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Behaviour of machine foundations resting on saturated sand granular tire rubber mixtures

F H. Rahil [1], S A. Abd-Almuniem [2]

[1] Assist Professor, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq,
Email: ffhhhzmr@yahoo.com
[2] M.Sc. Geotechnical Engineering, Civil Engineering Department, University of Technology, Baghdad, Iraq.
Email: eng.salwan91@gmail.com

Abstract. This study aims to investigate the behaviours of machine foundations resting on sand granular tire rubber mixtures after saturation. Kerbala sand with two relative densities, 35% and 60%, and granular rubber of sizes 0.07 to 3 mm, resulting from hashing scrap tires into small pieces, were used. A harmonic vertical mode of vibration was applied using a mechanical oscillator fixed on a square steel footing (200×200×20 mm). The footing was rested on sand inside a steel box of size 1200×1200×900 mm. Nine model tests were carried out on saturated sand to study the effects of 0, 8, and 12% mix ratios and 0.5 B and 1 B mixing depth for the two relative densities and two frequencies (69 Hz and 80 Hz) in terms of displacement amplitude, settlement, and excess pore water pressure generation in soil. The same number of models were tested for a comparison of dry sand under the effects of the same parameters. The results showed that, in general, the displacement amplitude decreased and the settlement increased for saturated sand compared to dry sand under the same conditions. Mixing granulated tire rubber with saturated sand decreased the displacement amplitude, settlement, and excess pore water pressure; the range of percentages of reduction were from 19% to 73%, 40% to 70%, and 24% to 60% respectively.

1. Introduction

The recent huge development in transportation systems and drastically increased number of cars has resulted in various issues, particularly natural contamination. Intense issues have begun to develop around waste tires, with millions of tons of waste being generated; for example, in the United States (USA) in 1990, over 240 million tons of consumer waste of this type was thrown away. In Iraq, the quantity is estimated to be around two million tons a year. Developed nations, as the United States and Great Britain, have had to develop strategies for creating covering materials using tires, as well as expending resources to prevent contamination from these materials in the process. They also seek to maintain a strategic distance from the genuine effects of concoction gases, which come about during covering procedures, such as sulphur dioxide and carbon gases.

The impact of thermo-elastic damping of sand using elastic ground rubber was inspected. By using a Drnevich torsional-longitudinal resonant column in the torsional excitation mode, the dynamic properties were measured. Vibration was improved by using synthetic rubber in the construction of earthen systems. The results of their experimental work, which observed the dynamic properties improvement of Ottawa sand of small-strain gained by mixing it with elastic ground rubber of the same size, illustrated a sequence increment in both the ratio of damping and shear modulus in the sand samples. These increments were achieved with an optimum percent by volume of the ground rubber based on thermo-elastic effects between the various particles forecast by utilising mechanical damping and Hertzian particle contact effects. The results were assessed, and the available data used to propose that the expansive distinction in the elasticity modulus for the test result between the two materials was due to the increment in contact zone of sand and ground rubber particles, which also increases the matrix stiffness. The high thermoplastic improvement of damping in the soil rubber mixture thus depends on the difference between the sand and rubber thermal expansion coefficients [1].

The dynamic responses of machine foundations resting on sand-granulated tire rubber mixtures was studied; the results showed that with increasing mixing ratio and mixing depth, the displacement amplitudes and settlement of the machine foundations resting on sand and granular rubber mixture decreased. For loose state relative density, the optimum depth of improvement and ratio of mixing are 0.5 B and 8%, respectively, for 69 Hz frequency, while for 80 Hz frequency, they are 12% and 1 B, respectively. For relative density (60%)m, the optimum ratios of mixing and depth of improvement are 8% and 1 B for both 69 Hz and 80 Hz frequencies. In general, they noted that a few seconds after the vibration application, the settlement became constant during the test [2].
This paper aims to study the behaviours of saturated sand mixed with granular tire rubber under the vibration of machine foundations as well as to study the dynamic response parameter amplitude of displacement, settlement of foundation, and excess pore water pressure in such mixes.

2. Materials Used

2.1 Sand
Karbala sand was utilized in the present study. Standard tests were performed to determine the physical properties, and table.1 shows the points of interest of these properties. Figure 1 presents the grain size distribution of this type of sand. The soil used in this study was classified as poorly graded sand (SP) under the unified soil classification system.

Table 1. Physical properties of sand used

Property	***Value***	***Specification***
G_s, Specific gravity	2.64	[3]
Curvature coefficient of, C_c	0.87	
Uniformity coefficient of y, C_u	2.37	
D_{60}, D_{30}, D_{10} (mm)	0.38, 0.23,0.16	[4] and [5]
USCS-soil type	SP	
Dry unit weight, γdmax, kN/m3	18.82	[6]
Dry unit weight, γdmin, kN/m3	15.32	[7]

2.2 Granular rubber
Granular rubber was created by hashing scrap tyres from a tire manufacturing plant in Iraq, Babylon, into small pieces. Table.2 shows the engineering properties of tire rubber as given by the tyre factory. Figure 2 shows the grain size distribution of granulated rubber used. According to ASTM D 854, the specific gravity of this material is determined as 0.88. The rubber is thus specified as granular rubber according to ASTM D6270-98, and the grain size of the waste tyre rubber is 0.07 to 3 mm.

Table 2. Physical properties of tire rubber

Property	***Value***	***Specification***
Void ratio, e	1.5-2.5 Uncompacted 1.2-0.9 Compacted	
Modulus of Elastic, E	1240-5173 kPa	[8]
Poisson's Ratio, μ	0.5	
Capacity of Water Absorption	2%-4%	

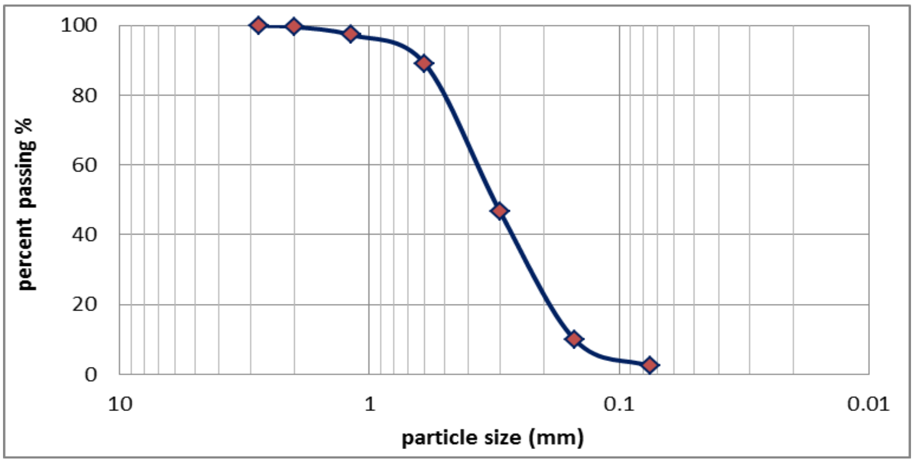

Figure 1. Grain size distribution of Karbala Sand

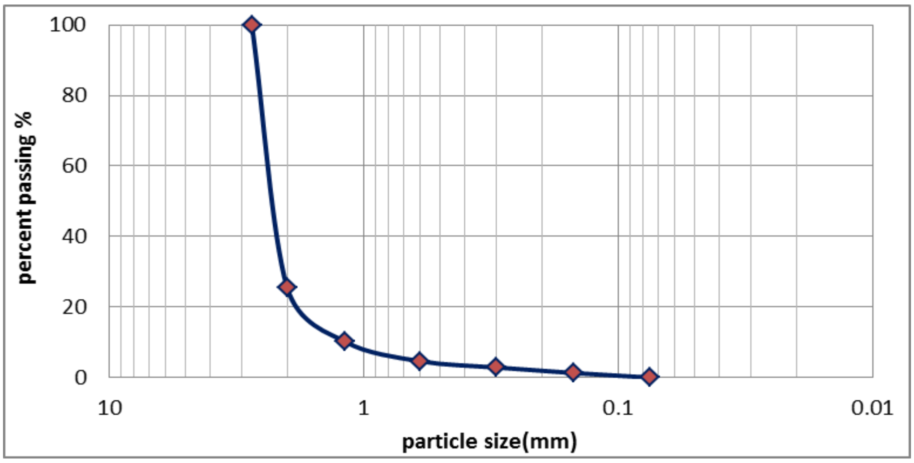

Figure 2. Grain size distribution of granular rubber

3. Model Preparation and Setup Used

The sand was poured into a testing tank at a predetermined weight with each layer being 100 mm thick; the size of the tank was 1200 × 1200 × 900 mm. Each layer was compacted to maintain the required thickness throughout the model, to achieve the required relative densities (35% and 60%). Two depths of mixing, 0.5 B and 1 B, where chosen, where the width of the foundation is B, and the ratios of inclusion by weight of sand were 8% and 12% for each mixing depth. The last layer was levelled, and a square steel footing of size 200 × 200 × 20 mm settled with a mechanical oscillator, with the highest point of the footing placed carefully in the centre of the tank.

For the saturation tests, the steel box was connected with a tank; the soil height in the steel box was lower than the water height in the tank by about 100 mm, to minimise losses from the water stream in the pipe. The saturation state of the soil was affirmed by allowing upward flow of the water and maintaining laminar and uniform flow conditions. A piezoelectric vibration pickup was set on the highest point of the foundation to measure the amplitude of displacement; this was connected to a system data acquisition. An LVDT was put on the edge of the footing to measure the settlement of the footing. A speed control unit was connected to the oscillator to achieve the desired frequencies 69 Hz and 80 Hz. During the saturation tests, the pore water pressure is generated rapidly; this pore water pressure was thus measured using model 3400 Geokon piezometer. The depth of the piezometer was 300 mm below the centre of the foundation. Figure.3 shows the model preparation and setup used.

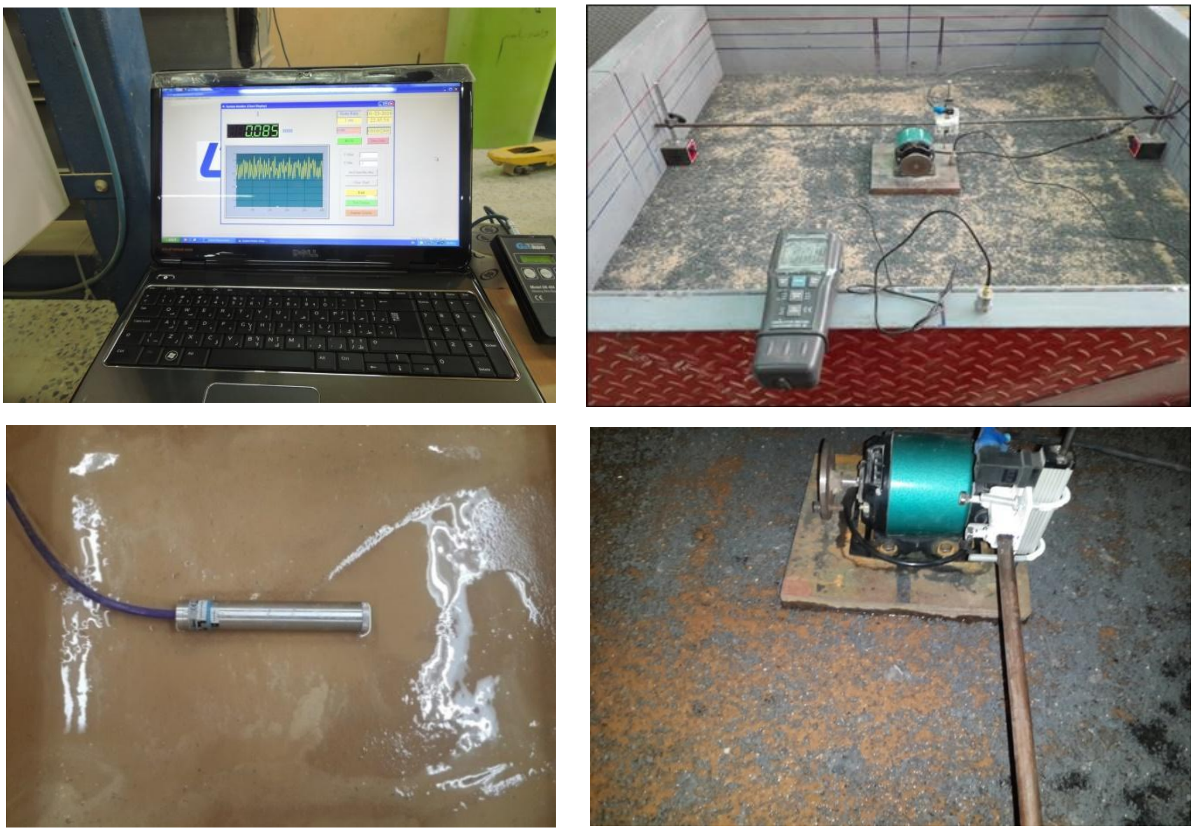

Figure 3. Model preparation and setup

4.Testing Programe and Testing Procedures

Eighteen model tests were performed. For saturation tests for sand without granular rubber and with granular rubber granular rubber under vertical mode of vibration nine models were tested. For relative densities (35% and 60%), and (69 Hz and 80 Hz) frequencies two models tested, while for sand with granular rubber five models were tested. Nine tests were performed for dry state for comparison under the same conditions as the saturation state. Two percentages of granular rubber by weight of sand were used: 8% and 12% for sand under the foundation at depths of 0.5 B and 1 B from the footing.

Two frequencies were used, 69 Hz and 80 Hz, for each relative density. After model preparation a harmonic load was applied at the foundation using a mechanical oscillator with a maximum speed of 6500 rpm. The results of displacement amplitude, settlement, and excess pore water pressure were recorded with timings on a PC.

5.Results and Discussion

The results of the experimental study of the saturated state and dry state are presented in this section. The presentation focusses on the effect of two main parameters, the mixing ratio of the granular rubber and the depth of the improved layer, on the displacement amplitude, settlement, and excess pore water pressure generated in the sandy soil. Mixtures for the two relative densities under the effect of the two frequencies, 69 Hz and 80 H, in the saturated state will be compared with the dry state under the same conditions.

5.1 Effect of Mixing Depth and Mixing Ratio on Saturated Sand with Granulated Tire Rubber at 35% Relative Density:

5.1.1 Amplitude of Displacement

The displacement amplitude in dry state was greater than in the saturation state for sand alone and for sand mixed with granular rubber; this appears to rely solely upon the operating frequency of the

machine. Figure 4 shows the relationship between displacement and time for the 69 Hz frequency; these tests are for saturated soil without granular rubber and saturated soil with a ratio of inclusion of 12% with various depths of improvement (0.5 B and 1 B). From the results of the tests, increased depth of mixing at the same value of mixing ratio decreases the displacement amplitude (Az) as the vibration fades with the increased depth of improvement. The reduction percentages (Az) are 73% and 28% for improvement depths of 1 B and 0.5 B, respectively, at a mixing ratio of 12% compared with sand alone. Thus, the preferred depth of mixing is 1 B for the 69 Hz frequency. For the 80 Hz frequency, the preferred depth of mixing and preferred mixing ratio is the same as in the dry state; it can be noted that the Az values of sand alone and sand with an improved depth of 1 B and a ratio of inclusion of 12% are less than for the 69 Hz frequency at this frequency. Thus, the best decrement in Az of a case of 12% inclusion at 1 B is 63% for the 80 Hz frequency. Figure.5 shows the results of the 80 Hz frequency.
In general, the presence of water and granular rubber in the soil significantly affects the decrease in displacement amplitude in the saturated state, and the granular rubber causes a steady state condition during vibration application depending on the depth of improvement layer and mixing ratios of the rubber. The values of displacement amplitude of machine foundations under loose dry and saturated sand, with and without granular rubber, at optimum depths of mixing (O.D.M) and optimum mixing ratios (O.M.R) for 69 Hz and 80 Hz frequencies, along with the percentage reduction for each case, are listed in Table 3 below. All Az values were taken between 600 to 800 seconds depending on the occurrence of steady state.

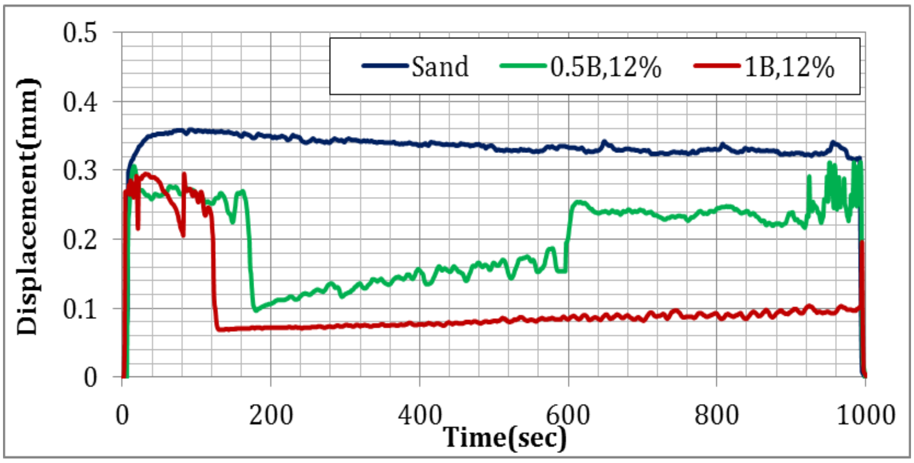

Figure 4. Relationship between displacement and time of 69 Hz frequency for saturation state

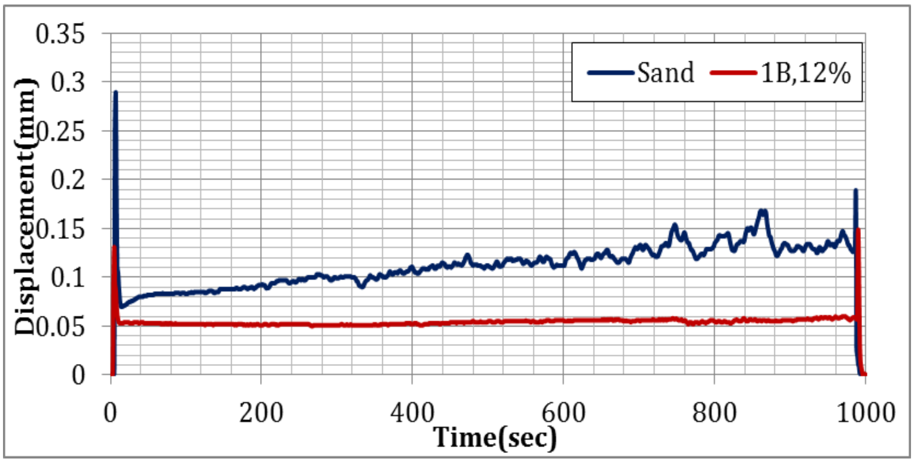

Figure 5. Relationship between displacement and time of 80 Hz frequency for saturation state

Table 3. Values of displacement amplitude of dry and saturated loose conditions

Soil State	*O.D.M and P.D.M*	*O.M.R %*	*Az (mm), 69 Hz*	*Az (mm), 80 Hz*	*Percent of reduction %, 69 Hz*	*Percent of reduction %, 80 Hz*
Dry Loose	0.5 B	0	0.219	--------	0	--------
		12	0.063	--------	71	--------
	1 B	0	--------	0.244	--------	0
		12	--------	0.055	--------	77
Saturated Loose	0.5 B	0	0.162	--------	0	--------
		12	0.117	--------	27	--------
	1 B	0	0.162	0.077	0	0
		12	0.043	0.029	73	63

5.1.2 Final Settlement

The final settlements of dry loose sand only and sand with granular rubber were less than half that of the saturated state for the same test conditions. With an increase in the machine operating frequency, the settlement increased. The optimum reduction in settlement of the foundation occurred at the optimum improvement depth and the optimum ratio of inclusion, due to the properties of granular rubber.For 69 Hz and 80 Hz frequencies, the best decrement in settlement (Stf) occurred at the improved depth of 1 B at a ratio of inclusion of 12% under saturation. With an increase in frequency, the settlement amplitude with time increased, but this was decreased with increases in the depth of improvement. The relationship between settlement and time for both frequencies is illustrated in Figures 6 and 7. If the machine foundation does not stop settling during operation in the case of dry and saturation tests, the footing will settle gradually and may experience permanent settlement, entering in the plastic zone; where granular rubber is mixed with soil, the settlement of the footing becomes constant during the process of operation, and the footing will stay in the elastic zone.

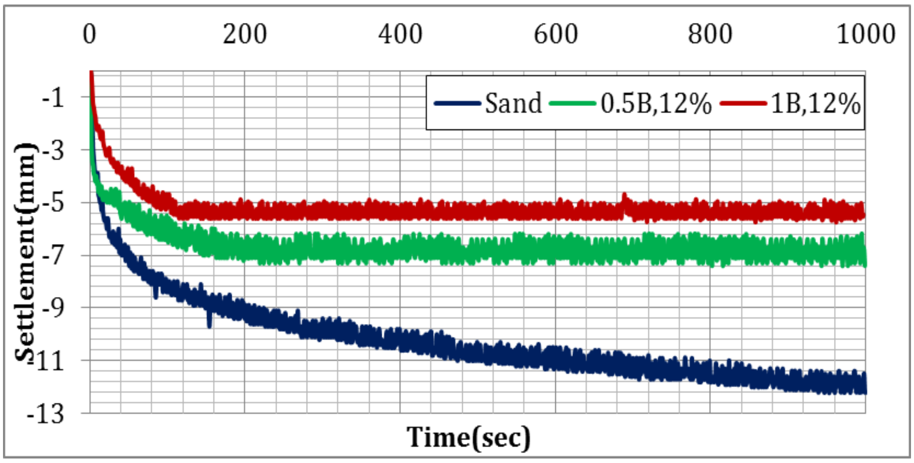

Figure 6. Relationship between settlement and time for frequency 69 Hz for saturation state

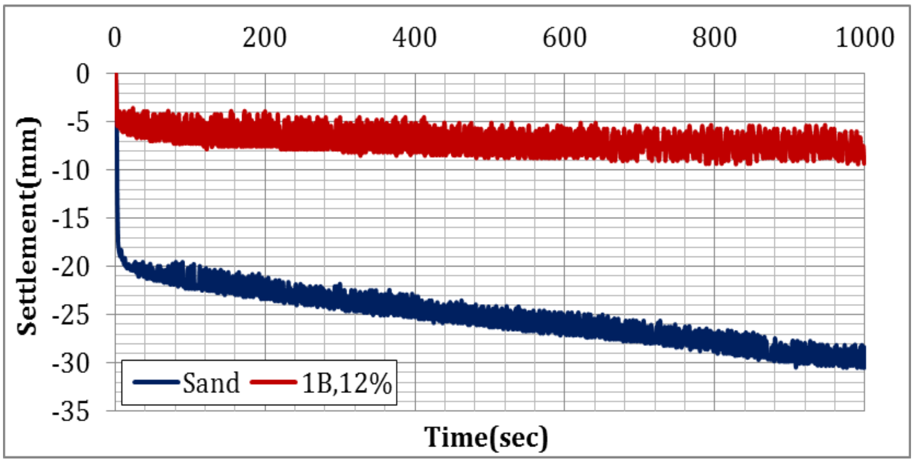

Figure 7. Relationship between settlement and time for frequency 80 Hz for saturation state

The values of settlement of machine foundations under loose dry and saturated sand, with and without granular rubber, at optimum depths of mixing (O.D.M) and optimum mixing ratios (O.M.R) for 69 Hz and 80 Hz frequencies, with percent reduction for each case, are listed in Table 4 below:

Table 4. Final results of settlement of dry and saturated loose conditions

Soil State	*O.D.M and P.D.M*	*O.M.R %*	*Stf (mm), 69 Hz*	*Stf (mm), 80 Hz*	*Percent of reduction %, 69 Hz*	*Percent of reduction %, 80 Hz*
Dry Loose	0.5 B	0	6.5	--------	0	--------
		12	1.8	--------	72	--------
	1 B	0	--------	21	--------	0
		12	--------	3.4	--------	84
Saturated Loose	0.5 B	0	12.2	--------	0	--------
		12	7.4	--------	40	--------
	1 B	0	12.2	30.4	0	0
		12	5.7	9.3	53	70

5.1.3 Excess Pore Water Pressure

During operation of the machine foundation, water pressure was generated, and a digital piezometer was used to measure this pressure. Furthermore, it was observed that the excess pore water pressure increased with increases in the machine operating frequency. In saturation tests, the final values of excess pore water pressure (E_{pwp}) for sand alone and for sand mixed with granular rubber did not transcend the effective stress at a depth of 0.3 m; thus, the liquefaction phenomena did not occur.

For the 69 Hz frequency, the E_{pwp} decreased by 31% and 60% for mixing depths of 0.5 B and 1 B, respectively, at the 12% ratio compared with saturated sand alone. In the same way, for the 80 Hz frequency, the reduction percentage was 37% for improvement depths of 1 B. For both frequencies the preferred improvement depth was thus 1 B. The relationship between E_{pwp} and time for 69 Hz and 80

Hz frequencies is shown in Figure 8. The results show that when improvement depth was increased to 1 B, the amplitude of E_{pwp} with time decreased. The E_{pwp} values for each test are recorded in Table 5.

5.2 Effect of Depth of Mixing and Mixing Ratio on Saturated Sand and Granulated Tire Rubber at 60% Relative Density

5.2.1 Amplitude of Displacement

The displacement amplitude may be increased or decreased depending on soil state (i.e., saturated or dry), relative density, and frequency; however, when relative density increases, the displacement will increase also regardless of whether the sand is dry or saturated, while for frequency, there may be an increase or decrease depending on the value of the resonance frequency. If this frequency is near resonance frequency, the displacement will increase, while after that it may be decreased.

In the saturated medium state with relative density, the displacement amplitude decreased, with the waves attenuating as the water and granular rubber absorbed them during the test. Thus, the optimal reduction in displacement happens either at optimum mixing depth or preferred mixing depth and optimum mixing ratio. The results showed that with an increase in the frequency, the values of Az decrease; the best reduction in Az for the 69 Hz and 80 Hz) frequencies occurred at the preferred mixing depth 1 B and the optimum mixing ratio 8%. The relationship between displacement and time for both frequencies is illustrates in Figures 10 and 11. The final Az values for each test are recorded in Table 6.

Table 5. E_{pwp} values for relative density 35% at 69 Hz and 80 Hz frequencies with different ratios of inclusion and improvement depths

Frequency, Hz	*Improvement depth*	*Ratio of inclusion, %*	*Epwp(kpa)*	*reduction Percent in Epwp, %*
	0.5 B	0	1.495	0
69		12	1.038	31
	1 B	0	1.495	0
		12	0.598	60
80	1 B	0	1.839	0
		12	1.154	38

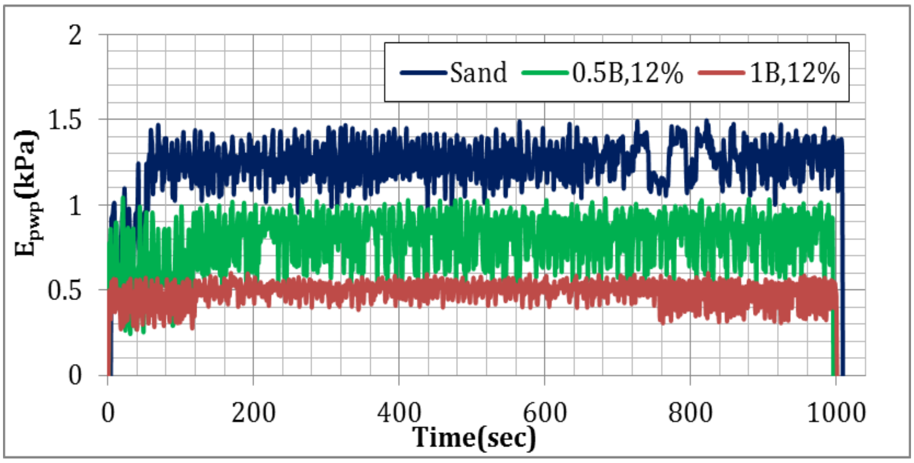

Figure 8. The relationship between Epwp and time for frequency 69 Hz

5.2.2 Final Settlement

The settlement decreased with increases in sand relative density in both dry and saturated states, while the amplitude of settlement increased with increases in sand relative density and machine frequency. The settlement of saturated sand reduced when granular rubber was mixed with saturated sand at the preferred depth of mixing and optimum mixing of inclusion (1 B and 8%, respectively). For 69 Hz and 80 Hz, a reduction percentage of more than 50% for the settlement of footing was seen compared with saturated sand without granular rubber. The relationship between settlement and time for 69 Hz and 80 Hz frequencies is presented in Figures 11 and 12 respectively. The final settlement values of dry and saturated tests are listed in Table 7.

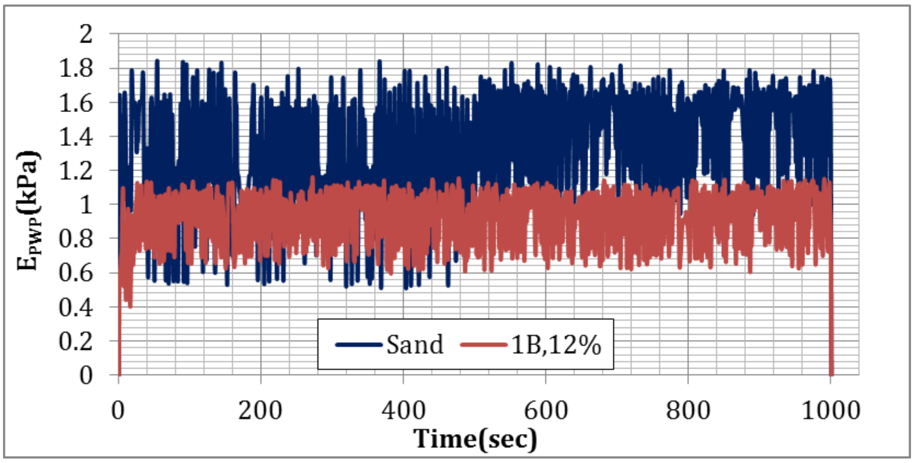

Figure 9. The relationship between Epwp and time for frequency 80 Hz

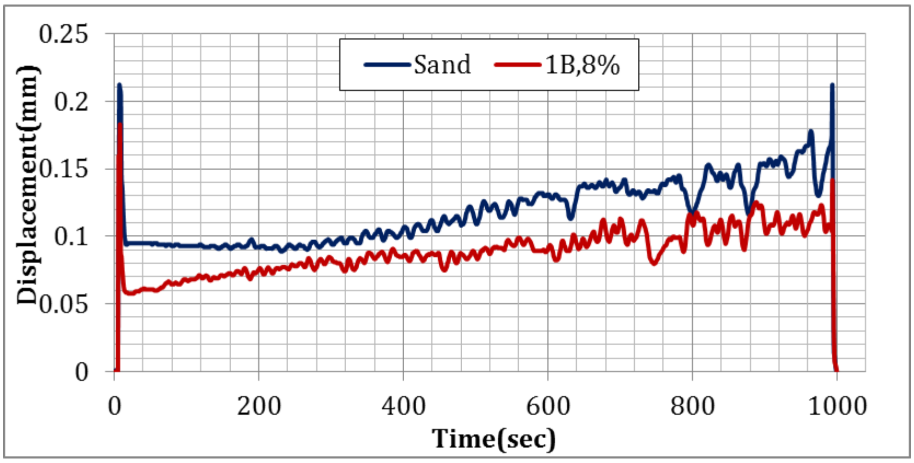

Figure 10. The relationship between displacement and time for frequency 69 Hz under a saturation state

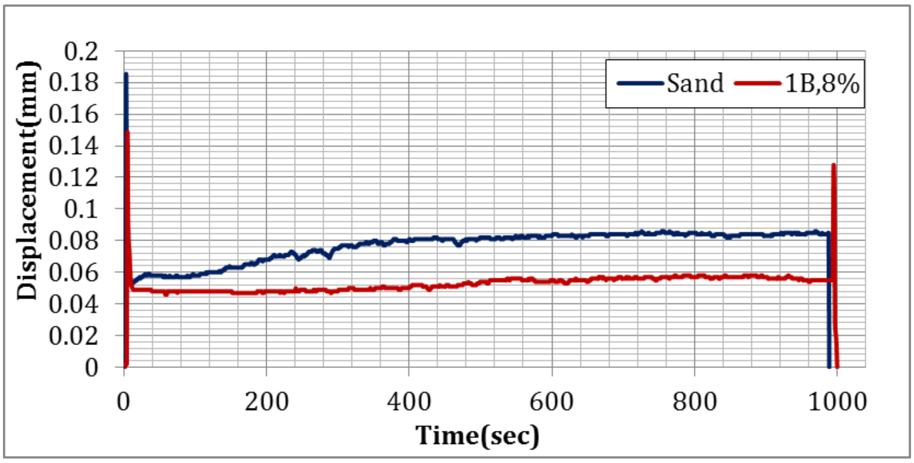

Figure 11. The relationship between displacement and time for frequency 80 Hz under a saturation state

Table 6. Displacement amplitude values of dry and saturated medium states

Soil State	*O.D.M and P.D.M*	*O.M.R %*	*Az (mm), 69 Hz*	*Az (mm), 80 Hz*	*Percent of reduction %, 69 Hz*	*Percent of reduction %, 80 Hz*
Dry Medium	1 B	0	0.154	0.084	0	0
		8	0.044	0.041	71	51
Saturated Medium	1 B	0	0.072	0.043	0	0
		8	0.058	0.029	19	33

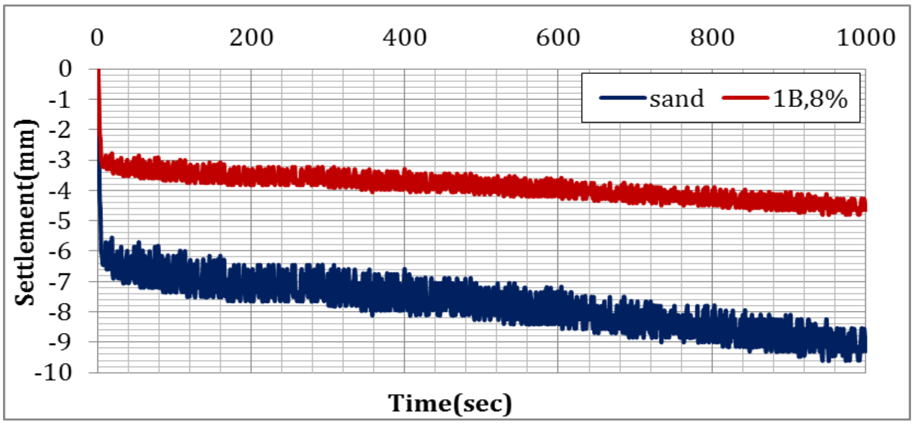

Figure 12. Relationship between settlement and time for frequency 69 Hz under saturation state.

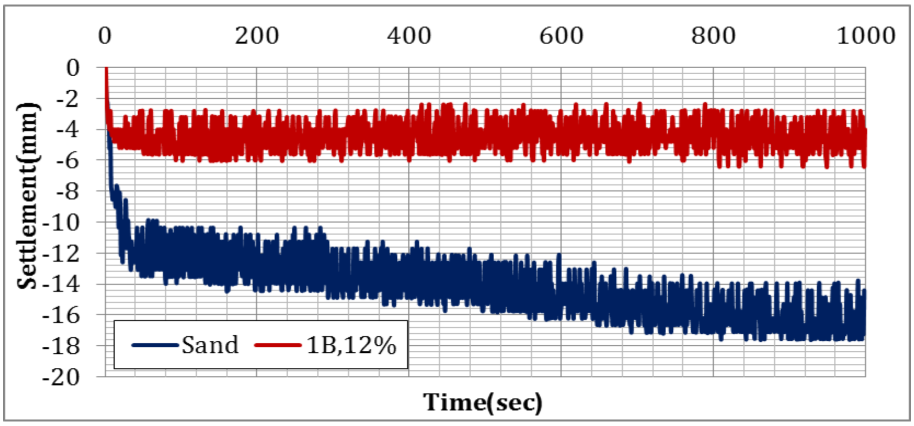

Figure 13. Relationship between settlement and time for frequency 80 Hz under saturation state

Table 7. Final settlement results for dry and saturated medium conditions

Soil State	*O.D.M and P.D.M*	*O.M.R %*	*Stf (mm), 69 Hz*	*Stf (mm), 80 Hz*	*Percent of reduction %, 69 Hz*	*Percent of reduction %, 80 Hz*
Dry Medium	1 B	0	5.1	6	0	0
		8	1.3	1	75	83
Saturated Medium	1 B	0	9.6	17.5	0	0
		8	4.8	6.4	50	63

6. Excess Pore Water Pressure

When relative density increased, the excess pore water pressure increased in the saturated sand, as the void ratio decreased and the soil stiffness increased. Furthermore, the excess pore water pressure increased gradually due to applied harmonic vibration from the machine. The relationship between time and excess pore water pressure for 69 Hz and 80 Hz frequency is presented in Figure 14 and 15 respectively. The final results of E_{pwp} of the dry and saturated tests are listed in Table 8.

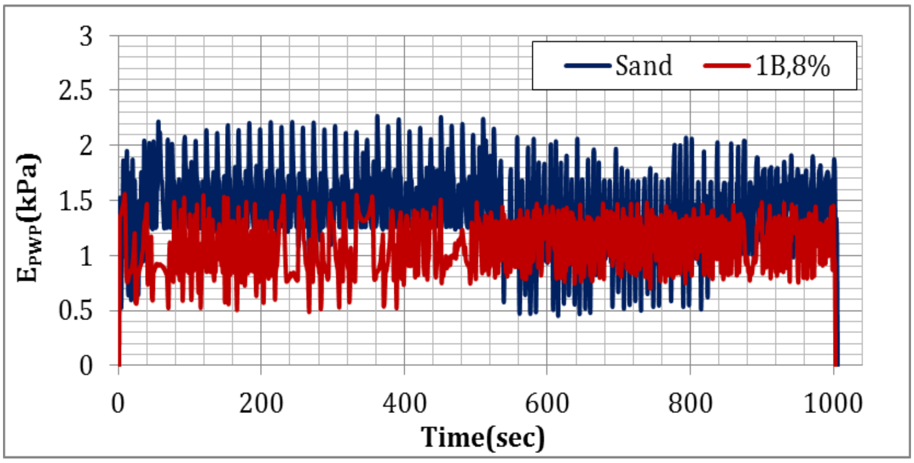

Figure 14. Relationship between (E_{pwp}) and time for frequency 69 Hz

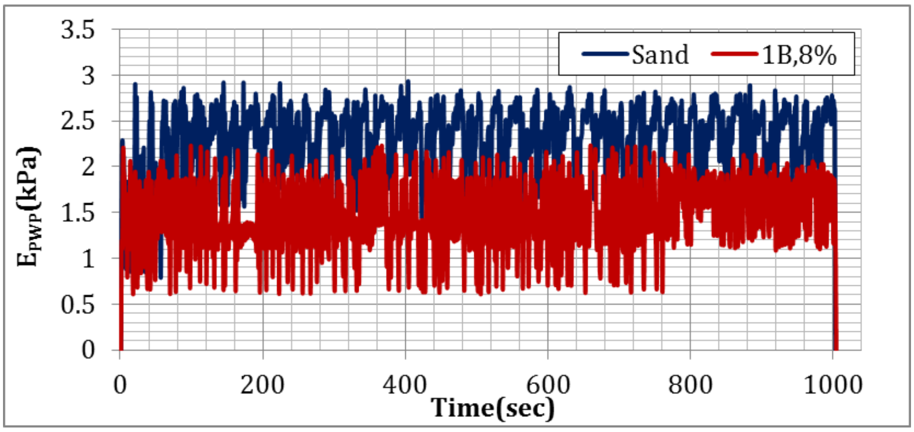

Figure 15. Relationship between (E_{pwp}) and time for frequency 80 Hz

Table 8. E_{pwp} values for saturated relative density 60% at 69 Hz and 80 Hz frequencies with different mixing ratios and improvement depths

Frequency, Hz	*Improvement depth*	*Ratio of Mixing, %*	*Epwp(kpa)*	*Reduction Percent in Epwp, %*
69	1 B	0	2.24	0
		8	1.55	31
80	1 B	0	2.93	0
		8	2.23	24

7. Conclusion

- For saturated sand mixed with granular tire rubber, the amplitude of displacement of saturation state is smaller than for dry state, due to the water and granular rubber working as absorption materials. The amplitude of displacement decreases with increases in the operating frequency in saturated conditions. The optimum reduction in displacement amplitude for relative density 35% occurs at the optimum mixing depth of 0.5 B and preferred mixing depth of 1 B, with the optimum mixing ratio being 12% for both frequencies (69 Hz and 80 Hz). For relative density 60%, the preferred improvement depth and optimum ratio of inclusion are 1 B, and 8% for 69 Hz and 80 Hz frequencies.
- Settlement of the dry state is less than in the saturated state for 69 Hz and 80 Hz frequencies and 35% and 60% relative densities, as the water causes a decrement in the stiffness of sand. When the granular rubber is mixed with sand, the amplitude of settlement decreases compared with sand alone over time. The greatest reduction in settlement happens at the preferred improvement depth of 1 B and preferred inclusion ratio of 12% for relative density 35% and for both frequencies, while for relative density (60%), the preferred depth is the same as for the loose state; the optimum mixing ratio become 8% for both frequencies.
- The amplitude of settlement decreases when the sand is mixed with granular rubber, due to the granular rubber having high damping properties. The sand will thus stay in the elastic zone when granular rubber is mixed with it rather than entering the plastic zone.

- In general, because the operation of the machine, excess pore water pressure will be generated and increase rapidly as the frequency increases. For the saturated loose state, the best reduction in E_{pwp} occurred at the preferred mixing depth of 1 B with the preferred mixing ratio of 12% for both 69 Hz and 80 Hz frequencies, while for saturated state, the optimum mixing ratio became 8%.
- In general, the E_{pwp} increases with increases in the sand's relative density in the saturation case, as the void ratio of the sand is reduced. The E_{pwp} also reduces due to the granular rubber's low void ratio.

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