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Laboratory study of granular soils reinforced with randomly oriented discrete fibres

Etude en laboratoire de sols grenus renforcés par des fibres dispersées dans le milieu

Après un bref état des connaissances sur le renforcement des sols grenus, on présente les premiers résultats de recherches effectuées en laboratoire sur le renforcement par des fibres. Le matériau renforcé est obtenu en mélangeant un sol grenu (gravier fin sableux) avec deux types d'armatures (fibres de polypropyline torsadées de 50 mm de longueur et bandes de 66 x 7 mm2 d'un matériau breveté à base de nylon et de polypropylène).
Une série d'essais de compactage a été réalisée et analysée statistiquement, à partir de sept méthodes de compactage différentes. Les résultats d'une série d'essais triaxiaux sur des échantillons de 103 mm de diamètre et de 165 mm de hauteur sont également interprêtés.
Ces essais montrent que le renforcement offre une résistance au compactage. Cette résistance (exprimée en terme de porosité finale) est proportionnelle à la densité de renforcement. Elle est indépendante de la méthode de compactage, mais varie avec les caractèristiques des armatures et l'état du sol. Le renforcement augmente la résistance au cisaillement et la ductilité des sols, mais de façon moins importante que prévue par suite de son influence sur la porosité finale. Le compactage par damage apparaît plus efficace pour l'augmentation de la résistance que le compactage par vibration. L'augmentation de ductilité du sol grenu est proportionnelle à la densité de renforcement, mais ne dépend pas de la méthode de compactage, ni des dimensions des bandes bien qu'elle soit fonction des caractèristiques mécaniques des armatures.

LITERATURE REVIEW

It is now well known that considerable improvements may be made in the mechanical properties of soils by the incorporation of inclusions in the soil, and that soil reinforcement is not a mid 20th Century invention. Much of the natural, animal and early man-made soil reinforcement is achieved through plant roots, and animals use combinations of soil and sticks in building their habitats. Man has used straw for many thousands of years to improve the quality of clay bricks, the Gauls used logs and earth to build early fortifications, dykes were built in China for thousands of years using earth and tree branches, and logs, timbers and fascines were used in roads over soft foundations in such places as colonial North America and Sweden.

In the 1960's application of the principle to modern geotechnical situations using modern materials was being undertaken in several parts of the world. Holtz (1975) reports the Japanese use of plastic (polyethylene) nets (Horimatsu 1965 and Yamanouchi 1970) and the Swedish use of two rows of short steet piles interconnected by steel anchor rods (Wager 1968) as 'reinforcement' in embankments. At the same time Vidal (1966) published an article which inter alia mentioned qualitatively the improvements in soil properties which could be obtained by the incorporation of small amounts of reinforcing materials such as metal, glass, plastic rods, fibres, or thin plates in the soil.

In the 1970's work on reinforced earth has centered almost exclusively on the use of long narrow strips of reinforcement material and discussion of these is outside the scope of this paper. However, the methods of explaining the strength carrying characteristics of reinforced earth is of direct relevance to the present study (eg Schlosser 1972 in France, Lee et al 1973 in U.S.A. and Hausmann 1976 in Australia.). All these have relevance in the interpretation of the present work on randomly reinforced soils.

Very little has been published on the direct use of discrete randomly orientated fibres incorporated into a soil mass. Considerable work has been undertaken into the properties of 'composites' where discrete reinforcement has been included in a matrix base such as concrete, asphalt, cement or plastics. These materials are of the much more 'factory produced' variety, and the statistical theory of structural composites is again outside the scope of this work. The work most relevant to this paper was the series of explanatory laboratory tests undertaken by Lee (1969). Most of them used dry angular quartz sand and a few used compacted silty clay. The reinforcement was in the form of 1" long thin narrow strips of various materials (wood shavings, mylar strips, shingle nails, fibreglass wool and cloth mesh). For each series of tests a predetermined amount of reinforcement was mixed with the soil and tests to measure the angle of repose, triaxial compression strength and deformation under a plate bearing load were performed. These explanatory tests were not intended to be conclusive or exhaustive but did generally indicate an increase in the angle of repose, an increase in the triaxial compression strength and an increase in the ductility over a similar unreinforced soil specimen.

OBJECT AND SCOPE OF STUDY

The study was undertaken as a preliminary investigation aimed at determining the feasilibility of using randomly oriented discrete fibres as a soil inclusion to improve the properties of a soil.

The laboratory tests (Georgiadis 1977) were aimed at investigating the resistance to compaction afforded by the reinforcement, and the soil strength and soil ductility obtained from the compacted soil mixture after given types and amounts of compactive effort have been applied.

EXPERIMENTAL PROCEDURES

Materials. The soil used for the tests was a 5-0.6 mm dry angular crushed sandy gravel. Two reinforcement materials were used: Reinforcement 1 was a proprietory 75% / 25% polypropylene/nylon fabric sheet (I.C.I. Terram 140) cut up into small strips of dimensions 66x7 mm, and Reinforcement 2 was polypropylene fibres in the form of propritory twisted 2" chopped staple fibre (Bridon fibres and Plastics Ltd.). The soil samples for each test were prepared so as to have a given Reinforcement Ratio ρ^{+} and were thoroughly mixed by hand methods so as to give a material of uniform consistency prior to compaction.

Compaction Tests. A total of 33 tests were performed using seven different compaction methods as detailed in Table 1. The soil sample containing the reinforcement was compacted in accordance with a test method and the resulting porosity n of the soil mixture calculated.$^{++}$

Triaxial Compression Tests. A total of 31 tests were performed on 103x165 mm diam. vacuum specimens which had been compacted with varying reinforcement ratios ρ by various compaction methods as detailed in Table 1.

Analysis of Results. The results of the laboratory tests were analyzed statistically. A linear regression analysis of the test data was performed. The Correlation Coefficient R for each case was calculated and tested for statistical significance using the method of Velz (1970).

+ Reinforcement Ratio ρ, defined as the percentage ratio of the weight of the reinforcement to the total weight of the soil plus reinforcement.

++ Porosity n, defined as the percentage ratio of the volume of the voids and the reinforcement to the total volume of the sample. An alternative definition was also used, viz n_s defined as the percentage ratio of the volume of the voids only to the volume occupied by the soil grains and air but not the reinforcement. Both indicate the closeness of the grains in the packing but n_s ignores the presence of the reinforcement. The difference in result for porosity calculated by the two methods for $o<\rho<0.5\%$ is about 1%. Thus only the first definition is used.
The possibility of a 'displacement effect' on the porosity results due to the incorporation of a relatively large volume of very lightweight material into the soil was investigated and again the error is small (for $o<\rho<0.5\%$ it is 2%).

RESULTS AND DISCUSSION

(a) Compaction Tests.
For each Compaction Method, the correlation between the amount of the reinforcement ρ and the resulting porosity n was plotted. The results are shown in Fig. 1. Table 2 gives details of the Regression Analysis.

The results indicate that the reinforcement provides resistance to the compaction causing a less dense packing with increasing ρ. A positive linear relationship exists between n and ρ which seems to be independent of the type of compaction but dependent on the type of reinforcement adopted.

No strip damage was observed in any test which implies that the limit of the resistance to compaction afforded by the reinforcement is due to a bond failure rather than a tension failure within the reinforcement. The resisting action of the reinforcement can be simply visualized in Fig. 2 where in situation (a) particles A and B prevent particle C from packing tightly until slippage occurs between soil and reinforcement which allows situation (b) to develop.

Compaction Method	Details of Method
CM L	Max. Porosity Test (Kolbuszewski 1948) by rapidly inverting 1000 cc measuring cylinder containing 1000 gm of soil and measuring the volume occupied.
CM 1	Standard Proctor Compaction (BS 1377)
CM 2	Compaction in the Triaxial former mould in 3 layers each vibrated under a surcharge of 2 kg for 60 sec by a Variac vibrating table at 50/60 v
CM 3	Dietert Compaction (ASTM Des. C181-76) but modified to 30 blows on each of 3 layers with one sided compaction.
CM 4	As 2 but with single layer without surcharge.
CM 5	As 5 but under 5 kg surcharge and 70/80 V output.
CM 6	As 2 but single layer under 2.3 kg surcharge
CM 7	As 1 but using Triaxial former instead of Proctor mould.

Details of Compaction Methods
TABLE 1

Compaction Method	$n = K_1\rho + K_2$	Correlation Coefficient	Significance Level
CM L	$n=0.111\rho+45.72$	0.98	98.75%
CM 1	$n=0.130\rho+36.70$	0.99	97.22%
CM 2	$n=0.156\rho+37.10$	0.97	90.50%
CM 3	$n=0.134\rho+30.72$	0.99	95.23%
CM 4	$n=0.129\rho+35.46$	0.93	95.45%
CM 5	$n=0.111\rho+37.49$	0.99	95.22%

Compaction Tests - Statistical Analysis

TABLE 2

Under these circumstances it is not the ultimate strength characteristics of the reinforcement material which controls the action of the mixture but the interactions between soil and reinforcement. This will include such factors as soil grading, particle shape, surface texture of the reinforcement as well as the specific surface area characteristics of the reinforcement[z] (which controls the effective area of the reinforcement over which the bond may develop). It is interesting to note that RM2 which has a much smaller specific surface area than RM1, gave a much smaller increase in n with increasing ρ than RM1.

[z] *Specific Surface Area* = $\dfrac{\textit{Surface area containing a volume}}{\textit{Volume contained}}$

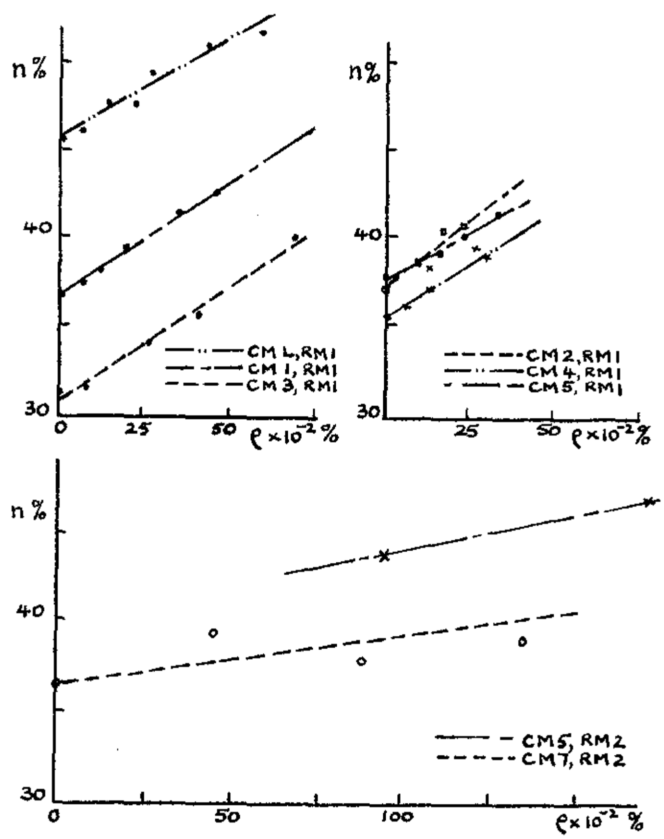

FIGURE 1. Compaction Tests: Reinforcement ratio-porosity relationship

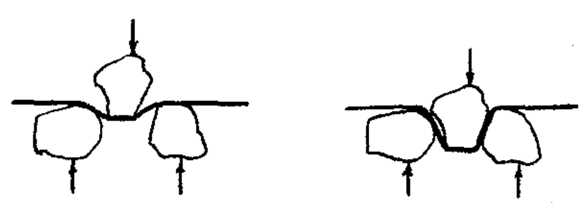

FIGURE 2. Mode of failure (a) before bond failure, (b) after bond failure

(b) Triaxial Tests.

Fig. 3 shows typical stress-strain curves for samples with various reinforcement ratios ρ.

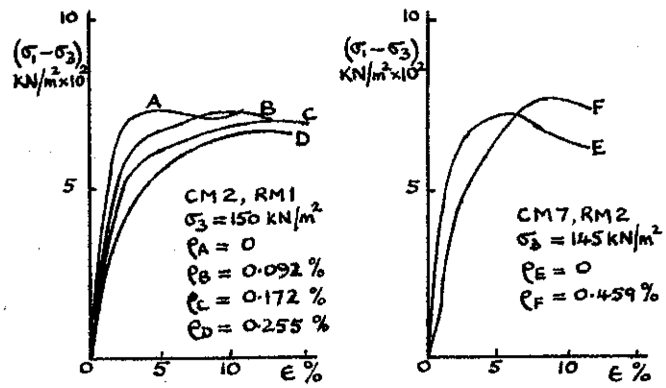

FIGURE 3. Typical Triaxial Test Results

Two parameters were selected as representing the most important characteristics of the shear strength behaviour: (i) Angle of Friction $\emptyset$ representing the strength of the material[y] (ii) Failure strain ε representing the ductility of the material.

(i) Strength Characteristics - The strength behaviour of the soil was considered as being a function of two variables, the amount of reinforcement material ρ and the porosity n. The results of the tests were put into four groups each relating to a specific reinforcing material and compaction method. Fig. 4a gives the experimental points connecting $\emptyset$ and n for ρ = 0. The variation in experimental points is such that no inference about the $\emptyset$-n relationship is justified. However Curve 2 shows experimental data obtained by Rowe et al (1964) for a different material and since it may be reasonable to assume that the shape (but not the absolute position) of the curve is similar for different materials, Curve 1 has been drawn through the experimental points parallel to Curve 2. Similarly Fig. 4b gives the $\emptyset$-n relationship for ρ=0.175%. It is felt that little confidence can be placed in the curve and that it is unfair to draw conclusions from them.

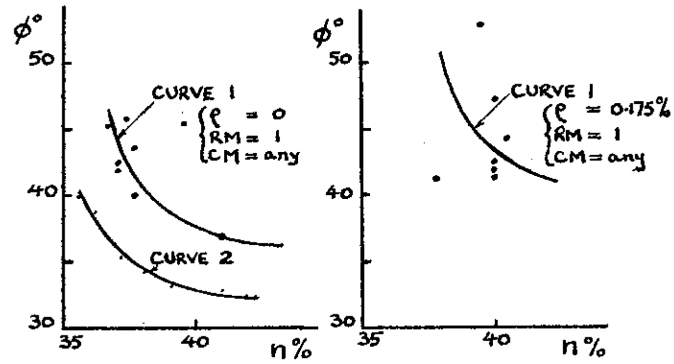

FIGURE 4. Triaxial Test: angle of shearing resistance-porosity relationship

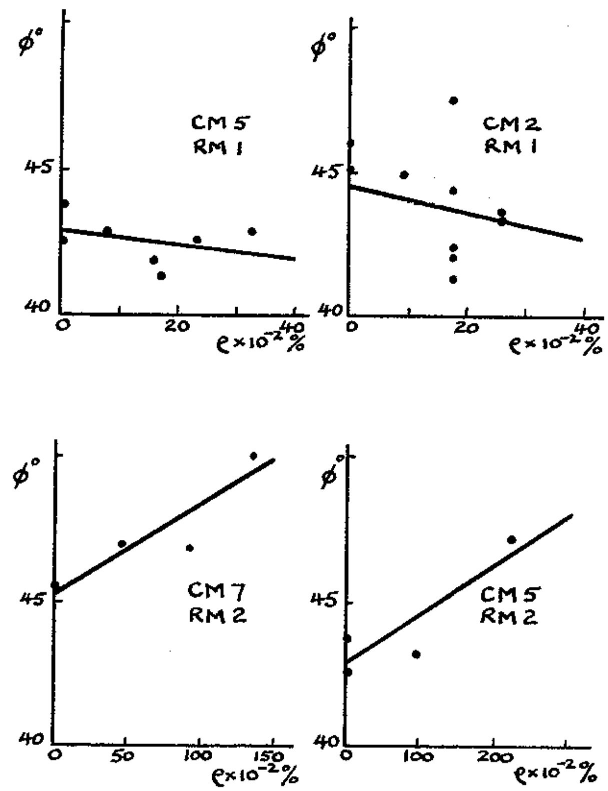

FIGURE 5. Triaxial Test: Reinforcement ratio-angle of shearing resistance relationship

[y] *The strength of the material was calculated for each test from;*

$$\emptyset = \sin^{-1} \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3}$$

The use of this method of calculation was necessary to avoid the much larger number of tests required to obtain $\emptyset$ by more precise methods, and was justified by the lack of any evidence of strip damage occuring during either Compaction or Triaxial Tests which leads to the assumption of the mixture behaving as a cohesionless material and therefore with $\emptyset$ constant with confining stress (Hausmann 1976).

The correlation between Ø and ρ for each group of tests is shown in Fig. 5. Statistical analysis (Table 3) shows a linear correlation having relatively high significance levels. A significant difference is observed between the direction of the slope of the Ø-ρ curves which seems to depend on the reinforcing material. It must be remembered that each graph relates to a particular reinforcing material and compaction method and thus the porosity n is not constant but increases linearly with ρ as already shown (Fig.1, Table 3).

Compaction Method	Reinforcing Material	$n = k_1 \rho + k_2$	Correlation Coefficient	Significance Level
CM 2	RM 1	$n=0.17\rho+6.1$	0.67	96.4%
CM 5	RM 1	$n=0.21\rho+5.4$	0.93	97.8%
CM 7	RM 2	$n=0.08\rho+4.1$	0.99	91.1%
CM 5	RM 2	$n=0.04\rho+6.5$	0.82	84.4%
CM 2	RM 1	$n=0.04\rho+44.5$	-0.23	52.8%
CM 5	RM 1	$n=-0.02\rho+42.9$	-0.35	60.5%
CM 7	RM 2	$n=0.03\rho+45.4$	0.89	87.6%
CM 5	RM 2	$n=0.02\rho+42.9$	0.88	87.1%

Triaxial Tests - Statistical Analysis
TABLE 3

Thus samples compacted with given compactive effort but with increasing ρ, experience a porosity increase and this gives rise to a certain reduction in strength Ø. The question is whether the increase in n caused by a marginal increase in ρ is sufficient to cause a net marginal reductionor increase in Ø. It would appear that with RM1, a net decrease in Ø occured, and with RM2 the effect was a net increase. Fig. 6 is a hybrid graph incorporating all triaxial tests performed on samples using RM1 and having a compacted porosity in the range 39% < n < 41%. It illustrates the point that when the large increase in n which occurs with RM1 is eliminated then a very considerable increase in Ø with ρ does nevertheless occur. The very large difference in operation between the two reinforcing materials under these circumstances is most likely due to their very different Specific Surface Areas as already discussed. Although in the Compaction Tests there seemed to be no difference in the n-ρ relationships between different compaction methods, Fig. 5 does show that a lower range of Ø is obtained with vibration compaction (CM5) than with ramming compaction (CM7). Fig 1 shows CM1 (which is very similar to CM7) to give a very similar n-ρ curve to CM5. An intuitive explanation of this is that in the vibration methods of compaction the reinforcing material tends to float in the soil as the mixture is being vibrated into a denser state (this floating

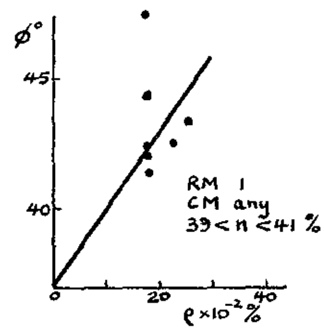

FIGURE 6. Triaxial Test: Reinforcement ratio-angle of shearing resistance relationship for constant porosity.

can be observed in practice). In the ramming methods of compaction however the reinforcing material does not move so much relative to the adjacent soil grains, and moves with the soil particles into the denser state. Thus more intimate contact is maintained between soil and reinforcement at every stage of densification with the ramming compaction methods and increased interlock and hence frictional resistance occurs. It is therefore suggested that the ramming methods of compaction are more beneficial to strength increase than vibration methods.

(ii) Ductility characteristics.
Fig. 7 and Table 4 show the effects of the reinforcement on the ductility of the reinforced soil. The correlations between ε and ρ were performed in four groups as before. The statistical analysis showed a

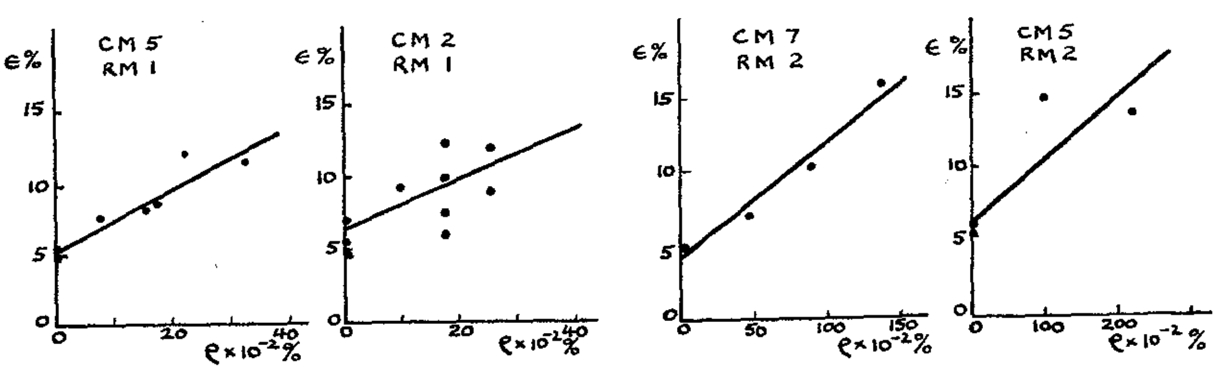

FIGURE 7. Triaxial Test: Reinforcement ratio - failure strain

positive linear correlation with a high degree of correlation. Thus it is clear that increasing the amount of reinforcement increases the failure strain of the soil mixture, and that this is independant of the compaction method.

CONCLUSIONS

1. Reinforcement provides resistance to the compaction of the soil. A positive linear relationship exists between resulting porosity and amount of reinforcement in the soil, which appears to be independant of the compaction method adopted, but dependant on the characteristics of the reinforcing material and the soil properties and their interaction.
2. Triaxial tests performed using various compaction methods showed that the reinforcement has beneficial effects on both the strength and the ductility of the soil. For samples with different amounts of reinforcement compacted by different compaction methods to constant porosity, a substantial increase in strength results. The strength increase will not be so big (it may even be negative), when a constant amount of compactive effort is applied to a range of samples with increasing amounts of reinforcement. This is due to the increases in porosity which occur with increasing reinforcement and the inherent decrease in strength which this porosity increase causes. Kneading methods of compaction (eg ramming methods) appear more beneficial to strength increase than vibration methods. A linear correlation exists between the amount of reinforcement and the increase in ductility of the mixture. This is independent of the compaction method but depends on the properties of the reinforcement.

CONCLUDING REMARKS

For the technique to have practical application (as for example a mix-in-place soil stabilization process for low cost overseas roads), sufficiently heavy compaction would need to be used to overcome the resistance to compaction afforded by the reinforcement. Provided that this could be provided, considerable increases in both strength and ductility of the soil would result both of which would be valuable in increasing the life of the pavement. Further research is needed to evaluate the economics and practical feasibility of the technique on a range of soil and reinforcement types.

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