THE CONSTRUCTION OF SELF-LOADING MICRO-MODELS OF REINFORCED SOIL USING ULTRA-WEAK REINFORCEMENT SIMULANTS

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ABSTRACT: The paper reports the results of 16 model tests using silica sand as the reinforced soil fill and tissue paper reinforcement with a failure extension of 5% - 7% and ultimate failure strength of 0.02 - 0.03 kN/m. These tests demonstrate a consistent and repeatable failure mode for reinforced soil. Initial back-analysis of the failed models shows that, applying current reinforced soil design theory, the nonwoven tissue papers are supporting model heights greater than those predicted. It is difficult to avoid the conclusion that this is caused by the widely accepted concept that the in-soil strength of a reinforcement is greater than its in-air test value. The models were all constructed using a technique that allowed stresses to build up in a realistic fashion. The outcome was that models failed at heights of around 0.44 to 0.66 m. Such small scale, realistic tests can each be constructed and tested in a single day. The author suggests that the model procedures adopted are the first steps towards demonstrating numerically the difference between in-soil strength of reinforcements and their in-air test strengths - particularly for nonwoven textiles.

1 INTRODUCTION

In earlier research work, the author developed a number of very low strength tissue paper products that can be used to represent geotextiles in micro-models of reinforced soil structures. The tensile strength apparatus, testing and properties of these papers have been described by Rankilor (2002).

A special test bench was made on which to build the models. This test bench comprised a constraining area and a frontal support system to enable individual wrap-round layers to be constructed in the same way as full size structures. This test bench was successful, producing reliably consistent experimental output.

Using tissue paper as a reinforcement and the test bench, 16 models were made and tested with dry silica sand that had been washed to remove very fine particles. These models were made with reinforcement layers of 22, 44 and 66 mm height. The reinforcements were wrapped round at the model face.

It was found that, according to current design theory, the models were higher at failure than they should have been for the tissue's ‚in-air' tensile strength. It is proposed by the author that the difference between the forecast heights and the achieved heights is accounted for by the increase in real strength of the reinforcements in soil. This phenomenon has been recognised for many years, but so far has never been quantified. The author tentatively proposes that this model work will lead on to the quantification of these values and the development of more economical reinforced soil design methods.

Two models were constructed separately that were built to below-failure height and then surcharged to failure. It was found that the surcharge failure mode is different from internal gravity-induced failure mode. These differences were recorded on digital video films but, owing to the lack of permitted space in this paper, will be reported in detail elsewhere.

This research work opens the way for extensive testing of many other aspects of reinforced soil design. In particular, the repeatability and forecastability of the design outcomes will permit the analysis of alternative design methods. It is expected that this work will lead to a better understanding and possible determination of the in-soil strength of both stiff and highly extensible geotextiles.

2 TISSUE IN-AIR STRENGTH VARIATION WITH HUMIDITY

In-air tensile tests in humidity controlled laboratories were undertaken at pre-set humidities at 20 deg. C. The paper was permitted to rest for 24 hours in a controlled humidity environment and then tested using the standard 200 mm x 100 mm test procedure for its in-air tensile strength and extensibility at failure.

Fig.1 shows a typical experimental result for the same paper at different humidities tested in the cross-machine direction. A certain experimental scatter is present, but considering that each test was undertaken several days apart, the repeatability is good. As expected, it can be seen that the ultimate strength at failure decreases with humidity.

Fig. 2 shows the same sample tests, in the cross-machine direction, but displays the variation of ultimate extensibility with change in ambient humidity. It can be seen that the extensibility increases with humidity.

It was interesting to note that whereas the ultimate tensile strength of the paper was inversely proportional to the humidity as expected, the extension at failure also changed and was directly proportional to the humidity.

Consequently, for that particular paper sample (S6 - the chosen test sample), all that was required for subsequent testing was to maintain the laboratory temperature at 20 degrees Celsius and to measure the humidity. The strength and elongation properties of the paper could then be read off the graphs accordingly.

Viewed in absolute terms for the particular sample, the ultimate strength varies between approximately 0.2 and 0.3 kN/m width. The elongation varies between approximately 5% and 7%. Although the variation in ultimate tensile strength, is small in global terms, it was recognised as a significant 50% variation in strength depending upon humidity. Therefore during this research work, relative humidity was monitored at the time of construction of models.

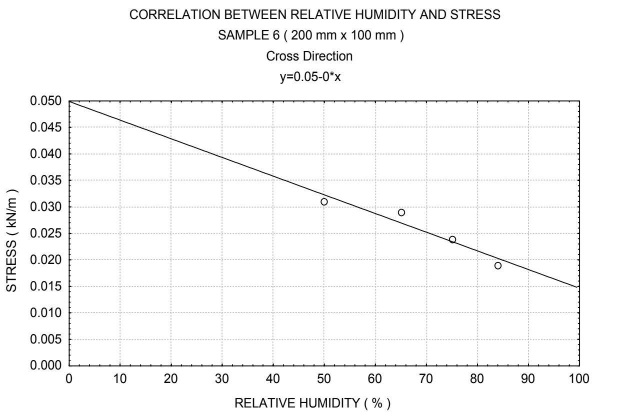

Fig. 1. Plot of change in ultimate tensile strength with change in ambient humidity at 20 deg. C. Cross-machine direction

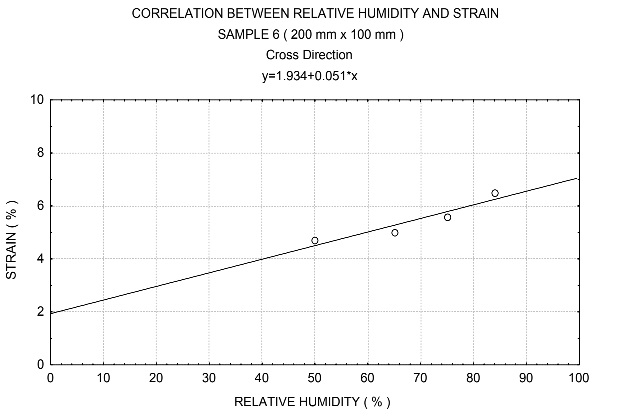

Fig. 2. Plot of change in ultimate extensibility with change in ambient humidity at 20 deg. C. Cross-machine direction.

The models were made with a standard British sand called Leighton Buzzard medium grain size. It was tested to have a poured dry density of 15.56 kN/m3 and an average 33.6 degree internal angle of friction.

3 DESIGN AND CONSTRUCTION OF THE TEST BENCH

It was necessary to design and construct a test bench for the purpose of conducting the work. The bench had to have a strong supporting frame and a tall construction enclosure. There had to be some method of building the wrap-round face of the vertical reinforced soil walls.

The smooth inside walls tapered slightly inwards towards the top. The width of the base of the model was therefore slightly greater than the top of the model. This was designed to ensure that, when the model failed, it was free to fall downwards. This is a most important and inexpensive feature since, if the sides are parallel or even inadvertently narrowing downwards, then the model, upon failure could jam into the side walls and not fall freely. In summary, the dimensions of the compartment in which the models are built are: 1.30 m high x 0.50 m from back to front x 0.77 m width at the base and 0.75 m width at the top.

Secondly, the author devised a novel method for supporting the face of the upper two layers of the model during construction, whilst allowing the basal layers to stand free and absorb construction stresses incrementally in exactly the same way as a full scale structure. The method for supporting the model face during construction of the ‘textile’ wrap-round facing comprises a number of wooden boards, supported by and restrained by a number of ordinary metal nails passing through pre-drilled holes.

The apparatus details are shown in Fig. 3 and a close-up photograph is shown in Fig. 4 below.

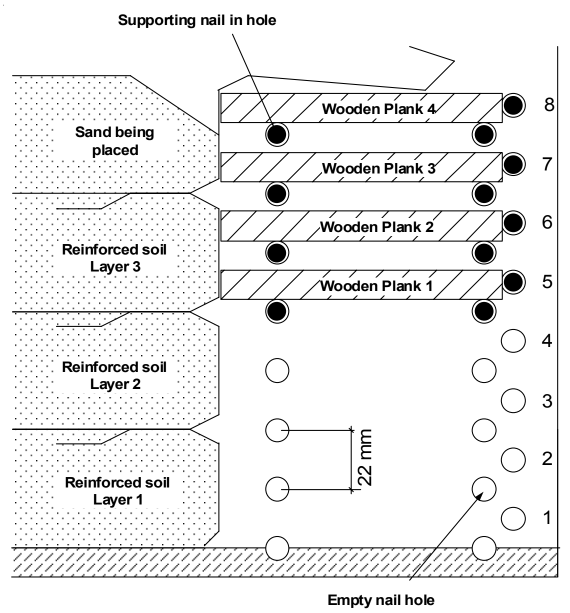

Fig.3 Cross section of the apparatus showing the reinforcement support system during construction of a reinforced soil wall. The front of apparatus is on the right hand side of the diagram.

The diagram in Fig. 3 shows a partial cross section of the support mechanism. On the right can be seen the outer edge of a vertical board with horizontal holes drilled through in a regular pattern. The holes come in groups of three. There are two holes to the left, at equal heights - these are to take nails, which support a board made of woodchip. The third hole, to the right and slightly higher, takes a nail that stops the board from moving outward under lateral pressure from the model. This is the ‘end-stop’ nail. These groups of three holes are repeated upwards at intervals of exactly 22 mm. This can be seen in Fig. 3.

The figure shows wooden plank 1, for example, supported on two nails and abutting onto a third nail at the right hand side. Similarly planks 2, 3 and 4.

Fig. 3 shows reinforcing layers being built at intervals of 44 mm. In this case, two wooden boards (planks) support the face of a single reinforcement layer. It can be seen that when, for example, reinforced soil layer 4 is completed, then the supports can be removed from in front of reinforced soil layer 3. Firstly, the plank 1 end-stop nail is removed and plank 1 is slid outwards from the model. This removes it very gently without placing any vertical disturbance onto the model face. Nails are placed in the holes above plank 4 and plank 1 is placed on them and fitted up to the end-stop nail. Similarly, plank 2 is then removed and fitted on nails above plank 1. Thus support is gently and gradually removed from reinforced soil layer 3. Reinforced soil layer 5 can now be built. This process is repeated and goes all the way up.

Fig. 4 below is a close up shot of the side of the apparatus with the support nails in their holes.

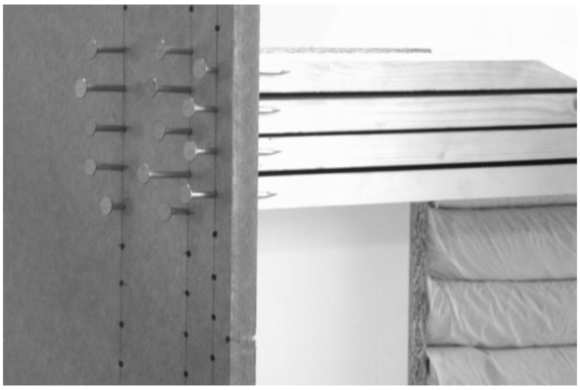

Fig. 4. Support nails holding the boards in place.

By removing support from the lower layers during construction, the author emulates the practical conditions of full scale construction.

Figs. 5 shows a model being built in the apparatus.

Fig. 5. Reinforced soil model with 44 mm layer thickness. Note that the test apparatus was subsequently increased in height to 1.3 m with a view to constructing higher models.

It may be noted that wooden boards were used at first to support the face, but these warped with time, making them difficult to place and remove, so they were replaced with woodchip boards which are more stable over time. These proved to be satisfactory.

The use of boards at 22 mm intervals allowed the author to vary the height of the reinforced layers from 22 mm through 44 mm and 66 mm to 88 mm, by simply using the wooden planks in different numbers. For a 44 mm reinforced soil layer, only two planks support each layer's face. For a 66 mm reinforced soil layer, three planks support each face and for an 88 mm layer four planks support each layer. In fact, the work so far has not used 22 mm layers, but it is intended to extend the work in this direction when time permits.

4 MODEL CONSTRUCTION AND TESTING

On average, models took about 3.5 hours to build to failure. Then the extraction of the torn paper reinforcements, their examination and the cleaning up of the failed sand took another 3.5 hours. Altogether, any model can be made and tested in one day.

The wrap round face of the tissue paper was reinforced by use of a thin strip of slightly stronger textile placed on the inside of the paper along the inside of the wrap-round of each layer.

A further full set of tests was undertaken with another successful 15 models using much denser copper slag granules (a similar particle size to sand) which cannot be reported here owing to lack of space permitted by conference regulations. However, it can be said that the copper granule tests fitted in with the performance behaviour of the silica sand tests.

The models were built up and each failed under its own internal gravitational loading. Layers were laid down, wrapped round and over-filled in the same way as real full scale structures. Each layer was 450 mm from front to back and behind the block of reinforced soil there was 50 mm of unreinforced sand.

A number of very interesting features were observed as part of the examination of the failure mechanisms. Some were revealed by observing the digital video films of the failure which, although occurring over about only one fifth of a second, could be observed extremely well by single step or slow motion replay on a computer. Some were revealed by physical observation and some by measurement.

Every layer of paper was to be measured from the face inwards to find its tearing point. In the event, it was found that the reinforcement to the face side of the failure surface was effectively 'shredded' by the failure motion of the sand. This itself merits further thought, if not further research. Consequently, the tearing point of the geotextile was measured from the back forward. It is interesting to note that none of the reinforcement on the 'retaining' side of the failure surfaces was shredded or damaged. Only a single tearing plane was observed. Further, all the failure surfaces were in a very close zone on all models. In order to show the shape of the failure surfaces, the tearing points of the reinforcements were plotted on graphs using a CAD program, so that all or any results could be superimposed on one another by using the layering system of the CAD package. Finally, one of the most interesting features of the failure results was that the lowest layer of all reinforcements was never torn. Sometimes even the second layer was not torn. What happens, as revealed by examination, is that the lower layers simply seem to 'roll out' so that the lower layer or two layers of the structure are not torn at all. This is all the more impressive when one considers that the lower layers are under the maximum stress which at the base of a 0.5 m model might be say 8 kN/m2 and the strength of the paper is 0.025 kN/m. So it is amazing that these lower layers were completely undamaged. The failure did not just pass over them, but they were involved in a compound type of failure at the base, in which the lower reinforcement was rolled outwards by the sand, which must have been moving similarly both above and below the wrap rounds. There is insufficient space in this publication to enter into this in detail, but the author will be examining this further and will report on it subsequently.

Figs.6, 7 and 8 describe the observed failure surfaces. Fig 6 shows all the valid failure surfaces for the 44 mm spacing models. (Valid means results that were not marred by accidental or erroneous failure from other causes). Fig. 7 shows the valid failure surfaces for the 66 mm spacing tests and Fig. 8 shows the failure surfaces for the 88 mm spacing tests.

We had two aberrant 66 mm model failures. These were attributed to failures caused by lack of experience in constructing the larger spacing models, when created for the first time. In one case the model failed from the left hand edge.

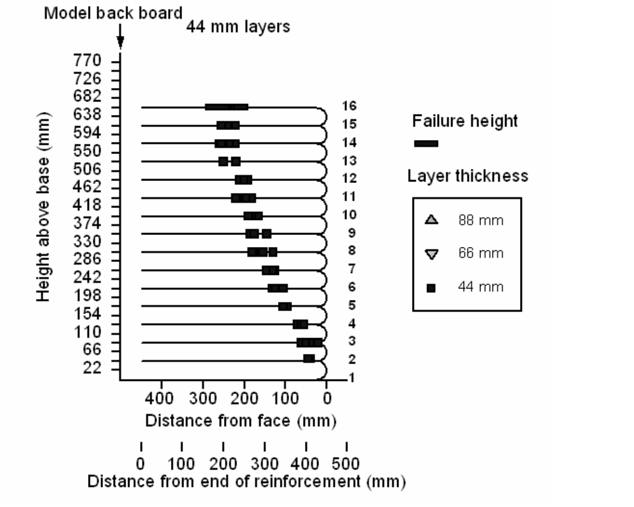

Fig. 6.All the recorded and measured tearing points forming failure surfaces for the valid 44 mm vertical spacing silica sand models. Note the consistency of failure heights and the closeness of the failure surfaces.

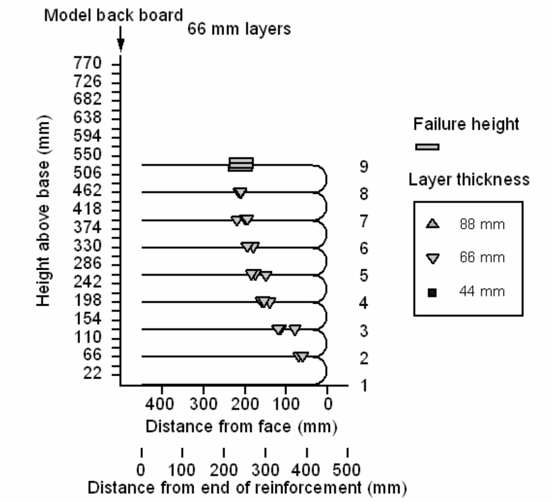

Fig. 7.All the recorded and measured tearing points forming failure surfaces for the valid 66 mm vertical spacing silica sand models. Note the consistency of failure heights and the closeness of the failure surfaces.

This was recorded on video and is interesting for this and for its early failure height. The other one was caused by the lack of sufficient wrap round on the face of the model. After this failure, which was preceded by large central bulging, the wrap round procedure was slightly altered to give the wrap-round a 'step' down which was covered by sand to hold the paper before the construction of the next overlying layer. This worked satisfactorily.

One of the 88 mm spacing models failed prematurely owing to lack of grip on the facing. It became clear that the bigger the spacing, the more care was needed to ensure that the facing wrap-round was properly gripped by the sand during the construction of the subsequent overlying layer. The distribution of points between the failure surfaces was remarkably close, reflecting a reliable and consistent experimental apparatus and technique. The number of aberrant failures was small and was related to the experimental learning curve and to the need to alter the apparatus at an early stage.

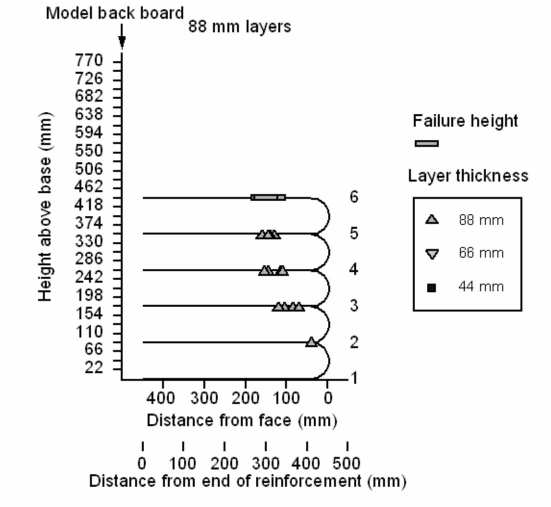

Fig. 8.All the recorded and measured tearing points forming failure surfaces for the valid 88 mm vertical spacing silica sand models. Note the consistency of failure heights and the closeness of the failure surfaces.

Although this paper does not extend to mathematical analysis of the models, it is interesting to note that all of the failure surfaces lay within a fairly narrow linear envelope measured at approximately 70 degrees. This approximates well to the zone of failure predicted by current reinforced soil design. Fig. 9 shows all of the failure surfaces from the tests, enclosed by two lines sloping at 70 degrees from the horizontal. It was considered an indication of the realism of the simulation and the efficacy of the apparatus, that the failure surfaces for all tests fell within such a narrow zone. This zone - or failure envelope - became even more accurate when the results of the failures were rescaled to fit into a non-dimensional unit height model of the vertically faced reinforced soil scenario.

Figure 10 shows the relevant construction ratios for a non-dimensional analysis of the position of the straight line failure envelope. Analysis showed that for these model structures, the internal distance A to the internal linear failure plane varies with both spacing of the layers and the density of the fill.

However, based on the conclusion that the ratio of spacing to structure height (S/H) should be less than 0.1 to maintain reinforced soil stability, then A varies between 0.13H and 0.16H - a very small difference. It is more conservative to take the larger distance, so it can be approximated to A = 0.15H as shown in Fig. 10.

Thus, to construct the first order approximate linear envelope for failure surfaces in reinforced soil walls, it should be reasonable, based on this research, to use A = 0.15H and B = 0.03H, a ratio of exactly 5:1. It is also clear that the inner envelope intercept with the wall upper surface (D) will always be equal to A + Tan20 H = 0.15 H + 0.36 H = 0.51 H = approximately 0.5 H.

So from the present research work, it would be reasonable to expect all reinforced soil failure surfaces both in models and in larger scale structures to occur within the confines of the above failure surface envelope. This also fits in well with current reinforced soil design for granular fills which says that the minimum length of reinforcement should be greater than 0.7H.

Subsequent mathematical analysis has shown that the failure surfaces are sufficiently definable and consistent that this analogy can be further refined and quantified more accurately. This work is to be published subsequently.

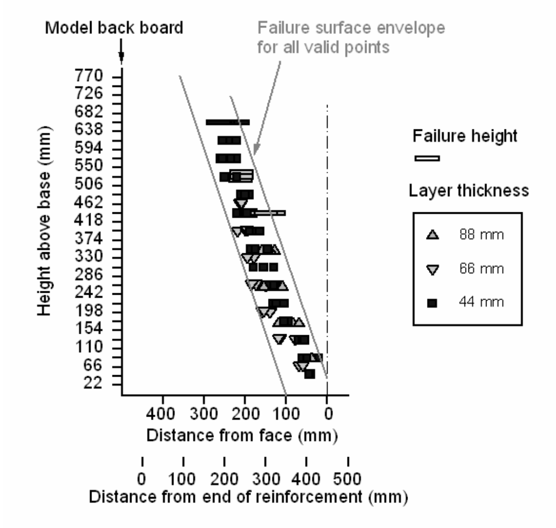

Fig. 9. Graph showing all failure surfaces in true dimension, shown to fall within a narrow failure zone envelope defined by two straight lines sloping at 70 degrees.

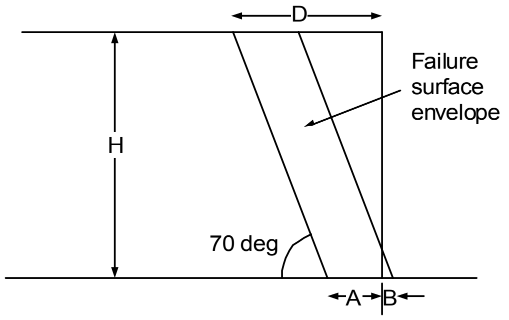

Fig. 10. Non-dimensional ratios for forecasting failure zones in reinforced soil structures. A = 0.15H, B = 0.03H and D = 0.5H.

Fig. 11 is a digital extract from a video film showing Experiment 2 in the process of collapsing. Althougth it looks static, it is actually a part of a very rapid collapse sequence. There are many things to be derived from the observation of the failure itself. Note in this case that the upper four layers 6, 7, 8 and 9 are intact and falling together in a tidy fashion and are overriding the lower layers. The failure does not follow a 'slip circle' behaviour once initiated, but follows a 'slip circle' behaviour during initiation. This failure mode has not been reported previously but, when considered, is a logical failure process.

The author's view of what happens is that whilst stresses are building up in the reinforced soil structure, then a circular stress surface is generated containing the minimum safety factor. This safety factor falls until the surface ruptures. Rupture is initiated in one of the lower layers of reinforcement (but not the lowest layer) and virtually instantaneously ripples upwards in a domino effect as stress is thrown upwards onto the remaining intact layers. This produces, virtually instantaneously, a free-standing block of reinforced soil which is internally reinforced but which is now externally unsupported. The lower part of the released block is thrust outward differentially as a single block. But then, during this collapse, the sand shears dramatically, tearing the outer block reinforcement into strips but leaving the wrap-rounds intact. The heavy but now-unreinforced upper block of the structure falls rapidly over the lower part of the structure which is constrained by it. The failed structure terminates with the upper layers stationary towards base level, over the top of the lower layers.

The outward thrust of the 30% height level in the model is reflected in the constantly observed greatest tension in the wrap-round elements during model construction. The author observed with the 16 layer models, that as construction proceeded, the wrap rounds on layers 4 - 5 became increasingly tensioned, indicating that the greatest differential forces were being generated at this kind of level.

Fig. 11. Model 02 collapsing. Numbered layers are actually 6 and 7. The '1' is the centre line of the model marked next to the layer number. Taken with video camera.

In Fig. 11, it can be seen that layers 5, 6, 7, 8 and 9 of a 9 layer model have thrust over the under layers. This rolling out or thrusting action possibly occurred because of failure initiation at level 4 or thereabouts. This work merits and will receive further study to observe which layer actually fails first.

5 CORRELATION OF FAILURE HEIGHT OF MODELS WITH RELATIVE HUMIDITY

It is clear from this research that the strength parameters taken for the reinforced soil paper tissue, as obtained from in-air tensile testing, varied according to atmospheric humidity and temperature. Clearly, the atmospheric humidity affects the entangled cohesion of the fibres as exerted in the mass. Tissue paper is made by mixing wood pulp fibre in a water slurry and then permitting it to dry out into a sheet on a moving belt. When the slurry dries out, there is a glutinous adhesion between the fibres. When tested in a tensile machine in-air, it is the strength and extensibility of the glutinous fibre mass entanglement that is tested and not the properties of the individual fibres.

It is also well recognised that the in-soil strength of a reinforcement is consistently greater than its in-air strength. The tests undertaken and reported in this paper confirm that this is correct. Therefore it is likely that the high in-soil strength of nonwoven products such as the reinforcement tissue is derived from the grip of the soil particles on individual fibres and not on the tissue surface as a whole.

In that event, if that is correct, then the atmospheric humidity should have no effect on the failure height of the models. Comparison of the test results shows this to be true. Fig. 12 below shows the recorded failure heights of all of the models plotted against the variations in humidity for the testing laboratory.

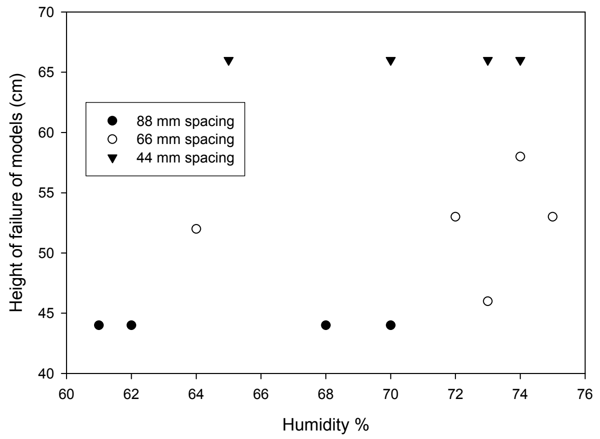

Fig. 12. Graph demonstrating the lack of correlation between humidity and height of model failure.

In Fig. 12 it can be seen that there is no correlation between humidity and failure height. Basically, this graph confirms that although humidity ranged from 61% to 74% during the course of the experiments, which should have created a 15% or more variation in in-air strength, there was no observable variation in failure height for any of the models.

In the author's opinion, this confirms that the grip on the textile is effected through very many, very small contact points created by the individual sand grains. Thus for future research work, it can be expected that this state of affairs will continue. It would be reasonable to say that the state of atmospheric humidity is not of great - if any - relevance to this model testing work, despite the fact that in common in-air experience, moisture makes tissue paper weaker. In soil, it does not. These conclusions seem valid for the range of atmospheric moisture observed so far during the research work (60% - 75%). Observation will still be made to record any extreme atmospheric moisture and thereby to extend the graph on Fig. 12.

6 CONCLUSIONS

The reported test results above show that the apparatus was ideal for the purpose. It now permits models to be constructed up to a height of 1.3 metres without obstruction. It also has the facility to widen the models if it is felt that an increased width/height ratio would be beneficial.

The test results for a series of silica sand modules are presented. These show that a consistent suite of failure surfaces can be produced that conform to reinforced soil theory in the first instance and which are capable of being refined into a more accurate mathematical theory of failure.

The test results show that small inexpensive models can be made to fail under self-induced gravitational loading in a fashion that reflects full scale structural behaviour. To the author's knowledge, this is the first time that this has ever been achieved and published.

The test work supports the concept that the in-soil strengths of geotextiles is actually substantially greater than their in-air test strengths. This model work is expected to lead to a means of defining that increased strength, to providing a test method for evaluating it and to evaluating the true, numerical in-soil strength of nonwoven, knitted, woven and geogrid geosynthetics.

The more the author investigates this superficially simple aspect of model construction, the more he realises there is to investigate and to learn. The author is continuing with several individual streams of research arising from this early work.

7 ACKNOWLEDGMENTS

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8 REFERENCE

Rankilor, P.R., Sarma, K.R., and Dawber, R., 2002, "The Testing of Very Weak Geosynthetic Layers for Use in Micro-models of Reinforced Soil", 2002, ICG7 - 7th International Geosynthetic Society Conference on Geosynthetics, Nice, France.