# Erosion Resistance of Compacted Soils

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There has been recent interest in overflow erosion on overtopped earth embankments, which are typically constructed from compacted cohesive soils. A study of the effects of compaction density and moisture content on the erosion resistance of a soil material is presented. Four soil materials were tested using a laboratory submerged jet testing apparatus. The results of the laboratory testing were used to quantify the changes in erosion resistance due to changes in compaction density and moisture content. Increases in compaction moisture content were observed to result in increased resistance to erosion. Increases in density at a constant moisture content were also observed to result in increased resistance to erosion. Proper control of these factors during embankment construction could make a difference in performance.

There has been recent interest in the overflow erosion on overtopped earth embankments for such applications as dams, levees, and highway and railroad fills, which is evidenced by the number of studies in this area (*1–4*). When embankments are overtopped by floodwater, erosion damage can be significant, involving economic as well as safety concerns. Powledge et al. (*1*) identified several factors as having a strong influence on the initiation and rate of erosion. Two of the factors identified were the type of material and the density of the fill. Clopper and Chen (*2*) concluded that soil type and compaction affect the erosion rates and patterns of erosion on embankments.

The objective of this study was to analyze the changes in the erosion resistance of compacted soils. This paper discusses the results of submerged jet tests conducted on four cohesive soils, comparing changes in resistance of the soils at equivalent hydraulic stress and varying compaction moisture contents and compaction efforts.

## BACKGROUND

### Compaction and Erosion Resistance

The nature and magnitude of compaction has a significant impact on the engineering behavior of the soil material. Therefore, the engineer must conduct compaction tests to determine the properties desired for the specific construction application of interest. The most common type of compaction test is the standard Proctor, which consists of placing soil in a mold and dropping a hammer on the soil from a specified distance a specified number of times. Compaction tests of this nature for samples at various moisture contents, $\omega$, result in a compaction curve in which the dry density, $\gamma_d$, increases to a peak and then decreases. The dry density and compaction moisture content at the peak dry density are the maximum dry density and optimum moisture content, respectively. Maximum dry density and optimum moisture content are relative, not absolute, terms, being dependent on the compaction effort and method. The portion of the curve that is less than the optimum moisture content is referred to as the dry side, and that portion that is greater than the optimum moisture content is referred to as the wet side. A discussion of the effects of compaction on the engineering behavior of soils is given by Lambe (*5*) and Barden and Sides (*6*). These investigators proposed conceptual models to explain the nature of the clay structure as a result of compaction. Lambe (*5*) proposed a microscale model in which orientation of the individual clay particles depends on the compaction effort and compaction moisture content. The soil structure changes from a flocculated structure to an oriented structure as the moisture content is increased at a constant compaction effort. Barden and Sides (*6*) proposed a macroscale structure in which the soil consists of particle clusters called macropeds. In this conceptual model, changes in the macroped interaction change with compaction moisture content at a given compaction effort. At low compaction moisture contents the macropeds have high strength and resist compaction effort without much distortion and remain relatively independent. As the compaction moisture content increases, the soil changes to a state in which the macropeds are distorted during compaction, filling the pore spaces. In this process the macropeds lose their individuality. Both models explain the observed changes in the engineering behavior of compacted soils. Paaswell (*7*), in his discussions on the state of the art of the mechanics and causes of cohesive soil erosion, pointed out that the physical structure of a compacted cohesive soil material plays a major role in erosion resistance. This structure is influenced by the compaction effort, compaction moisture content, and the method of compaction. One of the engineering properties that changes with compaction moisture content and compaction effort is the soil swell. The soil swell, upon wetting, is greater for a soil compacted on the dry side of optimum than on the wet side of optimum. If erosion is considered a surface phenomenon, swelling can only have an adverse effect on the resistance to erosion (*7*). Therefore, a soil compacted on the dry side of optimum is anticipated to erode more than a soil compacted on the wet side of optimum.

The effect of compaction on the erosion resistance of soils has been investigated in a number of studies (*8–14*). The results of these studies have not been altogether conclusive. Three of the studies did not investigate the effects of compaction moisture content, but rather the effects of increased density (*8,10,12*). These studies concluded that increases in compacted density resulted in increased resistance to erosion. Two other studies observed the effects of compaction moisture content at a constant compaction effort (*9,13*). Enger (*9*)

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observed that increased compaction moisture content decreased the amount of observed swelling. He also observed that the resistance to erosion also increased with increased compaction moisture content, with the exception that reuse of the same soil had the opposite effect. Shaikh et al. (*13*) observed that the resistance to erosion was independent of the compaction moisture content. Two other studies observed the effects of compaction moisture content and compaction effort (*11,14*). Grissigner (*11*) found in his studies that the effects of density and compaction moisture content were dependent on soil type and antecedent moisture conditions following compaction. Hanson and Robinson (*14*) investigated the effects of compaction moisture content and density on erosion resistance of a soil used in a compacted spillway study. They observed that increased compaction moisture content at a given compaction effort resulted in increased erosion resistance. They also observed that for a constant compaction moisture content, increased compaction effort resulted in increased erosion resistance.

## Jet Testing

Water jets have been used to measure the erosion resistance of materials for engineering applications. Litton and Lohnes (*15*) used a nonsubmerged jet testing apparatus to provide a method of comparing soil-cement mixtures for hydraulic structure applications. Dunn (*16*) and Hanson (*17*) used submerged jets to aid in assessing the erosion resistance of soil materials. A jet index, $J_i$, was developed by Hanson (*17*) to provide a common method of expressing erosion resistance. The relationship to determine $J_i$ is

$$D_s/t = J_i U_o (t/t_1)^{-0.931}$$

where

$D_s$ = the maximum depth of scour,
$t$ = time,
$J_i$ = the jet index,
$U_o$ = the velocity at the jet nozzle, and
$t_1$ = 1 sec or the time unit equivalent of 1 sec if $t$ is in time units other than seconds (i.e., if $t$ is in minutes, $t_1$ = 1/60 min).

The $J_i$ results were compared with erodibility of the same soils determined from open channel flow tests (*17*). Comparison of these results indicated that a highly erodible soil had a $J_i$ of approximately 0.020, whereas an erosion-resistant soil had a $J_i$ of approximately 0.005. In this study, $J_i$ was used to compare changes in resistance of soils due to changes in compaction effort and compaction moisture content.

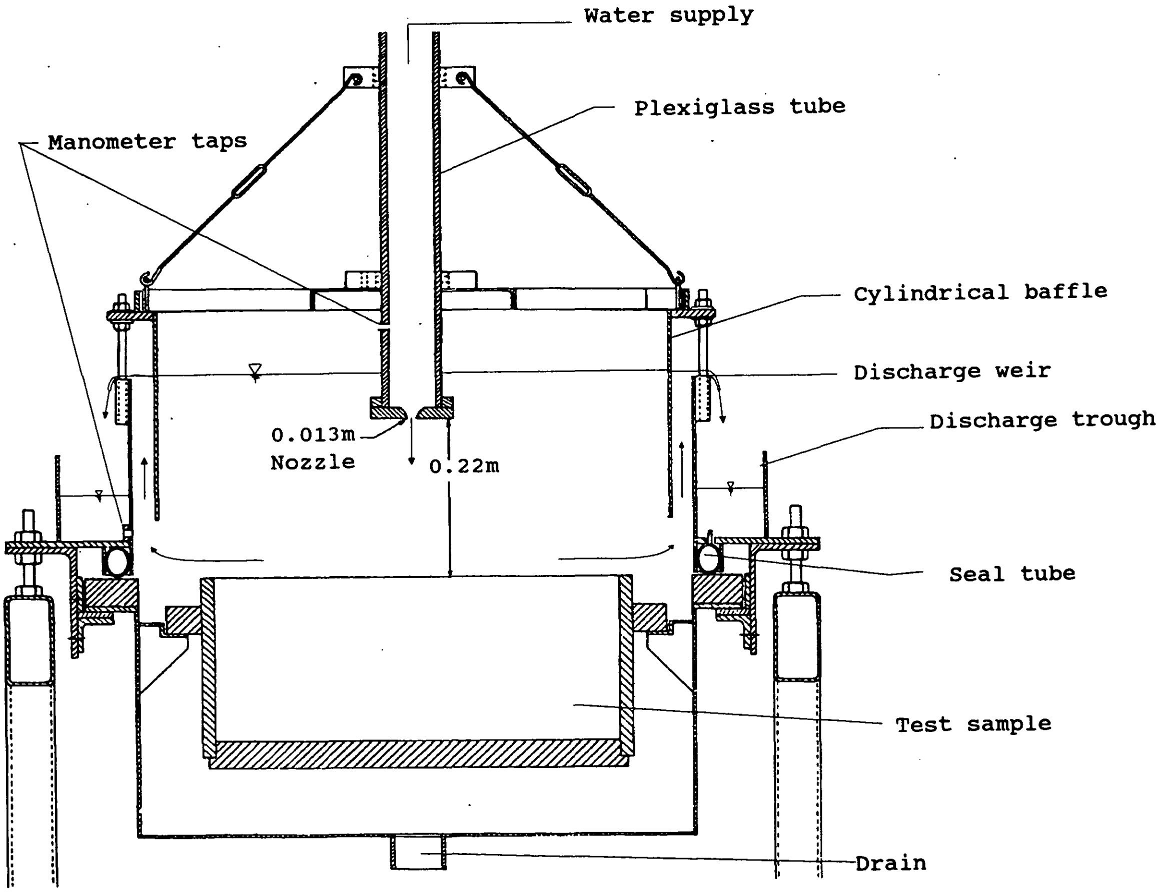

**FIGURE 1 Schematic of test apparatus.**

## TEST METHODS AND SPECIMEN PREPARATION

Erosion tests were concluded using a laboratory submerged jet testing apparatus as described by Hanson and Robinson (*14*). Circular soil samples were placed in a tank and slid under the jet apparatus. The soil samples are 0.44 m in diameter and 0.19 m in height, with a volume of 0.028 m$^3$. Water was fed under a constant head of 0.91 m, $U_o$ = 4.2 m/sec, through a rounded nozzle 13 mm diameter at a set height, 0.22 m, above an originally level bed of prepared soil. A schematic of the test apparatus is shown in Figure 1. The course of scour with time was measured with a pin profiler. Profiles were measured at set time intervals ranging over the test duration of 0 to 240 min.

Soil samples for laboratory submerged jet testing were prepared by dynamic compaction. Dynamic compaction was attained by dropping a 79.4-kg hammer 0.30 m and controlling the number of blows. The soils were compacted in three layers using from 1 to 24 blows per layer with the compaction effort varying 0.26 to 6.15 kg-cm/cm$^3$ respectively. The compaction effort of ASTM Standard Designation D698 is comparable at 6.05 kg-cm/cm$^3$. Moisture content was also controlled at the time of compaction. The moisture content, ω, was determined by the weight of water divided by the weight of solid in the soil element. The dry density, $\gamma_d$, was determined by the weight of solid in the soil element divided by the total volume occupied by the entire element. The samples were then wetted for a period of 20 hr before jet testing.

Four soil materials were used in testing, ranging from a nonplastic sandy loam to a clay loam having a plasticity index of 18 as indicated in Table 1. The gradations of the soil materials are shown in Figure 2.

**TABLE 1 Soil Classification**

| Physical properties | Soil A | Soil B | Soil C | Soil E |
|---|---|---|---|---|
| Liquid limit | 21 | 37 | 26 | 23 |
| Plastic limit | 17 | 19 | 20 | 14 |
| Plasticity Index | 4 | 18 | 6 | 9 |
| U.S.C. | CL-ML | CL | CL-ML | CL |
| A.S.C. | sandy loam | clay loam | loam | sandy-clay loam |

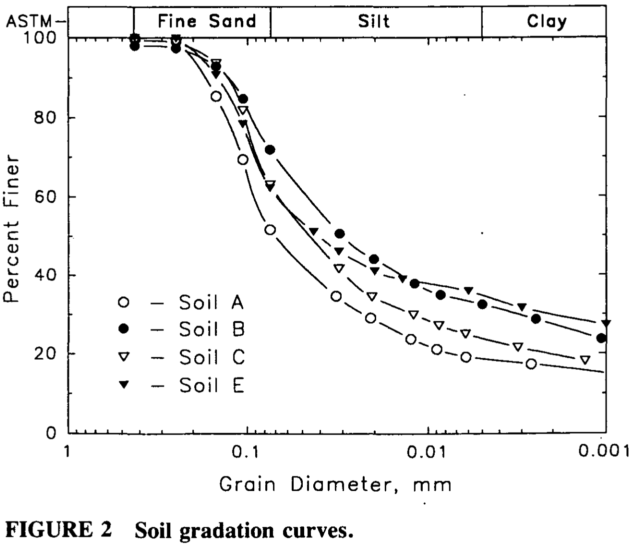

**FIGURE 2 Soil gradation curves.**

## TEST RESULTS

Soil Materials A, C, and E were dynamically compacted at equivalent compaction efforts, 6.15 kg-cm/cm$^3$ at various compaction moisture contents. The maximum depth of scour versus time for Soil Material A at various moisture contents is shown in Figure 3. There is a dramatic decrease in scour observed with increases in compaction moisture contents. A display of the test results to determine the $J_i$ is shown in Figure 4. A comparison of the moisture-density curve and the re-

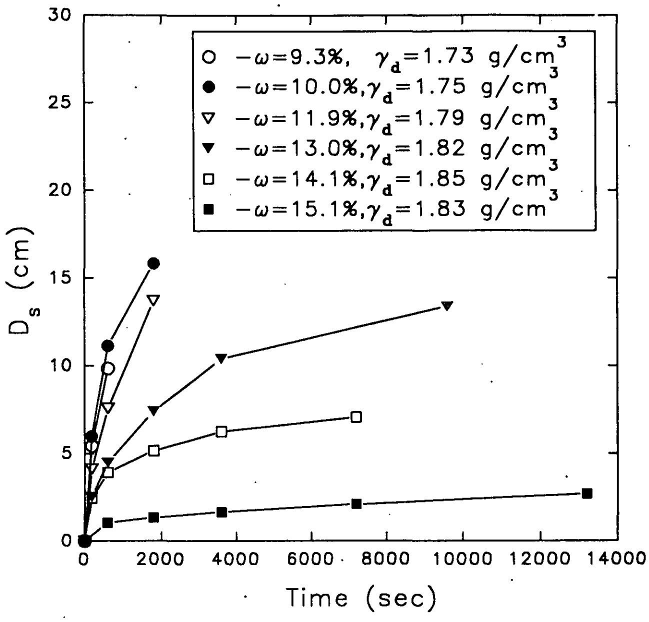

**FIGURE 3 Maximum depth of scour for different compaction moisture contents of Soil Material A at a constant compactive effort versus erosion testing time.**

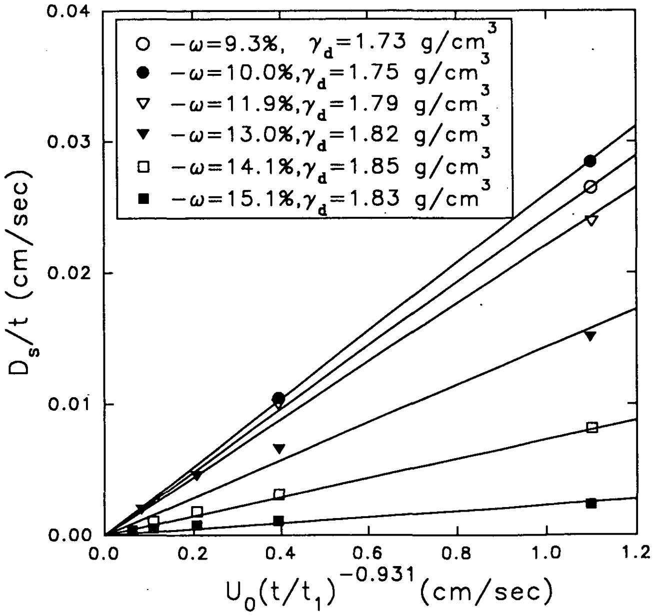

**FIGURE 4 The slope of each line represents the $J_i$ for each sample of Soil Material A tested.**

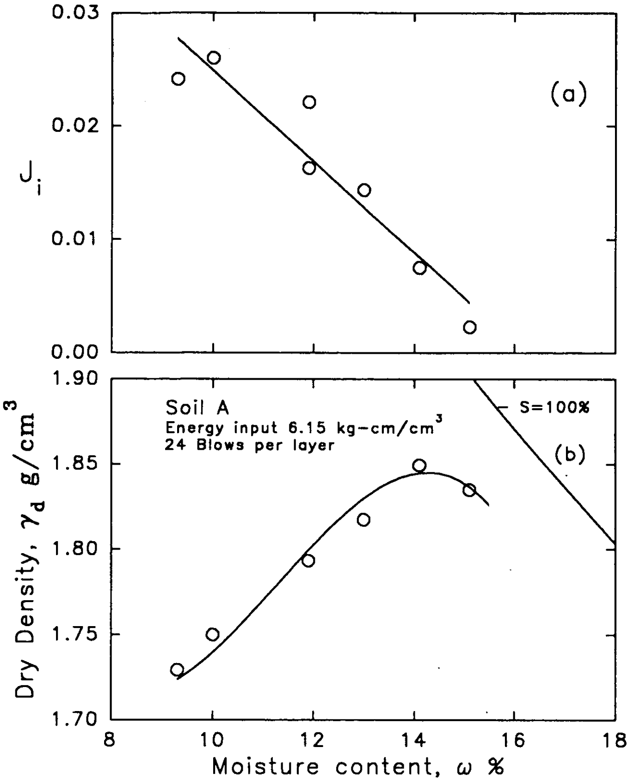

**FIGURE 5 Influence of the compaction moisture content on the erosion resistance of Soil Material A: (*a*) $J_i$ versus the compaction moisture content; (*b*) dry density versus the compaction moisture content.**

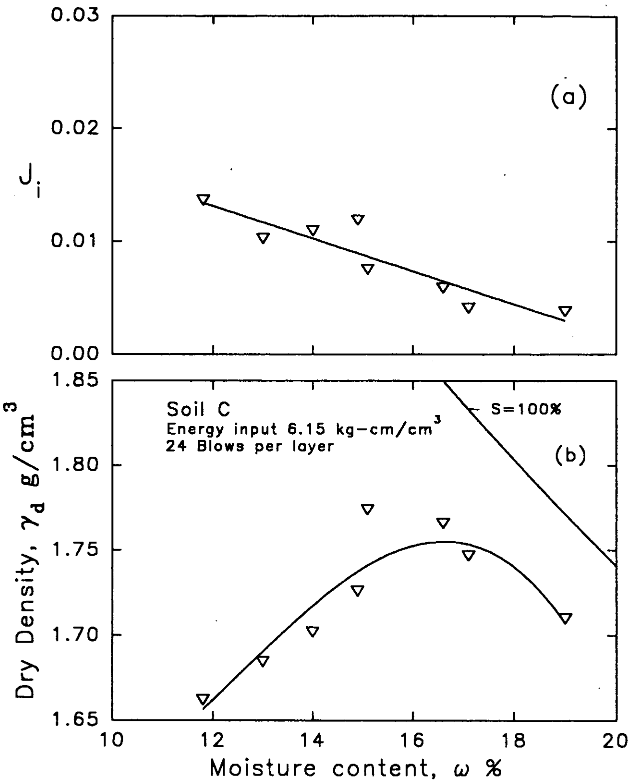

**FIGURE 6 Influence of the compaction moisture content on the erosion resistance of Soil Material C: (*a*) $J_i$ versus the compaction moisture content; (*b*) dry density versus the compaction moisture content.**

sulting $J_i$ for Soils A, C, and E is shown in Figures 5, 6, and 7 respectively. There is a consistent trend with each soil material displaying a decrease in the $J_i$ with an increase in compaction moisture content indicating an increase in erosion resistance with increases in compaction moisture content. The erosion resistance of Soil Material A shows significant sensitivity to changes in compaction moisture content, whereas Soil Material C in contrast is much less sensitive. The $J_i$ for Soil A at $\omega = 10$ percent was greater than 0.02, indicating a low resistance to erosion. The $J_i$ for Soil A at $\omega = 15$ percent was less than 0.005, indicating a high resistance to erosion. It may be concluded that in all cases, within a workable compaction moisture content range for the soils tested, there was an increase in erosion resistance with an increase in compaction moisture content.

Another question that was addressed in testing is the significance of compaction effort or density. To investigate this, Soils A, B, C, and E were compacted to various densities at 15.0, 17.0. 15.2, and 13.2 percent moisture contents, respectively. The results are shown in Figure 8. Increases in density reduced the $J_i$ significantly. The resistance of Soil Material B increased significantly from 1.3 g/cm$^3$ to 1.5 g/cm$^3$ and showed only minor increases with greater densities. The results show that increased density as a result of increased compaction effort has a beneficial effect on the soil's resistance. If a certain level of resistance is desired, compaction effort may be adjusted accordingly.

## DISCUSSION AND CONCLUSIONS

There may be significant benefits to controlled compaction of embankments for improving erosion resistance of the compacted cohesive soil material. Test results using $J_i$ as an indicator of changes in erosion resistance of a soil show that compaction effort and moisture content have a significant effect. Increases in compaction effort and compaction moisture content increased the soil materials' resistance to erosion. The soil erosion resistance was observed to vary in sensitivity to increases in compaction moisture content. Therefore, some soils may require more stringent moisture specifications at the time of compaction than others. The soils tested also indicated that if surface detachment is the only soil property of interest there may be cases where increased compaction effort beyond a certain level will provide only minimal improvement. The use of compaction becomes even more complicated realizing that compacted soils are expected to maintain these properties throughout the life of the structure. Change in resistance of

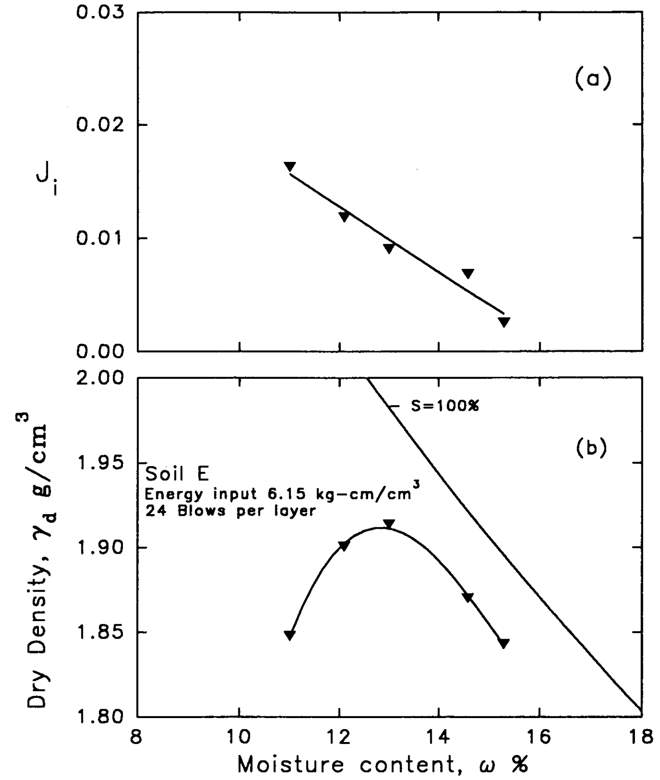

**FIGURE 7 Influence of the compaction moisture content on the erosion resistance of Soil Material E: *(a)* $J_i$ versus the compaction moisture content; *(b)* dry density versus the compaction moisture content.**

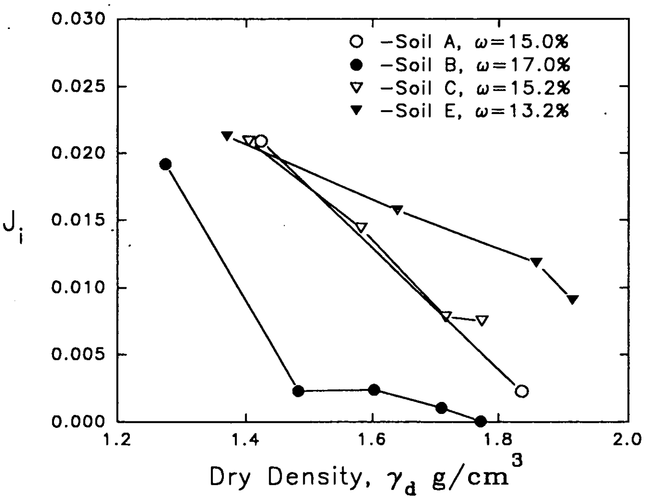

**FIGURE 8 $J_i$ versus the dry density for Soil Materials A, B, C, and E at constant moisture contents of 15.0, 17.0, 15.2, and 13.2 percent, respectively.**

a soil with time, particularly as the antecedent moisture condition changes, requires further investigation. Another area requiring investigation is the effects of the freeze-thaw cycle on the erosion resistance of compacted soils.

The purpose of this study was to investigate the influence of density and moisture content on the resistance to erosion of the soil materials tested. The maximum compactive effort used in this study is comparable with the industry standard ASTM Standard Designation D698. The advantage of this type of testing procedure is that specific environmental and design conditions may be addressed by conducting specific tests.

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