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Effect of the Addition of Dispersed Reinforcement on the Resilient Modulus of Slightly Cemented Non-Cohesive Soil

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Abstract: The aim of this article is to determine the effect of the addition of dispersed reinforcement on the resilient modulus of non-cohesive soil used as material for improved subgrade or subbase course of the pavement structure. Resilient modulus (M_r) is a parameter used in road construction, which characterises soil subgrade or base aggregates stiffness in flexible pavement subjected to the traffic load. This article presents laboratory test results of non-cohesive coarse material (gravelly sand – grSa – without fines) with the addition of 1.5% cement and dispersed reinforcement – polypropylene fibres in lengths of 12, 18 and 40 mm. Tests were conducted on the samples with various percentages of fibres (0, 0.2 and 0.3%) relating to the dry mass of the soil. Samples were compacted according to the standard Proctor (SP) and modified Proctor (MP) methods. Main laboratory tests were conducted in the triaxial apparatus enabling testing samples subjected to cyclic loads according to AASHTO T307 standard. Resilient modulus was determined after 7 and 28 days of curing. The results indicate the influence of fibre amount, fibre length, and curing time on the M_r of the soil modified with 1.5% of cement. The obtained results were also influenced by the method of compaction. The addition of polypropylene fibres decreases the resilient modulus of soil stabilised by 1.5% of cement. The best results of dispersive reinforcement were obtained for samples containing 0.3% of fibres with a length of 18 mm, compacted by the MP methods.

Keywords: cyclic loading, fibre reinforcement, cement stabilisation, compacted soil

1 Introduction

Subbase and subgrade are the foundation of the pavement structure. It has to provide a short-term surface for traffic and a suitable platform for the placement and compaction of the high-quality asphalt layer above. In addition, it has to work as a load-bearing system for the completed pavement during the required design period (Brown & Selig, 1991).

A measure of material stiffness, which is a parameter used in the mechanistic-empirical pavement design procedure, is the resilient modulus (M_r). It characterises the non-linearity of subgrade or subbase granular soil response to the traffic load. Repeated loading causes recoverable and irrecoverable components of deformation. The resilient behaviour of unbound materials used in pavement layers is dependent on a few factors, described in the literature (Lekarp et al., 2000; Kim & Kim, 2007): grain size distribution, maximum grain size, the content of fines, particle shape and aggregate type, density, moisture content, compaction method, stress level, number of load cycles, load duration and load sequence and freeze–thaw cycles.

The M_r is the parameter expressed as the ratio of applied cyclic deviator stress σ_d to recoverable (elastic/resilient) axial strain during unloading ε_r (Seed et al., 1962), as shown in Eq. (1):

$$M_r=\sigma_d/\varepsilon_r \tag{1}$$

and it is defined as an elastic modulus of the material under repeated loads. The M_r can be determined in the triaxial cell with the ability to the application of cyclic loading, named in the literature as repeated load triaxial laboratory test (RLT). During the test, certain confining

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pressure, axial stress and a number of cycles are applied in sequences according to different regulations.

To avoid large deformations caused by traffic load, pavement construction materials are improved by adding various additives. A lot of research was conducted on materials that might be used as additives, such as cement (Saxena et al., 2010; Ismail et al. 2014), lime (Ahmed et al., 2020; Yin et al., 2022), fly ash from different sources (Yilmaz, 2015; Mahvash et al., 2018; Noaman et al., 2022; Wang et al., 2022; Zimar et. al, 2022), and various types of fibres (Consoli et al., 2003; Yetimoğlu et al., 2003; Khattak & Alrashidi, 2006). The use of fibres as a reinforcement increases stiffness (Festugato et al. 2023), load-bearing capacity (Yetimoğlu et al., 2005; Rashid et al., 2017), the tensile strength of soils (Consoli et al., 2013; Li et al., 2014) and reduces potential liquefaction (Ibraim et al., 2010).

As the literature concluded (Consoli et al., 1998; Park, 2011; Hamidi & Hooresfand, 2013), cement addition increased the stiffness of the soil and its brittleness, while the fibres added to sandy soil changed its failure behaviour from brittle to more ductile one.

In tests conducted on compacted sand reinforced with 50 mm long polypropylene fibres, the soil monotonic mechanical parameters were improved (Festugato et al., 2023). Fibres also had an impact on the cyclic behaviour of dense sand evidenced by an increase in cycles to failure. Fibres incorporated in cemented sandy soil caused an increase in unconfined compression strength (Consoli et al., 2010, 2013; Khodabandehlou et al., 2023).

The aim of this article is to investigate the influence of the dispersed reinforcement – polypropylene fibres added in different lengths and amounts – on the resilient response of the coarse material with the slight cement addition (1.5%), used as a base or subbase in road pavement construction. Polypropylene fibres incorporated in the tested soil amended with cement had lengths of 12, 18 and 40 mm and were added in amounts of 0%, 0.2% and 0.3% by weight of dry soil.

The authors concluded from their previous research that it is not possible to provide the resilient modulus tests on non-cohesive soil without fines because the cyclic triaxial test destroys unbound non-cohesive soil (Zabielska-Adamska et al., 2021, 2023). The soil was tested as hydraulically bound with a 1.5% cement addition, chosen as the minimum amount that could improve the resilient characteristics of the tested soil. The fibre addition higher than 0.3% was not considered because it decreased the static mechanical properties of the tested soil (Zabielska-Adamska et al., 2023).

2 Materials and Methods

Laboratory tests were conducted on gravelly sand grSa (EN ISO 14688-1), which particle size distribution according to the EN 933-1 standard is illustrated in Figure 1. The tested non-cohesive soil is poorly graded (EN ISO 14688-2). Its coefficient of uniformity, C_U, and coefficient of curvature, C_C, were 5.04 and 0.66, respectively. As authors characterised material in earlier studies (Zabielska-Adamska, et al. 2021), the tested gravelly sand is a glaciofluvial soil (Pleistocene), collected in the Sokółka district in north-eastern Poland.

The gravelly sand (grSa) was tested alone, as soil stabilised with the addition of 1.5% Portland cement 42.5R, and with an addition of polypropylene fibres with variable lengths 12 mm, 18 mm and 40 mm, and diameters 0.030 mm, 0.034 mm and 0.90 mm, respectively. Fibres were added in the amount of 0.2 and 0.3% to the dry mass of the tested soil. In the case of fibres 40 mm in length, only an addition of 0.2% was used. The images of the fibres are presented in Figure 2.

It can be observed (Fig. 2) that the fibres with 40 mm long have a different structure than 12 and 18 mm reinforcement. It was also visible after mixing with the soil, that the mix with 12 and 18 mm was more homogenous than the soil with the reinforcement 40 mm long, which can be observed in Figure 3. Mixtures of soil and polypropylene fibres were mixed using a laboratory mechanical stirrer for a time of 4.5 minutes, which is of great importance for the homogeneity of the tested samples.

The compaction curves of gravelly sand and sand stabilised with cement are presented in Figure 4. The exemplary compaction curves of soil with fibres 18 mm long are presented in Figure 5. The specific density of the tested samples and their compaction parameters, optimum moisture content (w_{opt}) and maximum dry density ($\rho_{d\,max}$), are summarised in Table 1. The compaction parameters were determined by the standard Proctor (SP) and modified Proctor (MP) tests according to the EN 13286-2 standard.

Based on Figures 4 and 5 and Table 1, it can be concluded that the cement addition has an impact on the maximum dry density of the tested material. In both compaction methods, standard and modified, the $\rho_{d\,max}$ increased after cement addition, while the w_{opt} remained practically the same. In the case of soil with fibres addition, the optimum moisture content was slightly reduced after the addition of 0.2% and 0.3% of 18 mm fibres. The maximum dry density value increased significantly after fibre addition, hence the $\rho_{d\,max}$ values for soil with 0.2% and 0.3% of fibres do not differ much. The specific dry

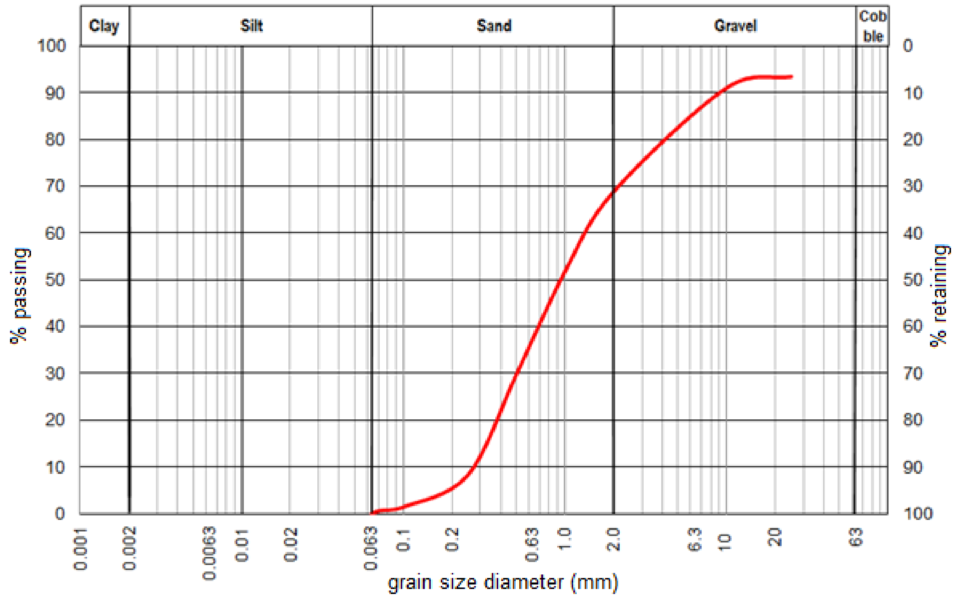

Figure 1: Grain size distribution curve of tested soil.

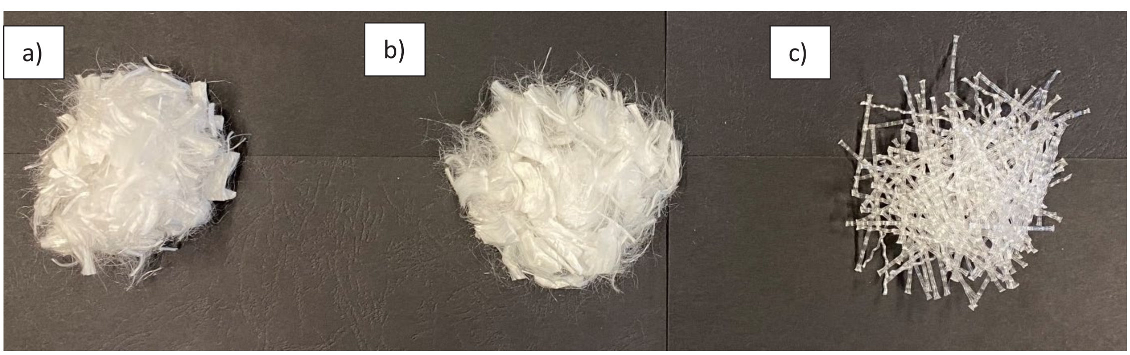

Figure 2: Different lengths (and diameters) of fibres in the amount of 0.2% in reference to the dry mass of the sample that was added to the coarse soil: a) 12 mm (0.030 mm), b) 18 mm (0.034 mm), c) 40 mm (0,90 mm).

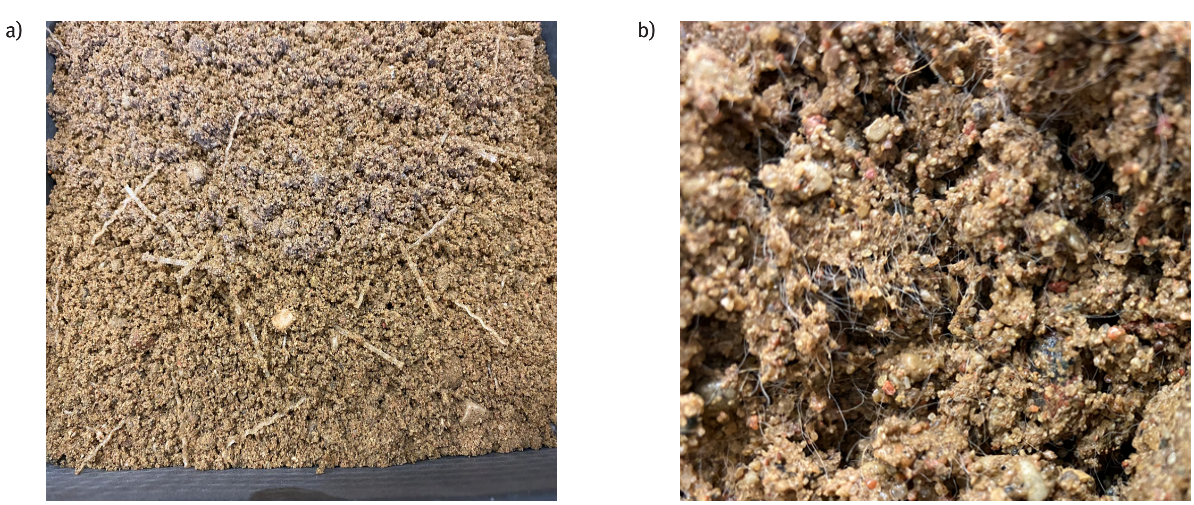

Figure 3: Soil mixed mechanically with fibres: a) 40 mm long; b) 18 mm long.

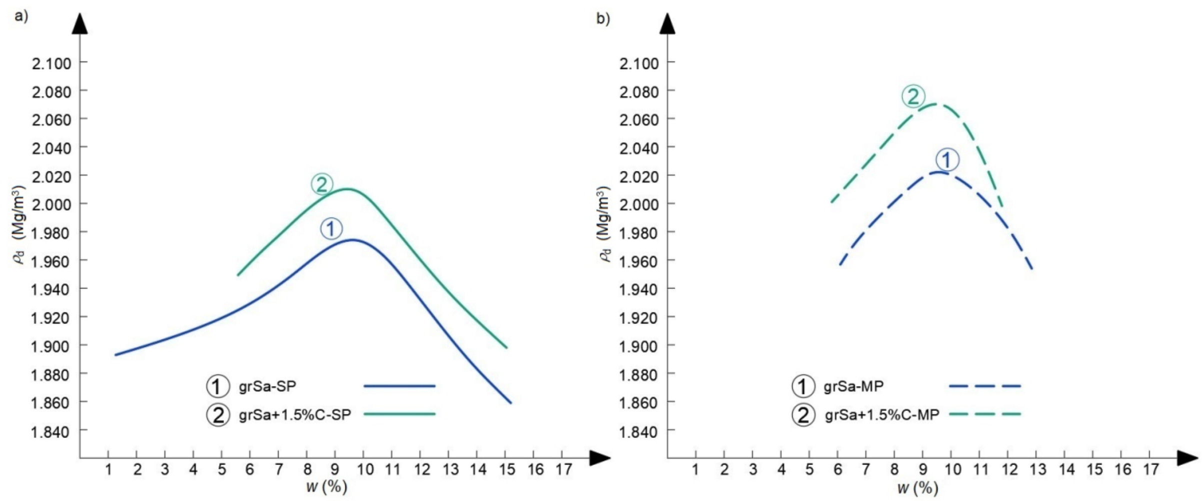

Figure 4: Compaction curves of gravelly sand and gravelly sand with 1.5% of cement addition compacted by two methods: a) SP, b) MP.

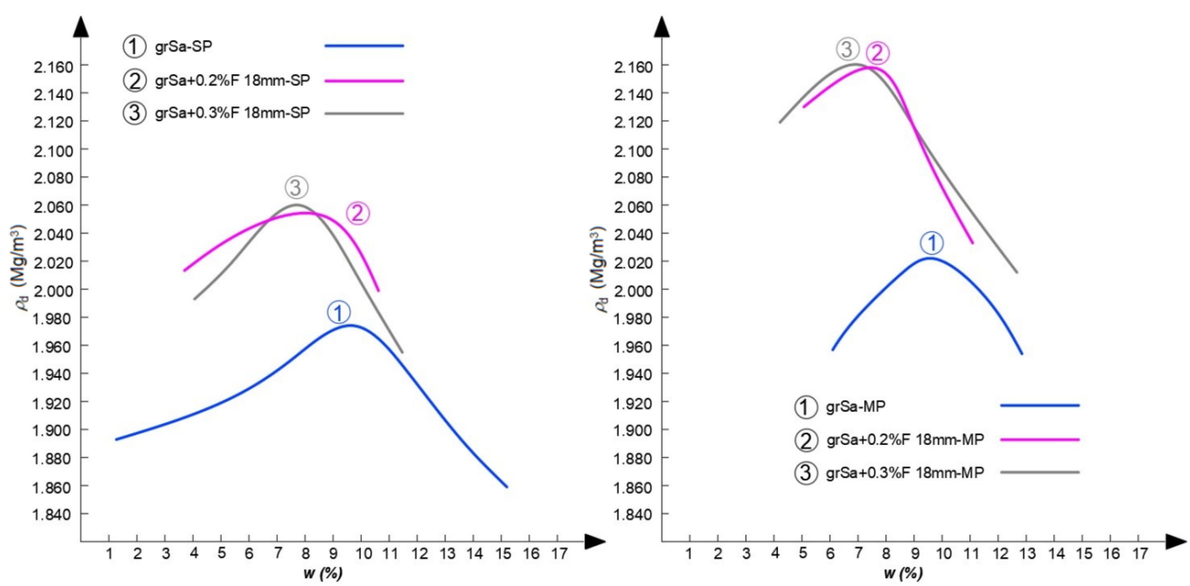

Figure 5: Compaction curves of gravelly sand with different amounts of fibres 18 mm long compacted by two methods: a) SP, b) MP.

density slightly increases with the addition of cement to the mixture, whereas the addition of polypropylene fibres commonly does not affect the specific dry density because of low fibre mass.

The main test of resilient modulus M_r was performed as repeated load triaxial test RLT using the triaxial cell designed to conduct the cyclic test in accordance with AASHTO T307 standard. In this type of test, a sample is subjected to 16 sequences of cyclic loading, where the first one – sequence 0 – is the conditioning of the sample (with a number of 500 to 1000 cycles), and 15 other sequences (with 100 cycles), with the different combinations of confining pressures and applied cyclic loads, depending on the cycle. The confining pressure ranged from 20.7 to 137.9 kPa and the maximum axial stress ranged from 20.7 to 275.8 kPa. The machine used repeated cycles of the haversine-shaped load pulse, where the load pulse lasted 0.1 s and the rest period 0.9 s. In the used cyclic triaxial apparatus, the confining pressure and axial load were put on pneumatically. Axial deformations of the tested sample were measured using two linear variable differential transformers (LVDTs). The data obtained during the test was collected by the computer. The results, M_r values, are calculated to 5 last cycles from every 15 sequences. The sum of the last 5 modulus readings is recorded as the resilient modulus of that sequence.

Table 1: The specific density and compaction parameters of tested materials.

Sample	ρ_s(Mg/m³)	Proctor compaction method			
		Standard		Modified	
		w_{opt} (%)	$\rho_{d\,max}$ (Mg/m³)	w_{opt} (%)	$\rho_{d\,max}$ (Mg/m³)
grSa	2.65	9.7	1.974	9.6	2.022
grSa+1.5%C	2.66	9.5	2.010	9.5	2.070
grSa+1.5%C+0.2%F_12 mm	2.66	9.4	2.075	7.9	2.150
grSa+1.5%C+0.3%F_12 mm	2.66	8.9	2.103	6.8	2.170
grSa+1.5%C+0.2%F_18 mm	2.66	7.9	2.066	7.0	2.183
grSa+1.5%C+0.3%F_18 mm	2.66	8.0	2.060	7.8	2.124
grSa+1.5%C+0.2%F_40 mm	2.66	8.8	2.108	7.5	2.144

where: C – cement addition, F – fibre addition

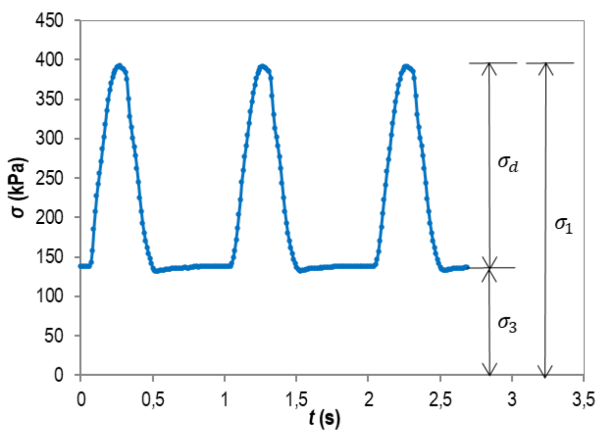

Figure 6: Principle of triaxial testing with cyclic loading

Figure 6 is an example of the cycles to which the samples were subjected during the resilient modulus test. The maximum applied vertical stress on the soil sample is σ_1, which is the sum of σ_3 (confining pressure) and σ_d (deviator stress).

Samples for resilient modulus tests were prepared in a bipartite mould of 70 mm in diameter and a height-to-diameter ratio of 2. At first, dry components: soil, cement and polypropylene fibres were mixed using the laboratory mechanical stirrer, and next the required amount of water was added to get optimum moisture content. The samples were compacted dynamically in three layers to the values of maximum dry density from the SP and MP compaction tests. The M_r tests were conducted on specimens after 7 and 28 days of curing in constant temperature and humidity.

3 Results

In Figure 7 one of the initial cycles of loading/unloading is shown, where the principle of the resilient modulus test is presented. In one cycle, the soil sample is subjected to loading and unloading and the permanent and recoverable deformations are visible. After each load application, granular material undergoes some irreversible deformation (Brown, 1996). Figure 8 presents the complete 100 cycles of the 15th sequence of loading and unloading according to AASHTO T307 standard. The reduction of permanent strain with successive load/unload cycles in a given sequence is clearly visible.

The data obtained from the resilient modulus M_r tests of improved gravelly sand after different curing times are presented in Table 2. The results presented as graphs for 0%, 0.2% and 0.3% of fibre contents are shown in Figures 9 and 10.

It can be observed (Tab. 2) that the addition of fibres can decrease the values of resilient modulus, especially in a shorter time of curing. In the previous article of the authors, the plasticisation of samples after fibre addition was proved (Zabielska-Adamska et al., 2023). Samples compacted by the SP method with fibres 18 mm and 12 mm (only 0.3%) gained lower M_r values after a longer period of curing. However generally, samples cured for 28 days achieved the highest values of the M_r, particularly in the case of samples compacted by the MP method. In the case of the MP compaction method, resilient modulus gained higher values than for the samples with the same amount of addition but compacted with the SP method. The increase of fibre content from 0.2 to 0.3% causes the increase of the M_r values, at similar densities of samples. The greatest values of the M_r were obtained for fibres of 18

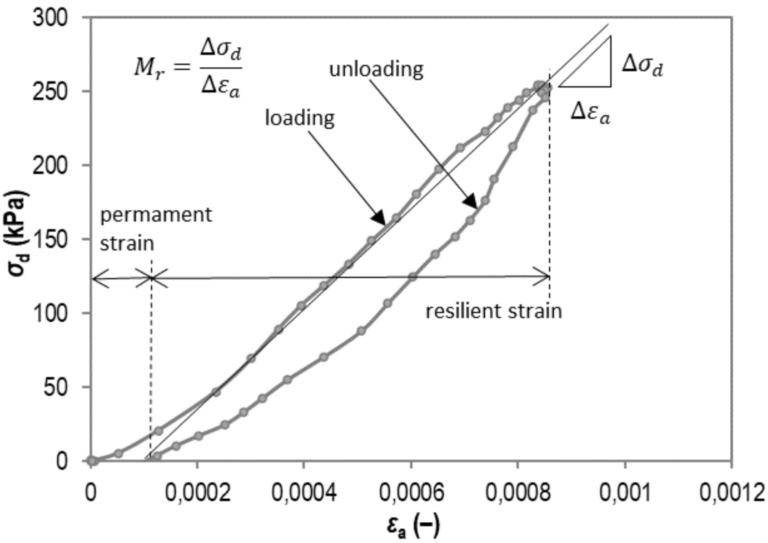

Figure 7: Sample behaviour under cyclic loading in a triaxial cell during one of the initial cycles of the 15th sequence subjected to grSa+1.5%C+0.3%F_18 mm sample compacted with SP method.

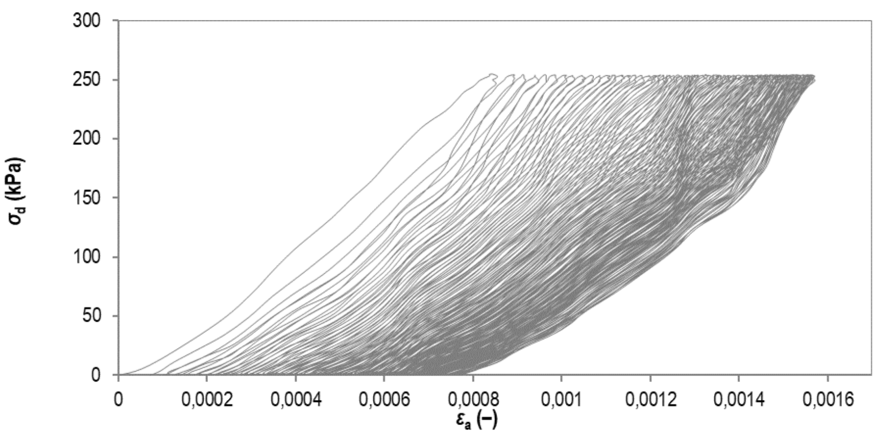

Figure 8: Sample behaviour subjected to cyclic loading/unloading in the triaxial cell during 100 cycles of the 15th sequence for grSa+1.5%C+0.3%F_18 mm sample compacted SP method, tested after 7 days of curing.

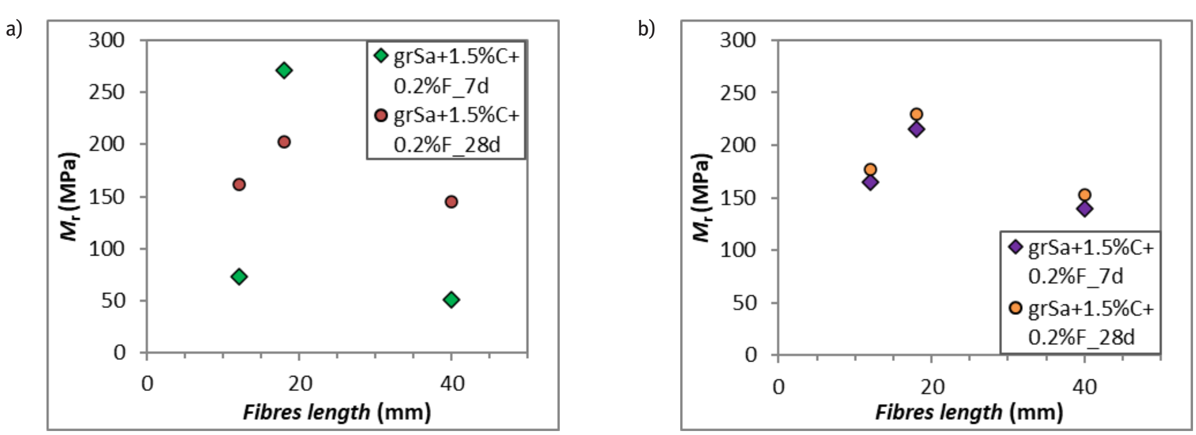

Figure 9: Resilient modulus M_r values obtained after 7 and 28 days of curing for samples with 1.5% cement and 0.2% fibres of different lengths compacted by: a) SP method; b) MP method.

Table 2: Values of M_r obtained for samples after different compaction and curing periods.

Samples	Resilient modulus M_r (MPa)		Curing period
	SP compaction	MP compaction	(days)
grSa+1.5%C	197	168	7
	272	353	28
grSa+1.5%C+0.2%F_12 mm	73	165	7
	162	177	28
grSa+1.5%C+0.3%F_12 mm	193	224	7
	178	236	28
grSa+1.5%C+0.2%F_18 mm	271	215	7
	202	230	28
grSa+1.5%C+0.3%F_18 mm	301	226	7
	214	241	28
grSa+1.5%C+0.2%F_40 mm	51	140	7
	145	153	28

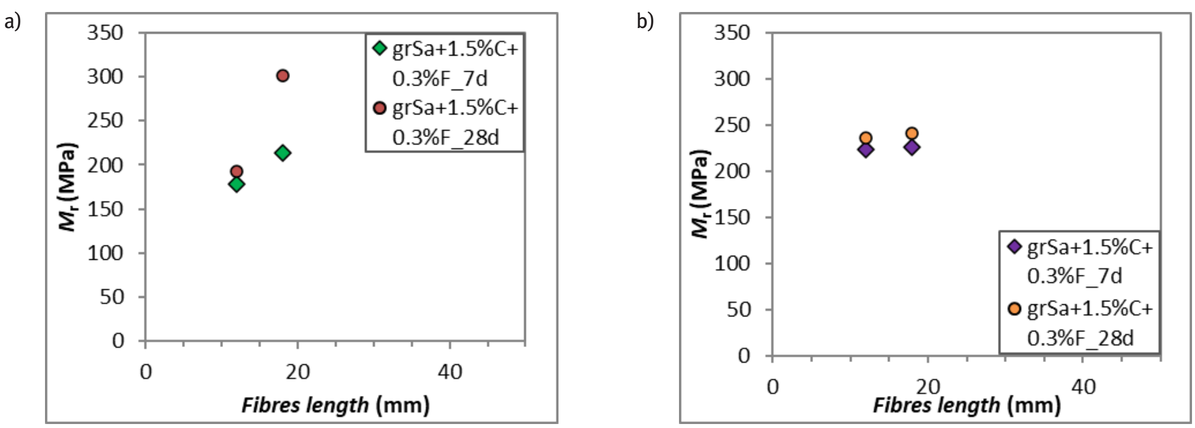

Figure 10: Resilient modulus M_r values obtained after 7 and 28 days of curing for samples with 1.5% cement and 0.3% fibres of different lengths compacted by: a) SP method; b) MP method.

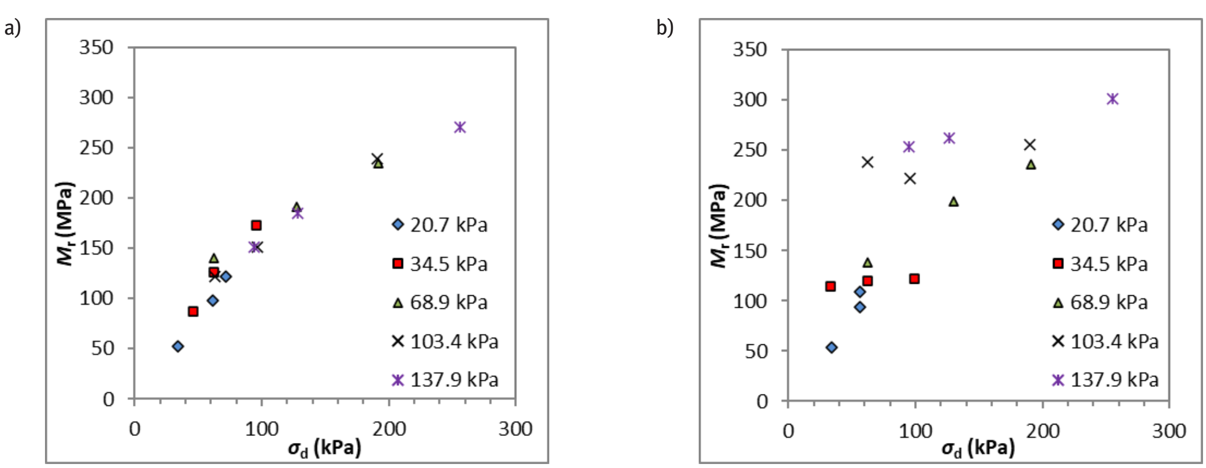

Figure 11: M_r values of samples tested after 7 days of curing compacted by SP method with different fibres content: a) grSa+1.5%C+0.2%F_18 mm b) grSa+1.5%C+0.3%F_18 mm.

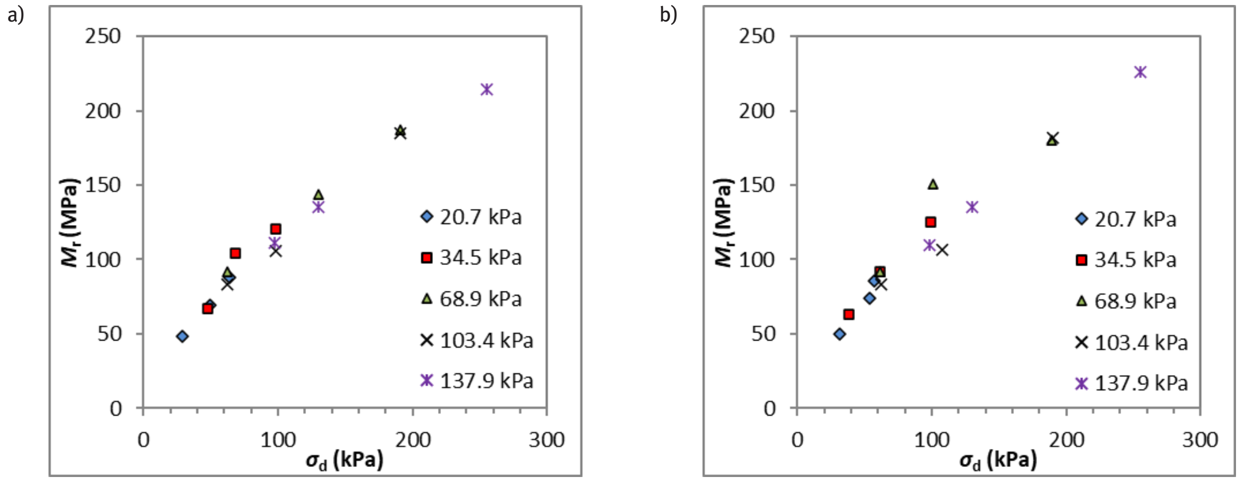

Figure 12: M_r values of samples tested after 7 days of curing compacted by MP method with different fibres content: a) grSa+1.5%C+0.2%F_18 mm b) grSa+1.5%C+0.3%F_18 mm.

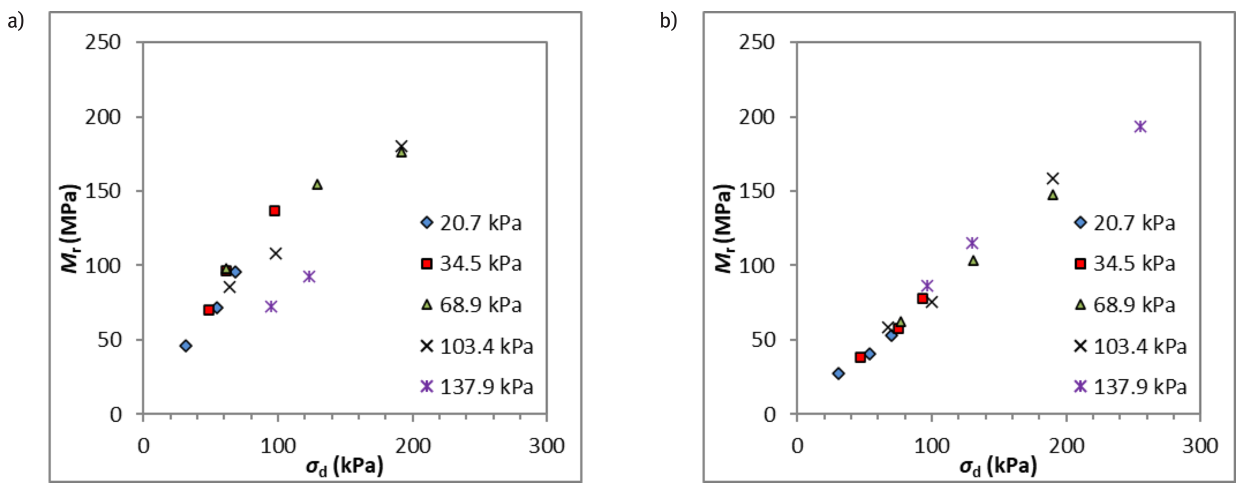

Figure 13: M_r values of samples tested after 7 days of curing compacted by SP method with different fibres content: a) grSa+1.5%C+0.2%F_12 mm b) grSa+1.5%C+0.3%F_12 mm.

mm in length, independent of the content of fibres, which is more visible at standard compaction. The lower values of the M_r were observed for fibres of 40 mm in length.

Depending on their position in the pavement structure, the structure materials are subjected to different loads from the traffic. The M_r values at the different magnitudes of traffic loading represented by confining pressures: 20.7, 34.5, 68.9, 103.4 and 137.9 kPa for samples with 18 mm long fibres were plotted in Figures 11 and 12, and for samples with 12 mm long fibres were plotted in Figures 13 and 14.

It can be concluded (Figs. 11–14) that the resilient modulus is affected by deviatoric and confining stress. The M_r value increases with rising confining pressure, but at the same confining pressure with rising maximum axial load. The same tendency was observed by Georgees et al. (2018). As stress increases, the sample becomes denser and therefore a lower recoverable strain is obtained. It is connected to the hardening behaviour of granular materials. Achievement of the highest values of the M_r for the modified compacted samples, which was observed for hydraulically stabilised samples (Zabielska-Adamska et al., 2021) is not so clear in the case of 1.5% cement-stabilised specimens with fibre addition, tested at the same confining pressure. The addition of fibres plasticises cement-stabilised samples (Zabielska-Adamska et al., 2023), which changes sample behaviour. Similar behaviour was observed in fibre-reinforced cemented sandy soil, where fibre addition changed the brittle failure behaviour to be more ductile (Sadek, 2010; Gao & Zhao, 2012). The greater values of the M_r were obtained for 0.3% of fibres compared to 0.2% of fibres for the same level of stress.

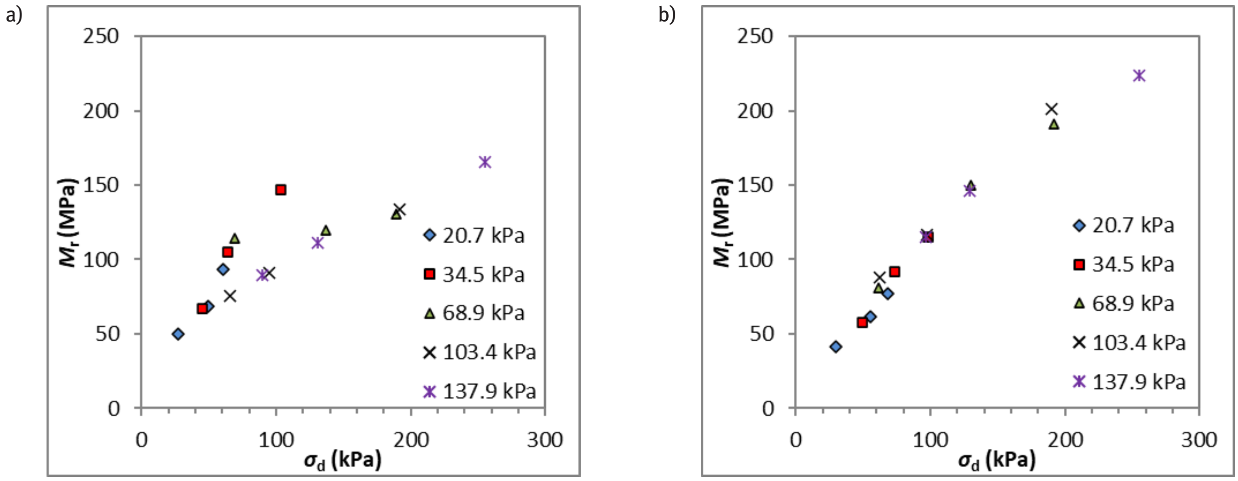

Figure 14: M_r values of samples tested after 7 days of curing compacted by MP method with different fibres content: a) grSa+1.5%C+0.2%F_12 mm b) grSa+1.5%C+0.3%F_12 mm.

4 Conclusions

Based on the test results of gravelly sand compacted with cement and dispersed reinforcement, the following conclusion can be drawn:

1. Addition of fibres to gravelly sand stabilised with 1.5% cement decreases the resilient modulus, independent of the percentage amount of fibres and their length.
2. Resilient modulus for gravelly sand with 1.5% of cement addition and different amounts of variable length of the dispersed reinforcement showed the lowest value in the case of fibres 40 mm long, regardless of the compaction method and curing time. It might be connected to the structure of the fibres and the low homogeneity of this soil–fibres mixture.
3. The highest M_r values were obtained for the addition of fibres with a length of 18 mm. Increasing the fibre percentage from 0.2 to 0.3 also increases the resilient modulus of the samples, although the density of the samples was comparable.
4. In the case of the SP compaction method, commonly the resilient modulus was lower for the samples cured for 7 days, than for the samples cured for 28 days. In the case of the MP compaction method, the differences between values obtained for various times of curing were slightly smaller.
5. During the resilient modulus test of the gravelly sand samples with cement and fibre addition, the hardening behaviour might be observed, as the M_r value increases with the increase in cyclic stress and confining pressure. However, this was more evident for samples with fibre lengths of 18 mm than 12 mm.

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