefore, RHA is the most desirable additive to add to pozzolanic cement [15]. In 2013, Gbinga studied the effects of RHA on soil permeability. The results indicated that the soil permeability coefficient (K) in all samples decreased with increasing amounts of RHA [23]. In 2014, Zinc investigated soil stabilisation using RHA and cement. The experimental results showed that the maximum improvement in soil strength occurred with 10 % RHA and 6 % cement [24]. In 2008, Mousa examined the potential of RHA for soil stabilisation. The results showed that the maximum value of the unconfined compressive strength (UCS) was observed in combination with 6 % to 8 % RHA [25]. In 2013, Montahar investigated the engineering properties of silty soils stabilised with RHA and lime and reinforced them with plastic waste fibres. The results showed that the selected method is very effective for improving the engineering characteristics of clay and silt in compressive, tensile, and shear strength sections [26]. In 2015, Zubidi investigated the physical and mechanical properties of cement mortar produced with RHA [27]. In 1992, Ali surveyed the geotechnical characteristics of chemically stabilised soil containing RHA and additives in Malaysia [28]. In 2005, Basha studied soil stabilisation using rice husk and cement. The results showed that both cement and RHA reduced soil plasticity. During compaction, the addition of RHA and cement reduced the specific dry weight of the soil and increased the optimum moisture content. From the perspective of plasticity, strength, density, and economic parameters, an optimal amount of 6 % to 8 % cement and 10 % to 15 % RHA is recommended [29]. In 2008, Brooks conducted a study on soil stabilisation using RHA and fly ash. Problematic clay was combined with RHA and fly ash, and resistance tests were conducted. The potential of the RHA–fly ash composition was studied as a swelling-reducing layer between the foundation and subgrade. 12 % of RHA and 25 % of fly ash are recommended for problematic subgrade soil [30]. In 2011, Hussein et al. conducted a study on soil stabilisation using a combination of RHA and cement kiln ash. Stabilised soil mixtures exhibit satisfactory durability and strength, and therefore can be used for low-cost construction and road infrastructure [31]. In 2011, Sabat conducted a study on the effect of marble ash on the strength and durability of problematic soils stabilised with RHA. The results showed that the addition of marble ash to a mixture of soil and rice husks increased its durability [32]. In 2008, Moses tested the permeability of lateritic soils improved with lime and RHA. The results showed that more than 6 % of RHA has a slight effect on the permeability of lateritic soil [33]. In 2013, Swamina then reviewed studies on the strength and durability of concrete in combination with RHA [34]. In 1999, Yu studied the reaction of RHA and $Ca(OH)_2$ solution (calcium hydroxide or dead lime) and the properties of the product [35]. In 2014, Ashango and Patra conducted a study on the static and cyclic properties of clay substrates stabilised with RHA and Portland slag cement. Based on the results, an optimal mixing plan including 82,5 % soil, 7,5 % Portland slag cement, and 10 % RHA was considered [36]. One of the experiments that makes it possible to study soil dynamic parameters is the cyclic triaxial (CT) experiment. CT strain control tests under non-drained conditions were performed to study the dynamic parameters of the soil stabilised with different strain amplitudes and frequencies. The hardness of stabilised soil compared with clay increased from 58 % to 87 % [37]. Dynamic loading conditions, such as earthquakes, may lead to high shear strain in the soil (more than 5 %). Typically, the dynamic properties of soils are estimated from experiments performed at 1 % shear strain by considering the symmetric hysteresis loop. For this purpose, three-axis cyclic strain control experiments were performed [38]. In this study, a series of CT tests with different vibration frequencies and cyclic stress ratios were performed to investigate the dynamic deformation and cyclic degradation of ultra-soft soil. Their results showed that vibrational frequencies have a significant effect on soil dynamic deformation [39]. A study was conducted to determine the dynamic properties of sandy soil stabilised with RHA and fibres and to investigate the application of RHA in the construction of deep foundations [40]. In this study, a

CT device was used. The results showed the positive performance of this additive (as a replacement of part of the cement with RHA) both in terms of improving the static and dynamic properties of clay and sand and in terms of seismic performance [40].
CT tests enable the study of dynamic soil parameters. Therefore, in this study, different percentages of RHA and cement were added as additives to sandy soil. Subsequently, using a triaxial cyclic test, the effect of the loading frequency on the dynamic properties of the stabilised sample and pure sand was investigated. Such investigations were not conducted in previously published studies. The results show that the frequency does not have a significant effect on the dynamic properties of pure sand, whereas its effect on the stabilised samples is noticeable. In addition, the results show that the dynamic properties (i.e., shear modulus G and damping ratio D) of stabilised sandy soil improved significantly with the addition of optimal percentages of cement and RHA.

## 2 Methods and Materials

To perform laboratory studies, Anzali sand from the shoreline of Guilan province in Iran (located south of the Caspian Sea) was used. RHA and cement were among the materials used to stabilise sandy soil. In the following, the properties and amount of the materials used are presented in detail.

### 2.1 Sand

The soil used was uniformly round carbonate sand. According to the unified classification system and the standard 2487D ASTM [12], the studied sand was SP. The uniformity coefficient (Cu) and coefficient of curvature (Cc) of this sand were 1,95 and 1,07, respectively. Additionally, the specific density of soil grains (Gs)was 2,65 and its equivalent coefficient (50D) was 0,21 mm (Table 1).

**Table 1. Physical characteristics of the studied sand and cement**

| Physical characteristics | Sand | Physical characteristics | Cement |
|---|---|---|---|
| **Parameter** | **Value** | **Parameter** | **Value** |
| $G_s$ | 2,65 | $G_s$ | 3,12 |
| $C_u$ | 1,95 | Initial Setting Time (Min) | 75 |
| $C_c$ | 1,07 | Final Setting Time (Max) | 195 |
| $e_{max}$ | 0,98 | Compressive Strength-3days | 205 kg/cm$^2$ |
| $e_{min}$ | 0,61 | Compressive Strength-7days | 288 kg/cm$^2$ |
| $D_{50}(mm)$ | 0,21 | - | - |
| $\gamma_{dmax}(gr/cm^3)$ | 1,68 | - | - |
| $\gamma_{dmin}(gr/cm^3)$ | 1,35 | - | - |

### 2.2 Cement

Although many types of cement can be used for soil stabilisation, Portland cement is the most common type. The cement used in this study was ordinary Portland cement (OPC). Figure 2 shows the grain size of the Portland cement used. The chemical composition of the OPC used is listed in Table 2.

### 2.3 Rice husk ash (RHA)

The most important feature of RHA that controls the pozzolanic reactions is the presence of amorphous silica. RHA is suitable for the formation of calcium silicate gel because of its highly active pozzolanic property, which is the product of its reaction with cement. When RHA and cement are mixed in the presence of water, the pH of the environment increases, and the active silica in RHA reacts with calcium hydroxide to produce calcium silicate hydrate gel. The reaction is described by Equations 1 to 3 [2, 13, 14, 35, 40].

$$CaO + H_2O = Ca(OH)_2 \quad (1)$$

$$Ca(OH)_2 = Ca^{2+} + 2(OH)^- \quad (2)$$

$$Ca^{2+} + 2(OH)^- + SiO_2 = CaO, SiO_2 + H_2O \quad (3)$$

The rice husks used in this study were obtained from Rasht. It was first dried naturally in the sun for three days. It was then burned to ash (this operation lasted three days). The burned ash was placed in a kiln at 600 °C for 2 h to decarbonise and increase the pozzolanic properties, and then milled for 1,5 h using a mill to prepare it for addition to cement and to create a higher specific surface area. Figure 1a shows the RHA used before milling, and Figure 1b shows the post-milling process. The granulation of the RHA used before and after milling is shown in Figure 2. The reason for grinding was to observe the fact that by increasing the specific surface area of the material, the number of surfaces ready to react increases, and consequently, the probability of the hydration reaction increases. Therefore, the milling process of each stabiliser can increase the specific surface area and reactivity potential, and thus increase the compressive strength.

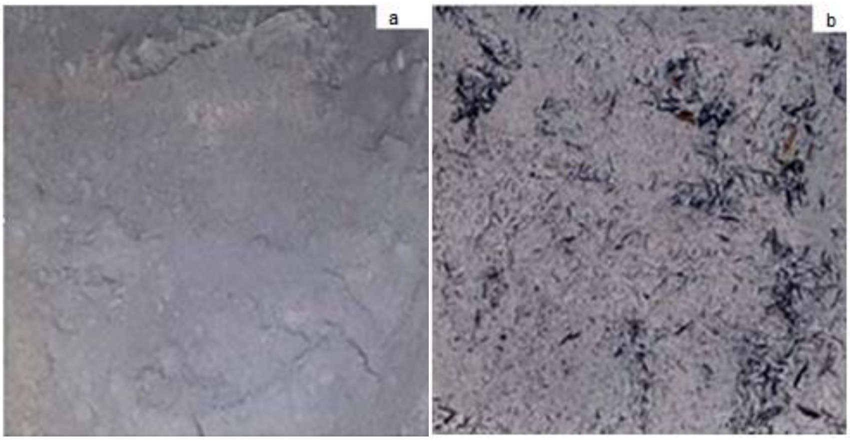


**Figure 1. Rice husk ash used: a) before milling; b) after milling**

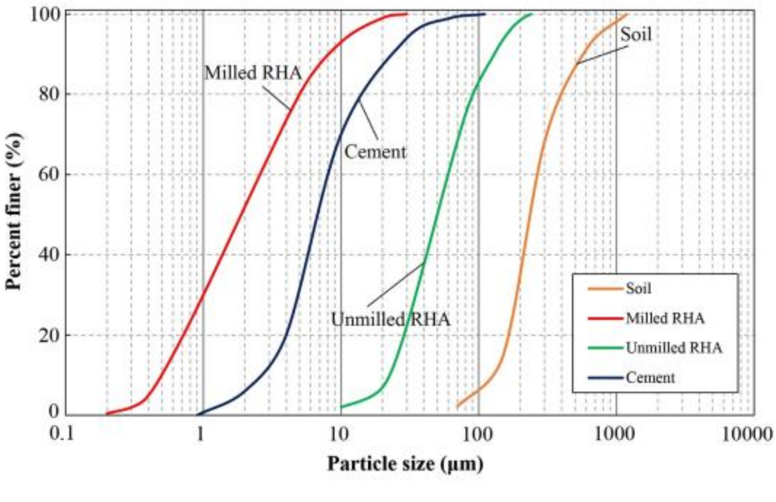


**Figure 2. Grain-size distribution curves of the studied sand, RHA, and cement [40]**

The chemical compositions of the cement and RHA used in the experiment, as determined using X-ray fluorescence (XRF) and X-ray diffraction (XRD) analyses, are presented in Table 2.

**Table 2. Chemical composition of the cement and RHA used**

| **RHA** (%) | **Cement** (%) | **Composition** |
|---|---|---|
| 90,60 | 21,00 | $SiO_2$ |
| 0,49 | 5,60 | $Al_2O_3$ |
| 0,73 | 3,30 | $Fe_2O_3$ |
| 1,51 | 63,20 | CaO |
| 0,88 | 1,10 | MgO |
| 0,22 | 0,17 | $Na_2O$ |
| 1,80 | 0,30 | $K_2O$ |
| 0,43 | 2,30 | $SO_3$ |
| 3,34 | 1,22 | L.O.I. |

## 3 Cyclic triaxial (CT) Test

The applied CT apparatus can measure cell and pore pressures of up to 1000 kPa. It has a dynamic loading capacity of 14 kN, a maximum allowable vertical displacement of 25 mm under dynamic loading conditions, and a loading frequency capacity of 70 kHz. A 13-channel data logger was used to acquire data. Figure 5 shows some of the other parts of the CT apparatus used. The results of the CT tests were used to evaluate the shear strength of the soil against earthquakes and other cyclic loads. Additionally, in this experiment, different amounts of effective pressure could be applied and used to determine the soil cyclic resistance; the value of this resistance is generally a function of many factors such as density, limited pressure, applied cyclic shear stress, stress history, grain structure, soil age, sample preparation method, frequency, uniformity, and cyclic waveforms. This test is applicable to both fine and coarse soils in the unified classification system, where samples may be intact or made in the laboratory. There are two test methods that use cyclic loading to determine the modulus of elasticity (E) and damping (D). In the first method, a cyclic load is applied to the sample (stress control). This method is used to determine the Young's modulus and damping under constant load conditions. In the second method, instead of a cyclic load, constant cyclic deformation is applied to the sample (strain control) [41].

### 3.1 Shear modulus (G) and damping ratio (D) in a loading cycle

To determine these dynamic properties, performing an experiment is the first step in seismic response analysis. In simulating the soil response to earthquake waves, the destructive waves caused by the earthquake are often assumed to be transmitted from the depth to the surface in the soil texture in the form of shear waves whose vibration direction is parallel to the horizon and their propagation direction is perpendicular to the ground. Assuming that the initial shear stress in the soil is zero, each complete loading and unloading cycle can be represented by a stress–strain curve as a closed hysteresis loop, as shown in Figure 3.

The shear modulus and damping ratio in the hysteresis loop are two important dynamic parameters. The shear modulus (sequential shear modulus) is equivalent to the linear slope that connects the endpoints of the hysteresis loop. By measuring the area inside the loop, which is equal to the amount of energy consumed during the occurrence of that cycle, and the area of the absorbed part, which is equal to half of the energy absorbed in that cycle, an equivalent linear damping ratio can be obtained using Equation 4.

$$D = \frac{loop\ area}{4\pi \cdot folded\ area\ tirangle} \tag{4}$$

By changing the shape of the hysteresis loop owing to repeated periodic loading and increasing the number of cycles or changing the shear stress range, the shear modulus and damping ratio also change with the strain rate. The changes in these parameters are nonlinear with changing shear strain (ASTM D3999).

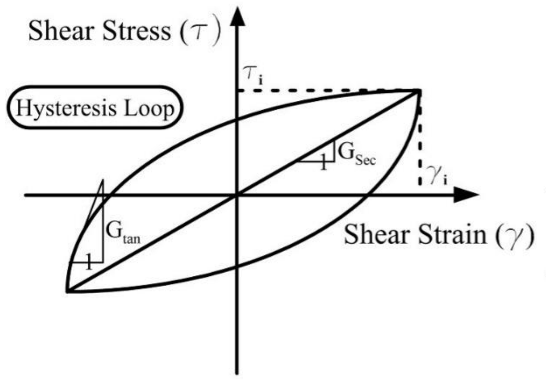


**Figure 3. Schematic diagram of a hysteresis loop in the CT test [41]**

## 3.2 Specifications of G-γ and D-γ diagrams

The shear modulus and damping at different strain levels play a very important role in seismic response analysis and therefore in the design and performance of structures built on the ground. The changes in these two components by changing the strain level can be divided into two parts: linear and nonlinear behaviours. The linear part is related to the elastic behavioural region of the soil at very low strain levels, and the nonlinear part is related to the area of elastoplastic and plastic behaviour of the soil at medium and high strain levels. Relevant graphs at a wide strain level were obtained using the results of the experiments performed in this study.

## 4 Experimental testing

The sample preparation in this study was in accordance with the ASTM D3999 standard. To create a uniform distribution of all composite materials, with a predetermined weight percentage of additives and sand, an electric stirrer with a rotating motor was used. Using this method, the materials were weighed based on the desired density, poured into 10 layers of 2 cm, and poured into each layer by percussion onto the surface of the layer to attain the desired density. Note that the bottom layers were slightly less dense than desired. This is because the density of the subsequent layers caused the underlying layers to become denser. Thus, for easy separation of the sample from the mould, the inside the mould was lubricated before the sample was created. Two clamps at the top and bottom of the mould were used to prevent the mould from opening or cracking during the pouring and compaction of the layers. Subsequently, by opening the mould clamp and carefully removing the sample from the mould, cracks and damage to the sample were prevented. Subsequently sample was then placed in a desicator for processing with moisture for 30 days. Before the experiments, the surfaces of the samples were coated with a thin layer of kaolinite powder (caps of the samples), resulting in a completely smooth and polished surface for proper vertical stress distribution. By measuring the dimensions of the sample after the processing period and placing the sample in the porous rock membrane, it was placed at the bottom and top of the sample. The cell was then placed on the device and filled with water. When the connection between the loading rods and fittings was complete, the rod was lubricated to prevent friction (Figures 4 and 5).

**Figure 4. Preparation of materials and sample**

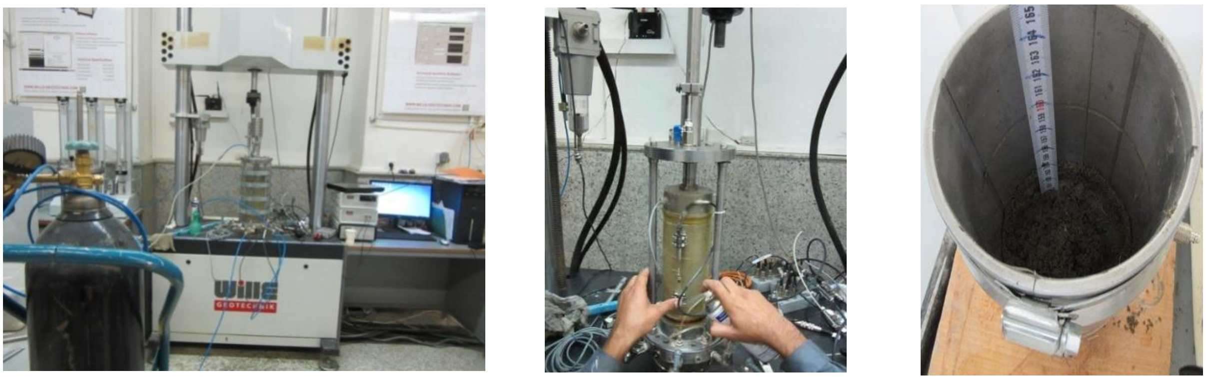

**Figure 5. Cyclic triaxial device (Wille Geotechnik) and internal strain LVDT installation**

## 4.1 Periodic loading

All experiments were performed under stress control conditions with a uniform sinusoidal load. At this stage, all axial strain changes measured using two types of local and non-contact strain gauges (LVDTs), as well as information about deflection stress, all-round stress, and pore water pressure were recorded. The order of the operations performed in this section was as follows:

- Closing drainage valves and placing the sample in non-drained conditions.
- Determining the deflection stress, number of desired cycles, and loading frequency in the software.

According to the ASTM D3999 standard, the uniform sinusoidal loading frequency in stress control experiments should be between 0,1–2,0 Hz; in the experiments performed in this study, frequencies of 0,5 and 1,0 Hz were considered. The number of applied cycles (40 cycles) was selected according to the ASTM D3999 standard. The magnitude of the deflection stress (q) changed during the tests. Deviation stress changes in the test process were such that in the first step, the lowest possible value that could be properly applied by the CT device was applied to the sample in the mentioned 40 cycles, and during these 40 cycles, the deviatoric stress was 150 kPa, according to the same value. The samples were fixed and subjected to a uniform cycle. The confining pressure in this experiment was 100 kPa.

## 4.2 Determining the shear modulus and damping ratio in periodic loading steps

The software output from the various loading steps included the following parameters: load rate, displacement, axial strains measured using local and non-contact strain gauges (LVDTs), confining pressure, stress deviation, pure water pressure, effective stress, and volume changes. The definitions of the G-γ and D-γ diagrams were based on changes in deviatoric stress versus shear strain. The following equation is sufficient to convert axial strain to shear strain:

$$\gamma = (1 + \upsilon) \cdot \varepsilon \tag{5}$$

Where:

ε is the axial strain,

γ is the shear strain,

ν is Poisson's coefficient.

Based on the results of the static triaxial tests and initial slope of the $\varepsilon_V$–$\varepsilon_1$ curve, the value of the Poisson's ratio for different cases of ordinary samples was the same and equal to 0,2. At each loading step, the sample was subjected to 40 sine cycles of deviatoric stresses. To calculate the shear and damping modul in each step, the tenth cycle was separated from each step, and the q–γ diagram was created using Equation (5), and using the deviation stress changes, it is obtained from the loop. This diagram was used to calculate the shear modulus and corresponding damping ratio. The tenth cycle was selected because, in most earthquakes that have occurred thus far, the most destructive loading cycle has been the tenth cycle; because the number of loading cycles affects the stress–strain behaviour of the soil, to have the most similar characteristics to the dynamic properties of soil in nature, the tenth cycle of 40 cycles per step is used to calculate the shear modulus and damping ratio. With the values of the shear modulus and damping ratio of the tenth cycle of each step, as well as the shear strains corresponding to these values, G–γ and D–γ diagrams can be easily plotted.

### 4.3 Dynamic test programme

To study, investigate, and determine the dynamic parameters (shear modulus and damping ratio) of pure sand and sand stabilised with RHA (4-10 %) and cement (4-10 %), a series of CT tests with a 30-day processing period and frequencies of 0,5 and 1,0 Hz were performed, as shown in Table 3. Note that to reduce the role of laboratory errors, each sample was fabricated with reproducibility. To determine the optimal value, a number of UCS tests were performed on different samples, and according to the values of UCS, the optimal value of the mixture ratio was determined. The optimum amounts of cement and RHA were determined as 8 % and 8 %, respectively. The details are reported in a previously published paper [40].

**Table 3. Programme of CT tests on sand**

| **Number** | **Sample name** | **Cement** | **RHA** (%) | **C+RHA** (%) | **CT** (f - Hz) |
|---|---|---|---|---|---|
| 1 | nC-nR | 0 | 0 | 0 | 0,5 Hz |
| 2 | nC-nR | 0 | 0 | 0 | 1,0 Hz |
| 3 | 4C-4R | 4 | 4 | 8 | 0,5 Hz |
| 4 | 4C-4R | 4 | 4 | 8 | 1,0 Hz |
| 5 | 8C-8R | 8 | 8 | 16 | 0,5 Hz |
| 6 | 8C-8R | 8 | 8 | 16 | 1,0 Hz |
| 7 | 10C-10R | 10 | 10 | 20 | 0,5 Hz |
| 8 | 10C-10R | 10 | 10 | 20 | 1,0 Hz |

## 5 Results of dynamic experiments on pure and stabilised sand

### 5.1 Damping behaviour results

According to the experiments performed on different samples introduced in the experimental programme, the damping results were calculated using a detailed method and are presented as follows: First, the results of the dynamic and damping experiments calculated for pure sand before stabilisation for two frequencies of 0,5 and 1,0 Hz are presented. As expected, the results indicated that the frequency had no effect on the damping of pure sand. However, such a relationship is not clear for stabilised soils. Therefore, the following graphs (Figures 6 and 7) are presented for each of the combinations and under the frequencies of 0,5 and 1,0 Hz.

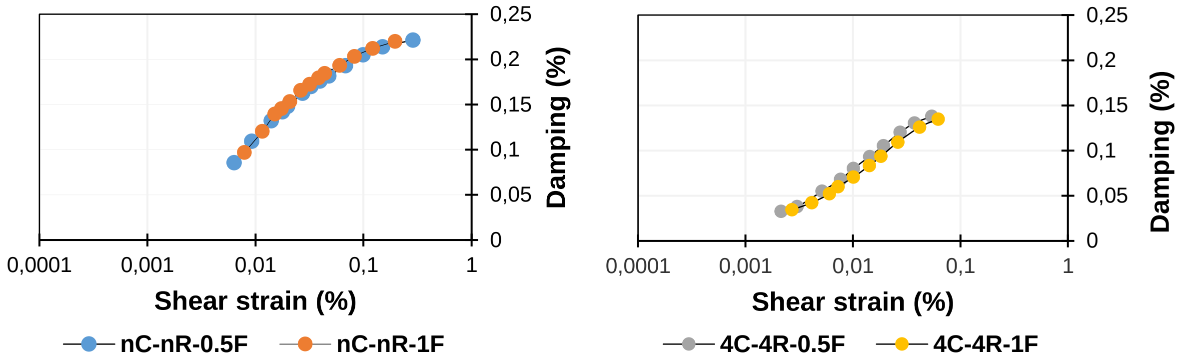


**Figure 6. Damping - shear strain diagram (NC-4C, f=0,5 and 1,0 Hz)**

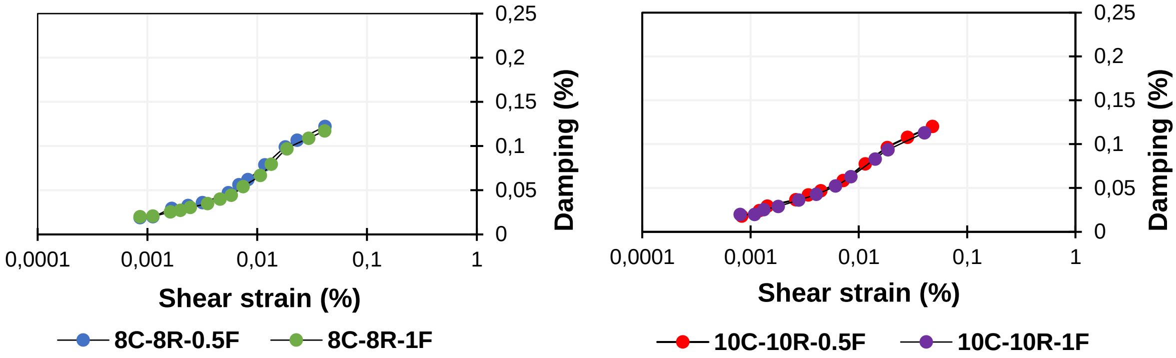


**Figure 7. Damping - shear strain diagram (8C-10C, f=0,5 and 1,0 Hz)**

## 5.2 Results related to shear modulus (G-reduction curve)

Results based on the calculation of shear modulus in the tenth cycle related to loading on each compound (each compound is controlled as a stress and loaded for 40 cycles) were used, and the shear modulus curve for different shear strains are shown in Figures 8 and 9.

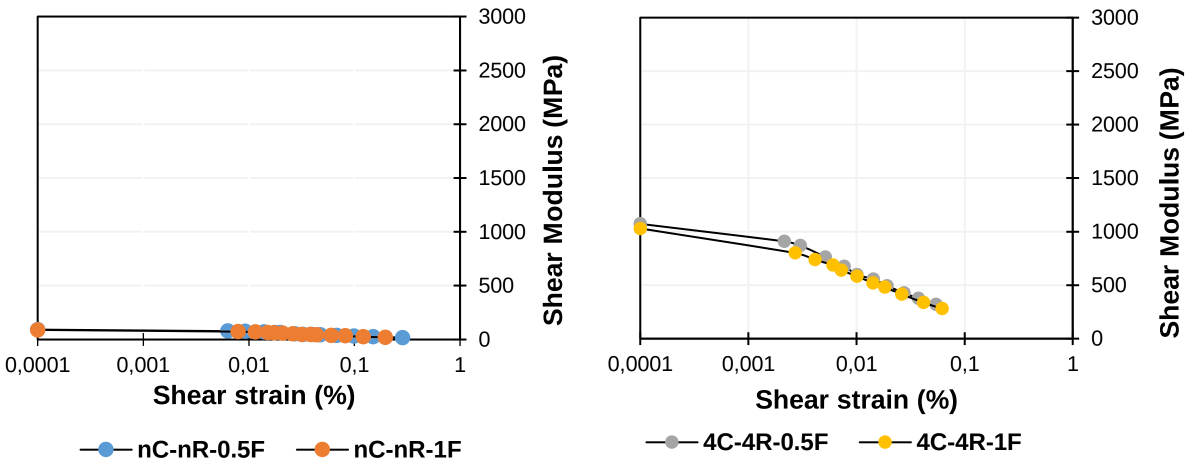


**Figure 8. Shear modulus - shear strain diagram (NC-4C, f=0,5 and 1,0 Hz)**

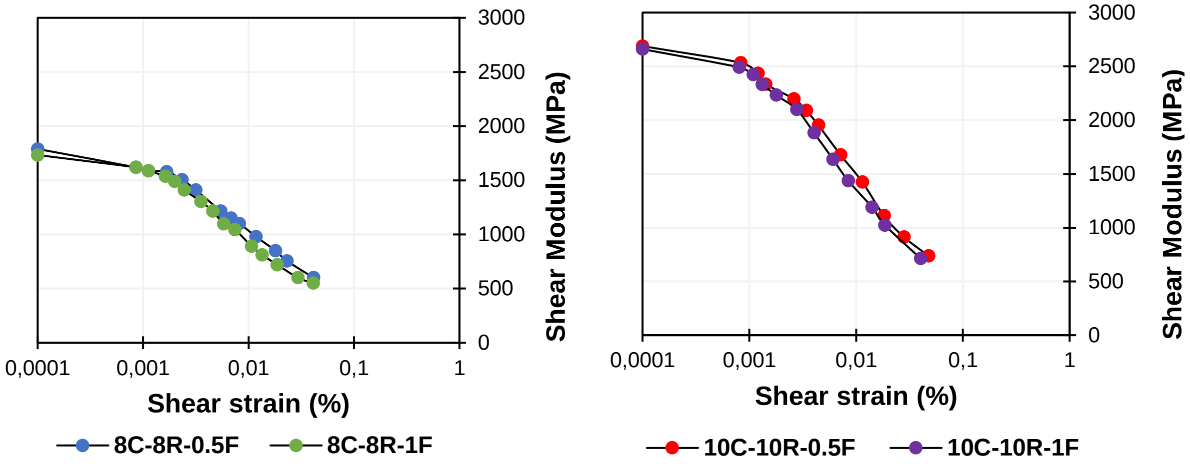


**Figure 9. Shear modulus - shear strain diagram (8C-10C, f=0,5 and 1,0 Hz)**

Based on the results of the static triaxial tests, the values of Poisson's ratio for the different sample cases were almost the same at 0,2; and the shear modulus of each cycle was calculated using the slope of the connection line of the maximum positive and negative cyclic shear points. The damping parameter was calculated using the stress–strain ring area (calculated using Origin software version 9,0) and the area of the triangle formed between the described line and horizontal axis.

## 6 Discussion

Figure 10 presents a comparison of the shear modulus and damping ratios for pure and stabilised sand at different frequencies for the shear strain with a value of 0,001. The change in damping ratio was from 7 % to 15 % with a variable sign (occasionally, the value was higher or lower) with no evident or connected preposition. The average change in the damping ratio from 0,5 to 1,0 Hz was 11 %. The change in the shear modulus was more stable and always appeared as a decrease for higher frequency values. The average percentage for reduced values of shear modulus was 7 %. Accordingly, for both observed parameters, the change in frequency for 0,5 to 1,0 Hz had no evident change and could be neglected.

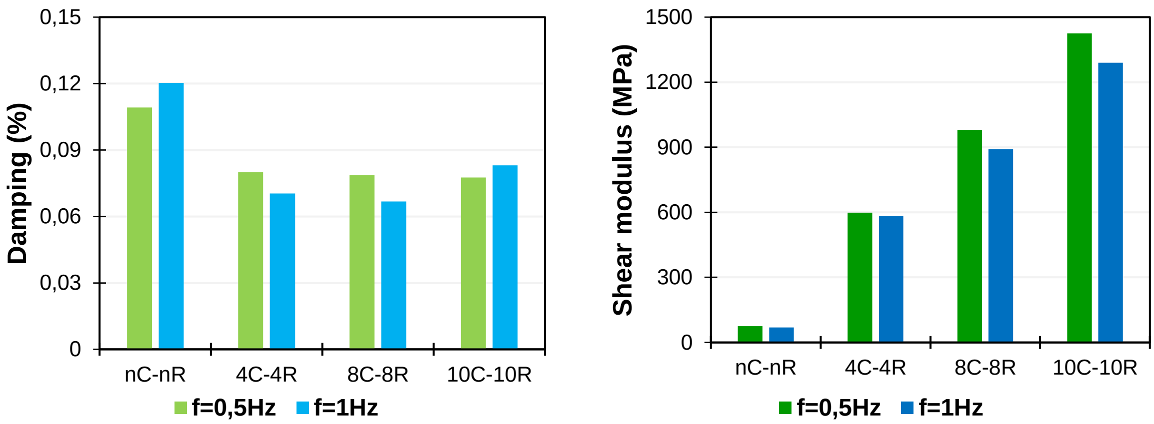


**Figure 10. Comparison of shear modulus and damping ratio of pure and stabilised sand at different frequencies (f=0,5 and 1,0 Hz)**

To present the possible behaviour and variation of the tested and calculated parameters with respect to the percentage of cement and RHA (C+RHA), Figure 11 shows results for a frequency of 1,0 Hz using dots in. The change in the damping ratio behaved like a polynomial function and decreased with the addition of C+RHA. According to the presented function, the lowest damping value was for approximately 12 % of the cement and RHA replacements. However, the addition of cement and RHA had a large influence on the shear modulus. This change can be represented by a linear function with an almost 60 % increase in the shear modulus for a one percent replacement of C+RHA. This phenomenon must be addressed.

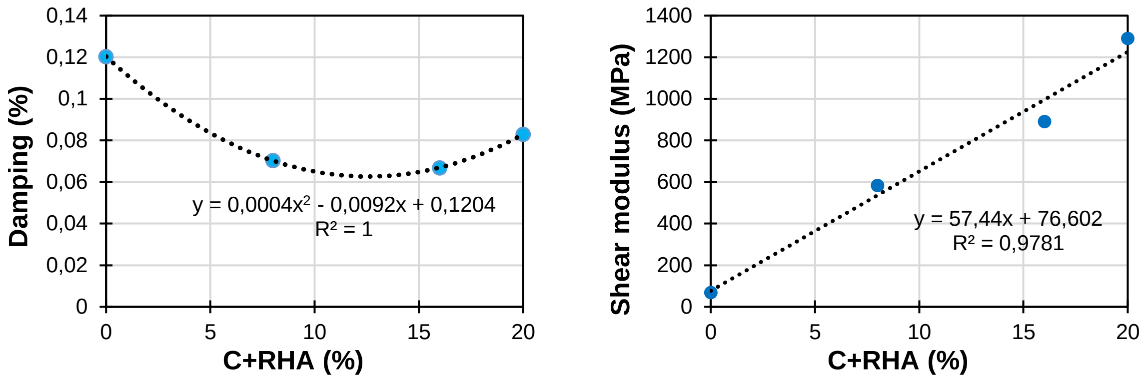


**Figure 11. Change in shear modulus and damping ratio of pure and stabilised sand at 1,0 Hz**

## 7 Conclusion

In this experimental study, the dynamic parameters (shear modulus and damping ratio) for pure sand (C+RHA = 0), cement-stabilised sand (C = 4,8,10) and RHA (RHA = 4,8,10) were examined. The material characteristics (granulation) and properties (XRD and XRF analyses) were determined. A standard sample was prepared within a 30-day processing period. Using a CT device, different percentages of stabilisers were used to prepare a relatively comprehensive graph. In addition, to investigate the effect of frequency on soil dynamic parameters (according to ASTM D3999 standard, uniform sinusoidal loading frequency in stress control experiments), two different frequencies (f = 0,5 and 1,0 Hz) were used. The results related to the damping and shear modulus obtained from the three-axis cyclic experiment are presented in the form of shear modulus–shear stress and damping ratio–shear strain diagrams after calculations for all samples. The results showed a slight effect of frequency on the damping and shear strain of pure sand. However, such a relationship is unclear for stabilised soils.

The main results of this study are as follows:

- The effect of frequency on the shear strain of the pure sand was negligible. This could be due to the lack of bonding between the sand grains.
- As the shear strain increased, the shear modulus decreased.
- Damping increased with increasing shear strain in all specimens.
- Damping decreased with the addition of C+RHA in all the samples, regardless of the replacement percentage.
- In all stabilised specimens, the shear modulus decreased with increasing frequency.
- The shear modulus increased with the addition of C+RHA in all samples by almost 60 % for 1 % cement and rice husk ash.
- The results revealed the positive effect of RHA as a partial substitute for cement because it cannot react with sand alone.

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