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Resilient response of coarse soil to cyclic load in different load conditions

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ABSTRACT: The study aimed to compare the resilient response of gravelly sand under various cyclic load conditions using the resilient modulus (M_r) test under drained and undrained conditions. The resilient modulus is the value of the repeatedly applied deviator stress in triaxial compression divided by the recoverable (resilient) axial strain. Tests were conducted on natural soil and soil improved with polypropylene fibers and/or 1.5-3.0% cement additives. The impact of compaction and curing time on the stabilized samples was also examined. During the undrained M_r tests, the gravelly sand was subjected to liquefaction, even after fiber reinforcement. The resilient modulus value for unbound sand could only be achieved under drained conditions. The addition of cement improved the M_r, and curing time influenced this parameter. The addition of fiber increased the resilient modulus of cement-treated soil.

KEYWORDS: Resilient modulus, cyclic loading, compacted soil, cement stabilization, fiber reinforcement.

1 INTRODUCTION

The stiffness of a material is defined as its ability to resist deformation induced by stress. The resilient response of granular material (Seed et al. 1962, 1967) called resilient modulus or modulus of resilient deformation, is the value of the repeatedly applied deviator stress in triaxial compression ($\sigma_1 - \sigma_3$) divided by the recoverable (resilient) axial strain (ε_r):

$$M_r = \frac{\sigma_d}{\varepsilon_r} = \frac{\sigma_1 - \sigma_3}{\varepsilon_r} \tag{1}$$

which relates to the elastic Young's modulus. Under cyclic loading, the modulus of elasticity can be replaced with the resilient modulus to account for non-linearity and the stress relationship during cyclic loading. Formula (1) corresponds to the formula for calculating the resilient modulus (ASTM T 307-99):

$$M_r = \frac{\sigma_{cyclic}}{\varepsilon_r} \tag{2}$$

where σ_{cyclic} is the amplitude of cyclic applied axial stress (Figure 1).

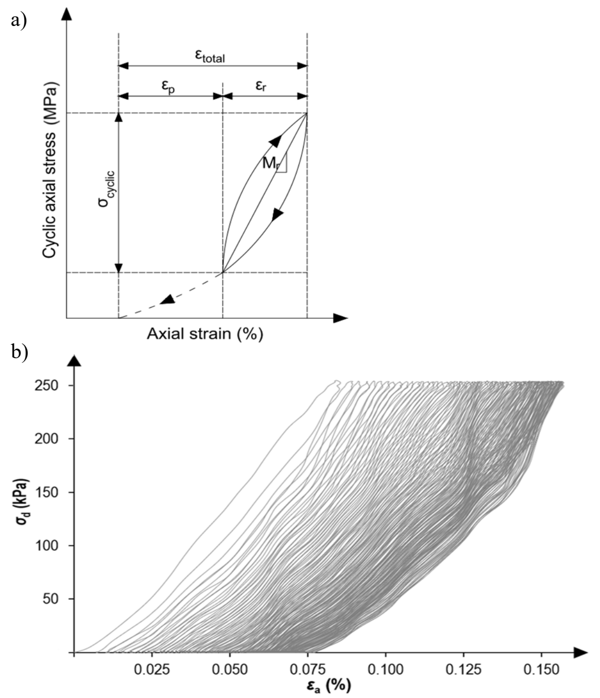

Figure 1. The cyclic load response in the resilient modulus test: a) a single cycle, b) one hundred load cycles.

The elastic limit of a material is the maximum value of a given load that does not induce permanent deformation. When this limit is exceeded and permanent deformation is induced, elastic deformations transform into plastic permanent deformations (ε_p). During repeated cycles of the same stress level acting on the soil, plastic deformations decrease and elastic deformations increase.

The literature on the resilient modulus of non-cohesive soils is very rarely presented. Researchers more often calculate resilient modulus using previously developed correlations between resilient modulus and other mechanical parameters, such as the California Bearing Ratio (*CBR*) or uniaxial compressive strength (q_u), e.g., Leung et al. (2013); Gajewska et al. (2017). It should be emphasized that the literature is dominated by the M_r test results obtained for cohesive soils.

Rahman et al. (2023) tested two poorly graded sands compacted by the Standard Proctor method at optimum water content (w_{opt}) and $w_{opt} \pm 2\%$. They stated the dependency of M_r on the water content at compaction. The M_r values decreased from 121 to 62 MPa and from 107 to 90 MPa along with water content. Jiang & Fan (2013) tested limestone crushed rock stabilized by 2−5% of cement. Samples were compacted by vibration or static pressure. Curing time gained 180 days. Research on coarse soils was also presented in the authors' previous works (Zabielska-Adamska et al. 2021; 2023).

The paper aims to present the influence of research conditions (drained and undrained) and soil improvements using cement and/or fiber additions on the resilient modulus of gravelly sand.

2 MATERIALS AND METHODS

2.1 *Materials*

The tested material is a fluvioglacial soil of Pleistocene origin. It has a large variation in relief surface and contains well-rounded quartz crumbles, as well as angular grains, with a considerable addition of lytic particles and feldspars. The two tested samples of gravelly sand (grSa) according to EN ISO 14688-1 are a poorly graded material based on EN ISO 14688-2. The unit weight of solids (γ_s) is 26.0 kN/m^3. Figure 2 shows the grain size distribution curves of the gravelly sand obtained by the sieve analysis. Grading parameters, including fine content (f_C), median diameter (D_{50}), uniformity coefficient (C_U), and coefficient of curvature (C_C), for both tested samples are presented in Table 1.

Laboratory tests were conducted on samples of gravelly sand and gravelly sand with the addition of 42.5R Portland cement in the amounts of 1.5% and 3.0% to the dry mass of soil, and their mixtures with 0.1, 0.2 and 0.3% of 18 mm-long polypropylene fibers.

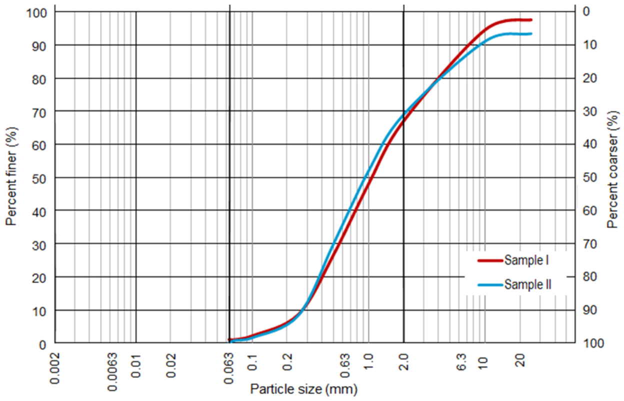

Figure 2. Grain size distribution of the two tested samples.

Table 1. Sample grading characteristics.

Sample	f_C	D_{50}	C_U	C_C
I	0.01	1.023	5.27	0.87
II	0.01	0.926	5.04	0.66

2.2 *Methods*

Laboratory tests of the resilient modulus were conducted using a cyclic triaxial shear test apparatus (Figure 3) on cylindrical samples approximately 70 mm in diameter and 140 mm in height. In these tests, confining pressure and axial load were applied pneumatically, and the samples were not saturated. The machine applied repeated cycles of the haversine-shaped load pulse, where the load pulse lasted 0.1 s and the rest period was 0.9 s. Samples were subjected to cyclic loading tests to determine the resilient modulus (M_r) according to AASHTO T307-99 standard for base and subbase materials. Loading sequence "0" is the conditioning of the sample at a confining pressure of 103.4 kPa. In the following fifteen sequences, the confining pressures range 20.7, 34.5, 68.9, 103.4 and 137.9 kPa, and maximum axial stresses range 20.7−62.1 kPa; 34.5−103.4 kPa; twice 68.9−206.8 kPa and 103.4−275.8 kPa, respectively. The number of cycles was 500 during conditioning and 100 in each remaining sequence. The M_r for sequences from 1 to 15 is calculated as the average value from the past five cycles of each load sequence.

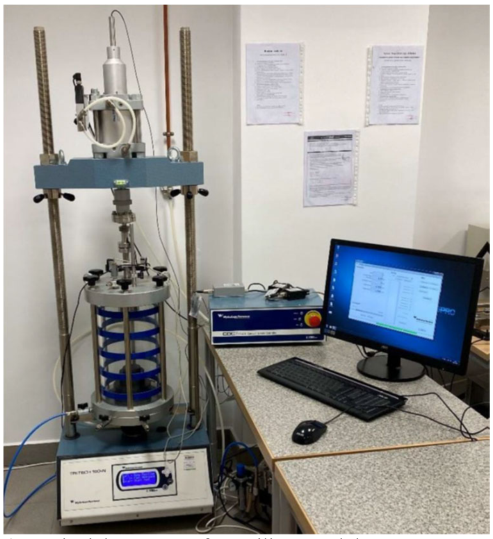

Figure 3. Triaxial apparatus for resilient modulus tests.

The cylindrical samples were prepared in a bipartite mold by dynamic compaction in three layers to achieve maximum dry density ($\rho_{d\,max}$) corresponding to the optimum water content (w_{opt}) obtained using the Standard (SP) and Modified Proctor (MP) methods (Table 2). The samples remained unsaturated during testing. They were tested immediately after compaction (unstabilized hydraulically samples) and after 7 and 28 days of curing at controlled temperature and humidity (stabilized samples).

The main tests were conducted under AASHTO T307-99 in drained conditions. Additional tests used closed drainage valves to simulate undrained conditions, with the samples having the optimum water content.

Table 2. Summary of compaction tests of the tested samples.

Sample	Cement (%)	Fibers 18mm (%)	Compaction method SP w_{opt} (%)	SP $\rho_{d\,max}$ (g/cm^3)	MP w_{opt} (%)	MP $\rho_{d\,max}$ (g/cm^3)
I	0	0	9.3	1.990	8.9	2.054
		0.1	8.9	2.032	8.2	2.121
		0.2	7.7	2.070	7.6	2.165
		0.3	7.4	2.076	7.2	2.177
	1.5	0	9.1	2.034	8.7	2.087
		0.1	8.2	2.059	7.2	2.174
		0.2	7.8	2.076	6.8	2.189
		0.3	7.6	2.078	6.7	2.196
	3.0	0	8.8	2.062	8.4	2.109
		0.2	7.5	2.165	6.5	2.228
		0.3	6.7	2.200	6.4	2.248
II	0	0	9.7	1.974	9.6	2.022
		0.1	9.8	2.003	8.8	2.104
		0.2	8.0	2.054	7.5	2.158
		0.3	7.7	2.060	7.0	2.160
	1.5	0	9.5	2.010	9.5	2.070
		0.2	7.9	2.066	7.0	2.183
		0.3	8.0	2.060	7.8	2.124
	3.0	0	9.2	2.046	8.7	2.090
		0.2	7.8	2.077	6.5	2.208
		0.3	7.0	2.128	6.7	2.240

3 TEST RESULTS

3.1 *Resilient modulus tested in drained conditions*

Gravely sand without additives achieved 248 MPa for the SP compaction and 255 MPa for the MP compaction, so it meets the ranges for M_r of poorly graded gravelly sand compacted at optimum water content that ranges 166−228 MPa (Mohajerani et al. 2016). The addition of polypropylene fibers increased the resilient modulus in most of the tested samples (Figure 4).

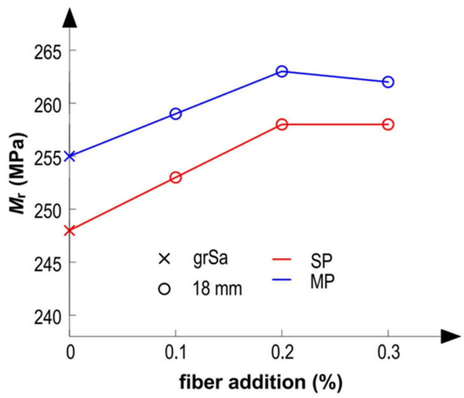

Figure 4. Dependence of resilient modulus on fiber addition.

The slightly highest modulus value was obtained with 0.2% fiber addition, and it was equal to 258 MPa for the SP compaction and 263 MPa for the MP compaction. Greater values of the resilient modulus were obtained for samples compacted using the MP method.

The addition of cement significantly improved the resilient modulus (Figure 5). Samples cured for 28 days achieved much higher values of the M_r in all cases, compared to samples cured for 7 days. Also in this case, the samples compacted using the MP method achieved considerably higher values of the resilient modulus than those compacted by the SP method. Gravelly sand samples with 3% of cement, after 28 days of curing, obtained 659 MPa for the SP compaction and 673 MPa for the MP compaction.

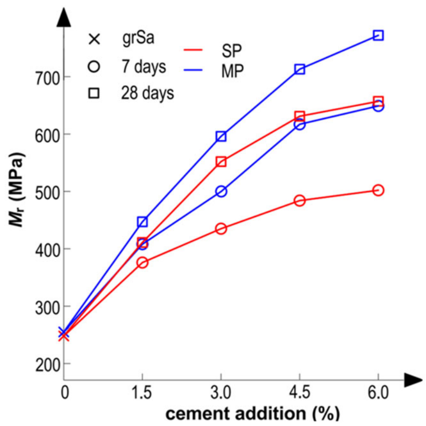

Figure 5. Dependence of resilient modulus on cement addition after 7 and 28 days of curing.

Figure 6 shows the relationship between the resilient modulus and fiber addition for stabilized samples compacted by the SP and MP methods. The greatest resilient modulus value equal to 685 MPa was achieved after 28 days of curing, for gravelly sand compacted using the MP method with the addition of 3% cement and 0.2% polypropylene fibers.

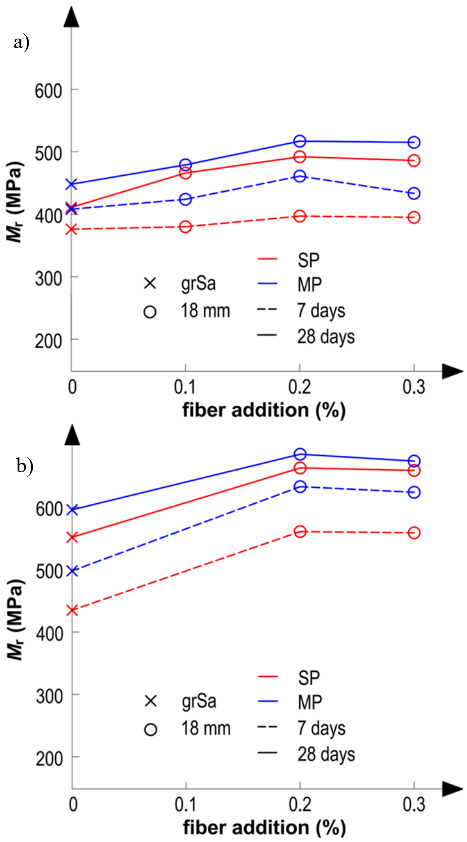

Figure 6. Resilient modulus vs. fiber addition for gravely sand tested after 7 and 28 days of curing with: a) 1.5% of cement, b) 3% of cement.

3.2 *Resilient modulus in undrained conditions*

In undrained tests, the gravely sand samples without cement addition were damaged, and determining the resilient modulus using the full test program was not possible. The gravelly sand was compacted by the SP method at a saturation degree of 77% and by the MP method at 83%, but the soil liquefied due to shear stress induced by cyclic loading. Similar observations were made for the gravelly sand sample with the 0.3% polypropylene fibers. Adding reinforcement to the natural soil resulted in only minimal improvement in cyclic properties. The gravelly sand sample failed during the first loading sequence, while the soil with 0.3% addition of 18 mm polypropylene fibers failed during the second loading sequence. It should be noted that a mechanically compacted gravelly sand cannot be installed in base or subbase if there is no possibility of water draining from the layer. Figure 7 shows the relation between the resilient modulus and the number of cycles for the gravelly sand sample and the soil sample after dispersed reinforcement, compacted using the SP method.

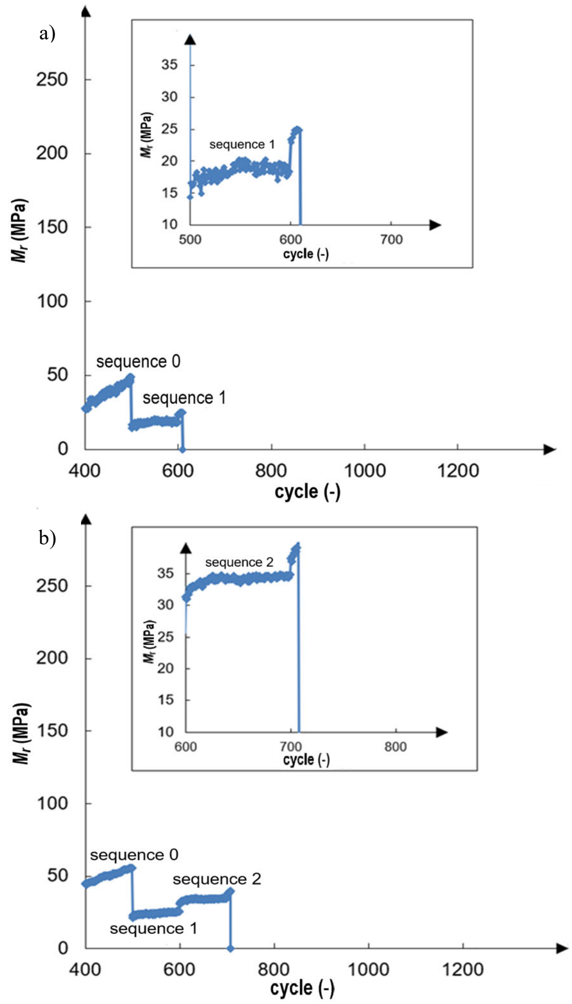

Figure 7. Dependence of M_r in undrained conditions on the number of cycles (Dobrzycki 2025): a) gravelly sand, b) gravelly sand with 0.3% fiber addition.

A minimum 1.5% cement addition strengthens the gravelly sand, which enables the resilient modulus test to be carried out. Increasing cement addition raises the M_r values (Figure 8). Gravelly sand samples with 3% cement, after 28 days of curing, gained almost twice the lower values in comparison to drained conditions − 370 MPa for the SP compaction and 402 MPa for the MP compaction.

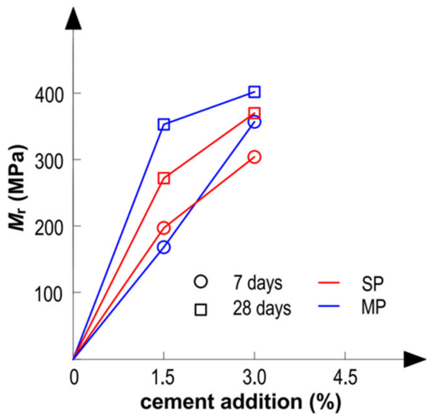

Figure 8. Dependence of resilient modulus in undrained conditions on cement addition after 7 and 28 days of curing.

Using fibers to cement stabilized gravelly sand improves the resilient modulus values, as shown in Figure 9. The highest resilient modulus was similar to that of the drained condition for gravelly sand with 3% cement and 0.2% polypropylene fibers, compacted by the MP method, after 28 days of curing. However, this M_r value, reaching 484 MPa, was nearly 1.5 times lower.

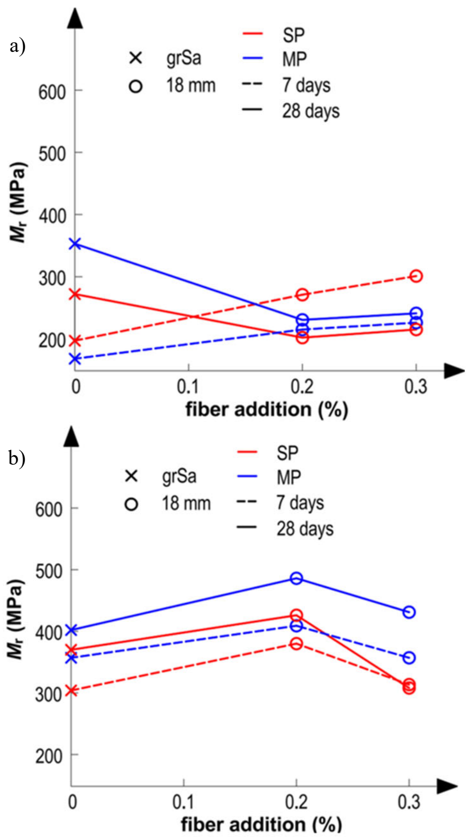

Figure 9. Resilient modulus versus fiber addition for gravely sand tested in undrained conditions after 7 and 28 days of curing with: a) 1.5% of cement, b) 3% of cement.

4 CONCLUSIONS

Load conditions are crucial in determining the resilient modulus. Adopting drained conditions, as per the AASHTO T 307-99 standard, allows for determining the parameter of gravelly sand in its natural state (without improvement). This is impossible under undrained conditions, where tested gravelly sand samples, compacted at optimum water content using the Standard and Modified Proctor methods, liquefy during testing without being saturated. The addition of dispersed reinforcement in the form of polyamide fibers only delays the liquefaction of the soil. The determination of the resilient modulus of gravelly sand is possible for soil stabilized with a 1.5% cement addition.

Adding cement increases the resilient modulus values of both samples tested under drained and undrained conditions. Usually, a similar trend is observed with fiber and cement additions; however, increasing fiber content does not always result in higher resilient modulus values. Higher resilient modulus values are achieved for the material compacted using the Modified Proctor method and after curing the stabilized samples for 28 days.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Dobrzycki, P. 2025. *The Resilient Modulus as a Measure of the Stiffness of Reinforced Soils*. PhD thesis. Bialystok.

Gajewska, B., Kraszewski, C., and Rafalski, L. 2017. Significance of cement-stabilised soil grain size distribution in determining the relationship between strength and resilient modulus. *Road Materials and Pavement Design* 19(4), 1−10.

Jiang, Y.J., and Fan, L.F. 2013. An investigation of mechanical behavior of cement-stabilized crushed rock material using different compaction method. *Construction and Building Materials* 48, 508−515.

Leung, G.L.M., Wong, A.W.G., and Wang, Y.H. 2013. Prediction of resilient modulus of compacted saprolitic soils by CBR approach for road pavement subgrade. *International Journal of Pavement Engineering* 14(4), 403−417.

Mohajerani, A., Nguyen, B.T., and Glavacevic, L. 2016. Estimation of resilient modulus of unbound granular materials using Clegg impact value and field stress levels. *Transportation Geotechnics* 7, 115–129.

Rahman, M.M., Gassman, S.L., and Islam, K.M. 2023. Effect of moisture content on subgrade soils resilient modulus for predicting pavement rutting. *Geosciences* 13(4), 103.

Seed. H.B., Chan, C.K., and Lee, C.E. 1962. Resilience characteristics of subgrade soils and their relation to fatigue failures in asphalt pavements. Proc. 1st International Conference on the Structural Design of Asphalt Pavements, Ann Arbor.

Seed, H.B., Mitry, G., Monismith, C.L., and Chan, C.K. 1967. Factors influencing the resilient deformations of untreated aggregate base in two-layer pavements subjected to repeated loading. *Highway Research Record* 190, 19−57.

Zabielska-Adamska, K., Dobrzycki, P., and Wasil, M. 2023. Estimation of stiffness of non-cohesive soil in natural state and improved by fiber and/or cement addition in different load conditions. *Materials* 16, 417.

Zabielska-Adamska, K., Wasil, M., and Dobrzycki, P. 2021. Resilient response of cement-treated coarse post-glacial soil to cyclic load. *Materials* 14, 6495.

American Association of State Highway and Transportation Officials, 2003. AASHTO T 307-99 *Standard method of test for determining the resilient modulus of soils and aggregate materials*. Washington: AASHTO.

European Committee for Standardization, 2018. EN ISO 14688-1 *Geotechnical investigation and testing – Identification and classification of soil – Part 1: Identification and description*. Brussels: CEN.

European Committee for Standardization, 2018. EN ISO 14688-2 *Geotechnical investigation and testing – Identification and classification of soil – Part 2: Principles for a classification*. Brussels: CEN.