Chapter 6
SUMMARY AND CONCLUSIONS

6.1 INTRODUCTION

Modern engineered landfills are designed to minimize or eliminate the constituents released to the environment. Solid and hazardous waste landfills are required by government or local regulations to cover waste materials prior to or as part of final closure. Moreover successful design and construction of soil liners and covers involve many aspects such as selection of material, determination of construction methodology, analysis of slope stability and bearing capacity evaluation of subsidence (settlement), and consideration of environmental factors (Daniel 1987; Daniel and Benson 1990).

Compacted soil is widely used as a material for landfill and waste impoundments. Most regulatory agencies require that the compacted soil liner and cover should be designed to meet the minimum design requirements. The compacted soil liner and cover system may also suffer damages from desiccation cracking and differential settlement problems, consequent increase in the hydraulic conductivity and reduction in the sealing effect of the cover system drastically.

6.2 TECHNIQUES DEVELOPED FOR THE STUDY

Even though it is well known that loss of water content in clay liners, will induce desiccation cracks, research in this area has been taken up only recently. Hence attempts to study the mechanism of development of cracks by simulating desiccation conditions in the laboratory, quantify the extent of crack formation and develop methods to control the formation and propagation of cracks, are limited.

6.2.1 Preparation of Specimens for Tests

When field condition of wetting and drying due to seasonal variations are simulated in laboratory, the time taken for specimens to get either fully saturated or fully dried by ponding water and by heating, both at the top surface only, is important, as this decides the total time taken, for one cycle. Similarly the effect of repetition of such cycles with regard to desiccation cracks is also important as the number of cycles required to get a final configuration of the cracks, is also a parameter to be investigated . The present series of tests in this direction has shown that wetting and drying for 7 days each and subjecting the sample to 2-3 wet/dry cycles will simulate conditions prevailing the field.

6.2.2 Measurement of Cracks by Digital Image Processing

Crack Intensity factor (CIF) is the most useful and effective parameter for quantification of desiccation cracks. Existing practices for determination of CIF, though existing practices, mainly by mechanical measurements, were tried initially and it was found to have serious limitations. The accuracy and reliability of assessing cracks through CIF had serious limitations owing to the following:

[1] The mechanical measurement of width and length of cracks lacked the accuracy required.

[2] The process of measurements interfered with the crack configuration of the samples

[3] Measurement of cracks in the same specimen when it passes through series of wetting and drying was almost impossible as techniques available led to disturbance of crack formation in the samples.

[4] Very fine cracks could not be accounted for, as they were not amenable to mechanical measurement.

[5] Personal errors were unavoidable

In this context, application of the digital image processing technique for measurement of crack was of tremendous advantage over the existing practices.

It was established in this work, in unequivocal terms that digital image processing can be used successfully for measurement of desiccation cracks, in all types of soils tested and for all amendments employed. Since it takes into account, the contrast in pixel intensity, even hair line cracks could be accounted for, which was almost impossible earlier. The repeatability of the tests could also be well established, as the variation in CIF from identical samples had a very narrow range of 0 to 2%. The significance of this technique is further underscored due by the fact that, this is a nondestructive testing procedure. This provides tremendous potential for further work in this direction as field study of performance of clay liners would not have been possible, by practices followed till date.

6.2.3 Experimental Setup Developed

To simulate the field conditions during summer, it was necessary to subject the specimen to a standardized heating, irrespective of the atmosphere conditions in the laboratory. The drier designed and developed, helped to provide a standard drying process for all specimens with very minimal variations in temperature.

Similarly, the tension test assembly developed to determine the tensile strengths of soil was also found effective and sufficiently accurate. Since cracks develop when the tensile stresses exceed the tensile strength, the results of tension tests are significant in the study of desiccation cracks.

6.3 DEVELOPMENT OF DESICCATION CRACKS IN LINER MATERIAL

The present study aimed at critically looking at the current practice of the installation of compacted clay liner using bentonite enhanced sand (BES). However, its behaviour, when subjected to alternate wetting/drying, had not been fully investigated especially with regard to development of desiccation cracks. The possibility of identifying a suitable or better alternative, was also investigated for which sundried marine clay (SMC) was selected.

6.3.1 Desiccation Cracks in Bentonite Enhanced Sand

Since BES apparently satisfied all the norms set by EPA, not much work had been done regarding how this will behave when subjected to series of wetting and drying caused by seasonal variations. The fact that BES is highly susceptible to the development and propagation of cracks, has been clearly brought out through a series of experiments. Determination of crack intensity factor by digital image processing, aided by MATLAB version 7 software, helped to quantity the crack formation and a comparative study was made possible. The crack intensity factor (CIF) which was only 18.09 for the first cycle, increased to 39.75 and 21.22 after second and third cycles respectively. A matter of greater concern was the depth of cracks which was over 5 cm, which brings down the effective thickness of the clay barrier. In the present case, the thickness was reduced to less than 50%. This promotes the permeation of leachate into the body of the liner and thus reduce the thickness further.

It has been established through a series of experiments and reliable measurement techniques, that the prevailing practice of installation of clay liners using bentonite enhanced sand suffers from serious limitations and the practice itself can be questioned. This prompted the studies for an alternative to bentonite enhanced sand

6.3.2 Desiccation Cracks in Sundried Marine Clay

Preliminary studies itself indicated sundried marine clay can be a better liner material. Even a visual comparison of the photographs of the desiccated samples of BES and SMC could lead to this conclusion.

The CIF of sundried marine clay was only 9.83% in the first cycle as against 18.09 of BES, and this steadily decreased with number of cycles unlike BES. The maximum depth of cracks was 0.7cm to 2.0 cm after the first cycle compared to 5 to 5.1 cm observed in BES sample. The ratios of the crack intensity factors BES to SMC are 1.84, 5.29 and 4.63 for the first, second and third cycles respectively.

From all the figures presented above, it could be safely concluded that the proposed alternative, namely the Sundried Marine Clay, is far superior to bentonite enhanced sand in almost all aspects. Yet another combination, 20% bentonite with 80% SMC, was also investigated to a limited extent and the results were encouraging.

6.4 IMPROVEMENT OF LINER MATERIAL BY AMENDMENTS

It has already been established that desiccation cracks is a serious problem faced in engineered land fills.Attempts were made to improve the strength characteristics of the two liner materials selected so as to control the development of cracks. The soil was reinforced with randomly distributed fibre reinforcement. The random distributions helped to maintain strength isotropy and to ensure that potential planes of weakness are absent.

Three types of fibres viz, nylon, polypropylene monofilament and polypropylene fibre mesh were used as soil reinforcement. The fibre contents selected ranged over 0.15% to 1.2% depending upon the ease in mixing and the 'balling' effect, experienced when higher fibre contents were tried.

6.4.1 Compaction Characteristics of Amended Soils

A series of standard compaction tests were conducted in soils with different percentage of nylon fibre. It was observed that the variation in OMC was in the range of -0.5% to +0.85% and maximum dry density varied between -0.32 kN/m^3 and+0.21 kN/m^3. Since the changes were marginal, the values of unamended soils as such were used for amended soils also for the further tests.

An equation for maximum dry unit weight (MDUW)could be developed from the test data as given below

$$MDUW = 1.0072 + 9.4927/OMC + 64.5824/OMC^2$$

with $R^2 = 0.9455$

6.4.2 Hydraulic Conductivity of amended Soils

Since EPA insists that the hydraulic conductivity of the liner material shall not exceed $1x10^{-9}$ m/sec, it had to be verified whether the reinforcements make the soil more permeable.

Hydraulic conductivity was measured with the help of consolidation apparatus, under three consolidation pressures of 6.25 kPa, 12.5 kPa and 25 kPa.

It was observed for BES that incase of nylon fibres, for fibre contents upto 1.0%, values were below $1x10^{-9}$m/s. Higher fibre contents can be allowed when polypropylene monofilament fibres are used. However polypropylene fibre mesh reinforcement adversely affected the hydraulic conductivity for fibre contents above 0.6%.

Sundried marine clay liners are not much affected by fibre reinforcement in this aspect. Even for higher fibre contents of 1.2%, the hydraulic conductivity was well within the permissible limit of 1×10^{-9} m/sec for nylon and polypropylene monofilament. For the fibre mesh fibre contents around 0.6% were quite acceptable.

In the hydraulic conductivity tests also, SMC proved superior to BES, as higher fibre contents could be permitted in the former, which can considerably improve the strength characteristics of the soil.

6.4.3 Improvement in Strength Characteristics by Amendment

Compacted clay liner should possess adequate shear strength to maintain its structural integrity. The stress-strain behaviour of the liner material can be controlled with the help of fibre reinforcement, which will improve the strength characteristics of the soil. These were established with the help of a series of unconfined compression strength tests and tension tests.

6.4.3.1 Unconfined Compressions Strength of Amended Soil

Unconfined compression strength tests were conducted on BES specimens, reinforced with all the three fibres. Nylon does not influence the strength or stress-strain behaviour of BES. The contribution from polypropylene monofilament fibres is also marginal. Addition of fibrillated fibre mesh influences the strength as well as the stress-strain behaviour of the soil to a great extent. For fibre contents of 0.6% and above, the residual strength of the soil after the peak stress is almost the same for a considerable range of strain. An addition of 0.8% of fibre mesh increases the strength from 171.28 to 307 kN/m^2 - an increase of 79.24%. Thus fibrillated polypropylene fibre mesh is the most ideal reinforcement for BES in case of unconfined compressive strength.

Unconfined compression strength tests on SMC specimens show that the influence of fibre content is not very significant. However, the stress strain curves show that the soil retains residual strength after the peak stress. In case of polypropylene monofilament fibre and fibre mesh the residual strength is almost equal to the peak stress. This indicates that the soil behaves more like a ductile material for fibre contents of 0.6 and 0.8% in case of the above two fibres.

Eventhough both soils do not show any notable increase in unconfined compressive strength, sundried marine clay has certain advantages due to the improved stress-strain characteristics.

6.4.3.2 Tensile Strength Characteristics of Amended soils

When clayey soils are subjected to drying, as in desiccation, soil water volume decreases and soil shrinks. If the shrinkage is restricted, soils crack. Cracks develop when the tensile stress in soil exceeds the tensile strength. Hence attempts were made to increase the tensile strength of the soil and the fibres could make significant contributions in this direction.

As shown by the results presented in the form of tables and graphs, it can be concluded that fibre reinforcement increases the tensile strength of soil. Nylon fibre are not helpful in case of BES. But addition of 1% of polypropylene monofilament fibre increases the tensile strength from 4.67 to 11.4 kPa - an increase of 144%. For fibre mesh the tensile strength increase from 4.67 to 11.94 kPa which gives an increase by 155% for a fibre content of just 0.8%.

In addition to increasing the shear strength, the reinforcement helps to provide a residual strength close to the peak stress for a considerable range of strain. For example, BES amended with 1% polypropylene monofilament fibre retains a residual strength of about 90% of the peak stress for a stretch of 0.4 to 2.25 mm. Such a behaviour helps to prevent propagation of cracks formed at peak stresses. This helps to prevent possible wide ruptures of the compacted clay liners.

In case of SMC also, amendment with fibre helps to increase the tensile strength significantly. For example for a nylon fibre content of 1%, the tensile strength increases from 9.34 to 43.09 kPa- an increase of 361%. For 1% polypropylene fibre content, the increase is 211% and for 0.8% fibre mesh content the tensile strength increass by 421%. These phenomenal increases will definitely delay the formation of cracks during desiccation, which in turn ensures better performance of the clay liner under adverse seasonal changes.

A comparison of the tensile strengths of BES and SMC again asserts the superiority of the latter. A fibre content of 1% of nylon, polypropylene and fibre mesh increases the tensile strength by 25%, 144% and 149% respectively in bentonite enhanced sand. In sundried marine clay, the corresponding values are 361%, 167%, and 426%. Obviously, sundried marine clay will show a lesser tendency to crack, when subjected to desiccation.

6.4.3.3 Desiccation Tests on Sundried Marine Clay Sample

It has been convincingly established that sundried marine clay is superior to bentonite enhanced sand. A few desiccation tests were coducted on SMC for a comparative study of different percentages of fibre contents. Comparing samples amended with different fibre contents, it could be shown that the increase in fibre content reduced the cracks, fully endorsing the earlier findings. With another series of desiccation tests, it could be shown that polypropylene fibre mesh was the most effective out of three reinforcements tried, as shown by the value of crack intensity factor.

Thus the present study has succeeded in bringing out the serious limitations and disadvantages of a liner material i.e. bentonite enhanced sand, which is at present the most accepted material for compacted clay liner. In place of this, it has been shown that a new material viz. sundried marine clay, is far superior and has several advantages over the existing practice, especially when the possibility for desiccation is also taken into consideration.