Design of Slope Protection Systems and Maintenance Procedures To Minimize Erosion

Dennis Duffy and Hilda Hatzell

Effective control of erosion on highway slopes involves assessing the erosive environment correctly, predicting the erosion resistance of materials before their placement or exposure on the slopes, and using slope maintenance and traffic control in order to minimize slope erosion-resistance damage. A laboratory testing process was developed that simulates the typical slope erosion environment. The relative importance of precipitation and flow over the slopes was explored. The relationship between precipitation and overland flow to slope erosion is such that both must be considered or erosion resistance will be overestimated. The erosion resistance of soil and prospective slope protection systems are evaluated and compared with field erosion damage. Excellent agreement between the predicted slope response and field observations was found. Crushed rock, resistant to weathering, was found to function effectively when placed on slopes as steep as 2:1. Angular particles, larger than 0.187 in., were stable on slopes for the 50-yr, 30-min event when the concentration of these particles was greater than 20 percent. Erosion resistance was found to increase as the ratio of longest particle axis length to the shortest particle axis length increases. The phenomena of natural slope armoring was examined and guidelines were developed for recognizing soil armoring.

The Arizona Department of Transportation (ADOT) authorized a study of erosion on freeway slopes in the metropolitan Phoenix area. The study area contained segments of two freeways: Interstate 10 and State Route 360. The slopes studied were a combination of cut and embankment sections totaling more than 25 mi. In an attempt to minimize slope damage, a number of erosion-reducing techniques had been applied, including application of decomposed granite. However, because of serious problems with these techniques ADOT was interested in developing more effective methods for protecting freeway slopes. Also, these methods had to be compatible with the arid climate and aesthetic concerns involved in roadside development. The research reported in this paper was a result of that interest.

GENERAL EROSION CONCERNS AND FIELD OBSERVATIONS

The importance of slope and length of surface exposed to erosions was recognized early by Duley and Hays (*1*), Zingg (*2*), and Musgrave (*3*). Soil loss was related to slope in percent raised to the 1.37, 1.35, and 1.7 power for midwestern soils (*2* – *4*). Using soil loss data from Texas to Wisconsin, Zingg (*2*) concluded that the average total soil loss varies as percent slope to the 1.37 power and horizontal slope length to the 1.6 power.

When under cultivation, midwestern soils were reported to yield sediment Q at a rate $Q = 0.43S + 0.3S + 0.043S^2$ in tons per acre. S is the slope angle in percent (*5*). In more recent research Wischmeier and Smith (*6*) have used a single topographic factor, LS, to describe the effect of slope angle and slope length. Farmland under cultivation, with natural rainfall and 3 to 18 percent slopes and lengths of from 30 to 300 ft has a value of LS that is predicted by

$$LS = (\&/72.6)^m \, (65.41 \sin^2 0 + 4.56 \sin 0 + 0.065)$$

where & is slope length in feet, 0 is angle ot slope in degrees, and m varies from 0.2 for 1 percent slope to 0.5 for a 5 percent slope.

These values of LS, which would be used in the Universal Soil Loss Equation (USLE), would be applicable to slopes that have a uniform gradient. When slopes are susceptible to rilling, such as on construction sites, the m values may exceed 0.5 (*7*).

Erosion on slopes steeper than 2:1 was of interest as erosion concerns became part of the construction sequence. Steepness factors were developed for slopes steeper than 1.5:1 (*6*).

The importance of reducing slope length became apparent, particularly on steep slopes. If the slope length is reduced by one-half, the calculated amount of erosion decreases by 70 percent (*6*).

In addition to the constraints that are appropriate for the erosion-predicting techniques, it is also important to recognize that erosion is not uniform on a slope. The erodibility of a slope with uniform soil increases down the slope (*8*). The soil removal rate increases down a typical soil slope as a result of the increased probability of the occurrence of channel or overland flow. Both raindrop impact and water flowing over the soil surface were recognized by Wischmeier and Mannering as mechanisms that contributed to erosion (*9*). The problem of predicting the potential for erosion of slopes that contain coarse materials and at angles of up to 27 degrees in arid regions has only recently received attention (*10,11*).

Predictive techniques for soil erosion, such as applying the USLE, are not easily applied to highway slopes for several reasons. Steep slopes involve a complex flow and gravitational

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environment. Soil materials not subjected to cultivation develop a natural increase in their resistance to erosion if cementation or coarse particles are present in the soils. Early studies of rock particles mixed with soil showed significant increases in erosion resistance (*12*). When rocks larger than 2 in. were removed, erosion rates increased sixfold (*13*). The coarser particles interact with each other, forming an armored surface similar to the desert pavements that are formed by wind ablation in arid regions. The effect of this resistance change is to make the actual erosion process time dependent. The USLE recognizes neither the effect of time nor of event sequence relative to previous flow.

During the planning stage of the project, a storm hit SR 360 in October 1987 and produced extensive erosion damage in an area protected with a decomposed granite (Figure 1). There were no rain gauges along the alignment; however, adjacent stations recorded a maximum precipitation rate of 0.55 in./hr during the storm (personal communication with C.F. Kenner, Maricopa County Flood Control District, Phoenix, Arizona). A side view of the slope (Figure 2) provides another perspective of the damage. The rills were not only uniformly placed, with a spacing of 3 to 8 ft, but they also started at the same location.

The rills started at a break in slope that separates the upper and lower slope segments. The upper slope segment had an angle of from 6 to 14 degrees. The angle of the lower segments varied from 8 to 24 degrees. The observed erosion was widespread, occurring wherever the granite protection was used within the storm limits. The granite designated as SRG8 had 100 percent passing the 1 in. sieve size and 72 and 0 percent passing the numbers 4 and 200 sieves sizes, respectively. The nominal thickness of the granite on the slopes was less than 1 in.

The length of upper slope necessary to produce the rill cutting for the October 1987 storm was approximately 15 ft. When less than 15 ft of upper slope existed, rills did not form. The slope areas that had an upper segment greater than 15 ft always had rilling in the granite.

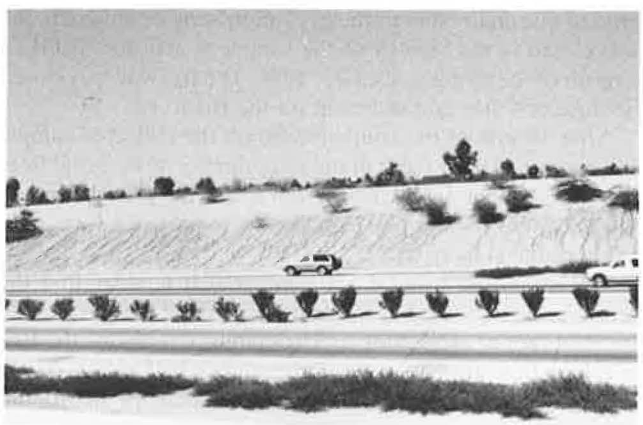

FIGURE 1 Erosion damage SR 360, Phoenix, Arizona.

FIGURE 2 Erosion damage, SR 360.

Laboratory Testing Program

A laboratory testing program was developed to assess the combined effects of precipitation falling on a slope and overland flow delivered by a microcollecting basin on the upper slope segments. An erosion cell that contained three replicated panels 2.5 ft wide by 2.67 ft in the slope direction by 2.5 in. deep was constructed. The three panels were used to provide an estimate of the variability of the erosion response.

The erosion cell was designed to be placed at variable slope angles. A spray head utilizing a full cone spray pattern was used to simulate precipitation on each panel. Flow was metered through each of the three spray heads to ensure a uniform application rate. The spray head assembly applied the water at a rate that was greater than the 50-yr, 30-min intensity event expected for the greater Phoenix, Arizona area.

The overland flow portion of the testing was accomplished by building a simulated channel flow delivery system constructed from 3-in.-diameter acrylonitrile-butadiene-styrene (ABS) pipes. These channels were constructed on a frame that allowed the pipe slope to vary from 2 to 16 degrees. By varying the delivery channel slope, the water velocity could also be varied. To better simulate the field channels delivering runoff to the lower slope segments, the ABS pipes were lined with Mirafi 6000 plastic with the filter fabric removed. The 6000 plastic was placed with the extrusions into the flow to produce a roughness closer to field conditions. Each flow channel had a flow meter to enable identical flows to be applied to each of the replicated panels. The overland flow assembly is shown in Figure 3.

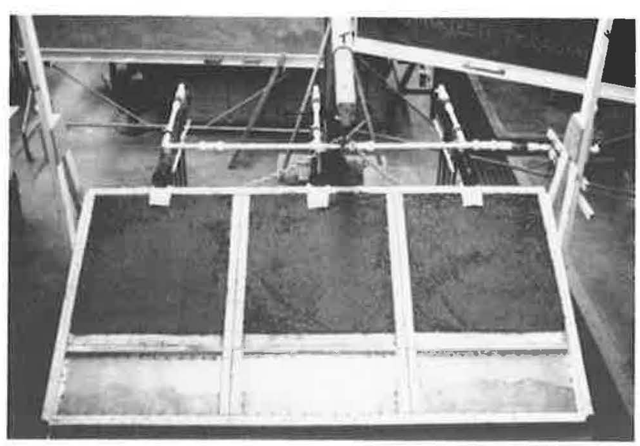

FIGURE 3 Erosion cell apparatus.

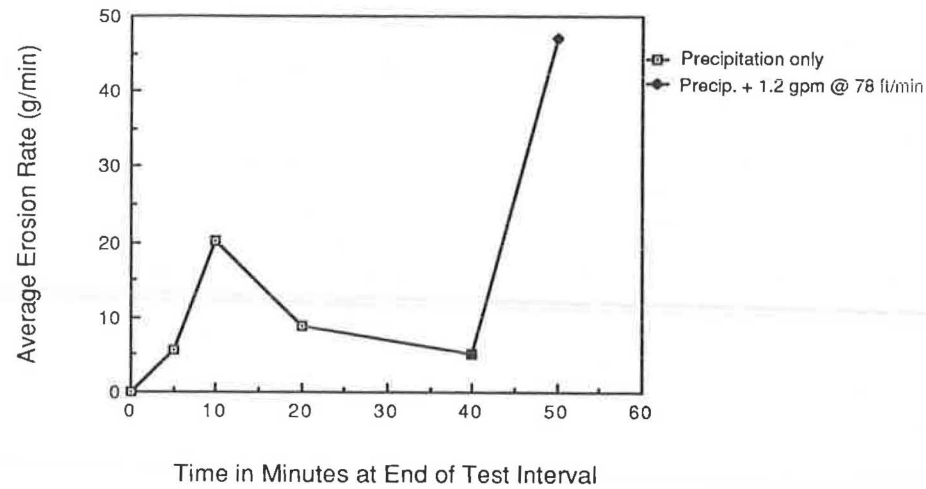

FIGURE 4 SRG1 erosion versus time for combined flow conditions.

A typical coarse-grained soil response to the erosion testing is provided by the SRG1 material (Figure 4). SRG1 is a granite slope protection material applied to existing slopes on SR 360. The SRG1 testing demonstrated the ability of a coarse fraction to develop increased erosion resistance through armoring. Armoring is the development of a surface protection through accumulation of soil particles too coarse to be transported from the slope by flow events to that point in time. The SRG1 material had 51 percent plus number 4 size material before erosion testing. The erosion increased to a maximum value 10 min after the test was begun and continually decreased to a minimum value at 40 min. The initial increase in the rate of erosion is believed to have been caused by surface irregularities left after panel preparation and "poorly" placed coarser particles that are in rather unstable positions at the start of precipitation.

After completion of the 40-min test increment, the SRG1 soil had developed an effective surface armor comprised of primarily plus number 4 size particles. What was observed in the laboratory was a high initial loss of fines followed by steadily decreasing sediment transport from the panel. The sample collected was 99 percent finer than the number 4 sieve size particles and 57 percent finer than the number 10 sieve size. The grain size analysis for the samples collected at 30 and 40 min after the test was begun show similar results. It is the minus number 4 sieve size particles that are transported by precipitation alone under the particular test conditions.

The fact that the precipitation portion of the SRG1 test eroded essentially fine particles is interesting because SR 360 was closed in the vicinity of the sample source for SRG1 as a result of the storm in October 1986. The freeway was closed because of water and sediment on the road.

After 10 min of the combined flows, the collected sample still contained 88 percent of the plus number 40 material finer than the number 4 sieve size. Even under the added stress of the 1.2 gpm flow the plus number 4 size particles were relatively stable (Figure 5).

When Figures 4 and 5 are compared it is clear that the erosion rate increased at the same flow but at a higher velocity. The rate of erosion of approximately 47 gpm for the first overland flow after 10 min is 5 times greater than the rate of erosion for the second interval, with a velocity of 141 ft/min.

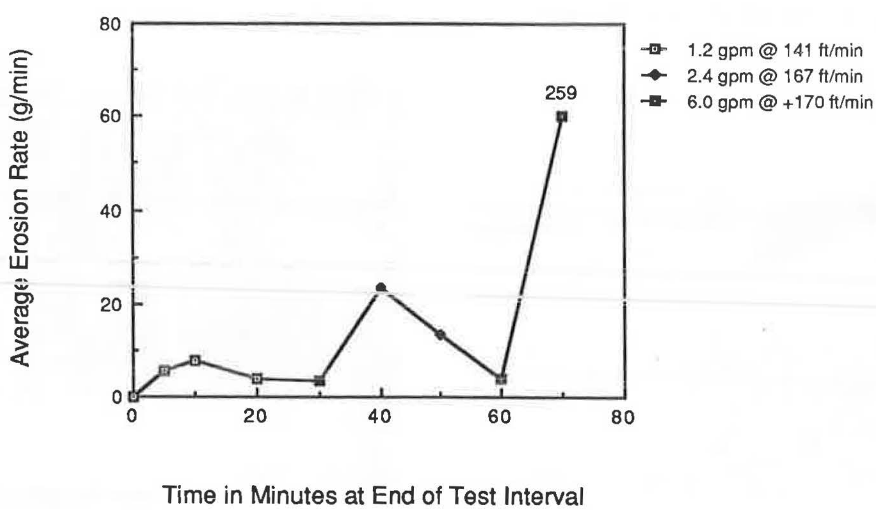

FIGURE 5 SRG1 erosion rate versus time, 2:1 slope.

The increase in the rate of erosion (Figure 5) between 5 and 10 min is believed to be caused by the relocation of coarse particles. When the velocity of flow increased by more than 80 percent, some particles were unable to resist the new flow environment without an adjustment in position. The combined samples of the plus number 40 material that eroded after 10 min at the higher velocity flow were 95 percent finer than the number 4 sieve size. Not only does the slope continue to armor, as demonstrated by the reduction in the rate of erosion, but also the transport of particles smaller than the number 4 sieve size continues. At the 60-min point in the test no plus number 4 size particles were collected.

The relationships shown in Figures 4 and 5 demonstrate clearly that with time the rate of erosion will decrease. If the slope is not disturbed, surface protection is available to resist erosion during subsequent flows. Should the surface protection that has developed be damaged, the rate of erosion would increase with the next flow until the armor can reform.

To establish the upper resistance of the SRG1 material, the flow rate was increased to 6.0 gpm with a corresponding velocity increase. The increased severity of the overland flow portion of the event produced a rapid removal of material (Figure 5).

Panel 3 of SRG1 was selected for testing with an overland flow rate of 6.0 gpm. The rate of erosion increased tenfold as the flow rate increased from 5.0 to 6.0 gpm (Figure 6). The removal of the armoring that had been formed during the previous testing began when the flow reached 6.0 gpm; the surface protection was being damaged. Slope surface particles as large as 0.75 in. were being transported. When the flow rate is 1.2 gpm and the velocity is less than 141 ft/min, the slope of SRG1 material will armor itself. As can be observed in Figure 7, the erodibility of the SRG1 material was not increasing even when the erosion stress was increasing.

The overland flow was increased to 8.0 gpm, which resulted in failure for two of the panels (Figure 8). These data and the data from the first series of SRG1 tests exhibit similar behavior. The precise flow at which the slope fails appears to lie between flow rates of 6.0 and 8.0 gpm.

An example of the variability to be found on replicated panel surfaces is shown in Figure 9. The results of Panel 3 present proof that for an advantageous arrangement of surface particles, even SRG1 material is resistant to combined flows

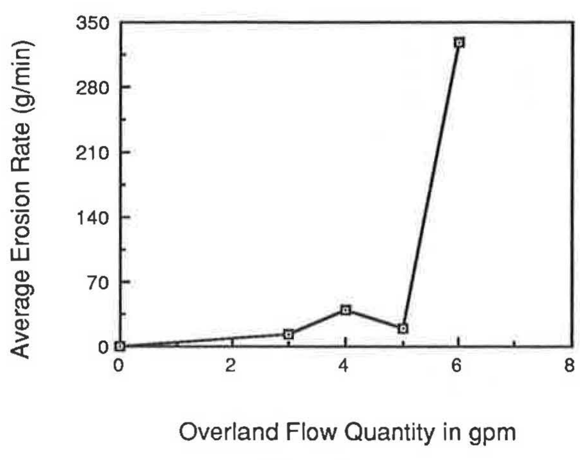

FIGURE 6 SRG1 Panel 3 erosion rate versus overland flow rate.

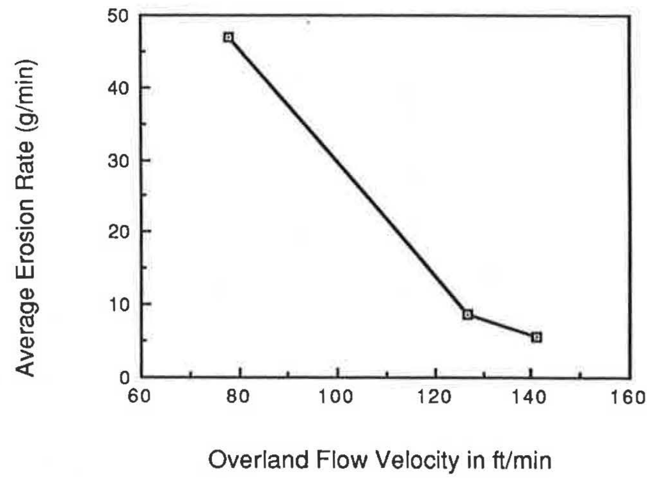

FIGURE 7 SRG1 erosion rate versus overland flow velocity.

with an overland component of 8.0 gpm. Considerable movement and erosion occurred before the development of this rather stable surface. The sample collected at the end of the 8.0- gpm, 10-min event contained no particles larger than the number 4 size.

A sample of the granite surface protection that was shown in Figure 1 (SRG8) was also tested at 2:1 slopes. The material was so permeable that no surface flow could be sustained below 6.0 gpm. Without surface flow, erosion would not occur (Figure 10). All three panels were able to resist eroding. When the slope was increased to 2:1, one panel was able to resist the 6.0 gpm condition though the other two panels did not exhibit formation of channels.

To assess the effect of dust and maintenance activities that would eventually reduce the permeability on slopes, the test was modified. The SRG8 was placed in the same manner as in the first two test series, then 1300 g of minus number 40 soil derived from soils immediately below the field granite protection were sprinkled on each test panel. Each panel was wetted from the spray heads alone until the soil had been transported into the pore spaces of the SRG8. The erosion testing then proceeded with the combined effects of precipitation and overland flow. At the 2:1 slope, all panels failed within seconds of the application of combined flow with an overland component of 6.0 gpm (Figure 10). The failure was rapid and took the form of a straight channel until the Mirafi 6000 material was exposed.

One additional test series was performed using the SRG8 material. This test simulated the field condition in which a thin, 0.5-in.-thick layer of SRG8 was placed over a 2.0-in.-thick layer of low permeable soil. A fine-grained soil was selected from SR 360 for testing and designated SRP5. Only 8 percent of the particles on SRP5 were larger than the number 4 sieve size. SRP5 was used for the underlaying material, and 0.5 in. of SRG8 was placed over it. This test condition examined the erosion resistance when the permeability remained high but because of the thin section of SRG8, water would be forced to move across the surface. When tested under the combined flow conditions with an overland component of 2.4 gpm, failure occurred (Figure 10).

The series of tests using the SRG8 material demonstrates the complexity of the slope erosion environment both as placed and as it may potentially change over time. It is not enough

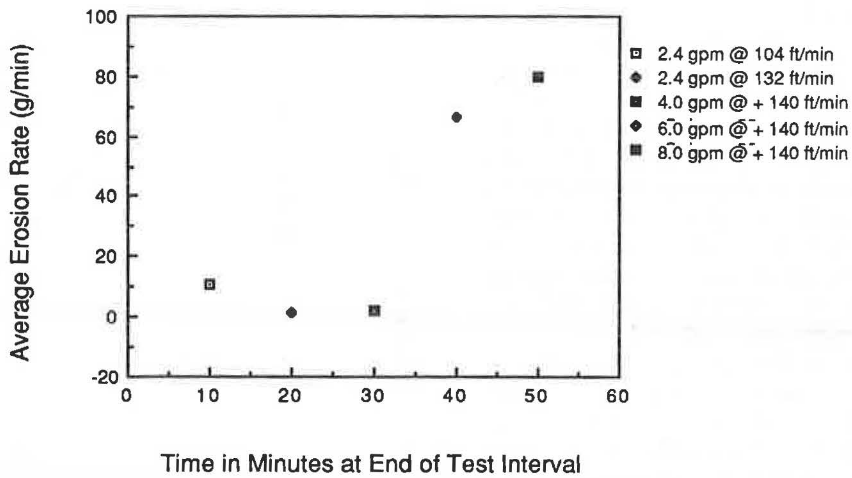

FIGURE 8 SRG1 Panels 1 and 2 erosion rate versus time, 2:1 slope.

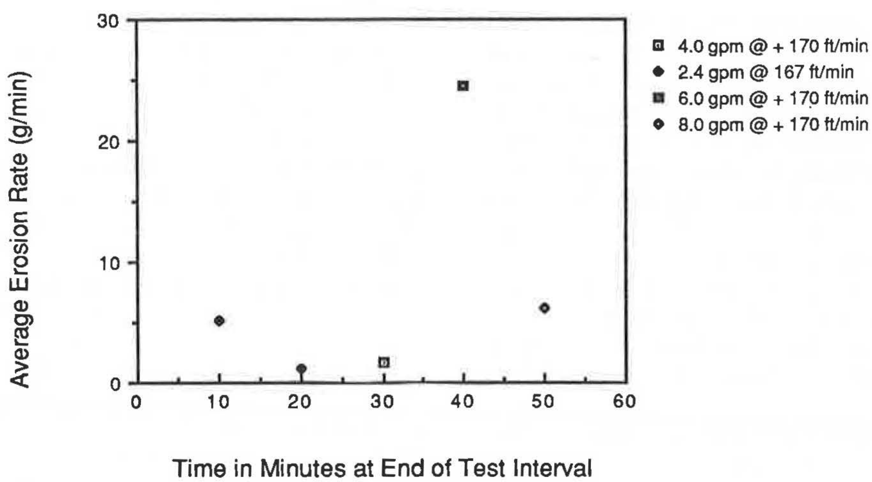

FIGURE 9 SRG1 Series 2, Panel 3 erosion rate versus time.

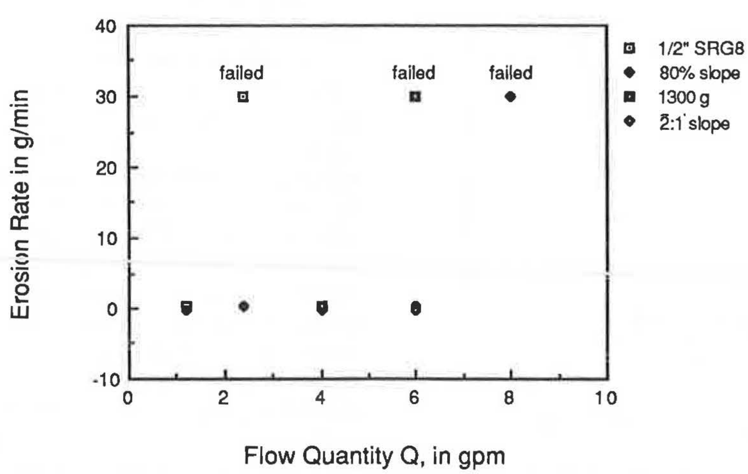

FIGURE 10 SRG8 erosion rate versus flow rate.

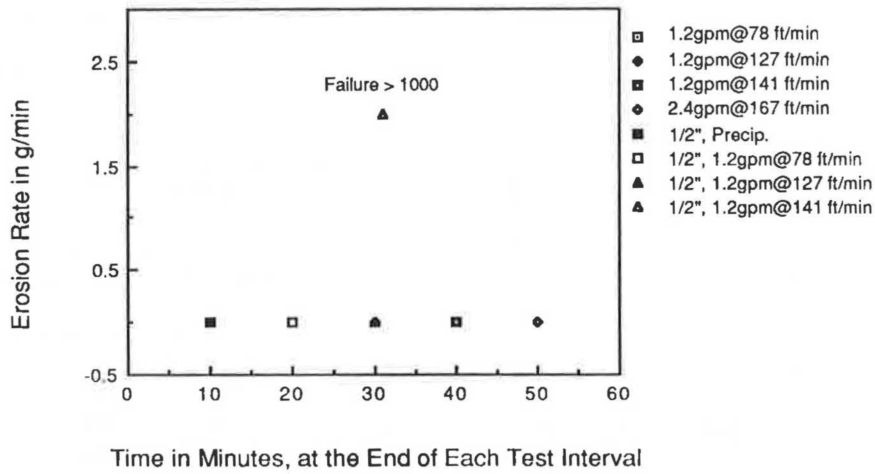

FIGURE 11 Erosion rate versus time, IG1 and IG1 ½ in. thickness.

to perform a slope erosion test and then proclaim success when little or no erosion occurs. Instead, the designer must understand why the erosion resistance is high and thus why the test is successful. If the results are due to high permeability, the role of thickness and long-term permeability in future erosion resistance must be developed. Insufficient knowledge now exists to enable the time-plugging relationship to exist for any slope-protecting material. The designer does not need that specific information; it is sufficient to recognize that the effects of time will reduce the protection.

The interest in the role of surface protection thickness led to another series of tests using material that came from Dysart Road and I-10 and designated IG1. The IG1 material had a high surface permeability similar to the SRG8 samples. A series of tests terminating with a combined flow environment and containing an overland component of 2.4 gpm with a velocity of 167 ft/min produced neither sediment nor failure (Figure 11). A new series of panels was prepared with a 0.5-in.-thick layer of IG1 material over the same soils applied to the SRG8 panels. The testing was repeated but this time the panels failed when the minimum combined flow with an overland component of 1.2 gpm was applied (Figure 11). The reduced thickness could not support the flow within the section. The erosion channels that formed in the laboratory were similar in geometry to those observed on the freeway slopes. Like the SRG8 materials, the correlation between field and laboratory for the IG1 panels was remarkably good (Figures 12 and 13).

So far the reported testing has dealt with materials that have been used on the slopes as protection. A soil, IP9, was selected for testing because unlike the IG1, SRG1, and SRG8 materials it had only 6 percent of particles larger than the number 4 sieve size. The IP9 soil failed during precipitation testing while at the 2:1 slope (Figure 14); it could not develop an effective armoring system because of the paucity of plus number 4 size particles.

The IP9 panels had microchannels that developed as soon as precipitation started. As the duration of flow increased, larger portions of the surface were affected. Each rill was in effect developing an overland flow component that increased minute by minute. The net effect of this increasing flow was the acceleration of the rate of erosion to failure. The results of IP9 are graphic indicators of erosion when the development of armoring is lacking. Once the incisement process started,

FIGURE 12 Rill caused by rumble strip, Interstate 10, Phoenix, Arizona.

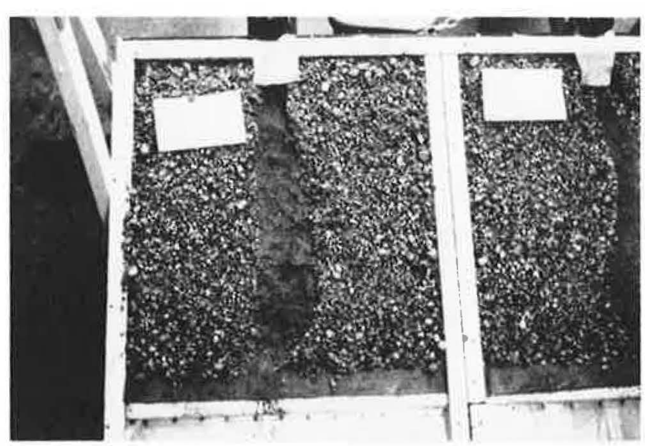

FIGURE 13 Laboratory rill.

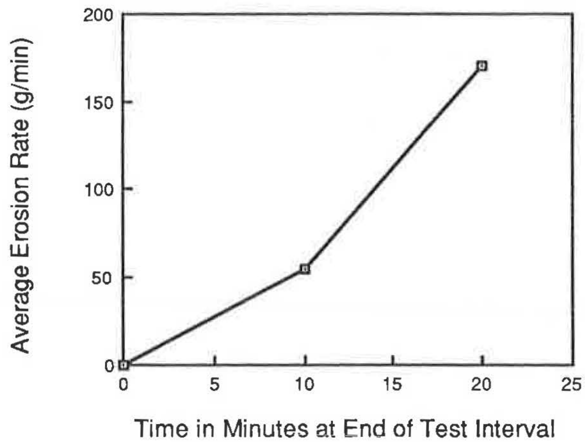

FIGURE 14 IP9 erosion rate versus time 2:1 slope, precipitation only.

the flow regime was able to transport larger particles from the surface. The analogy of a piping failure is applicable because with piping each particle removed increases the gradient, and thus the rate of removal increases.

When SRP5 was tested under the stress of precipitation alone on a 2:1 slope, the 10-min erosion rate was 125 gpm (Figure 15). This erosion rate was compared with the IP9 initial 10-min rate of 185 gpm. The SRP5 slopes did not fail. When precipitation was applied with an overland component of 1.2 gpm, a rate of erosion of 1549 gpm was produced (Figure 16). The rates are developed by relating the amount of plus number 40 material eroded to the starting percentage of the same size fraction. The rate of erosion is adjusted to reflect this estimate of the total amount eroded.

To evaluate how erosion resistance of IP9 soil is affected by coarse particles, varying amounts of large particles were mixed with the SRP5 soil (Figure 15). The numerical values given for the percent aggregate were determined by sieve analysis after the soils were mixed and before erosion testing. The percentages shown with the material added to the SRP5 soil were the measured amounts of materials by weight. The added SRG1 particles were all retained on the 0.5-in. screen. The Slate Creek material was obtained from SR 87 and sieved to pass the 1.5-in. mesh and be retained on the 0.5-in. sieve. A considerable reduction in rates of erosion was observed when the amount of aggregate added was greater than 29 percent.

When rate of erosion caused by precipitation alone and with overland flow is plotted against the percentage of plus number 4 material in the soil for the SRP5 base soil, the results are as shown in Figure 16. When the percentage of particles larger than the number 4 sieve is greater than 10 percent, a significant reduction in erosion potential occurs. A very small change occurs beyond 20 percent.

One other aspect of aggregate considered was the shape factor influence. The ratio of the longest to the smallest particle dimension was established for these additives. This dimension ratio is defined as the shape factor (SF). The SF values were 2.0 for SRG1, 2.1 for IG1, and 8.4 for Slate Creek aggregate. The SRP5 erosion rate versus aggregate shape factor for the 30 percent aggregate additive soils is shown in Figure 17.

The Slate Creek aggregate is the most efficiently shaped aggregate to reduce erosion. Nevertheless, the data indicate that shape factor is not nearly as important as the total percentage of plus number 4 size particles available. Whenever a choice in particle shape factors is available, the material with the higher SF value should warrant special consideration.

The research team examined the effects of resistance to erosion of natural soil particle shape. A sample was selected from SR 360 for testing and identified as SRS1. This material

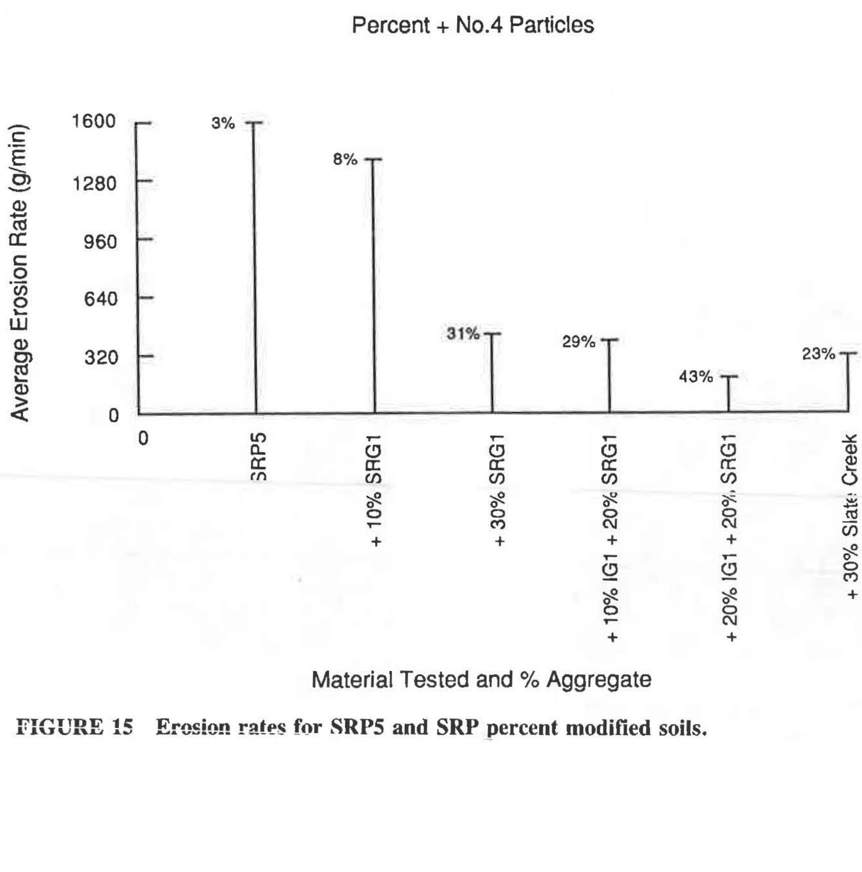

FIGURE 15 Erosion rates for SRP5 and SRP percent modified soils.

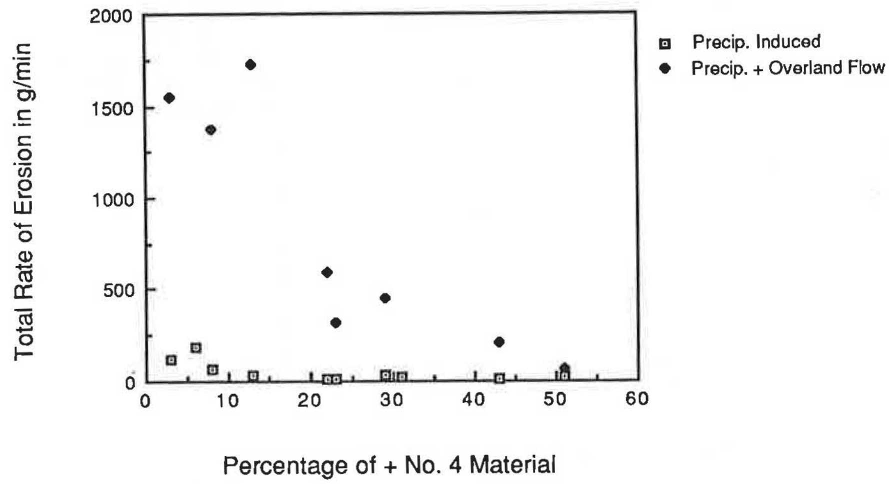

FIGURE 16 SRP5 erosion rate versus amount of coarse aggregate.

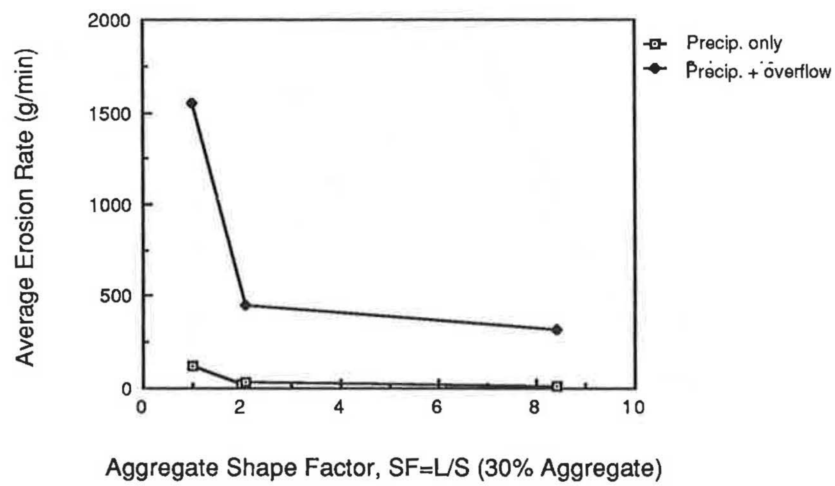

FIGURE 17 Erosion rate versus aggregate shape factor, SRP5 base soils.

contained 22 percent plus number 4 size material. The maximum particle size the soil contained was 2 in. To examine the change in erosion resistance when the material larger than 1 in. was removed (Figure 18), an identical test series was conducted. The material with 100 percent passing the 1-in. sieve size was designated SRS1 −1 in. The results of the precipitation testing for these two materials can be observed in Figure 19. Both samples behaved the same until after 20 min of testing. At 30 min the difference in coarse size fraction, which was 22 versus 13 percent of plus number 4 size particles, was observed. The difference in erosion resistance continued to increase as the test continued (Figure 18).

The reason for the failure appeared to be related to the round shape of the coarse particles. SRS1 contains a large number of rounded $CaCO_3$ particles, which tend to roll on the 2:1 slope. The more spherical a particle becomes, the less efficiently the particle interlocks with others to form the surface armor. During the erosion tests, particles were observed rolling down the slopes. The same relationships of size and shape observed by Meyer and Monke (*14*) were apparent with the SRS1 soil. The smaller particles rolled first followed by the larger particles as the overland flow quantity increased. Particles as large as 0.5 in. were collected at the flow rates applied. Once started, most of these rolling particles did not stop until they rolled off the panel.

The SRS1 testing shows the importance of the larger size particles in developing erosion resistance and the influence of particle shape. When the same flow was applied to the other materials with particles larger than 0.5 in., the particles were retained on the panel. Therefore, in addition to the shape factor, particle angularity is an important aspect of mitigating slope erosion.

CONCLUSIONS AND DESIGN RECOMMENDATIONS

The prediction of highway slope erosion resistance should involve an evaluation that addresses both precipitation and overland flow. The erosion test cell functioned well, simu-

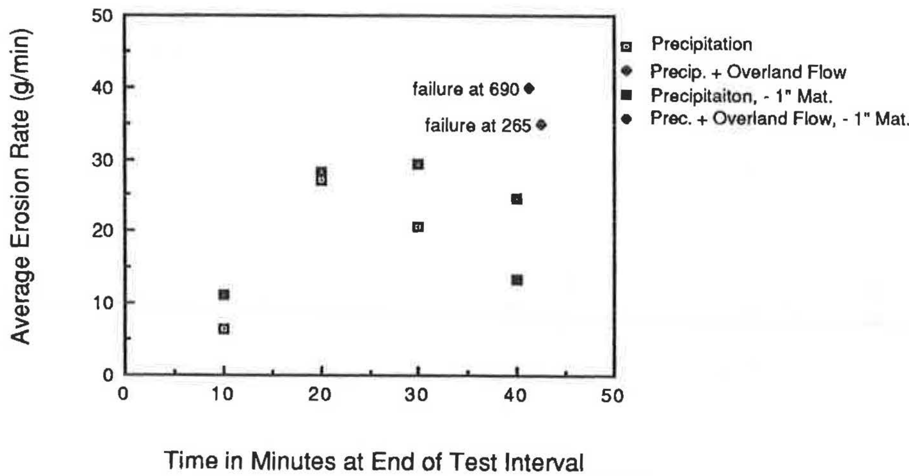

FIGURE 18 Erosion rate versus time for SRS1 and SRS −1 in. with overland flow.

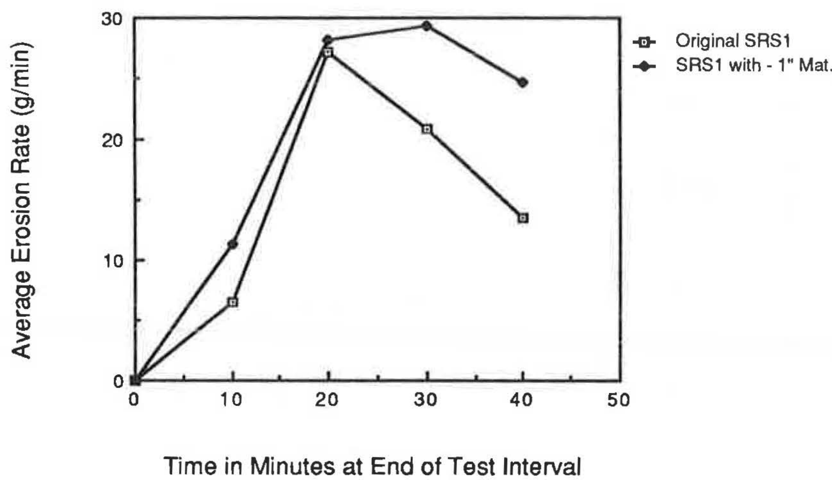

FIGURE 19 Erosion rate versus time for SRS1 and SRS −1 in. soils precipitation only.

lating both aspects of erosion and enabling comparisons to be made between observed slope erosion resistance and laboratory resistance for alternative materials.

Effective slope protection can be provided by using crushed rock or similar materials. Such surface protection must be resistant to weathering, and must be placed with sufficiently large particle size to prevent transport during the design storm. The use of crushed rock to protect slopes simulates the naturally occurring armoring that soils with coarse particles develop. Slopes as steep as 2:1 can be protected. The minimum acceptable rock particle size must be determined by simulating both precipitation and overland flow on the slope. The rock particles should be as angular as possible. Because particle shape affects erosion resistance, the particles should have a shape factor range of between 2 and 8. Rounded particles tend to roll on slopes under the influence of overland flow and should be avoided. The particles should also be resistant to weathering.

A well-graded crushed rock with maximum particle size greater than 1.5 in. will protect a 2:1 slope against channel flows as high as 6 gpm with a velocity produced from a simulated 16-degree upper slope segment. The permeability of the rock protection may be sufficiently low as to allow surface flow to occur. When placed over low-density soil, the rock must be supported. There are geotextiles available that would provide adequate support.

Slope materials that have a surface permeability high enough to prevent surface flow may exhibit adequate erosion resistance when first placed. Should these materials experience a reduction in permeability over time that is sufficient to cause surface flow, they may then easily erode. A sufficient thickness of high permeability material to prevent surface flow is a function of the design event as well as slope geometry. Slope maintenance activities should ensure that the required thickness of such materials not be allowed to decrease with time. When the rock protection is permeable enough to prevent surface flow, it can sustain applied flows as high as 6 gpm with a maximum rock size less than 0.5 in. However, should rock plugging occur, producing flow across the surface, or should the thickness decrease to 0.5 in., failure will occur at flow rates on the order of 1.2 gpm.

Particles larger than 0.187 in. were relatively stable on 2:1

slopes for the 50-yr, 30-min intensity events when their concentration was greater than 12 percent. Therefore, whenever possible, natural slope materials with as much plus 0.187-in. angular particles as possible should be used. When soil concentrations of these particles reach 12 to 20 percent, they form effective surface protection.

The overland flow component of slope erosion is orders of magnitude greater than the precipitation component alone. Because overland flow controls slope erosion for most slopes, slope design should minimize the development of channel flow on the slope. Minimizing slope height, grading upper slope segments to drain away from the slope face, and the use of slope materials to reduce water velocity are important.

To minimize the destruction of naturally occurring erosion resistance produced through armoring, slope traffic should be prevented. The rate of erosion increases when the surface protection is disturbed. Slope traffic also aids in the development of microchannels that accelerate erosion.

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