Resilient Modulus as a Technical Parameter for Evaluating the Cement-Stabilized Soil

Patryk Dobrzycki, Katarzyna Zabielska-Adamska, and Mariola Wasil

Abstract The design and construction of road pavement substructures involves compacting aggregate in conditions close to optimum moisture content. The recommendation introduced by AASHTO, obliges designers to use mechanistic-empirical design methods by using the resilient modulus. The value of cyclic resilient modulus is determined based on cyclic triaxial tests, in which elastic axial strain and cyclic deviator stress are measured. Laboratory tests were performed on natural (gravelly sand) and chemically stabilised (CEM I 42.5 R) soil. The study compared the effect of different cement additives (1.5, 3.0, 4.5, 6.0%) on the resilient modulus tested on samples which were compacted using the Standard Proctor method. The addition of cement increased the stiffness of the soil and the resilient modulus, while the elastic axial strain has decreased. The samples were tested after 7 and 28 days of care. A longer period of treatment increased the resilient modulus. The gravelly sand stabilised with cement obtained high values of resilient modulus.

Keywords Resilient modulus · Cyclic load · Stabilised soil

1 Introduction

The road base is the part of the pavement structure whose main function during exploitation is to transfer and distribute the stress caused by the movement of vehicles on the road. Subbase layers may be made of asphaltic concrete, unbound mixtures or binder-bound mixtures. Depending on the type and position of the substructure in the structure, the materials permitted for their construction may be different [1]. The American Association of State Highway and Transportation Officials (AASHTO) standard introduced the resilient modulus (M_r) [2] as a basic parameter of mechanistic design for pavement and pavement layers to determine layer thickness and overall

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system response to traffic loads in the case of flexible pavements. The formula for determining M_r is related to applied cyclic axial stress (σ_{cyclic}) and relative resilient axial strain (ε_r).

$$M_r = \sigma_{cyclic}/\varepsilon_r \quad (1)$$

Cyclic loading causes an increase in the resilient modulus of unsaturated soil. It is related to the plastic strengthening of the soil, which, as a result of successive cycles of the same stress, corresponds to a decrease in plastic deformation and an increase in elastic deformation [3]. In Fig. 1, it can be seen the stress in the test specimen changes during cyclic loading.

The review of the literature shows that many researchers have investigated the effect of different parameters on the resilient modulus of various types of soil. The elasticity of unbound materials is most often assessed using a triaxial apparatus, but other methods can also be used, including a simple shear test, torsional resonance column test, a hollow cylinder test and a true triaxial test. The most frequently studied parameters are the influence of deviator stress and confining pressure, the time and frequency of loading, the number of loading cycles, the grain size and density of the material and the degree of saturation [3]. In the literature, various mathematical models for predicting the elastic response of materials under repeated loading can

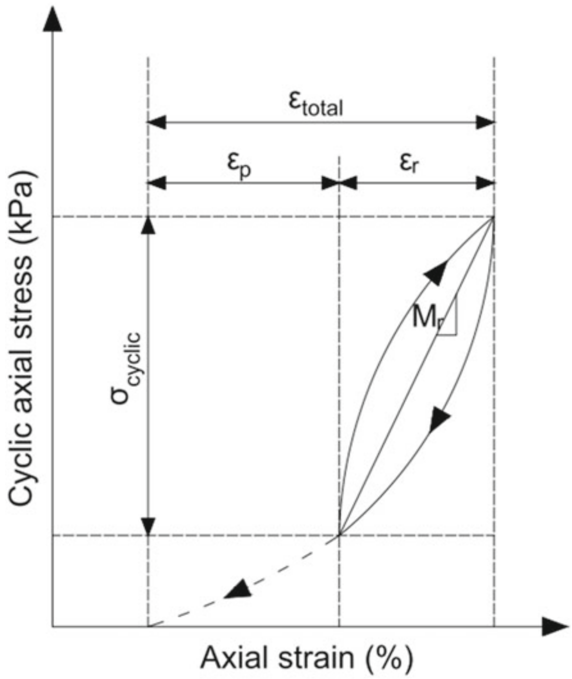


Fig. 1 Specimen response to cyclic loading during resilient modulus testing; ε_p is the constant relative deformation and ε_r is elastic relative deformations

also be found. They present, inter alia, the modelling of permanent deformation as a function of the number of load applications and stress conditions.

The significance of elastic modulus in design is discussed by Nazarian et al. [4]. They used different pavement design models to demonstrate the importance of resilient modulus values for the required pavement thickness and to prove the importance of obtaining a reliable elastic modulus measurement for mechanistic-empirical pavement design. Various pavement analysis algorithms and material models have been analysed to demonstrate the influence of resilient modulus on mechanistic-empirical pavement design. The study showed that inaccuracies in analysis algorithms and testing procedures have a significant impact on the design.

Another important parameter that affects the resilient modulus is the effect of the stabilizing additive. The vast majority of publications refer to lime-stabilised soils. The effect of lime addition and curing time on the modulus of elasticity is most commonly evaluated [5]. An increase in resilient modulus values was observed with the percentage of (0–8%). In the case of lime addition at 4, 6 and 8%, the effect of curing time is evident.

Significantly lower numbers of publications and literature refer to cement stabilization. The amount of cement used to stabilize the soil depends on the soil grain size, composition and requirements. Cement affects the cohesive soil by increasing its cohesion and reducing its water absorption and plasticity. Its content in stabilization is usually in the range of 4–10% [6]. Larger amounts of cement addition increase the strength but also increase the risk of shrinkage and cracking.

The aim of the research is to consider the impact of various percentages of cement additives: 1.5, 3.0, 4.5, and 6.0% on the resilient modulus and quick shear strength of non-cohesive soil used for the construction of road base and subbase.

2 Materials and Methods

2.1 Materials

Laboratory tests to determine the resilient modulus were carried out on soil–cement mixtures. The cement that was used as a stabilizer was Portland cement 42.5R. The cement was mixed with the soil in different proportions in the range of 1.5–6%. The cement percentage referred to the dry weight of the cement relative to the dry weight of the coarse soil in the test sample.

One of the basic tests to determine the granulometric composition was sieve analysis, which was performed in accordance with the EN 933–1 standard [7]. The results of the test are presented in Fig. 2.

Comparing the results with EN ISO 14688–1 [8], the tested soil is gravelly sand (grSa). In order to determine whether the soil is well-graded, the coefficient of homogeneity $- C_U$ and the coefficient of curvature $- C_C$, were calculated from the grain-size curve. The values of $C_U = 5.45$ and $C_C = 0.87$ indicate that the tested soil is

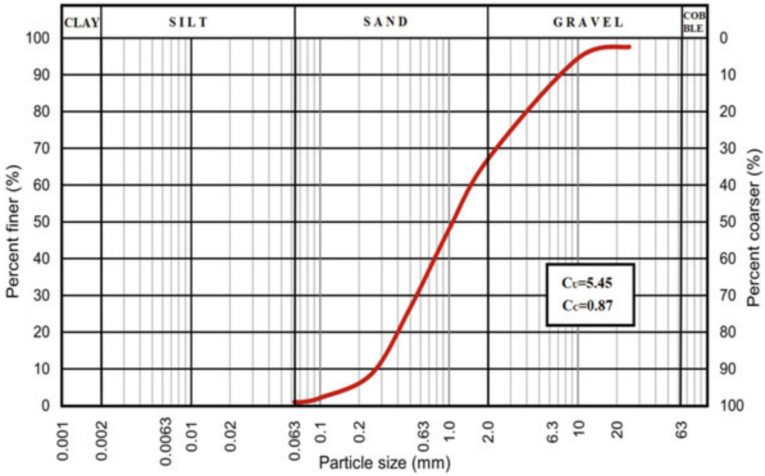


Fig. 2 The grain-size curve of tested soil

poorly grained [9]. The tested soil can be used as base or subbase course material (gradation D) with a lower percentage of fine fractions as it meets the requirements of EN 13,242 [10].

The gravelly sand is a post-glacial soil, which is characterized by a large variation in x of grain. The soil contains well-rounded quartz crumbs and angular grains, with significant lithic and feldspar particles [11].

Another laboratory test performed was the standard Proctor test, which was carried out in accordance with EN 13,286–2 [12]. It was carried out to determine the optimum moisture content (w_{opt}) and the maximum dry density ($\rho_{d\ max}$). Tests were conducted on gravelly sand and sand with different cement additions (1.5, 3, 4.5 and 6%). The results of the tests are presented in the compaction curves in Fig. 3.

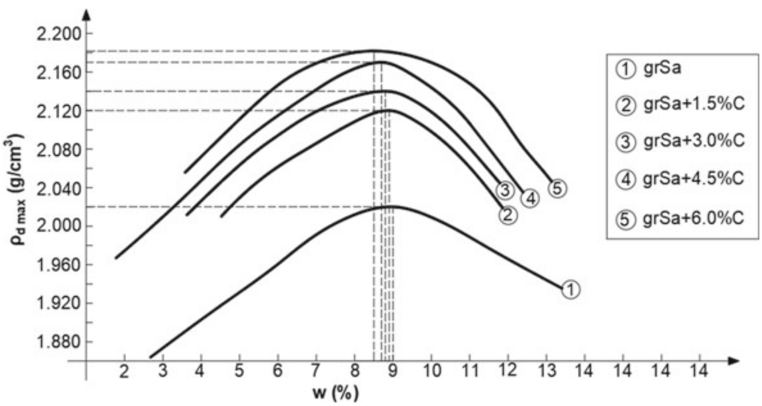


Fig. 3 Compaction curves of tested materials

Table 1 Geotechnical parameters of the tested materials

Material	w_{opt} (%)	$\rho_{d\ max}$ (g/cm^3)	e (−)	ρ_s (g/cm^3)
grSa	9.00	2.020	0.31	2.65
grSa + 1.5%C	8.90	2.120	0.25	2.66
grSa + 3.0%C	8.80	2.140	0.24	2.66
grSa + 4.5%C	8.70	2.170	0.23	2.67
grSa + 6.0%C	8.50	2.182	0.23	2.68

C-cement addition

Table 1 provides the compaction parameters (w_{opt} and $\rho_{d\ max}$), the initial void ratio $-e$ and the specific dry density $-\rho_s$.

The addition of cement increases the maximum dry density of soil and slightly decreases the optimum moisture content. A review of the literature shows that many researchers have also confirmed this relationship [13, 14]. The void ratio e decreases with increasing cement addition, while the value of ρ_s increases insignificantly.

2.2 Methods

Tests were performed on compacted specimens of gravelly sand with cement additions. Initially, the dried soil was mixed with cement, then sufficient amount of water was added to obtain the optimum moisture content for each material (see Table 1). The samples were prepared in a bipartite cylindrical mould by compacting the material in three layers. The height of the sample was approximately 140 mm, and the diameter was about 70 mm.

The main test apparatus was the Dynatriax Cyclic Triaxial System shown in Fig. 4, which allows full automation and control of all the parameters that are required to perform a cyclic triaxial test. Specimen deformations are measured using external LVDT sensors built into the actuator piston and at the top of the chamber.

The design manual introduced by AASHTO specifies the parameters to be used when testing the resilient modulus [2]. The specimen is loaded cyclically in 16 sequences in which parameters such as chamber pressure, axial stress, cyclic stress and contact stress are changed. The number of cycles for sequence 0 is 500–1000 cycles, and for the other sequences, the number of cycles is constant and is 100. Sequence "0" is the conditioning of the sample. In the next fifteen sequences confining pressures range from 20.7 to 137.9 kPa, and maximum axial stresses range from 20.7 to 275.8 kPa. The resilient modulus M_r for sequences from 1 to 15 is calculated as the average value from the past five cycles of each load sequence.

Fig. 4 Laboratory equipment

Once all sequences have been completed the quick shear tests have proceeded. The confining pressure in the chamber during the test was 34.5 kPa. The applied load generated axial deformation at a rate of 1% per min. The test was stopped when the specimen failed (drop in force, increase in deformation).

3 Results and Discussion

All stabilised specimens passed the cyclic loading tests, hence the calculation of the resilient modulus was possible, which was not obtained for gravelly sand alone [11]. The specimens failed only after the quick shear test. Figure 5 shows a graph of the change in resilient modulus during the execution of all loading cycles for a gravelly sand sample with 1.5% cement added, cared for 28 days. M_r increased rapidly at the beginning and became almost constant after 600 loading cycles, which can be observed in sequence 1. This behaviour may be due to the cyclic compaction of the sample under increasing maximum axial stress. Another observation is that the highest increase in modulus could be seen during the three sequences (sequences 0, 12 and 15) when the highest increase in axial stress occurred. The highest value of modulus for all the tested specimens was obtained in sequence 15. The reason for this is that confining pressure and max applied axial stress have the largest values and

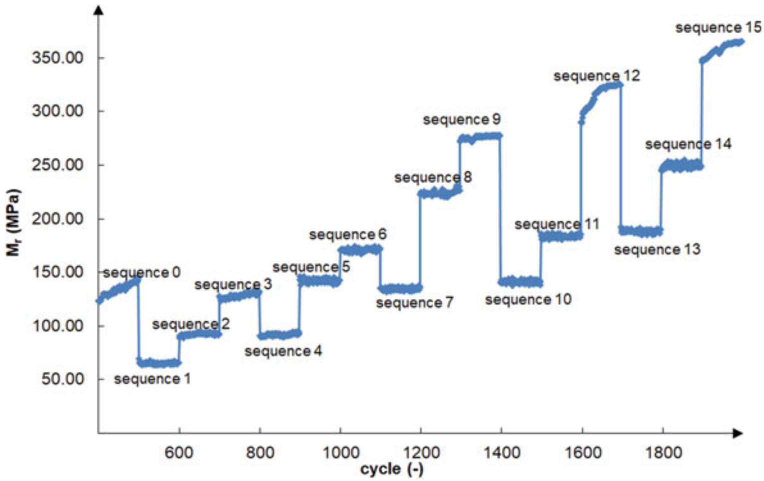
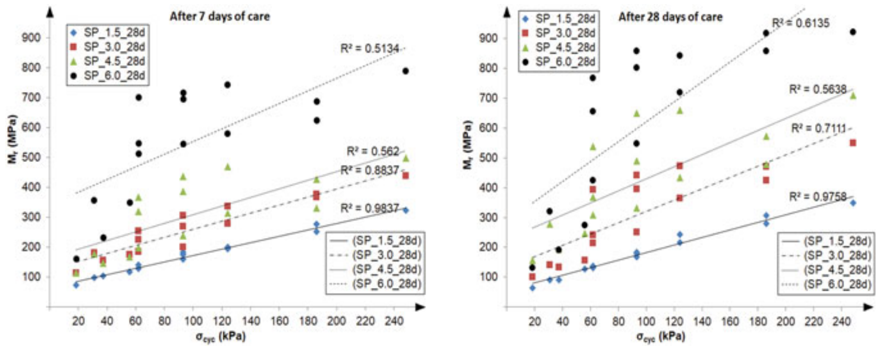


Fig. 5 The plot of change in resilient modulus during all load cycles for a specimen with 1.5% cement added and cured for 28 days

are respectively: 137.9 and 275.8 kPa. The lowest modulus values occurred during sequence 1, where σ_3 and σ_1 were the lowest and had the same values −20.7 kPa.

The resilient modulus increased as a result of increasing confining pressure and maximum axial load. Figure 6 shows the dependence of the resilient modulus on varying cyclic applied axial stress. It is shown in two plots as a function of specimen care length. The addition of cement has a significant effect on the increase of the elastic modulus values. Increasing the cement addition by 1.5% increased the resilient modulus values by around 50% in most cases evaluated for the same sequence. Another similarity is that samples cured for 28 days had a higher M_r value than those cured for 7 days. Samples stabilized with 1.5–6.0% cement addition achieved elastic modulus values in the range 63–789 MPa after 7 days of curing and 73–921 MPa after 28 days. Another relationship that can be deduced from Fig. 5 is that the lowest coefficients of determination R^2, but explaining more than 50% of the variables, were for samples with cement additions of 4.5 and 6%. In both cases, this may be due to the drying of the samples during curing.

Table 2 shows the resilient modulus and quick shear strength (axial stress σ_1 at failure) as a function of the percentage of cement content and the length of care. It can be observed that both parameters increased with rising cement addition in the sample. A similar relationship was found for the length of care. Samples, after 28 days, achieved higher values of both parameters than those that were cared for 7 days. Samples with 1.5 and 3% cement addition achieved similar values despite the different lengths of care. The specimen with 6% cement addition, cured for 7 days, and the specimens with 4.5 and 6% of cement cured for 28 days, were not destroyed during the quick shear test performed after cyclic loading. The apparatus reached a maximum contact force of 10 kN.



(a) (b)

Fig. 6 Dependence of resilient modulus on cyclic applied axial stress after 7 and 28 days of care

Table 2 The resilient modulus and axial stress as a function of time of curing

	After 7 days of care		After 28 days of care	
Material	M_r (MPa)	σ_1 (kPa)	M_r (MPa)	σ_1 (kPa)
grSa + 1.5%C	324	855	349	1180
grSa + 3.0%C	439	1375	549	1518
grSa + 4.5%C	498	1572	709	>2600
grSa + 6.0%C	789	>2600	921	>2600

4 Conclusion

Based on the test results the following conclusions were reached:

(1) The addition of cement significantly increases the resilient modulus values obtained and reduces the relative elastic axial strain. Increasing the cement addition by 1.5% resulted in approx. 50% increase in the resilient modulus value in most cases evaluated. Increasing the curing time of the sample from 7 to 28 days also has a positive effect on the resilient modulus value, increasing it.

(2) The addition of cement, as well as the length of care, has an effect on the quick shear strength. All samples were subjected to 16 cyclic loading sequences and finally, the quick shear test was performed. The axial stress at failure increases with an increase in cement addition and time of curing.

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