

Model Tests on Strip Footing on Reinforced Sand

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Abstract. Results of bearing capacity tests on model strip footing on sand layers show beneficial effect of reinforcement with fibrillated polypropylene fibers. The ratio of the width of the reinforced zone to the footing width (L/B) has been varied from zero to six. Also, the ratio of the reinforced zone depth to footing width (H/B) has been varied from zero to three. The test results indicate a significant increase in the bearing capacity and stiffness of the subgrade and a modification of load-settlement behaviour of footing with size of the reinforced zone and amount of reinforcement. On the basis of the present test results, the optimal width and depth of the reinforced layer are $4B$ and $2B$ respectively.

Introduction

The current interest in soil reinforced by synthetic materials stems largely from research by Vidal [1]. In Arabian Peninsula the concept of combining straw with mud dates back several centuries. Straw is added to clay-water mixture to minimize the loss of strength when it comes in contact with water and to prevent cracking due to hot dry weather conditions. An early investigation by Lee *et al.* [2], indicated that the strength of sand reinforced with wood shavings increased by a factor of about 4 and with a dramatic increase in deformation modulus. Gray and Al-Refeai [3] and Al-Refeai [4] performed triaxial tests on sand reinforced with randomly oriented discrete fibers. Their test results indicated that increasing the fiber's aspect ratio increased the ultimate strength and stiffness of reinforced sand and strength increase is proportional to amount of fiber. They also found that failure in sand reinforced with short fibers, or tested at low confining stress, occurred by slippage of fibers. This behavior is depicted in Fig. 1

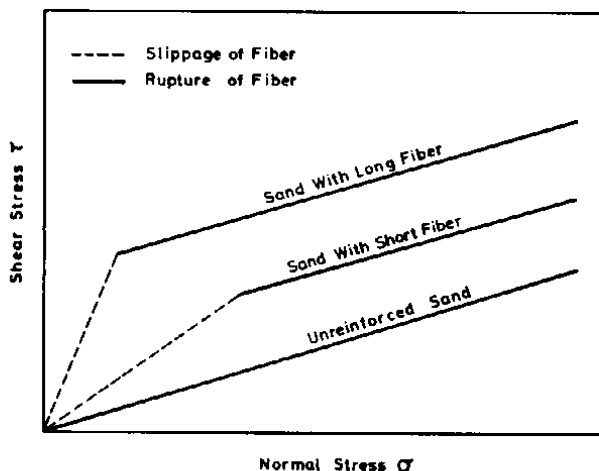


Fig. 1. Qualitative results of triaxial tests on fiber reinforced sand

The main purpose of sand reinforcement technique is to increase the bearing capacity and to reduce the settlement. The improvement in the load bearing capacity and stiffness of sand using synthetic fabric or fibers as tensile reinforcement under footing has been reported by Haliburton and Lawmaster [5] and Akinmusuru and Akinbolade [6]. Haliburton and Lawmaster [5] performed model plate bearing tests on sand reinforced with four different geotechnical fabrics. Akinmusuru and Akinbolade [6] studied the bearing capacity of a square footing supported by sand which was reinforced by multilayers of oriented robe fibers. The aim of this study is to present the fiber effects on bearing capacity and settlement through laboratory bearing capacity tests of model strip footing resting on sand reinforced with discrete randomly oriented fibers.

Experimental Work

Materials

The sand used in the testing program was obtained from Al-Thumamah near Riyadh and is a subrounded fine to medium poorly graded sand. The basic sand properties are presented in Table 1.

The fiber used in the tests was a 50 mm long fibrillated polypropylene fiber, properties of the fiber as supplied by the manufacturer (Synthetic Industries) are listed in Table 1.

Table 1. Properties of materials

Sand	
C_r	2.68
D_{10} (mm)	0.12
D_{50} (mm)	0.30
C_u	2.75
Unified classification	SP
e_{max}	0.659
e_{min}	0.415
ϕ (deg.) At $D_r = 70\%$	42
Standard compaction (ASTM D 698-70)	
MDD (KN/m^3)	17.9
OMC (%)	0
Fiber	
G_s	0.9
Single fiber tensile strength (GN/m^2)	0.36
Young's modulus (GN/m^2)	3.5
Elongation at Break (%)	17 ± 5
Equivalent Diameter (mm)	0.40

Laboratory testing

Bearing capacity tests on strip footing resting on the surface of reinforced sand were performed in a box with 20 mm thick perspex plates in order to minimize friction between soil and tank walls and provide direct observation during compaction and testing. The sides of the box were supported by steel stiffeners outside to prevent lateral displacement. The principal dimensions and the experimental setup are shown in Fig. 2. The strip footing was 50 mm wide, 20 mm thick and made of aluminium with sand glued to its base to simulate a rough base condition. To minimize friction at the interface of the strip footing and the longitudinal sides of the testing box, the same method used by Hanna [7] was employed in this study, where a 3 mm cut was made in the footing material at both ends and replaced with flexible foam. One side of the foam was glued to the footing, while the other side was covered with polyethylene. The footing was centered in the box with its length parallel to the width of the box. A schematic diagram of the test arrangement used in the study is shown in Fig. 2. The footing was loaded at a constant axial displacement rate of 0.15 mm/min to failure. The deformations were measured by means of two dial gauges placed on the two outside sections of the footing.

For model tests on unreinforced sand, the dry sand was mixed with the same amount of water used for reinforced sand where sufficient moisture (5% by weight)

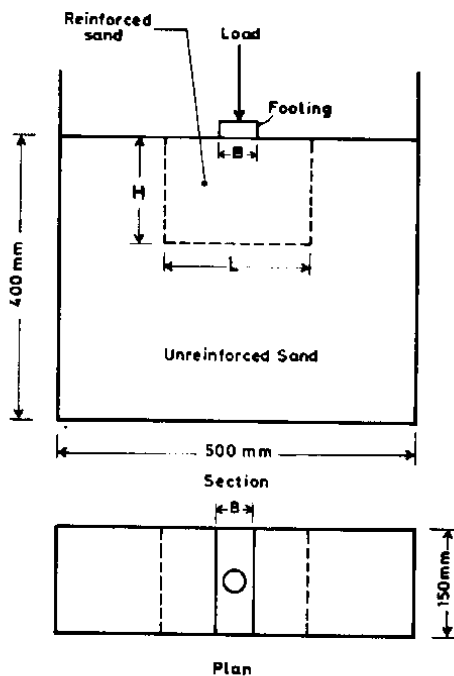


Fig. 2. Experimental model setup

was added to the sand to prevent segregation of the sand and the fiber during mixing and forming the fiber reinforced sand layers. A predetermined weight of moist sand needed to produce a dry density of 17.7 KN/m^3 ($D_r = 70\%$) was compacted in 50 mm thick layers, compaction was accomplished by placing wooden board on the sand surface and hitting the board with a hammer. Drained triaxial tests angle carried out on moist sand at this relative density indicate that sand's angle of internal friction (ϕ) was found to equal 42° . The final depth of the sand in the box was 400 mm, which was considered large enough to assume a semi-infinite soil medium.

In the case of tests on reinforced sand subgrade, the moist sand was mixed thoroughly with a desired weight percentage of fiber (ρ) by hand to ensure uniform mixture. Reinforced sand was deposited in form of trench below the footing. For making the trench, different wooden plates were used to create trenches with width/footing width (L/B) ratios of 1, 2, 4 and 6 and height/footing width (H/B) ratios of 1, 2 and 3. When the desired height of unreinforced sand layer was reached, the wooden mold was centrally fixed in the test box on the compacted unreinforced sand. The

unreinforced sand was then compacted in 50 mm thick layer, then the inserted wooden mold was removed, leaving a trench. A predetermined weight of fiber reinforced sand mixture was then deposited into the trench and compacted in 50 mm thick layers (equal to fiber length) using wood board of the same size as the trench. This process is repeated until the desired trench is created. Fiber reinforced sand was compacted to the same dry density as the sand alone (*i.e.* $D_r = 70\%$). The model footing was centrally placed on the top of the reinforced sand in the trench and it was loaded to failure.

Tests Results and Discussion

Triaxial tests

In order to make a complete investigation of the behavior of fiber reinforced sand, a series of triaxial compression tests has been performed on reinforced ($\rho = 0.5\%$) and unreinforced sand using 100 mm diameter samples. Fig. 3 shows the principal stress envelope for the reinforced sand, which consists of two straight lines. Each of them has a different inclination angle. The point of intersection of the two lines occurs at a critical confining stress below which failure of the reinforced sand is due to the lack of the development of sand-fiber bond stress.

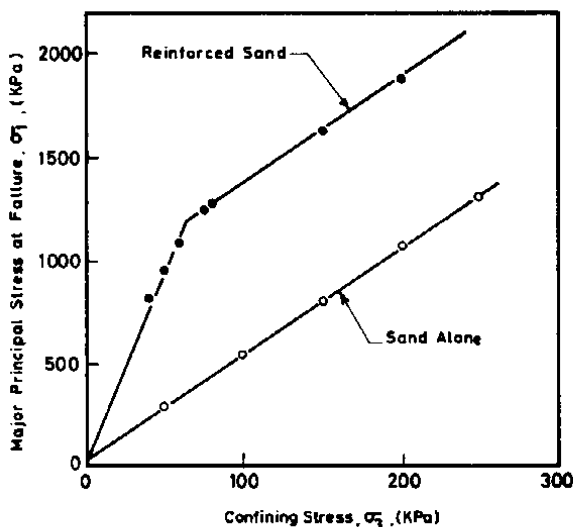


Fig. 3. Principal stress envelopes - triaxial compression tests on sand

At low confining stress (< 60 KPa) the failure of reinforced sand is due to loss of friction between the fiber and soil matrix. Drained triaxial tests carried out on fiber reinforced moist sand at low confining pressures indicated that it possessed an apparent angle of internal friction of 62° . The apparent friction angle (ϕ_r) which is typical for reinforced sand which fails by slippage between reinforcement and soil [8] determined using a failure envelope plotted on p-q diagrams as shown in Fig. 4.

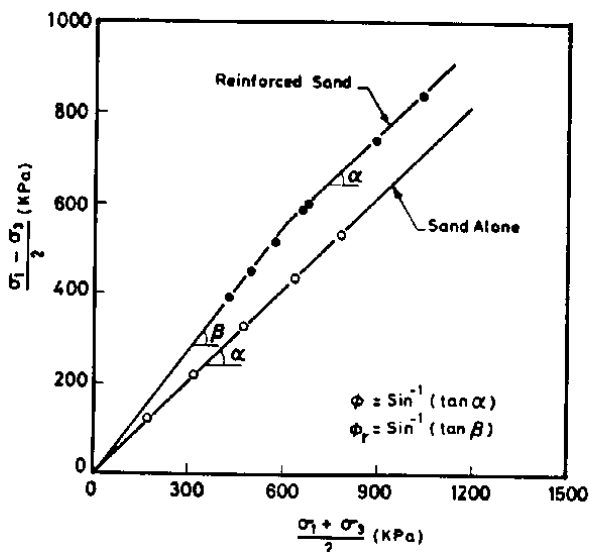


Fig. 4. Improvement in shear characteristics of reinforced sand

The additional strength, in the excess of the frictional strength of unreinforced specimen may be interpreted as being the effect of an anisotropic pseudo - cohesion developed in the reinforced sand [9], or due to an equivalent confining stress increase induced by the tensile restraint in the reinforcement [10].

No breaking of the reinforcement was observed when high confining pressures were applied indicating a frictional failure in all the tests. This is due to the fact the inclusions used have a large rupture strain ($> 17\%$) and are classified as relatively extensible inclusions [11].

Model tests on unreinforced sand

Figure 5 shows a typical plot of bearing pressure (q_0) on the model foundation and the corresponding settlement ratio (S/B) for test on unreinforced sand. The

observed load settlement curve exhibits the typical general shear failure, with an ultimate bearing capacity of 127KPa occurred at a settlement of 7% of the width of the footing. The predicted theoretical bearing capacity employing Meyerhof's factors [12] was lower than the observed one. Ko and Scott [13] and Chummar [14] have pointed out that better agreement between theory and experiment for bearing capacity of strip foundation is obtained by using plane strain rather than triaxial friction angle data. Hanna [7] and Hansen [15] have shown that the angle of shearing resistance from plane strain tests is 10% higher than the one from the triaxial test for dense sand. The observed values fell between those predicted using the triaxial friction angle and using the estimated plane strain friction angle. The used moisture content had no significant effect on the stiffness and stress-deformation properties of the sand.

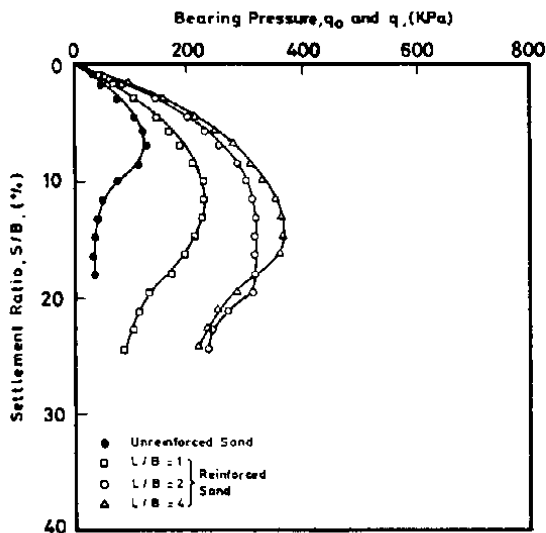


Fig. 5. Load - settlement relationships
($H/B = 1$)

Model tests on reinforced sand

Load-settlement behavior

Two series of tests were conducted to examine how the load-settlement relation is influenced by varying the depth (H) and width (L) of the reinforced zone below the footing base. Prior to testing; it was necessary to select a suitable fiber concentration to be used in the model tests. Trial sand-fiber mixes with different concentrations

were used to build sand reinforced trench ($L/B = H/B = 2$). It was necessary to increase the compaction effort to maintain the desired relative density with increasing fiber concentration. Sand reinforced with a fiber concentration of $\rho = 0.5\%$ was selected because it was easily and efficiently compacted, with minimum disturbance to the surrounding compacted unreinforced sand layers.

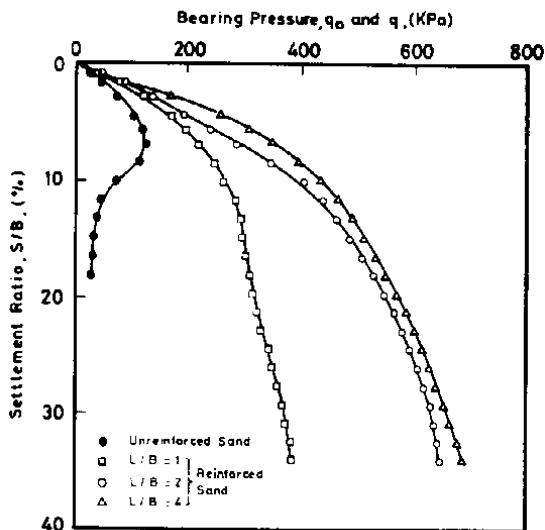


Fig. 6. Load - settlement relationships
($H/B = 2$)

The pressure-settlement curves for some tests are shown in Fig. 5 and 6. It is clear that the increase in bearing capacity and stiffness is significant. It appears that the reinforced zones resist the lateral displacement of soil underneath the footing and create a sand-confinement situation. Furthermore, the fibers modify the uniform pattern of strain which usually develop in unreinforced sand, to a more complex deformation mechanism and hence increase the bearing capacity.

Figure 5 shows the load-settlement curves for model footing resting on shallow reinforced zone ($H/B = 1$) with L/B ratio varied from 1 to 4. The nature of load-settlement obtained is primarily of general shear type. The reason for this is probably that the failure surfaces starting from the footing edges extend and pass through a greater depth of unreinforced sand.

For the case of deep reinforced zone ($H/B = 2$) the general shear failure mode is completely eliminated, in contrast with unreinforced case in which a well-defined general shear failure plane was visible. The degree of curvature of the load-settlement curves decreased with increasing L/B ratio, as shown in Fig. 6.

It is interesting to note that, in none of the reinforced tests a reduction in stiffness did occur. In their work, Andrawes *et al.* [16] have found that for strip foundation on geotextile reinforced sand, the presence of the geotextile had little effect on the load-settlement behaviour of the footing until the settlement reached approximately $0.08 B$.

Effect of reinforced zone depth

For convenience in expressing and comparing test data a dimensionless bearing capacity ratio, which has been introduced by Biquet and Lee [17], is used in this study. The bearing capacity ratio was defined as $BCR = q/q_0$, where q and q_0 are the bearing pressure for reinforced and unreinforced sand respectively, both measured at the same vertical settlement. As a majority of the load-settlement curves obtained did not show a well-defined failure point, and because fiber reinforcement continued to influence ultimate bearing capacity at relatively large settlements, the BCR values corresponding to $S/B = 7\%$ were adopted as representative values for comparison.

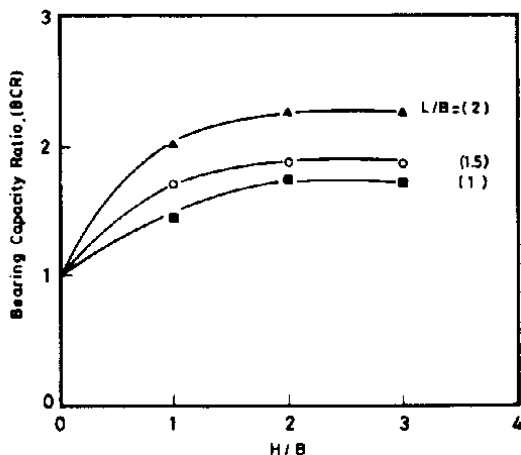


Fig. 7. Effect of H/B on BCR

A series of tests were conducted to investigate the effect of the reinforced zone depth (H) on the BCR. The test results are given in Fig. 7. These tests were carried out with L/B ratios of 1, 1.5, and 2. The BCR increases rapidly with increasing H/B ratio up to a maximum value, after which it remains practically constant. There is no significant difference in the BCR between the reinforced zones with H/B equal to 1 and 2. This suggests that the optimal value of reinforced zone parameter H/B exists between 1 and 2. Reinforcing to a depth greater than $2B$ has no effect on the bearing capacity of the footing because the zone of active and radial shear deformation beneath the footing extends no deeper than twice the footing width. Haliburton and Lawmaster [5] observed similar results in their model footing tests on sands reinforced with geotextiles.

Effect of reinforced zone width

Figure 8 shows the variation of BCR versus the reinforced zone width ratio (L/B) for H/B of 1 and 2. The magnitude of BCR increases with L/B and reaches a maximum value at about L/B between 2 and 4. From Fig. 8 it can be realized that for $L/B > 4$, the magnitude of BCR remains constant. Akinmusuru and Akinbolade [6] observed similar results for model footing tests on sands reinforced with oriented fibers.

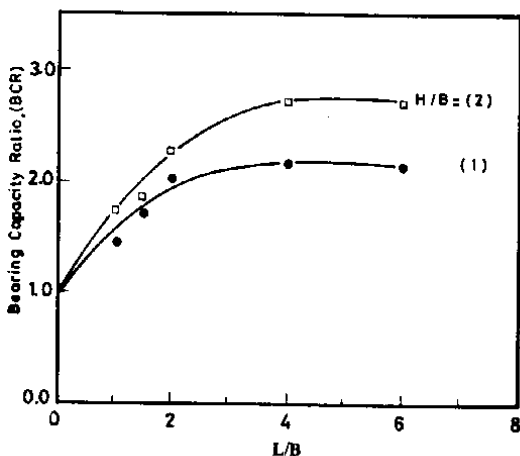


Fig. 8. Effect of H/B on BCR

Settlement of footings

The objective of using fiber reinforcement is not to maximize the strength of reinforced sand at the expense of the stiffness, but rather to improve the global prop-

erties of the reinforced composite body, *i.e.* to maximize its strength and/or minimize boundary deformations. The BCR variation with settlement of footings on reinforced zone with different values of H/B and L/B ratios is shown in Fig. 9. It is found that the contribution of fiber reinforced zone to the bearing capacity increase is high as the settlement of footing increases. The most effective width and depth of reinforced layer obtained from Fig. 9 are $L = 4B$ and $H = 2B$ respectively.

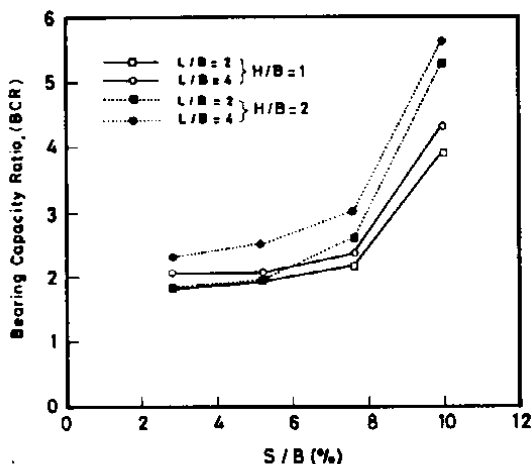


Fig. 9. BCR variation with settlement of footing for various H/B , L/B ratios

Effect of fiber concentration

A number of tests were performed with H/B and L/B ratios of 3 and 2 respectively to investigate fiber concentration effect on the bearing capacity and settlement of surface footing. The soil dry density was kept constant ($D_r = 70\%$) for this series of tests. The observed relationships between the load and settlement are given in Fig. 10. The plots demonstrate a significant increase in the stiffness and the bearing capacity was gained by increasing the fiber concentration. There seems to be no significant difference in the effect of improvements for fiber concentration $> 0.4\%$. The response to the applied load of footings on sand reinforced with low fiber concentration (0.1 - 0.2%) is of a general shear failure mode, while for those on sand reinforced with high fiber concentration $> 0.3\%$ is of a progressive failure type. In Fig. 11, the effect of fiber reinforcement is plotted as the BCR values calculated at $S/B = 7\%$. The BCR increases with the fiber concentration almost linearly up to a maximum value and remains practically constant thereafter.

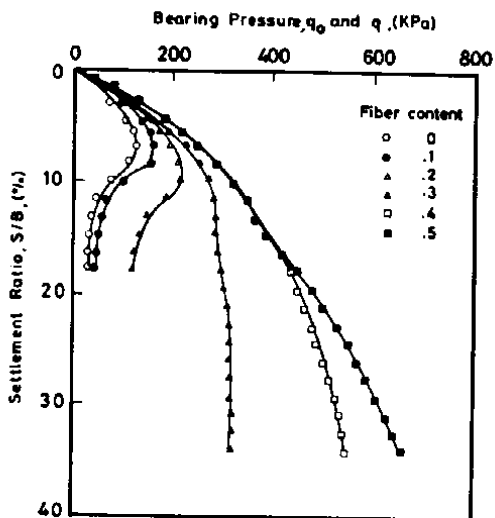


Fig. 10. Effect of fiber concentration on load - settlement relationships ($H/B = 3$, $L/B = 2$)

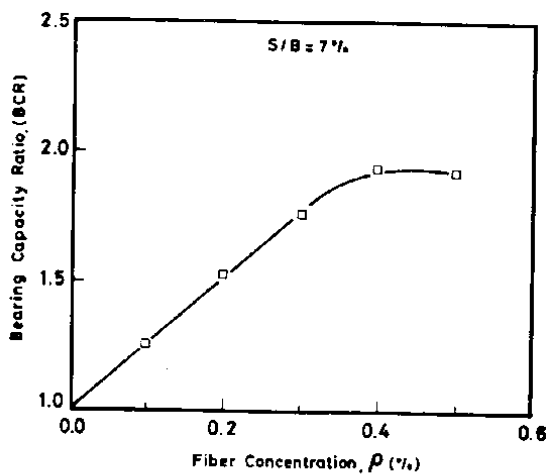


Fig. 11. Effect of fiber concentration on BCR ($H/B = 3$, $L/B = 2$)

Conclusions

Laboratory model test results for bearing capacity of a strip surface foundation resting on a fiber reinforced sand have been presented. Based on experimental investigation, the following conclusions have been drawn:

- 1) Inclusion of discrete, randomly oriented fibers below a foundation in sand increases the load carrying capacity and stiffness.
- 2) The bearing capacity and stiffness increase as the depth and width of the reinforced zone are increased.
- 3) Foundations on a fiber reinforced zone with suitable dimensions can tolerate larger settlement before failure.
- 4) The optimal depth and width of reinforced layer for increasing the bearing capacity and stiffness are $2B$ and $4B$ respectively. Greater depths and widths of reinforcement are ineffective in increasing bearing capacity.
- 5) Increasing the fiber concentration increases the bearing capacity and considerably increase the footing settlement at failure up to some limiting concentration. Thereafter, the bearing capacity and stiffness approach an upper limit.
- 6) Large-scale field tests are necessary to verify the present findings.

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اختبارات على نموذج لقاعدة شريطية فوق رمال مقواة

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(استلم في ١٥/١/١٩٩١م، قبل للنشر في ٥/٦/١٩٩١م)

ملخص البحث. يعرض البحث نتائج اختبارات التحمل على نموذج لقاعدة شريطية فوق تربة رملية مقواة باللياف البوليبروبيلين. حيث تم تغيير عرض المنطقة المقواة باللياف من صفر إلى ٦ أمثال عرض القاعدة، وبعث يتراوح بين صفر إلى ٣ أمثال عرض القاعدة. وقد دلّت التجارب على أن الزيادة في حجم المنطقة المقواة وكذلك في كمية الألياف المضافة تؤدي إلى زيادة كبيرة في قوة التحمل وصلابة التربة وكذلك تحسين سلوك الهبوط مع الحمل المؤثر على القاعدة.

كما دلّت الدراسة على أن العرض الأمثل للمنطقة المقواة باللياف هو ٤ أمثال عرض القاعدة وبعث يساوي ضعف عرض القاعدة.