EXPERIMENTAL STUDY OF RANDOM REINFORCEMENT BY POLYMERIC FIBRES

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Abstract: The term "random reinforcement" describes a technology of mixing short fibres (10 - 100 mm) with soil. These fibres can be made of different kinds of material: steel, synthetics, glass or natural resources like coir, sisal, etc. Experience proposes that this treatment method can be used only for fine soils and sand. Grains of gravel are too big to be treated by fibres.

Therefore, the random reinforcement by fibres is quite interesting option for soil treatment. Admixture of the short fibres, in particular, is improving shear strength and bearing-capacity of the soil. Micro-reinforced soils are not very much explored and it means that it is not so easy and reliable to use it in field conditions. Some authors have conducted research on this theme but hardly any comparative results are available. In addition, every country or territory has different possibilities for gaining fibres and this implies that fibre properties can be variable. However, all published papers provided useful information for use in design of the laboratory tests reported here.

Results of laboratory testing realized with mixtures of two types of polymer (polyester, polypropylene), three kinds of soil (silty clays - loess loam, fine sands and fly ash), three different content of fibres and two different lengths of the fibres (25 mm; 75 mm) are described below. The following set of tests were carried out: shear box tests, Proctor Standard tests, triaxial tests, CBR tests, tests of the unconfined strength and tests of the compressibility and permeability. Laboratory tests will be used to define marginal conditions of soils that form part of extensive field trials planned for the next year.

Keywords: fibre reinforced soil, fibre, ground improvement, laboratory test, soil improvement, soil reinforcement.

INTRODUCTION

The technique of reinforcing soil by different kinds of fibres mainly vegetable-ones is known for a long time. The first mention we can find in 1440 B.C. when ziggurat Agar-Quf (in the territory of today's Iraq) was built. Another example of using natural fibres is a construction of the Great Wall in China. Of course it was not exactly what we think today when speaking about fibre reinforcement. In these constructions there were used reed, straw and tamarisk branches. But the reasons for their use were the same – make the construction stronger, more stable and more resistant. The first mention about something similar in Czech Republic is from the 10th to 12th century when a fortification of Prague's Castle was built.

The random reinforcement by fibres (often called as micro-reinforcement as well) is quite interesting option for soil treatment. Admixture of short fibres, in particular, is improving shear strength and bearing-capacity of the soil. Micro-reinforced soils are not very much explored and it means that it is not so easy and reliable to use this technology in field conditions. While studying materials about abroad experience with fibre reinforcement we have noticed that there is no common feature to all experiments (Bahar et al. 2002, Falorca, Pinto 2002, Falorca, Pinto 2004, Falorca et al. 2006, Kumar et al. 1999, Kumar, Tabor 2003, McGown et al. 2004, Minegishi, Makiuchi 2002). Every author used different soils (sand, clay, fly ash) with different properties, different kind of fibres (material, type, length and diameter) and realized different tests. Therefore it was impossible to define clear conclusion about fibre reinforcement for any field test.

A lack of experience with fibre reinforced soil and the potential of the method was the impulse to plan our extended trials in order to understand the behaviour of this composite soil and to investigate experimentally its feasibility.

The first results of the project granted by the Ministry of Industry and Trade of the Czech Republic are presented here. The project was started because the potential of this relatively new method seems promising for use in traffic constructions. In the scope of the project these trials have been planed: shear box tests, Proctor Standard tests, triaxial tests, CBR tests, tests of the unconfined strength and tests of the compressibility and permeability. These trials have been carried out with three kinds of material (silty clay - loess loam, fine sand and fly ash) and two kinds of synthetic fibres (PET, PP). The laboratory tests will be used to define of marginal conditions of the great trial tests in the field planned later this year.

MATERIALS AND TEST PROCEDURE

Test materials

Soils

The soils used in the tests are both fine and coarse. The coarse soil was sand prepared by removing all material retained on the 16 mm sieve. It is classified as sand with fine particles (S-F) according to the USCS classification. The main properties of the sand are summarised in Table 1. The fine soil is loess loam classified as CI according to the USCS classification. The main properties of the loess loam are summarised in Table 2.

The sand has a maximum dry unit weight (density) of 2015 kg/m^3 and an optimum moisture content of 9,0 %. For the loess loam, the optimum water content was 15,5 % and its maximum dry unit weight was found as 1800 kg/m^3.

Table 1. Summary of geotechnical parameters of sand

Parameter	Value
Moisture content w_n (%)	3,8 %
Optimum moisture w_{opt} (%)	9 %
Uniformity coefficient C_u (-)	24,8
Coefficient of curvature C_c (-)	1,3
Particle density ρ_s (kg/m^3)	2635
Unit weight ρ_d (kg/m^3)	2015

Table 2. Summary of geotechnical parameters of loess loam

Parameter	Range
Moisture content w_n (%)	14,1 – 17,5 %
Optimum moisture w_{opt} (%)	14 – 17,5 %
Liquid limit w_L (%)	31 – 38
Plastic limit w_p (%)	15 – 20
Plasticity index I_p (-)	12 – 18
Consistency index I_c (-)	0,96 – 1,22
Particle density ρ_s (kg/m^3)	2695 – 2700
Unit weight $\rho_{d, max}$ (kg/m^3)	1750 – 1890

Fibres

The synthetic fibres are made of polypropylene and polyester. They were supplied by local manufacturer in the form of polyester staple fibres (Figure 2a) with round cross section and polyester fibrillated fibres in the form of small nets (Figure 2b). Both types of fibres were cut to nominal lengths of about 24 mm and 70 mm. The percentage of fibres used to reinforce the sand samples was determined by the dry unit weight of the soil. Three different percentages of fibres are studied: 0,5 %, 1,0 % and 1,5 %. These contents were chosen to cover whole interval of different contents from different authors.

Linear mass density of polypropylene fibres is 27 000 dtex. Linear mass density of polyester fibres is 220 tex.

Figure 1. Fibres: 1 – polyester staple fibres, 24 mm; 2 – polyester staple fibres, 70 mm; 3 – polypropylene fibrillated fibres, 24 mm; 4 – polypropylene fibrillated fibres, 70 mm

Preparation of test samples

Fibre reinforced samples were prepared by hand mixing the fibres with moisted soil (with optimum water content). The degree of dispersion in the mixture was determined by visual inspection. During the mixing of the specimens with polypropylene fibrillated fibres were observed, that fibres were not becoming part of the mixture and remained separated from the soil. Better behaviour was achieved with moister soil, but the difference in behaviour of polypropylene fibres was negligible. The almost same behaviour was observed for polypropylene fibrillated fibres mixed with sand and loess loam as well. The shorter fibres were more convenient then longer ones because longer fibrillated fibres did not form fairly uniform mixture. Structure of the specimen looked like a sandwich structure – layer of soil, layer of long PP unyielding fibres, another layer of soil etc. Therefore the layering was evident.

The polyester staple fibres exhibited much better behaviour then the fibrillated ones. During the mixing with moist soil the fibres became part of the mix. The best results were observed with the highest water contents (sand – 13 %, loam – 19 %). The more water content the more effort was needed to achieve uniform distribution of fibres in specimen. While mixing with dry soil, fibres electrify and formed clots, it was impossible to obtain uniform distribution of fibres in the mixture. As described by Falorca, Pinto (2002): the greater the fibre percentage, the greater the compactive effort required to maintain a given density.

Testing procedures

The experimental program was performed on exactly calculated mixtures of soil with synthetic fibres, randomly oriented, in order to establish the effect of fibres on unit weight, optimum moisture, compressibility and CBR values of the composite.

Proctor Standard Test

The tests were carried out in accordance with EN 13286-2: Unbound and hydraulically bound mixtures. Test methods for the determination of the laboratory reference density and water content. Proctor compaction.

CBR Test

The tests were carried out on samples compacted in the CBR mould and undertaken in accordance with EN 13286-47: Unbound and hydraulically bound mixtures. Test method for the determination of California bearing ratio, immediate bearing index and linear swelling.

Compression Test

The tests were carried out in accordance with CEN ISO/TS 17892-5: Geotechnical investigation and testing - Laboratory testing of soil - Part 5: Incremental loading oedometer test.

The loading steps were chosen to be 50 kPa, soaking, 100 kPa, 200 kPa, 300 kPa and 500 kPa. For every oedometer ring an individual mixture was prepared in order to reach the exact content of 0,5 %, 1,0 % or 1,5 % of fibres in the mix. The specimens were prepared by hand compaction into the ring.

RESULTS AND DISCUSSION

Oedometric Test Data

The trials were carried out only with sand because of shortage of time. Table 3 contains a summary of results. The mixtures with polyester staple fibres are not so much compressible as the mixture with polypropylene fibrillated fibres. With the growth of contain of fibres in the specimen the compressibility is growing up. However, the trials proved growth of compressibility of both types of specimens. In case of sand with polyester the compressibility doubled and in case of sand with polypropylene even tripled. The results of specimens with fibrillated polypropylene fibres are not so surprising, because their preparation was more difficult in comparison with the specimens with yielding polyester staple fibres. The best behaviour in the matter of compressibility had shown short polyester staple fibres (Figure 2).

Table 3. Summary of results of tests carried out in oedometer with sand

Material	**Description of mixture**	**E_f (MPa)**	**ε (-)**
S*	Without fibres	78,59	0,011
S+PET**	0,5%, 70mm	46,67	0,023
	1,0%, 70mm	39,96	0,022
	1,5%, 70mm	39,37	0,030
S+PET	0,5%, 24mm	52,33	0,020
	1,0%, 24mm	34,89	0,029
	1,5%, 24mm	37,60	0,020
S+PP***	0,5%, 70mm	35,45	0,029
	1,0%, 70mm	33,79	0,031
	1,5%, 70mm	33,01	0,038
S+PP	0,5%, 24mm	40,34	0,020
	1,0%, 24mm	42,95	0,034
	1,5%, 24mm	26,75	0,038

* Sand
** Sand with polyester fibres
*** Sand with polypropylene fibres

CBR Test Data

The best behaviour has shown mixture of sand with polyester staple long (70 mm) fibres. California Bearing Ratio value was noticeably higher (almost doubled in comparison with the specimen of sand without any fibre). In case of the same mixture however with shorter fibres (24 mm) a growth of the ratio was smaller.

Polypropylene fibrillated fibres had proven themselves to be useless for reinforcement of sand, because the values of CBR even drop down.

Almost all mixtures of loam at least doubled the CBR value (in comparison with loess loam without fibres), except the mixtures with content of 1,5 % of fibres. The CBR values after soaking were even six-times higher in comparison with loess loam without fibres.

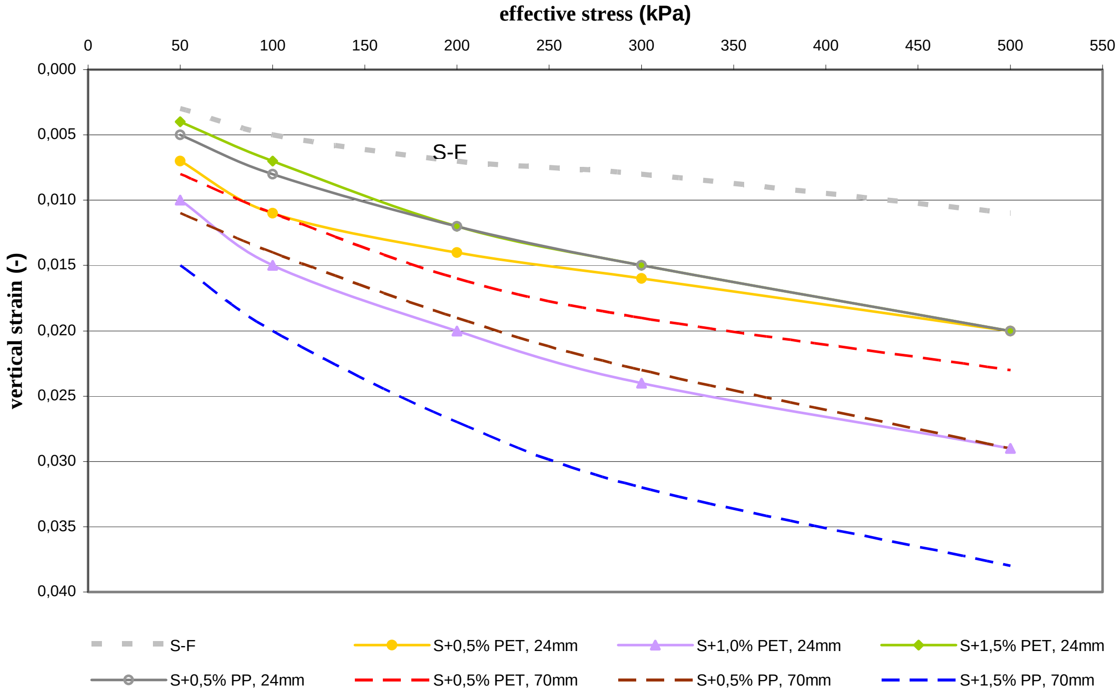

Figure 2. Relation between effective stress and vertical strain

Table 4. Summary of CBR tests results

Material	Description of mixture	CBR value		Material	Description of mixture	CBR value	
		instantly	after soaking			instantly	after soaking
S	Without fibres	32,2	48,9	**M**§	Without fibres	10,2	1,1
S+PET	0,5%, 70mm	74,4	66,7	**M+PET**§§	0,5%, 70mm	20,7	6,7
	1,0%, 70mm	60,1	80,6		1,0%, 70mm	27,1	6,0
	1,5%, 70mm	75,0	89,2		1,5%, 70mm	11,6	13,4
S+PET	0,5%, 24mm	36,8	55,5	**M+PET**	0,5%, 24mm	22,6	4,5
	1,0%, 24mm	39,1	53,4		1,0%, 24mm	18,8	5,8
	1,5%, 24mm	44,7	37,7		1,5%, 24mm	14,5	10,0
S+PP	0,5%, 70mm	20,6	27,5	**M+PP**§§§	0,5%, 70mm	23,0	5,7
	1,0%, 70mm	25,5	24,2		1,0%, 70mm	23,2	3,6
	1,5%, 70mm	21,4	34,2		1,5%, 70mm	15,5	2,9
S+PP	0,5%, 24mm	25,6	28,2	**M+PP**	0,5%, 24mm	23,7	3,1
	1,0%, 24mm	23,2	20,3		1,0%, 24mm	23,8	6,1
	1,5%, 24mm	22,4	21,3		1,5%, 24mm	14,9	2,7

§ Loam
§§ Loam with polyester fibres
§§§ Loam with polypropylene fibres

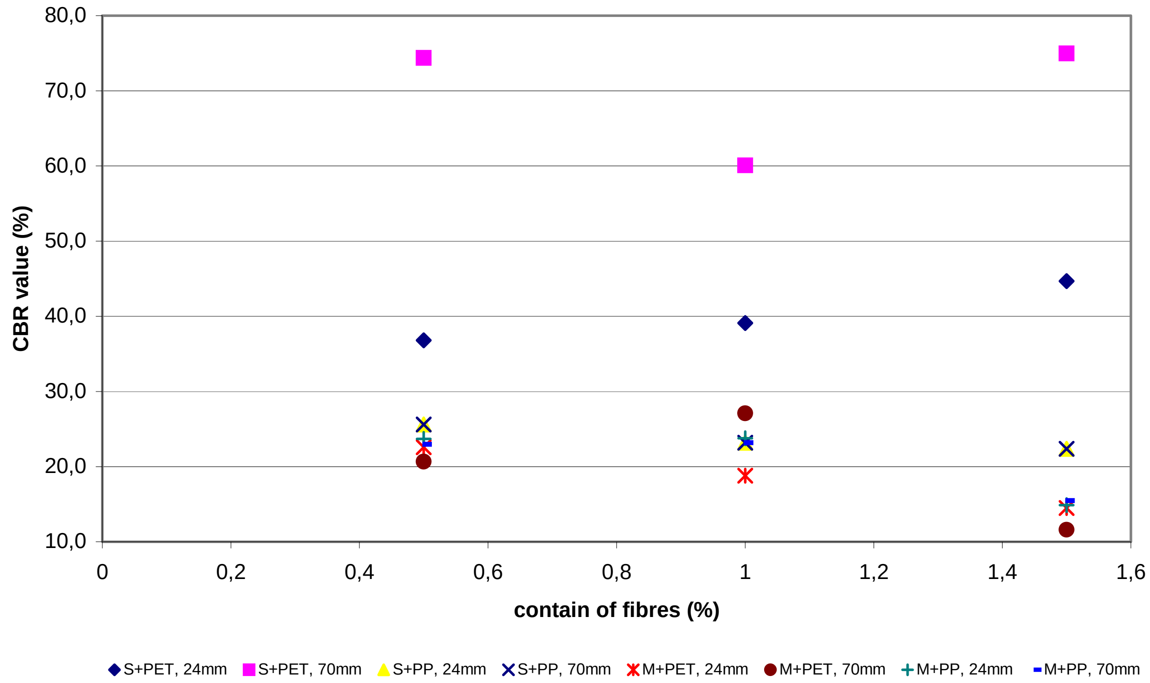

Figure 3. Relation between content of fibres and CBR value

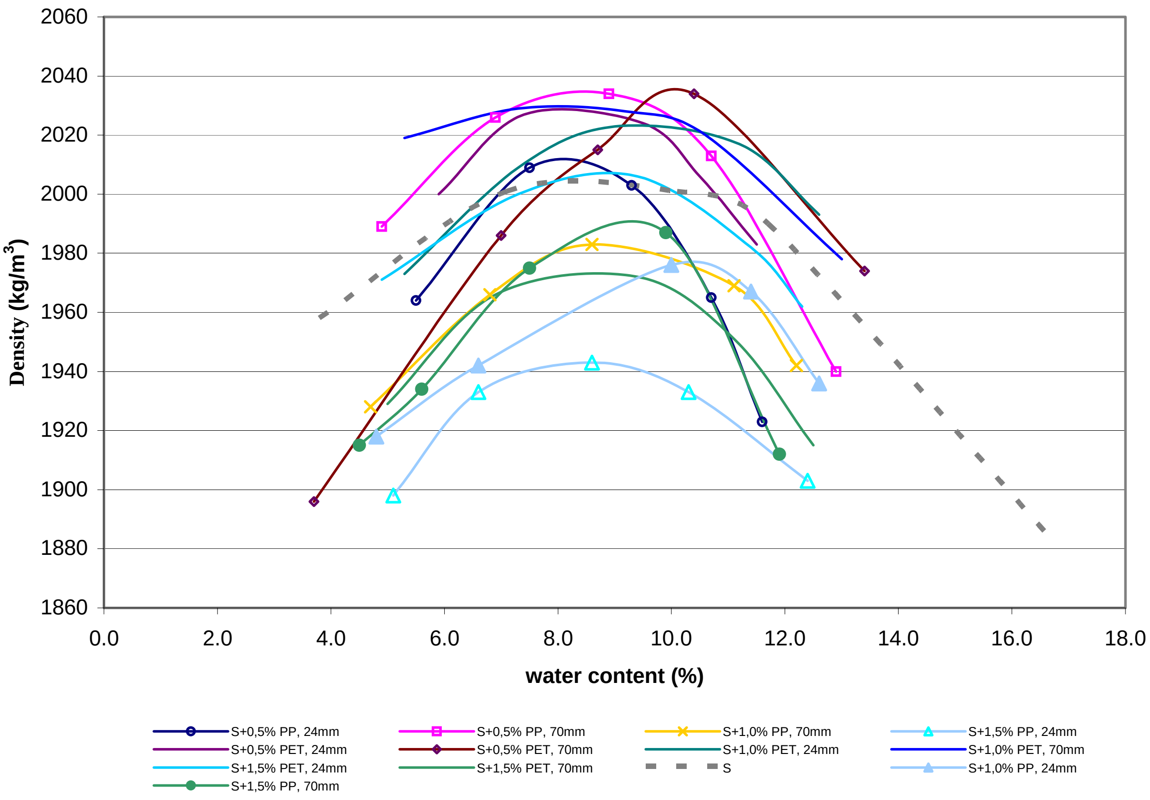

Figure 4. Relation between maximum unit weight (density) and optimum water content of sand

Proctor Standard Test Data

Data from Proctor Standard test (Table 5, Figure 4) of sand shown that the value of maximum unit weight of the individual specimens vary between 19,45 kN/m^3 and 20,30 kN/m^3. In three out of four mixtures it was observed a trend when the maximum unit weight is dropping down with increasing content of fibres. It is possible to suggest that the value of maximum unit weight of the specimen of sand with 1,5 % polypropylene fibres is unreliable and therefore it is supposed that this trend is the same for the fourth mixture as well. Further a small difference between the mixture with polypropylene and mixture with polyester was observed. In case of mixture with polypropylene maximum unit weight is dropping down faster. It is probably caused by the fact mentioned earlier, that the polypropylene fibres are not becoming a part of the mixture and therefore restrain to grain of soil to surround them perfectly. The optimum water content of the sandy mixtures vary around optimum water content of sand without fibres and in most of cases the highest optimum water content had specimens with 1 % content of fibres.

Table 5. Summary of the results of the Proctor Standard test

Material	**Description of mixture**	**Unit weight** $\rho_{d,max}$ (kg/m^3)	**Optimum moist** w_{opt} (%)	**Material**	**Description of mixture**	**Unit weight** $\rho_{d,max}$ (kg/m^3)	**Optimum moist** w_{opt} (%)
S	without fibres	2015	9,0	**M**	without fibres	1800	15,5
S+PET	0,5%, 70mm	2030	10,4	**M+PET**	0,5%, 70mm	1760	16,8
	1,0%, 70mm	2030	8,5		1,0%, 70mm	1790	16,3
	1,5%, 70mm	19,75	8,5		1,5%, 70mm	1725	17,4
S+PET	0,5%, 24mm	20,30	8,2	**M+PET**	0,5%, 24mm	1750	17,0
	1,0%, 24mm	2025	9,8		1,0%, 24mm	1745	17,0
	1,5%, 24mm	2005	8,9		1,5%, 24mm	1720	16,0
S+PP	0,5%, 70mm	2035	8,5	**M+PP**	0,5%, 70mm	1750	17,2
	1,0%, 70mm	1985	9,3		1,0%, 70mm	1760	16,0
	1,5%, 70mm	2000	9,0		1,5%, 70mm	1750	16,0
S+PP	0,5%, 24mm	2010	8,2	**M+PP**	0,5%, 24mm	1765	16,0
	1,0%, 24mm	1975	10,0		1,0%, 24mm	1710	16,5
	1,5%, 24mm	1945	8,3		1,5%, 24mm	1700	17,5

Data from Proctor Standard test (Table 5, Figure 5) of loess loam show that the value of maximum unit weight of the individual specimens vary between 17,00 kN/m^3 and 17,90 kN/m^3. For the specimens with short fibres (24 mm) it is evident the trend of decreasing of the maximum unit weight with increase of the content of fibres. However, the values of maximum unit weight of specimens with long fibres (70 mm) are somehow erratic. The lowest maximum unit weight has the specimens with the highest fibre content.

The optimum water content increased for all loamy specimens with fibres in comparison with loess loam without fibres and vary between 16,0 and 17,5 %.

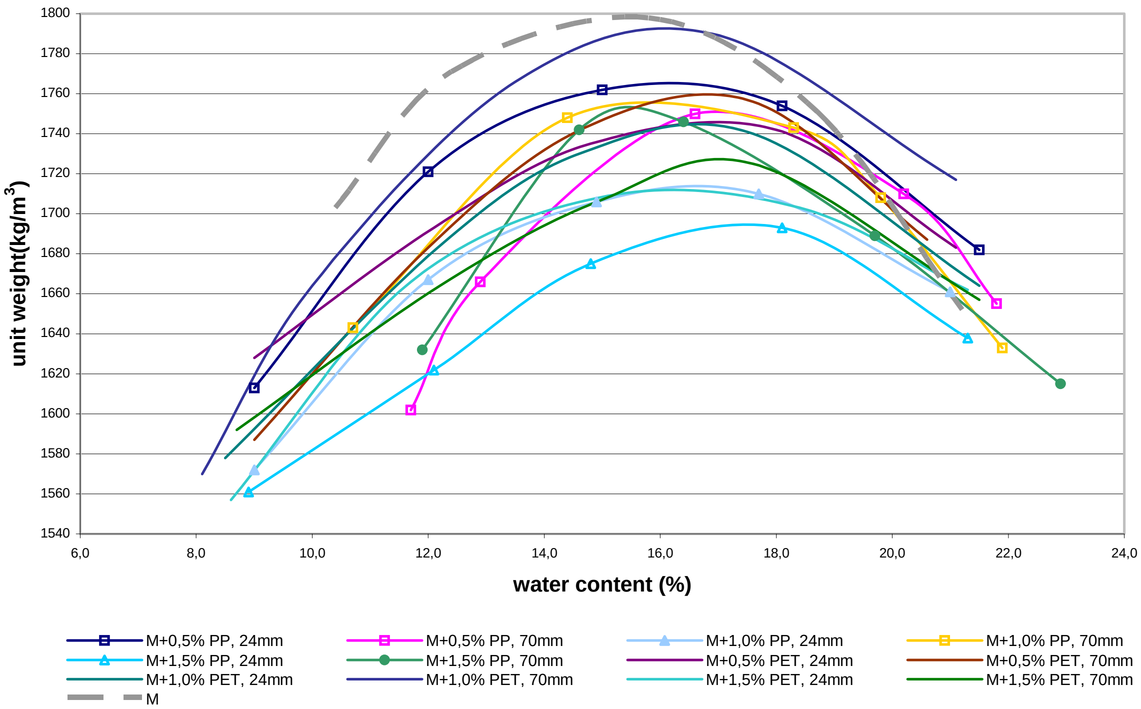

Figure 5. Relation between maximum unit weight and optimum water content of loess loam

The ranges of the maximum unit weights of both soils are almost the same. However, in case of sand the values oscillate around the value of maximum unit weight of sand without fibres and for loess loam all values are below the value of the maximum unit weight of loess loam.

Figure 6. Examples of sandy specimens with short polypropylene fibrillated fibres and long polyester staple fibres

CONCLUSION

Conclusions resulting from laboratory tests are as follows:

- Polyester staple fibres represent better material for micro-reinforcement. They can also be easier mixed into soil.
- Fibre reinforcement increases bearing capacity and decrease stiffness.
- Fibre reinforcement increases settlement, however, in comparison with the increase of bearing capacity this parameter is negligible.
- Polypropylene fibrillated fibres are less suitable for reinforcing of coarse soils in case we need to reduce settlement.
- Changes of the maximum unit weight are smaller for sand and negligible for sand with polyester staple fibres.

All tests identify that the polyester staple fibres are better option for micro-reinforcement. Laboratory test will continue and they will be followed by in situ trials in order to identify marginal conditions of utilisation of this technology in engineering practice.

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