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SIDEWALK UNDERMINING STUDIES

Phase III — Field and Model Studies

by

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Virginia Highway & Transportation Research Council
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SUMMARY

The results of the early studies of the undermining problems are summarized in the initial portion of this report. Additionally, the design and use of a model sidewalk for testing procedures for preventing undermining are described.

Based upon tests with the various model setups the following conclusions are made:

1. Close to maximum compaction of the subgrade soil does not prevent sidewalk undermining.
2. A No. 21-A stone compacted as a sidewalk subbase prevents sidewalk undermining, but may transfer the undermining to another location.
3. Modification of the subgrade soil by the addition of 2% agricultural grade hydrated lime prevents sidewalk undermining, while the transfer phenomenon could be prevented by modifying the strip of soil from the back of the sidewalk to the edge of pavement.

Through the observation and evaluation of field test sites and sidewalk undermining sites the following conclusions are made:

1. Close to maximum compaction of the subgrade soil, either with or without use of cut-off walls, does not prevent sidewalk undermining.
2. A drainage system constructed under the sidewalk has been very effective in preventing sidewalk undermining.
3. The reuse of existing sidewalk slabs is feasible for sidewalk repair.

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INTRODUCTION

The Fairfax Residency of the Virginia Department of Highways and Transportation spent $4.92 million between FY71 and FY77 replacing or repairing deteriorated or undermined sidewalks and combination curb and gutter.(1) Of this total, $4.65 million were spent for replacing or repairing these items along secondary roads in Fairfax County alone.(1) The residency is currently allocating several million dollars per year, a large percentage of its combined normal maintenance and maintenance replacement allocation, for replacing sidewalks and curbs and gutters. Additionally, residency personnel believe that an estimated $50.0 to $55.0 million would be needed at present to correct the existing sidewalk problems throughout Fairfax County.*

While the problems connected with the maintenance of incidental construction items in the area are severe, the most formidable problem is represented by the many sidewalks — and, in a few instances, combination curb and gutter sections — that have been undermined through erosion of the immediately underlying soil layer. Undermining removes the support for the sidewalks and results in faulting of the joints and peripheral drainage problems. More importantly, the distortions of the sidewalk can create serious pedestrian safety hazards.

Because of the Department's policy of accepting sidewalks into the secondary system along with the adjoining subdivision pavements, the responsibility for maintenance of the sidewalk is assumed by the Department. On the average the Department accepts 48 km (30 miles) of Fairfax County roads into its secondary system each year. Most of these roads have sidewalks on both sides. Thus, maintenance problems will continue to multiply unless changes are made in specifications for sidewalk construction and design standards are adopted to prevent undermining and early deterioration in sidewalk construction.

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*Conversation with D. E. Ogle, February 1979.

The aid of the Research Council in determining a solution to the undermining problem was requested through a memorandum dated March 22, 1974, from District Engineer D. B. Hope to then Director of Program Management H. G. Blundon. Explicitly called for in this memorandum was the Council's cooperation in developing measures that would be applied at the time of initial sidewalk construction to prevent the occurrence of undermining. In the initial stages of the project it became quite obvious, through discussions with residency personnel, that any assistance with maintenance procedures, particularly assistance oriented toward cost reduction, would be appreciated.(2)

Therefore, the initial report on this study dealt with interim recommendations on maintenance procedures and hydrological considerations.(2) The report on Phase II described the procedures used to correlate sidewalk undermining with soil characteristics and site conditions.(3) The present report offers conclusions relating to changes in the specifications for sidewalk construction and standard designs that will preclude undermining in sidewalk construction. The conclusions are based on observations and evaluations of field test sections and an analysis of data taken on a sidewalk model constructed in the Research Council's laboratories.

THE PROBLEM

In March 1971, the undermining of sidewalks and other incidental construction items in the Fairfax Residency had reached such proportions that a study committee was formed comprising representation from the Residency Office and the Fairfax County government.(4) An important product of the committee's work was the identification of the general conditions necessary for undermining to occur.

The committee found that undermined sidewalks were typically located on longitudinal grades of 3% or more and were customarily downgrade from drainage areas encompassing a portion of one or more square blocks. Additionally, the yards adjoining residences usually sloped steeply upward from the sidewalks such that all the runoff from roofs as well as the rest of the drainage area flowed over or along the sidewalk to reach the storm drains in the roadway. These observations were supported by facts presented in the Phase II report which will be summarized subsequently.

The development of undermining where longitudinal grades exceed 3% is related to the fact that drainage is predominately across the walks until the longitudinal grade exceeds the 2% cross-slope provided in standard sidewalk construction. Once that cross-slope is exceeded by the longitudinal grade, drainage becomes predominately longitudinal, with the sidewalk serving as a paved ditch which can easily undermine if underlain by erodible soils. The tendency toward functioning as a paved ditch is further intensified by the existence of a sodded utility strip from 0.3 to 3.6 m (1' to 12') wide between the sidewalk and the roadway curb. Because in normal growth the grass in both the utility strip and the adjoining yards is higher than the sidewalk, the sidewalk functions as a paved ditch to carry much of the drainage.

A hole along the edge of the sidewalk, or an open joint or crack in the sidewalk itself, allows water to readily reach the unprotected subgrade soil and initiate undermining. Figure 1, taken from a color slide made during a rainstorm, demonstrates the process. The color slide clearly showed water coming up through opening A and carrying soil particles down the sidewalk to opening B, where it disappeared under the sidewalk. Additionally, the photo evidences the paved ditch phenomenon hypothesized previously.

Undermining of a sidewalk typically is evidenced by dislocation of the joints and distortion or rotation of the slabs in either or both the longitudinal and transverse directions. However, undermining may be present where there is little or no distortion of the sidewalk. The severity of distortion that may materialize is exemplified in Figure 2. The soil eroded from underneath the sidewalk is usually deposited at the low point of the vertical curvature, although it may accumulate at intermittent joints or points along the edges of the sidewalk. After a heavy rainstorm soil particles are present on the sidewalk in very noticeable amounts, even though most of the eroded material is transported into the storm drain system. The soil particles on the sidewalk are an excellent indication of undermining, especially the early stages of undermining when distortion is not very evident. The depth of the voids under the sidewalks ranges from just a few inches to a couple of feet (see Figure 3).

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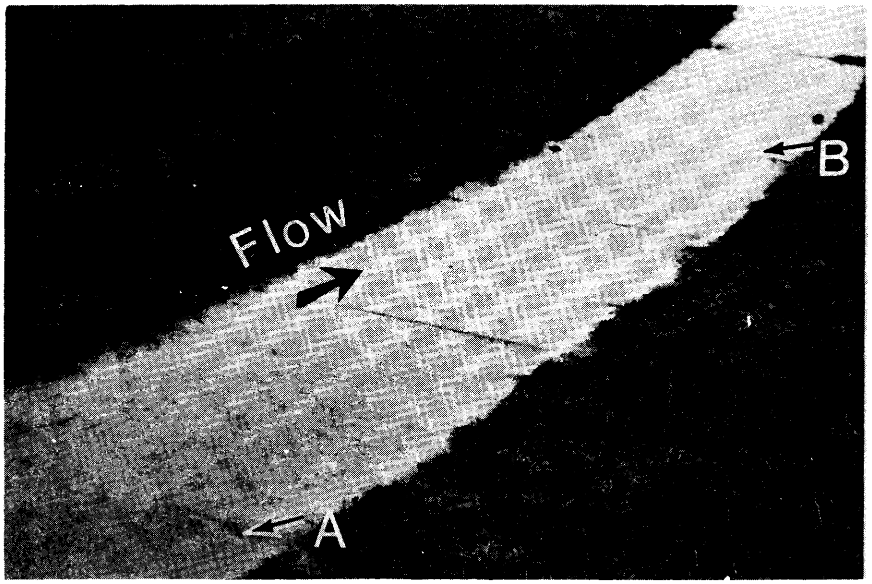


Figure 1. Undermining of sidewalk.

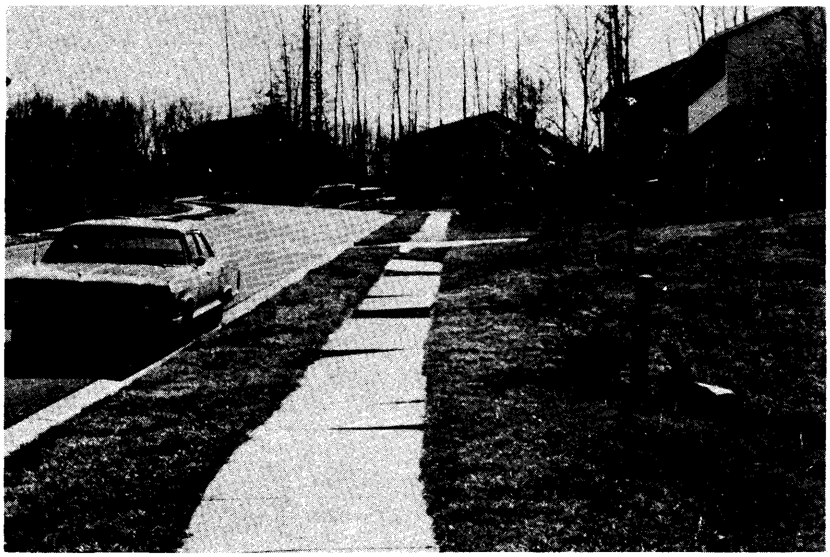


Figure 2. Severe distortion of sidewalk due to undermining.

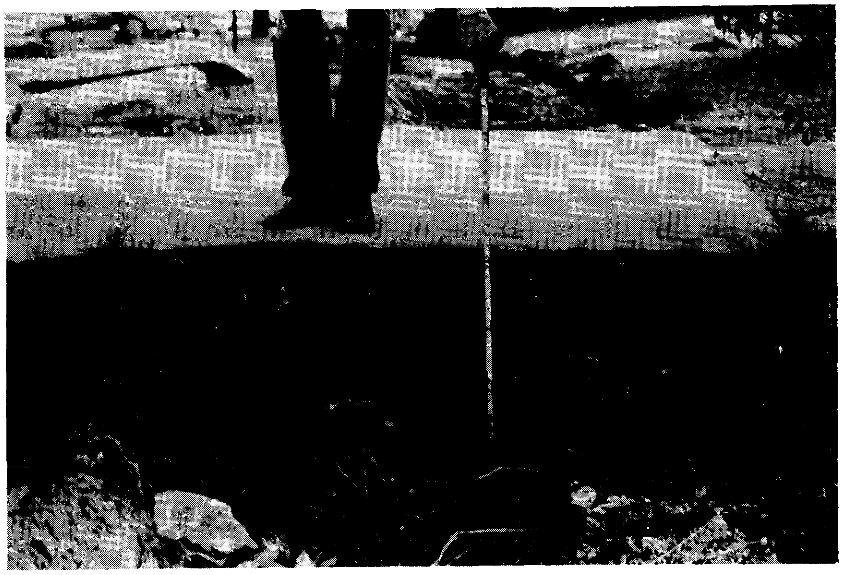


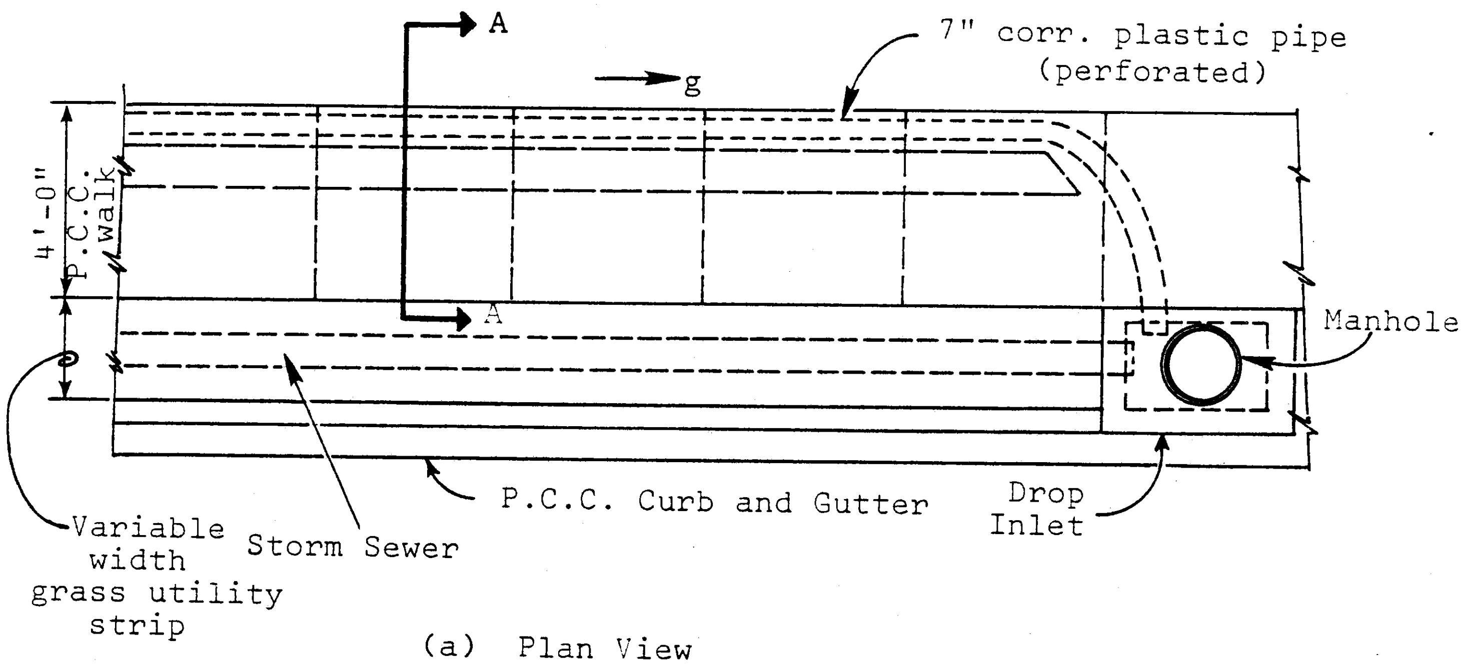
Figure 3. Severe undermining of entrance to driveway.

REVIEW OF PHASE I

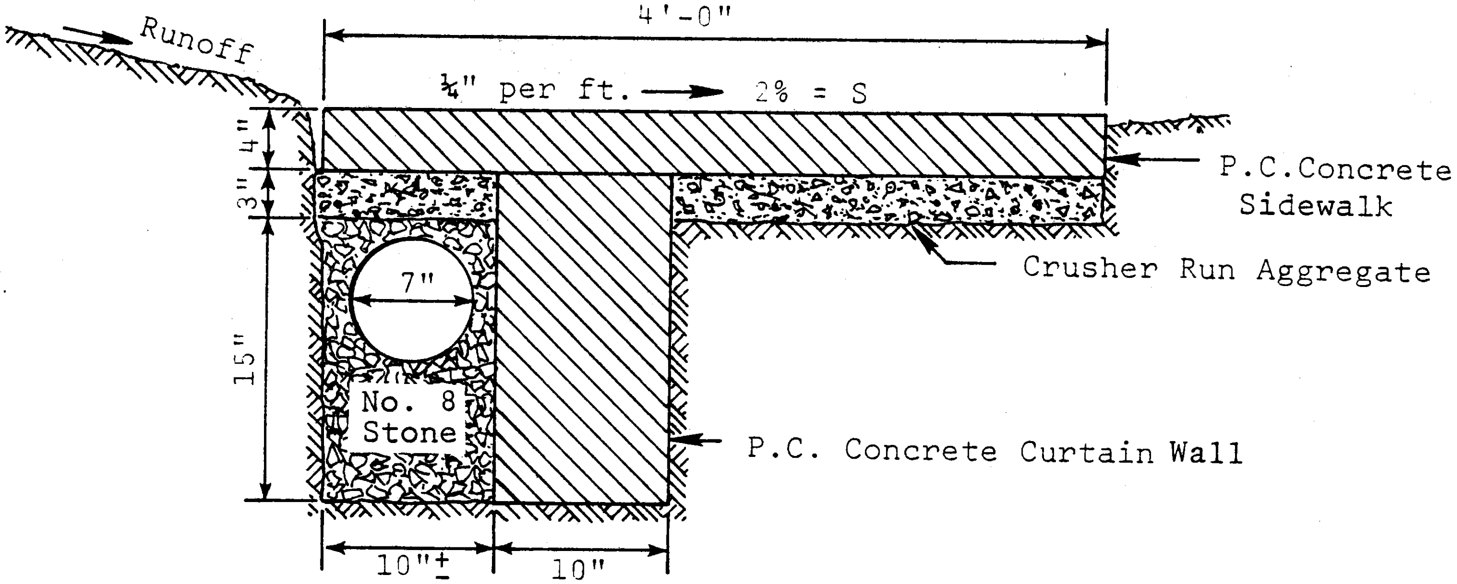
Because it was obvious from an inspection of the problem sidewalks that a considerable volume of water might flow under a sidewalk at times, and because of some disagreement concerning an exact amount of flow, the first phase of this project studied and reported on the hydrological factors involved in sidewalk undermining.(2) Additionally, the report on Phase I detailed the establishment, and subsequent acceptance by the Fairfax Residency, of a maintenance replacement procedure differing from the one used previous to the Council's involvement with the problem. Detailed study by others of several occurrences of undermining had led to the conclusion that it would be difficult to prevent the infiltration of runoff into the area beneath the sidewalk.(5,6) Consequently, for maintenance replacement purposes, both Fairfax County and Fairfax Residency personnel had decided that it would be best to protect the erodible soil by the use of an aggregate base and a longitudinal curtain wall under the rebuilt sidewalk, and to remove infiltrated water by placing drainage pipe under the sidewalk and on the yard side of the curtain wall. Theoretically, the curtain wall directs the infiltrated water into the drainage pipe, which is connected to the existing storm drain system. A schematic of this replacement procedure is shown in Figure 4. While this method of replacement was successful in that undermining has not recurred to date, it was very expensive and there was general disagreement concerning the sizes of pipe to be used on the various grades encountered in the maintenance replacement program. Hydraulic studies performed during this initial phase yielded a nomograph from which pipe sizes could be determined for particular field conditions, and from the studies it was concluded that a 178 mm (7") diameter pipe would be adequate for most practical cases.(2)

On the assumption that all the infiltration could be handled by underdrains, it was resolved that a less costly scheme could be developed wherein the longitudinal curtain wall could be eliminated. After much discussion, an alternative technique for replacing undermined sidewalks was recommended and adopted. With this technique, shown in Figure 5, the subgrade soil is protected by polythylene sheeting and the infiltrated water is directed through a highly porous medium to a perforated pipe connected to the existing storm drain system. Since this scheme was devised as a maintenance replacement procedure, the vertical dimensions are shown as variable, depending on the conditions encountered. This technique showed a 53% cost savings over the previously used curtain wall method.(2)

Since there are situations in which the use of the underdrain system is not practical because there is no conveniently located storm drain system or other type of drainage facility, the Phase I report further suggested the experimental use of the scheme without an underdrain illustrated in Figure 6. The suggestion was based on the two assumptions: (1) that the design would prevent most of the infiltrated water from reaching the subgrade soil, and (2) that the small amount of water that did make its was to the soil would not cause undermining. While the designs with and without underdrains have been incorporated as standard procedures in contracts let to replace undermined sidewalks, the design with the underdrain is used in most cases. The system without the underdrain has been used sparingly in situations where (1) short sections of sidewalk are replaced and existing drainage systems are not conveniently located, and (2) at the upper part of vertical curves where undermining is normally very minor and it is not financially justifiable to replace additional entrances and excavate in order to put in the underdrain system. The sidewalks at the middle and lower segments of vertical curves normally undergo moderate to severe undermining, and in replacing them the underdrain design is used.



(a) Plan View
(Not to Scale)



(b) Section A-A
(Not to Scale)

Figure 4. Sidewalk reconstruction with curtain wall and drainage system. (1 in. = 25.4 mm)

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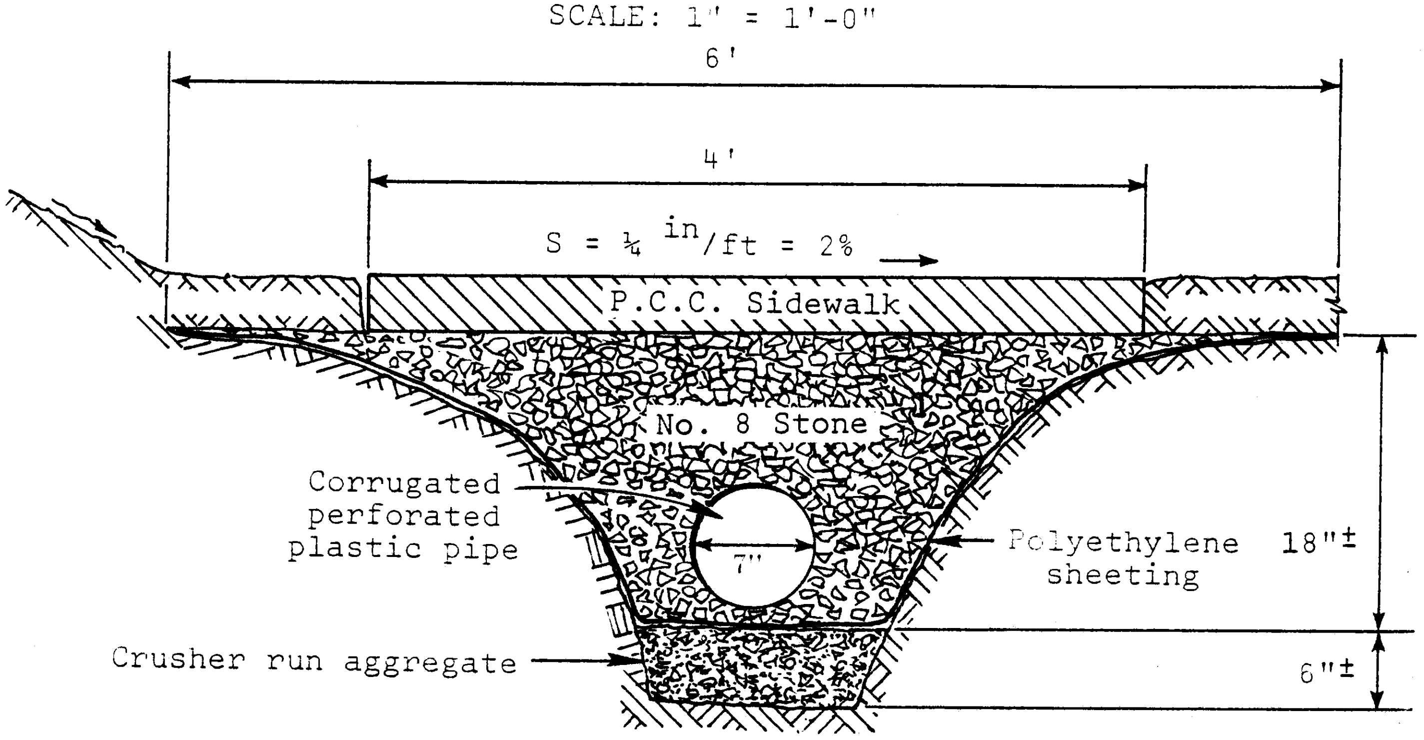

Figure 5. Cross section of experimental sidewalk installation. (1 ft. = 0.3 m)

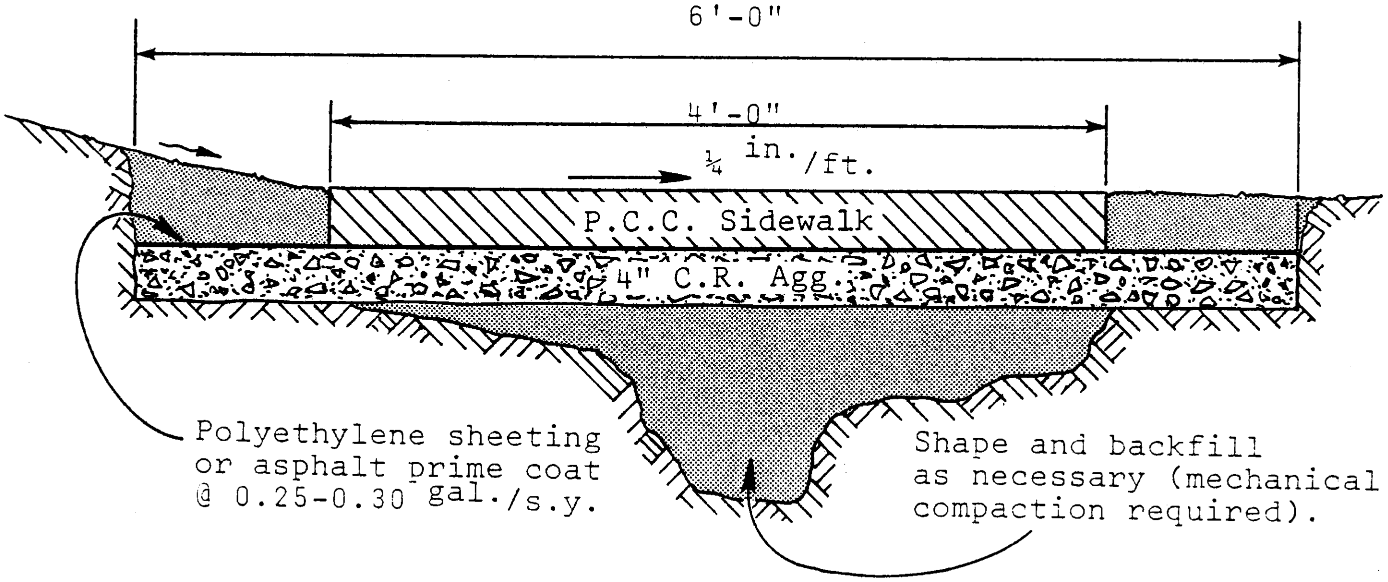

Figure 6. Proposed sidewalk replacement without underdrains. (Metric conversion 1 ft. = 0.3 m).

The effectiveness of the design without underdrains is somewhat questionable, especially if it is used as the singular repair procedure in a severe situation. A similar method of prevention was studied with the use of the model sidewalk set up in the Council's laboratories and will be discussed later in this report.

REVIEW OF PHASE II

The second phase of the project was undertaken to establish the relationship between undermined sidewalks and particular soil characteristics. It had long been suspected that the soils in areas where sidewalk undermining occurred were highly erodible, but this suspicion had never been fully confirmed through the technological means available. Soil samples were taken from various locations throughout Fairfax County. These samples were taken at locations adjacent to sidewalks that either undoubtedly or very possibly were experiencing undermining problems and at locations next to sidewalks showing no evidence of undermining.

Standard laboratory procedures were used to determine coarse and fine gradations, Atterburg limits, optimum moisture content, and the maximum density of each sample, and the soils were classified according to the AASHTO system. A specific gravity test and a hydrometer analysis were also performed on each sample, to provide data for a complete grain-size distribution curve. Finally, a test was made on each sample to determine its organic matter content.(3)

The soil testing provided the information needed for the establishment of an erodibility factor (K) for each soil sample through the use of an erodibility nomograph developed by Wischmeier, Johnson, and Cross.(7) The soil parameters needed for use of the nomograph were (1) percentage of silt plus very fine sand (from 0.002 to 0.10 mm), (2) percentage of sand (from 0.10 to 2.0 mm), (3) percentage of organic matter, (4) a soil structure index, and (5) a permeability class code. The first two parameters were calculated from the grain-size distribution curve, and the third was established directly from the results of the test for organic matter. The final two parameters were determined through the use of generalized guidelines in chart form developed by the author.(3)

Additionally, the effect of the length and slope of the particular sample site were combined into a single topographical factor designated LS, by using mathematical procedures developed by others(8,9) and described in the Phase II report.(3) Ultimately, the K and LS factors were combined into a modified universal soil loss equation to compute an undermining potential index (UPI) as

$$UPI = 100 \cdot K \cdot LS$$

The magnitude of the UPI correlated extremely well with the occurrence and absence of sidewalk undermining. In all instances where the UPI was less than 21 there was no evidence of sidewalk undermining at the sample site; and in almost all cases in which the UPI was equal to or greater than 21, undermining of the sidewalk at the sample site was either very probable or definite. The few discrepancies that were encountered were partially, if not completely, rationalized in the report.(3)

The Phase II report further concluded that even though the UPI system seemed very efficacious in establishing the potential for sidewalk undermining at a particular site, it would be quite costly and difficult to employ. Thus, further analysis of the data resulted in the development of an alternate system whereby the erodibility of the soil is estimated from soil tests currently required as a normal procedure and the topographical factors affecting undermining are generalized. This alternate system defines the factors that are necessary and sufficient for sidewalk undermining to develop as follows:

1. a soil having 34% or more passing the No. 200 sieve and a plasticity index of 13 or less;
2. a longitudinal gradient of 3% or more; and
3. a potential for drainage from more than two residential lots to drain toward the street.

The relationship of undermining to the soil's erodibility characteristics as defined in this alternate system is shown graphically in Figure 7. Because of the economy and ease with which this system can be applied, it was recommended for use in new sidewalk construction to identify sites where there is a high probability that sidewalk undermining will occur.(3)

Finally, an examination of soil survey reports of other counties showed strong correlations between the soil types found in Fairfax and those in other counties in the Piedmont region. Consequently, the Phase II report concluded that sidewalk undermining could become a problem any place in the Piedmont region where sidewalks are built with a geometric arrangement similar to that used in Fairfax.(3)

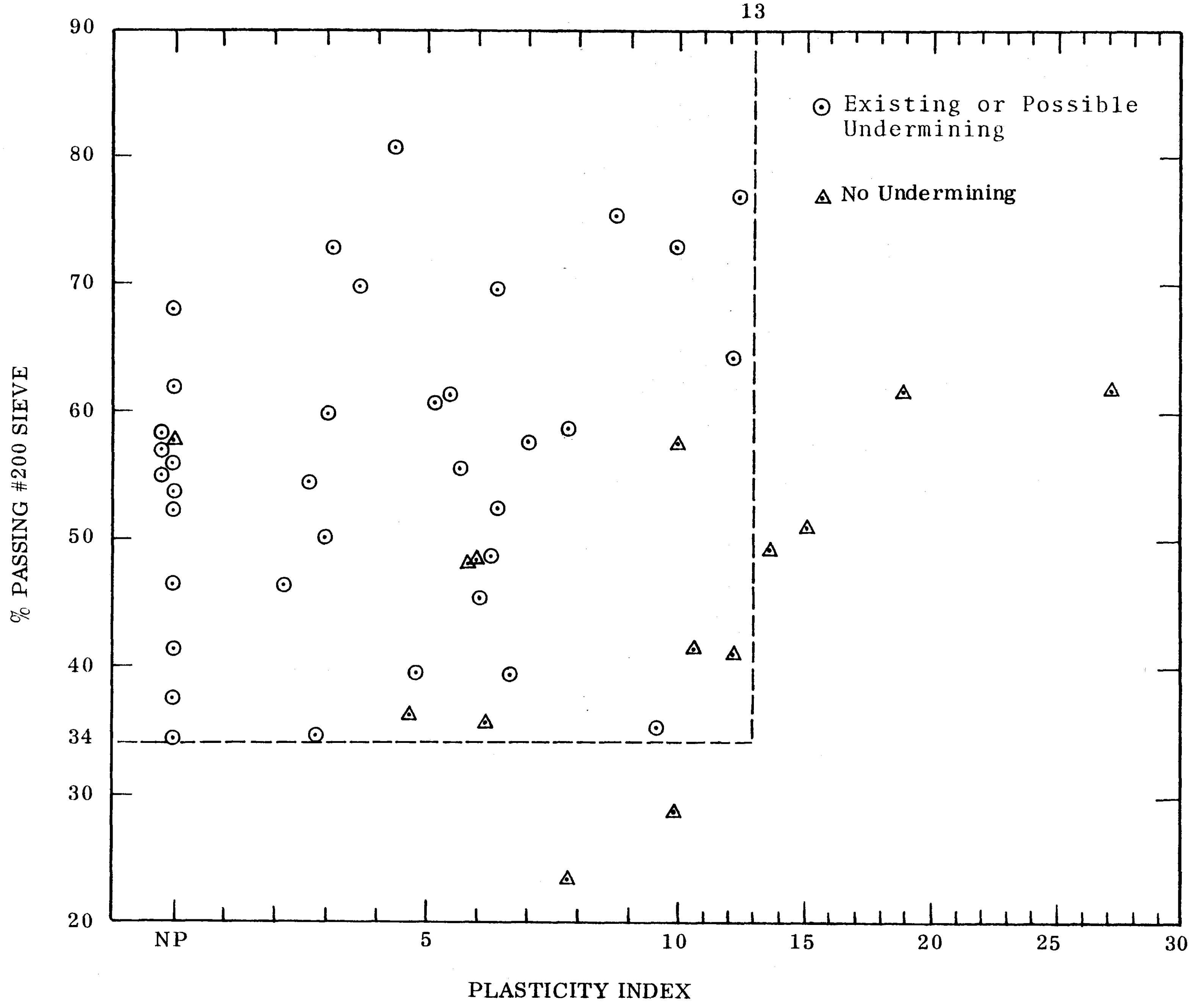

Figure 7. Undermining of sample sites plotted as percent passing #200 sieve versus plasticity index.

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SURVEY OF VIRGINIA CITIES

Upon the suggestion of the Pavement Research Advisory Committee, a survey of the independent cities in Virginia was made to ascertain their sidewalk construction specifications and standard designs. The survey also inquired about any problems the cities were experiencing with the undermining of sidewalks, or other problems that could logically be investigated as part of this research project. The survey proved to be unproductive in that no cities reported such problems.

However, the following rather unique construction specifications or requirements were noted.

1. Alexandria uses the standard sidewalk cross-slope of 2% but requires the cross-slope of the utility strip to be 4% minimum.
2. Fredericksburg uses a drainage fill under the sidewalk, when required by the Director of Public Works, that conforms very closely to Virginia aggregate size No. 56.
3. Radford requires a minimum of some 50 mm (2") of stone beneath the sidewalk, and further specifies a minimum of 150 mm (6") of concrete on the outside edges of the sidewalk with 100 mm (4") in the center.
4. Richmond does not allow sand to be used as fill material under the sidewalk because of previous erosion problems when sand was used.
5. Winchester requires a minimum of 50 mm (2") of stone under the sidewalk to serve as a drainage field.

In support of the requirement of the city of Alexandria, the Asphalt Handbook published by the Asphalt Institute also suggests that the cross-slope of the utility strip should be twice or more the cross-slope of adjacent sidewalk to assure proper runoff.

While no definite sidewalk undermining problems were reported, numerous replies stated that the major maintenance problem with sidewalks was the damage caused by tree roots. This problem is also very prevalent in the Fairfax area. Even though a recommendation to correct this situation is beyond the scope of this project, the proper authorities should be informed of the problem and they should develop a feasible solution.

The survey was extended into the state departments of transportation in a number of states, in particular, Pennsylvania, Maryland, North Carolina, South Carolina, and Georgia. Again, the survey results were unproductive, mainly because sidewalks are not controlled at the state level in those states as they are in Virginia. However, it is known that some suburban Maryland counties in the Washington, D. C. area do have problems with undermined sidewalks, and it is at least conceivable that counties in the other states are experiencing sidewalk undermining problems, if they build with the same geometric configurations Fairfax uses.

FIELD TEST SECTIONS

As is generally done in this type of research, field test sections were established to evaluate different procedures for possible use in preventing the occurrence of sidewalk undermining. Fortunately four test installations had been made on newly constructed sidewalk in 1971, by the Sidewalk Failure Study Committee with the cooperation of land developers in Fairfax County. All of the sites for the installations meet the last two of the three requirements of the generalized system previously mentioned; i.e., they have a greater than 3% longitudinal slope and the drainage from at least two residential lots drains toward the street. They differ only in the magnitude of these variables.

At each site, the sidewalk on the left side of the street was constructed using normal practices, with the addition that a minimum compaction of 95% was attained and concrete transverse cut-off walls were installed on both sides of drive aprons and at each expansion point in the sidewalk.(10) These cut-off walls are approximately 200 mm (8") deep and extend at least 150 mm (6") on each side of the sidewalk.(10) The right side of the street in each location was given special consideration. Table 1 lists the special construction procedures being tested at the sites, and shows that the average soil characteristics in the areas are well within the criterion for the proposed generalized system, used to identify sites likely to experience undermining.

The dimensions of the test installations are given in Figures 8, 9, and 10. Pertinent features not shown are the extension of the curtain wall to the full length of the sidewalk at test site 3, and the connection of the underdrain pipe to the drop inlet at the lower end of test site 4. At each site close control was maintained over the construction to ensure that a minimum of 95% compaction was obtained on the subgrade, that a good quality concrete was used, and that the placement procedure followed good construction practices. All of these installations were made between May and July of 1971. Their precise locations are given in reference 11.

Table 1

Test Installations Made by Sidewalk Failure Study Committee

Test Area No. +	Construction Procedure Tested	Average Soil Characteristics at Site	
		% Passing #200 Sieve	PI
1	Crushed gravel subbase without cut-off walls	55.5	2.4
2	Crushed gravel subbase with cut-off walls	73.0	7.0
3	P.C.C. curtain wall built monolithic with and on high side of sidewalk	69.7	4.2
4	Underdrain placed under high side of sidewalk	75.9	7.4

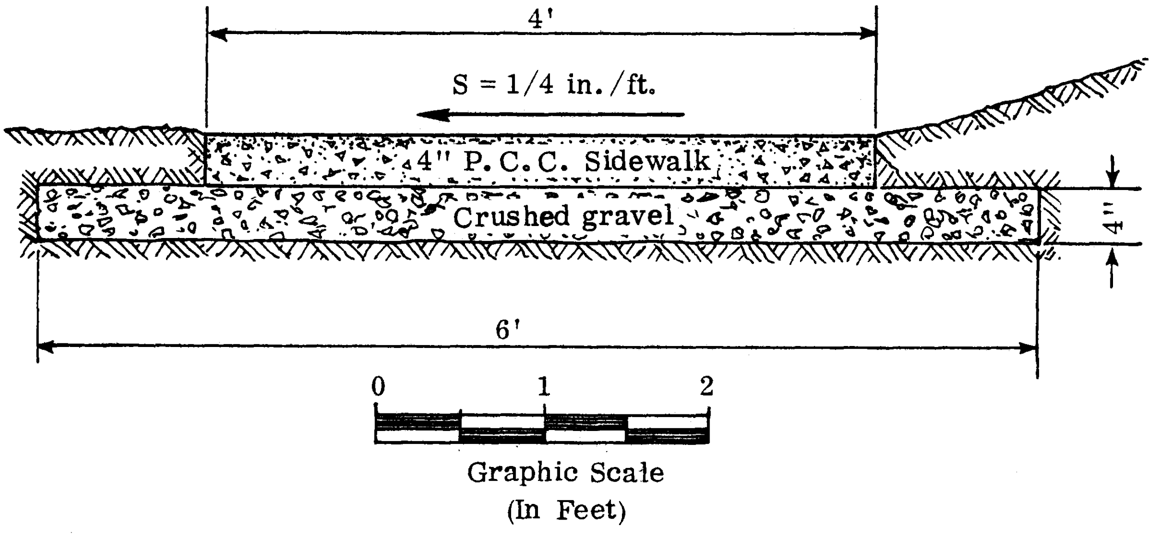


Figure 8. Design of installations made at test sites 1 and 2.

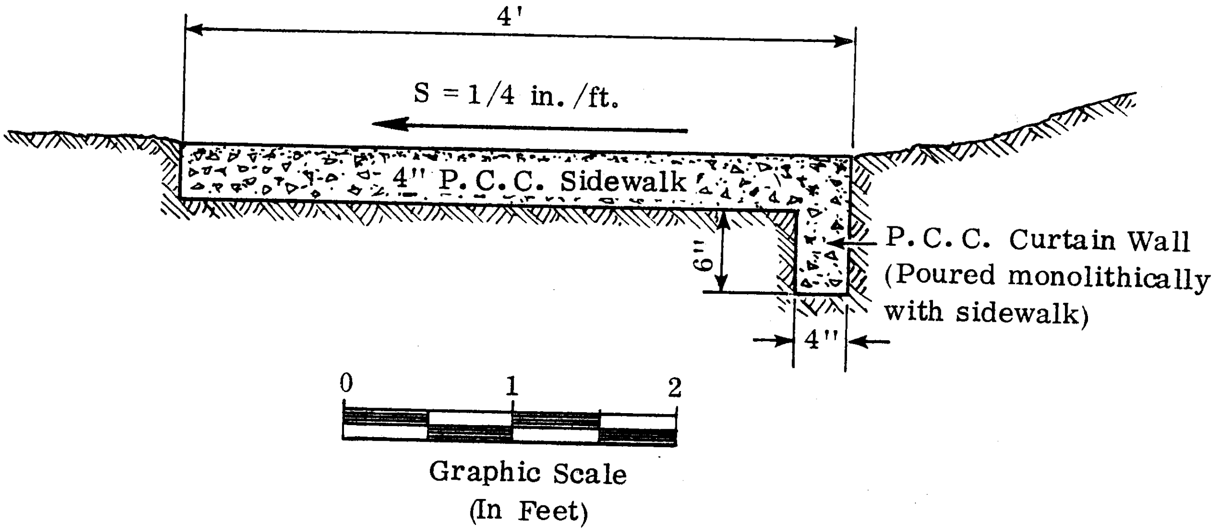


Figure 9. Design of installation at test site 3.

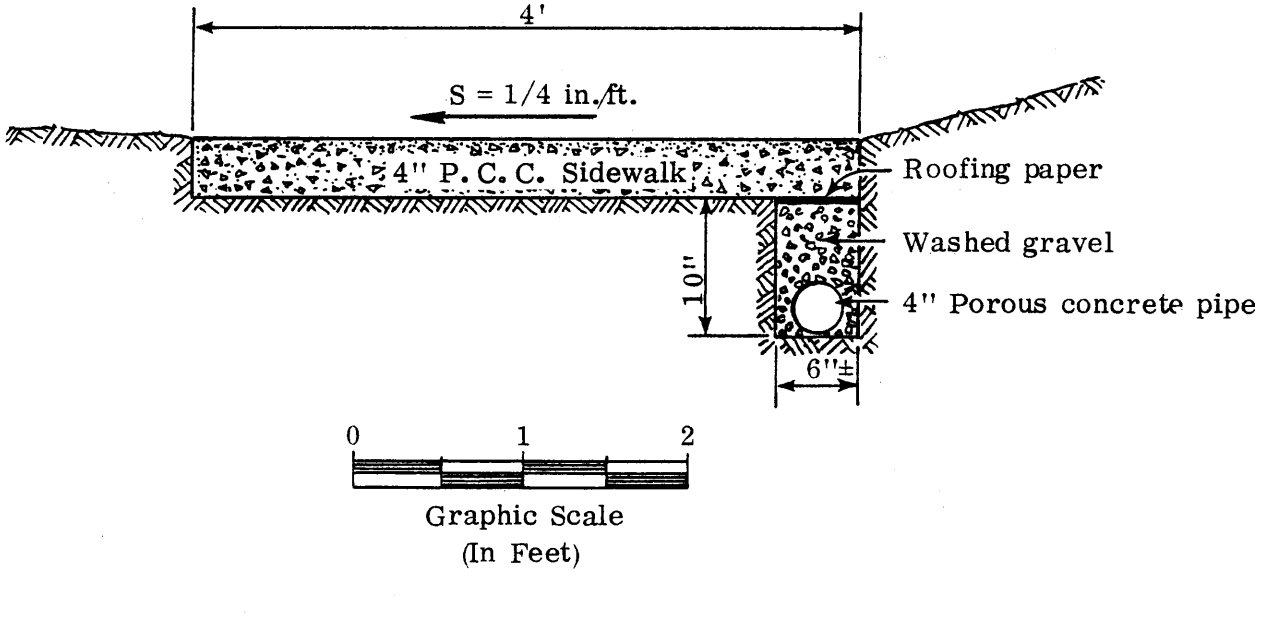


Figure 10. Design of installation at test site 4.

Test site 5 is the location of the initial installation of the underdrain system proposed by McGhee in Phase I and shown schematically in Figure 5 of this report. This installation was made in August 1974 by a maintenance crew of the Fairfax Residency in replacing an undermined sidewalk at a site that obviously does meet the criteria for identifying sites likely to experience undermining. It should be emphasized that even though the underdrain design has been used almost exclusively in replacing undermined sidewalks since its adoption, it was recommended as an interim solution until a more economical solution could be found.(2)

A sixth procedure was tried at three locations with the cooperation of the contractor on a sidewalk replacement contract. One installation was made in October 1976 and the other two in May 1977. Two of the sections were at sites sampled in the soil correlation studies phase of this research project and the third was only one block from one of these two. Obviously, all three sites meet the conditions of the generalized identification system. The procedure tested called for modification of the subsurface drainage system presently used. The modification consisted of the installation of a single section of underdrain pipe at the drop inlet to transfer any infiltrated water from the #8 stone to the drop inlet, while the remainder of the pipe and the base material (refer to Figure 5) were omitted. It is felt that this modified underdrain system would function as well and obviously be more economical than, the system currently used. This observation will be elaborated upon subsequently.

MODEL SIDEWALK SIMULATING UNDERMINING

Observations and evaluations of many undermined sidewalks have not led to the establishment of a time frame within which the undermining will occur, mainly because of the large number of variables involved, including length of time for a sidewalk to undermine are (1) the magnitude of the longitudinal slope, (2) the total area of land draining toward the street, (3) the length of the sidewalk, (4) the amount of rainfall received in a given period of time, (5) the percentage of saturation of the subgrade soil, and (6) the erodibility factor for the subgrade soil. Additionally, the author's August 1975 investigation and evaluation of the four test sections established by the Sidewalk Failure Study Committee were inconclusive.(12) Not only could no evidence of undermining be found at any of the sites which had been given special treatment, but also no unmistakable conclusions could be drawn from the so-called normal construction sites.(12)

In light of the above, it was decided to attempt to simulate sidewalk undermining through the construction of a model in the Research Council's laboratory. The factors affecting sidewalk undermining, which were listed above, were simulated in a severe degree in the model and were kept constant, while the treatment of the subgrade to prevent undermining was varied. The severity of conditions created in the model enabled the testing of a given treatment in a relatively short time. Yet, the factors used were realistic as compared to values in the field, except for the intensity of the simulated rainfall, which will be discussed later.

General Details of Model

An overall view of a typical setup of the model sidewalk is shown in Figure 11. The trough in which the subgrade soil was placed was constructed with interior dimensions of 2.4 m (8') by 0.6 m (2') and on an approximately 9.4% longitudinal slope. The interior surfaces of the trough were waterproofed with an RC-250 liquid asphalt and then sprinkled with sand to provide frictional resistance against the movement of the soil. The vertical wall on the right-hand side of the trough in Figure 11 was constructed of plexiglass to permit observations of the undermining process. Additionally, for the same purpose, it was decided to use plexiglass to represent the sidewalk.

Because of the lack of friction between the plexiglass sidewalk and the subgrade soil in the model, the plexiglass was enclosed in an aluminum frame rigidly attached at the upper end of the trough to prevent sliding. The total width of the plexiglass sidewalk and its aluminum frame was 360 mm (14"). The sidewalk was given no transverse slope, because a zero cross-slope of a sidewalk is encountered very often in field situations and to provide ease of testing.

The model sidewalk was composed of numbered pieces of plexiglass of a constant width that were placed in the same sequence in the aluminum frame for each setup of the model. Most of the pieces were layed end-to-end with the seam simulating a crack in a concrete sidewalk. Spacers were inserted between some pieces to simulate opened joints and/or cracks in the concrete sidewalk. Very often in field situations the material placed in an expansion joint deteriorates after some period of time and allows water easy access to the underlying soil. In the model the joint openings were left unfilled so as to accelerate this process. Additionally, the plexiglass "slabs" were of varying lengths to simulate the differing distances between cracks and/or opened joints that have been observed in the field.

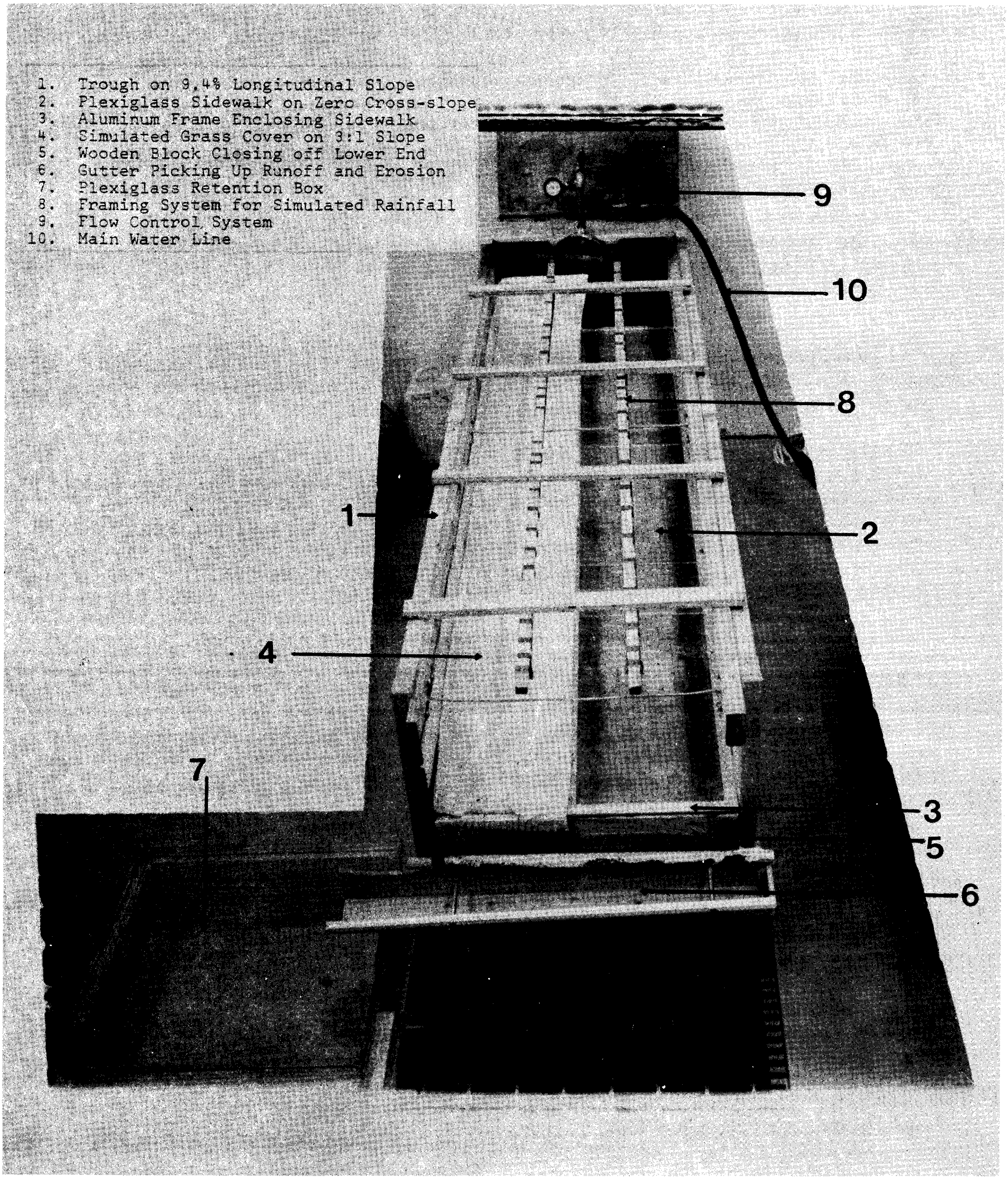


Figure 11. Typical setup of model sidewalk.

In the remaining 200 mm (8") width of the trough, soil was built up on a 3 to 1 slope from the inside edge of the aluminum frame (i.e. in the middle of the trough) to the left vertical side of the trough as shown in Figure 11. This area represented the yard draining toward the sidewalk and, again, the magnitude of the slope used in the model is often encountered in the field. Three layers of Hold/Gro erosion control fabric were placed on top of the simulated yard to represent grass cover. This particular fabric was used only because of its availability at the Council. It did perform well in that no substantial erosion of the slope occurred due to the impact of the simulated rainfall, and yet it did not prevent the seepage of water into the underlying soil.

The lower end of the trough was closed off with a wooden block 100 mm (4") in height, which was the depth of the soil underneath the plexiglass sidewalk. Observation of many undermined sidewalks in the field resulted in the conclusion that a "blocking off" effect very often occurs at the fillet of a sidewalk — the widened section of the walk almost always found at the intersection of two subdivision streets. As previously mentioned, a utility strip normally is constructed between the sidewalk and the edge of pavement. But at the intersection the utility strip is eliminated, and the sidewalk is widened to abut the back face of the combination curb and gutter.

As noted before, the soil eroded from underneath a sidewalk usually is deposited at the low point of the vertical curve. In innumerable cases this low point occurs either at or near the fillet, as illustrated in Figure 12. From the photograph it is obvious that part of the soil eroded upgrade has been deposited under the fillet and forced the sidewalk slabs upward. An additional portion of the eroded soil has been washed out through an opening in the sidewalk or an opening at the interface of the sidewalk and the back face of the combination curb and gutter, as is obvious in the foreground. The remaining portion of eroded soil probably was carried to the storm sewer system. The hypothesized "blocking off" effect, which was the reason for closing off the lower end of the trough in the model, occurs because the back face of the combination curb and gutter is 330 mm (13") high while the abutting sidewalk is only 100 mm (4") deep.

Finally, as identified in Figure 11, a short section of aluminum gutter was attached along the closed-off lower end of the trough. The gutter served to direct all runoff and eroded material into the large plexiglass container (maximum capacity approximately 27-3/4 gallons, or 105 liters) that is also identified in the figure.

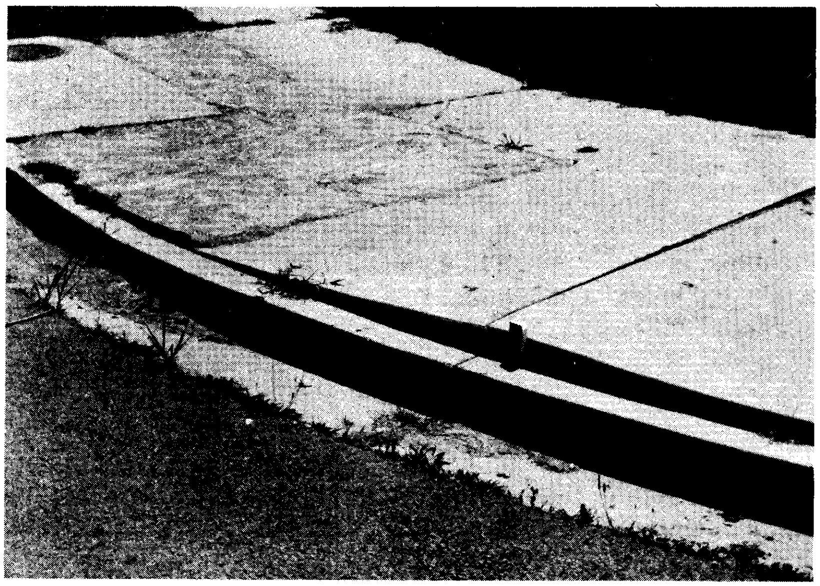


Figure 12. Typical fillet of sidewalk forced upward by undermining upgrade.

After each simulated rainstorm was applied to a model setup, the eroded material was allowed to settle, the excess water was siphoned off, and the dry weight of the eroded material was determined. The total amount of erosion for each rainstorm was computed in metric tons per hectare (tons per acre) by dividing the dry weight of the material by the area of the plexiglass sidewalk.

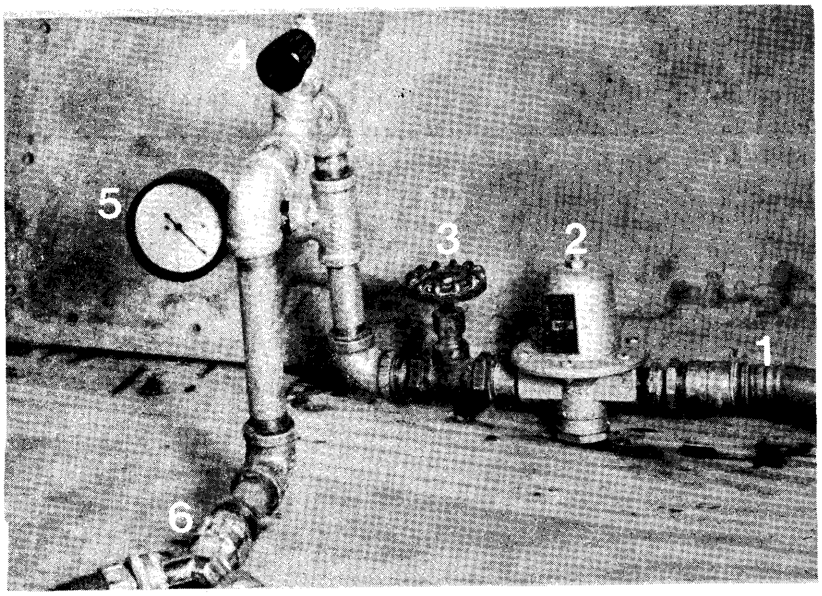
Rainfall Simulation

Connected along the top of the trough in Figure 11 is the framing system to which was attached two lines of spray hose utilized to simulate rainfall over the inside of the trough. Since undermining results from the detachment and deportation of the subgrade soil by flowing water, no attempt was made to accurately produce raindrops. Instead, the intent was to obtain a good distribution of water over the inside area of the trough at a constant, reproducible flow rate. It is felt that these goals were achieved.

A close-up of the flow control system is given in Figure 13. The pressure flow from the main water line was reduced and controlled by a diaphragm type pressure-reducing valve. A gate valve placed next in the system was used to cut the water on and off in the simulated rainstorms. Next, a needle-type valve installed in the top of a loop was used to bleed off any air that might become entrapped in the spray hoses. Finally, a pressure gauge with 860 Pa (1/8-psi) gradations was positioned as a monitoring tool, and the water flowing past this gauge was divided into two spray hoses by a y-shaped splitting device. The purchased spray hoses were modified by making additional openings in them to produce an even distribution of water over the inside area of the trough.

The desired intensity of the simulated rainfall was established through experiments without the soil, plexiglass sidewalk, or simulated grass slope in place. By establishing the average flow rate for the duration of such a dry run, the intensity of the simulated rainstorm was easily calculated from the Rational Formula, since the drainage area was known and the coefficient of runoff was equal to one for a dry run.

Storm sewer systems in the Fairfax area are designed for a 10-year frequency storm, which has an intensity of 130 mm/hr (5.1" per hour) and a duration of 15 minutes. Initially it was intended to use this design intensity but with a duration of 30 minutes, for a model run, a combination that approximates a 100-year frequency storm.



1	Main Water Line
2	Pressure-Reducing Valve
3	Cut-off Valve
4	Air-bleeder Valve
5	Pressure Gauge
6	Y-shaped Splitter

Figure 13. Flow control system for model sidewalk.

The pressure-reducing valve was adjusted to permit a flow rate that seemingly corresponded to the desired intensity. In making repeated dry runs on the model to ensure that the calculated intensity was reproducible, it was found that the flow rate increased until it peaked and stabilized. This increase in the flow rate was deduced to result from a self-cleansing effect in the system. Readjustment of the flow rate to the magnitude initially desired would have meant a further reduction of the pressure in the line, which at this time was only 14 kPa (2-1/8 pounds per square inch). The accuracy of any lower pressure readings was questionable and, furthermore, readjustment of the flow rate would have entailed additional time required for corroborating an average flow rate and ensuring its reproducibility. Since the intensity of the simulated rainfall to be used would have no effect on the success or failure of the model, it was decided that the flow rate would not be readjusted.

Thus, the intensity of the simulated rainfall employed in the model was approximately 160 mm/hr (6.2 inches per hour). The magnitude of this intensity necessitated a reduction in the duration of the rainstorm to 25 minutes in order that the plexiglass box would not overflow during an actual run on the model. Through extrapolation of intensity-frequency-duration curves for the Washington, D. C. area, the simulated rainstorm was found to approximate a 250-year frequency event. Finally, it was concluded from the drying and drainage rate that repetition of the simulated rainstorm at 24-hour intervals would allow elimination of the subgrade soil saturation factor as a variable in the model.

Properties of Soil Used in Model

The final variable for which it was necessary to maintain consistency in order to attain a reasonable comparison between successive setups of the model was an erodibility factor for the soil used. Soil samples were obtained from different locations in Fairfax County and each was subjected to the complete series of tests noted in the Phase II report.(3) The sample having the largest erodibility factor was for use in the model sidewalk. An enormous volume of the chosen soil was then transported to the Research Council and, through a random sampling procedure, was placed in fifty 75-l (20-gallon) containers for storage.

Preliminary calculations had established that approximately five 75-l (20-gallon) containers of soil would be needed for each setup of the laboratory model. Thus, by establishing the total number of operations to be tested by the model and by allowing for realizable errors in estimations and possible modification of the model, the total volume of soil to be needed was estimated. These preliminary estimates were necessary to ensure consistency in the soil used for the different setups of the model.

To verify the accuracy of the random sampling procedure employed in splitting the soil into a size practical for handling, samples from two different containers were subjected to a complete test series and the erodibility factor was determined. Table 2, which lists the physical properties of each sample tested, shows that the consistency of the soil was maintained for the successive setups of the model.

Furthermore, as with the other variables, the erodibility of the soil used in the model was realistic and yet rather severe, since only 20% of the samples analyzed in the soil-undermining correlation study for this project had an erodibility factor equal to or greater than 0.34.(3)

Table 2

Physical Properties of Soil

Property		Sample #1	Sample #2
Percentage Passing	— 1" Sieve*	100.0	100.0
	— 3/8" Sieve	99.9	100.0
	— No. 4	99.3	99.9
	— No. 10	95.9	96.1
	— No. 40	79.6	80.4
	— No. 100	54.6	55.2
	— No. 200	40.3	40.9
Liquid Limit		28.8	29.6
Plasticity Index		NP	NP
AASHTO Classification		A-4(1)	A-4(1)
Max. Dry Density, pcf		108.5	108.8
Optimum Moisture Content, %		17.0	15.7
Specific Gravity		2.72	2.73
Percentage Sand (0.10 to 2.0 mm)		47.9	46.6
Percentage Silt plus very fine sand (0.002 to 0.10 mm)		44.5	45.0
Percentage Clay (less than 0.002 mm)		3.5	4.5
Percentage Organic Matter		1.0	1.0
Structure Index		3	3
Permeability Class		3	3
Erodibility Factor		0.34	0.34

*Metric conversion: 1 inch = 25.4 mm.

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Compaction of Soil for Model Setup

The most difficult problem encountered in the establishment of the model sidewalk was the attainment and subsequent testing of the compaction of the soil. Because of the size of the trough, it originally was felt that devices normally used in the laboratory for soil compaction would not be efficient, and obviously compaction devices customarily used in field work would be too large.

A wooden mold with a removable collar was constructed such that the compacted soil in it would measure 0.6 m x 0.6 m x 100 mm (2' x 2' x 4") which equals a volume of 0.038 m^3 (1-1/3 $ft.^3$). The mold was used as a Proctor in that the dry unit weight of the soil and, therefore, the percentage compaction was determined from the total wet weight and the moisture content. It was also used for testing different compaction devices and compactive efforts in selecting the most efficient method for use in the model setups. Additionally, the size of the mold allowed moisture and density counts to be taken for each compactive effort in these trial tests with a Troxler 2401 nuclear gauge in the backscatter position. The moisture and density counts resulted in a calibration of the gauge that was used in determining the percentage compaction and moisture content of the soil in the actual model setups.

The first device used to compact the soil in the trial tests with the wooden mold was a Black and Decker Hammer-Drill. Approximately 94% compaction was attained with this device, but it was eliminated from consideration because of its extreme noisiness and questionable durability. A device tested and rejected because of its ineffectiveness in attaining compaction was a scaled-down version of a vibratory sled constructed by rigidly attaching a hand-held concrete vibrator to a heavy steel plate.

Since these two tools were rejected for use and no commercial device small enough to be used in the laboratory model could be found, it was decided that a drop-hammer would be used for compacting the soil in the model. Instead of using the drop-hammer normally employed in running Proctors by the AASHTO T-99 method, a Marshall hammer with a 170 mm (6-3/4") by 216 mm (8-1/2") by 13 mm (1/2") plate attached to the bottom was used with the wooden Proctor mold. This arrangement had been employed in previous work performed at the Research Council in the calibration of a nuclear-moisture-density device. Through repeated trials with the wooden mold it was established that 300 blows of the hammer for each of 2 layers (50 mm [2 in.] per layer) of soil resulted in approximately 95.5% compaction. Since the wooden Proctor mold was one-fourth the size of the trough, this effort converted to 1,200 blows for each of 2 50 mm (2 in.) thick layers of soil compacted in the trough.

For possible increased efficiency, it was decided to try a Marshall hammer with a 100 mm (4") by 100 mm (4") by 13 mm (1/2") plate attached. This configuration did prove to be more efficient in that 250 blows of the hammer for each 2 layers of soil achieved approximately 98% compaction. Obviously, this effort converts to 1,000 blows per layer of soil compacted in the trough and, therefore, a reduction in the manual labor involved in compacting the soil for a model setup. In the trials, the soil was compacted at or very near optimum moisture content.

In compacting the soil in the wooden Proctor mold the optimum moisture content was attained by adding water through the use of a Lancaster Mixer available in the Council's concrete laboratory. This mixing procedure gave a good distribution of water throughout the soil, and it was used in the subsequent tests on the model setups. The capacity of the Lancaster Mixer enabled the mixing of a batch consisting of one 75-*l* (20-gallon) container of soil. Since, as previously mentioned, about 5 of these containers of soil were needed for each setup, the total time involved necessitated that the process of mixing the soil to its optimum moisture content be performed on a Friday and with the actual placement and compaction of this soil in the trough taking place on the following Monday. Thus, several rainfall simulations were possible prior to weekend interference. Little or no moisture loss occurred during this time interval, since each container was tightly sealed.

As mentioned before, a moisture-density calibration for the nuclear gage was obtained so that the percentage compaction and moisture content of the soil placed in the trough could be determined. This calibration was found to be inaccurate because of differences in the wooden Proctor mold and the trough. The main differences were (1) that the trough was coated with a bituminous emulsion while the mold was not, and (2) the bottom of the trough had timber supports while the mold didn't. These differences caused incorrect calculations of the wet density and of the weight of water in the soil. However, plots of the number of blows versus the percentage of compaction attained at optimum moisture for each of the two hammers through repeated tests with the wooden Proctor mold showed that the desired soil compaction would be attained in each setup of the model.

RESULTS OF TESTS WITH MODEL

Once all the identified problems were solved and the basic concepts of the model were established, a setup of the model was made to test its validity. The results with the test setup were to be used as a base for comparisons of the compaction obtained with subsequent setups of the model. Tests on an initial setup of the model were performed without the lower end being closed off as discussed previously. A netting with 10 mm-(3/8")square openings was placed across the opened lower end to prevent the soil from falling off the trough due to its lack of cohesion while not retarding the erosion of the soil by water flowing across it. The netting performed as expected, but it was concluded that the closed-off lower end resulted in a better simulation of the typical undermining found in the field, as will be substantiated subsequently. Therefore, the data from this initial setup are not reported.

78% Compaction

The trial tests on the model were made with the soil compacted to 78% maximum dry density as obtained by the AASHTO-T99 method. This particular percentage was chosen because the density of a soil in an undisturbed state would usually be between 75% and 80% and many sidewalks have been constructed on undisturbed soil. Additionally, as stated previously, the results from tests on the first setup were used as a base against which results from subsequent tests on the subgrade soil in the model could be compared. In this setup the soil was compacted in the trough at its optimum moisture content by using the Marshall hammer with the 170 mm x 216 mm x 13 mm (6-3/4" x 8-1/2" x 1/2") plate attached.

As evidenced by Figure 14, a definite erosion channel was formed underneath the plexiglass sidewalk by the initial simulated rainstorm in the tests on this control setup of the model. Observations made during this initial rainstorm were as follows:

1. The seams at abutting plexiglass slabs which simulated cracks did allow a substantial amount of water to gain entry to the underlying soil;
2. the openings in the plexiglass sidewalk allowed a large amount of water access to the subgrade soil;
3. even though care had been taken to obtain a smooth, even subgrade, the slightest imperfection of the subgrade enabled a small amount of water to flow underneath the plexiglass sidewalk at the beginning of the rainstorm, to erode the soil, and, eventually, to establish an erosion channel; and
4. until the erosion channel was established, the water seemed to "boil" at the openings in the plexiglass sidewalk and in doing so eroded some soil particles.

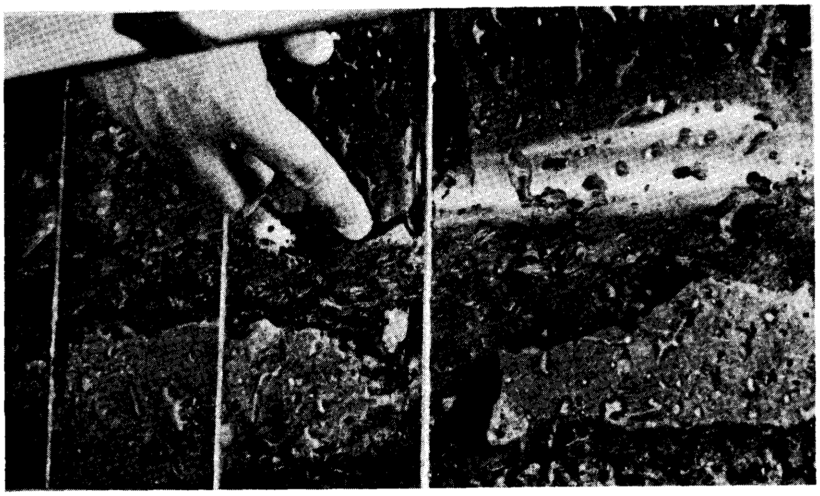

Figure 14. Erosion channel developed by initial simulated rainstorm with soil compacted to 78% maximum dry density.

At 24-hour intervals, three additional simulated rainstorms were run with this setup of the model. These caused the erosion channel formed during the first rainstorm to widen and deepen, but resulted in no additional channel being established. Figure 15 evidences the undermining caused by the four simulated rainstorms. The only supplementary observation made during the last three rainstorms was that, due to surface tension, some of the water flowed on the underside of the plexiglass sidewalk instead of along the subgrade. This phenomenon resulted in less soil being eroded from the model.

As previously mentioned, it was concluded that the model having a closed-off lower end provided a closer simulation of sidewalk undermining than did the model with an open lower end. Not only did closing off the lower end of the trough simulate the "blocking off" effect discussed earlier but also, in the author's opinion, produced the effect resulting from the longitudinal gradient flattening at the sidewalk fillet. At many undermined sidewalks the longitudinal gradient has been observed to form a compound vertical curve. Typically, undermining is shallow at the top of the curve, where the slope is small; deepest in the middle, where the slope is the largest; and shallow again at the bottom, where the gradient flattens. The longitudinal shape of the erosion channel in the model with the lower end closed-off was much the same. Therefore, it was resolved that the model accurately reflected field conditions and could be used to test various procedures for preventing sidewalk undermining.

Figure 15. Erosion channel developed by four simulated rainstorms on control setup of model.

98% Compaction

The initial procedure to be tried in preventing undermining in the model was to obtain a high level of compaction of the subgrade soil. The soil was compacted in the trough to 98% of its maximum dry density by employing the Marshall hammer with the small square plate attached. It became apparent during the imposition of the simulated rainstorms on this model setup that four sequential rainstorms resulted in insufficient data for comparison to the results obtained on the control setup. Thus an additional four rainstorms were run with the lapsed time between the fifth and sixth rainstorms being 72 hours instead of 24 hours because of an intervening weekend. An identical rainstorm sequence was followed for subsequent setups of the model.

Figure 16 illustrates the undermining that resulted from the eight rainstorms. A small amount of erosion of the simulated yard slope is noticeable in the upper portion of the figure. This was caused by one particular stream of water hitting the vertical side of the trough and flowing underneath the fabric, and it is obviously negligible as compared to the amount of soil eroded along the edge of the plexiglass sidewalk. Even though the location of the undermining in the model is not representative of that normally observed in the field, it was concluded that the undermining in the model was caused by flowing water and not the impact of the simulated rainstorm. Therefore, a comparison could be drawn between the results from this setup and those from the control setup.

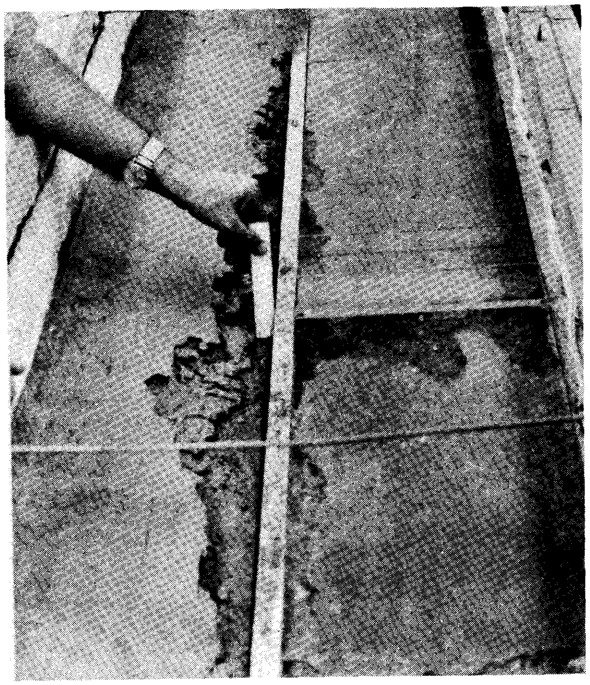

Figure 16. Erosion channel developed by eight simulated rainstorms on soil compacted to 98% maximum density.

Many of the observations made with the control setup were also noted for this setup. Additionally, there was a large amount of swell of the soil, about 9-1/2%, as can be noted in Figure 17. The soil swell also promoted the buckling of some of the plexiglass "slabs" as demonstrated in Figure 18. A CBR test performed on a sample of the soil soaked for four days at this time resulted in a swell of approximately 1-1/2%. The difference in these values are reasonable when one considers that the plexiglass weighs much less than the 56 N (12-1/2 pounds) of weight placed on a CBR specimen during the soaking period. Nevertheless, it is conceivable that the same swell pressure was present in each case.

The author's conclusions concerning the swell phenomenon are as follows:

1. Since the plexiglass did not accurately represent the weight of a concrete sidewalk, the large amount of swell noted would not occur in field situations, and therefore was a deficiency in the model tests.

2. The large amount of swell may be the reason for the unusual location of the undermining in this model setup.

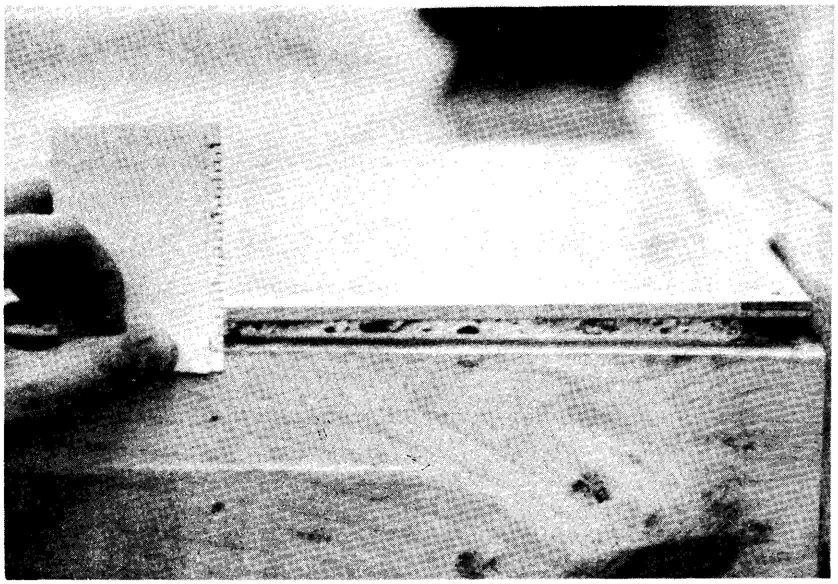

Figure 17. Swell of subgrade soil after eight simulated rainstorms with soil compacted to 98% maximum density.

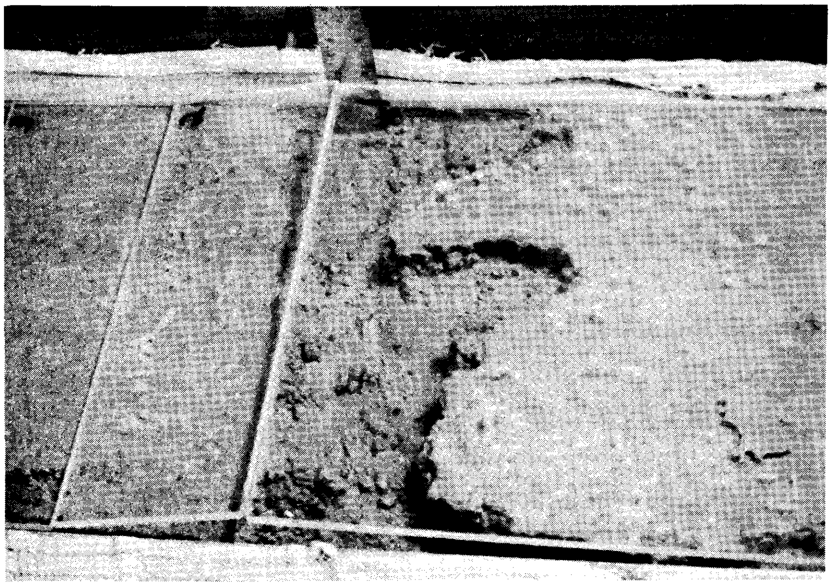

Figure 18. Buckling of plexiglass slabs developed under eight simulated rainstorms with soil at 98% maximum density.

3. The swell pressure of the subgrade soil could exist in the field and, due to the weight and continuity of the concrete sidewalk, may be distributed in the transverse direction, and thereby enhance sod growth along the edges of the sidewalk, which growth intensifies the paved ditch effect discussed earlier.

In comparing the data for this setup of the model to those of the control setup, it became obvious that the higher degree of compaction of the soil lengthens the time necessary for undermining to occur and reduces the amount of soil eroded, but does not prohibit undermining altogether.

#21-A Stone Subbase

The next setup of the model was designed to test the use of #21-A stone as a subbase for the sidewalk to protect the underlying erodible soil and prevent undermining. In this setup about 75 mm (3") of soil were compacted to 98% of maximum density in the trough using the same technique as before. The soil was overlaid with approximately 25 mm (1") of #21-A stone compacted to at least 95% maximum density. As before, a total of eight simulated rainstorms were imposed upon the model, with the final result being as shown in Figure 19.

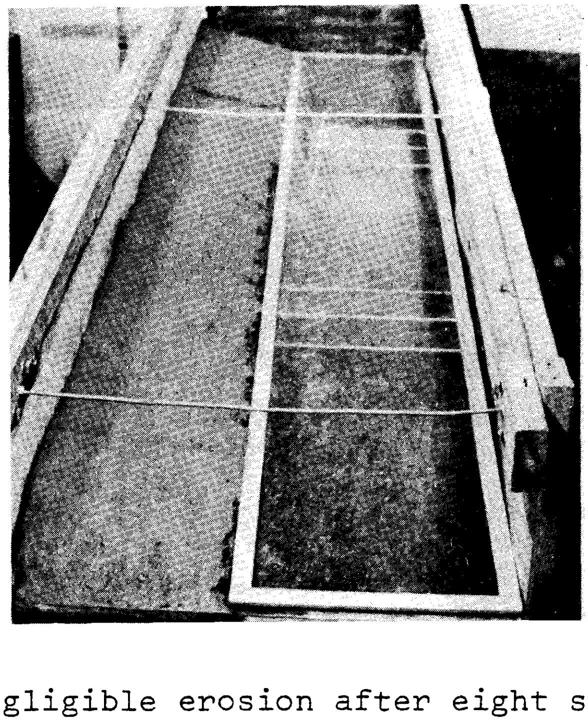

Figure 19. Negligible erosion after eight simulated rainstorms on model setup incorporating #21-A stone subbase.

A very minimal amount of soil was eroded along the inside edge of the plexiglass sidewalk, but no undermining of the sidewalk occurred. Again, a small amount of erosion of the simulated yard slope was noted at the same location and for the same reason as before, but in this setup the eroded material was retained in the stone subbase. Additionally, the vast majority of the material by weight, eroded during this model setup was formed by the finer particles of the stone subbase and not by the soil particles.

It should be pointed out that a considerable volume of water flowed across the surface of the stone subbase and eventually was caught by the gutter and carried into the plexiglass box. Furthermore, with the model design used it could not be determined if in a field situation a stone subbase would prevent undermining of the sidewalk but in doing so transfer the undermining to another location. Such a transfer is considered a strong possibility by some people, including the author, and therefore should be a prime consideration in the selection of a technique to prevent sidewalk undermining, as is discussed in more detail later in this report.

2% Lime Modification

The final possible solution to the undermining problem tested through the use of the model was the modification of the soil by the addition of 2% agricultural grade hydrated lime by dry weight. Results of a standard Proctor test performed on the modified soil using the AASHTO T-99 method indicated that the maximum dry density and the optimum moisture content deviated very little from the values developed for the unmodified soil. The necessary lime was added to the soil sample approximately 24 hours in advance of performing the Proctor test to reproduce the procedure that was to be followed in the actual setup of the model. Additionally, the soil was found to be lime-reactive through the application of a procedure developed by Anday(13) in which the unconfined compressive strength of specimens cured in the laboratory for 2 days at 49°C predict the strengths of specimens field cured for about 45 days. In particular, specimens made with 2% lime modified soil and receiving accelerated curing had unconfined compressive strengths about 2-1/2 times the strengths of specimens made with the unmodified soil and also subjected to accelerated curing.

Tests on an initial setup with the modified soil, made following the same time table used in the other setups, resulted in little inhibition of the undermining. In these tests, the proper amounts of lime and water were added to the soil on a Friday and the soil mixture was compacted in the trough on the following Monday. The first rainstorm was induced upon the model within an hour or so after it was set up, which allowed essentially zero curing time. The soil was compacted in the trough to 98% of its maximum density, but with no curing there was almost as much undermining as there had been with the control setup.

To allow for curing of the lime-modified soil and still maintain the same rainstorm sequence as before, a second model setup was made with the soil-lime mixture being produced on a Thursday and compacted in the trough to 98% of maximum density on Friday. This setup was allowed to cure for 3 days at laboratory temperatures before the application of the first simulated rainstorm on the following Monday. It was reasoned that in a field situation a lime-modified sidewalk subgrade could be protected from rainfall and thereby cure for a minimum of 3 days with relative ease and at very little, if any, additional cost.

After the 3-day curing time the model setup was subjected to the established eight-rainstorm sequence. The final result is shown in Figure 20. Obviously, there was no substantial erosion of the soil with this setup. In the author's opinion the undermining was prevented by the increased strength and bonding of the soil resulting from the addition of lime.

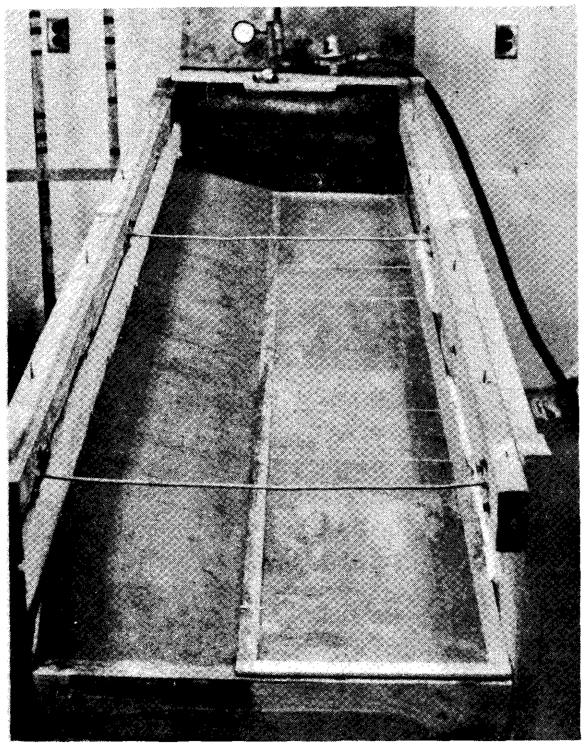

Figure 20. Essentially no erosion after eight simulated rainstorms with lime-modified soil.

As noted previously for the model setup with the #21-A stone subbase, a considerable volume of water flowed across the subgrade surface; so it is reemphasized that the model did not permit study of the possible transfer of undermining to another location.

Summary of Tests on Model

As described earlier, after each rainstorm the eroded material was allowed to settle in the plexiglass box, the excess water was siphoned off, and the dry weight of the eroded material was determined. The total amount of erosion experienced in Kg/m^2 (tons/acre) was then calculated for each rainstorm by dividing the dry weight of the eroded material by the area of the plexiglass sidewalk. The Universal Soil Loss Equation predicts erosion in identical units.

In Figure 21 the cumulative soil eroded versus the number of simulated rainstorms is plotted for each setup of the model. An examination of the plots results in the following conclusions:

1. Compaction of the subgrade to 98% maximum density reduces the total amount of soil eroded and lengthens the time necessary for undermining to occur, but does not prevent undermining.
2. A subbase of #21-A stone protects the highly erodible soil subgrade and, essentially, prevents undermining.
3. The addition of 2% agricultural grade hydrated lime by dry weight to the problem soil, with a minimum of 72-hours curing of the soil-lime mixture, prevents undermining, probably through increasing the strength and bonding of the soil.

It was previously noted that during the runs of the model with the #21-A stone subbase and 2% lime-modification, a large volume of water flowed along the underside of the plexiglass sidewalk. In the author's opinion this phenomenon could conceivably develop in the field. Therefore, to prevent the development of other problems, where either one of these techniques is used, transverse drains should be provided at drop inlets to intercept the infiltrated water and carry it into the storm sewer system.

Additionally, it was stated that the model sidewalk did not allow study of the possible transfer of the undermining from the sidewalk to another location. With lime-modification, this possibility could be eliminated by modifying the soil from the back of the sidewalk through the utility strip to the edge of pavement. If a stone subbase is used, then there is no logical way to prevent the possible transfer of undermining, although transverse

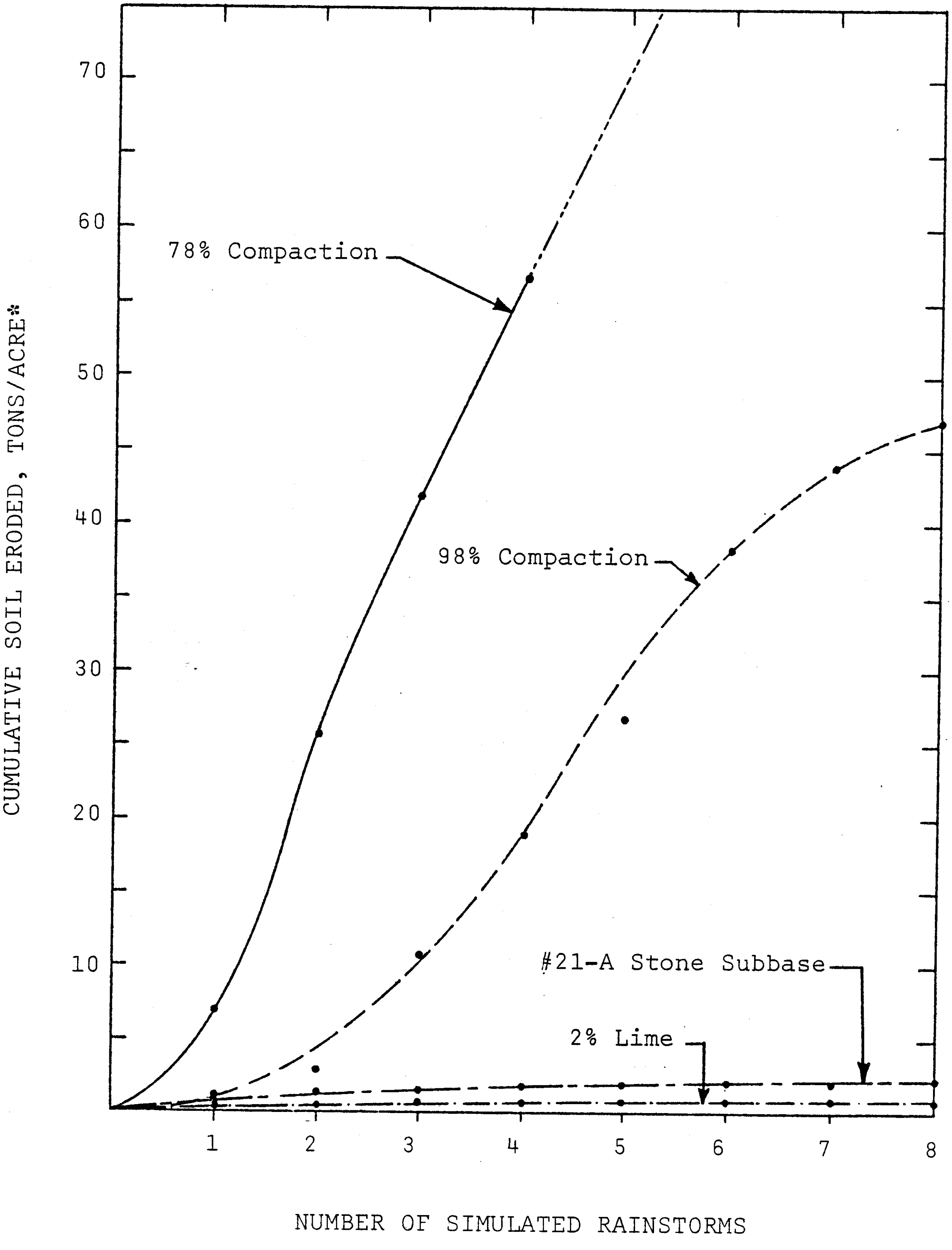

Figure 21. Plots of cumulative soil eroded versus number of simulated rainstorms for each setup of the model. (*Metric conversion 1 ton/acre = 0.22 kg/m^2.)

drains may do so. Thus, of the solutions to the undermining problem tested through the use of the model sidewalk, lime-modification of the soil would seem to have the best overall potential.

EVALUATION OF FIELD TEST SECTIONS

While the sidewalk model was being developed and tested, field test sites were visited at various times to determine if undermining was occurring. As mentioned previously, the initial evaluation of the test sections by the author and others in August 1975 proved to be inconclusive.(13) Subsequent visits to the sites were also fruitless, except that at 3 of the 4 so-called normal construction sites of the test areas established by the Sidewalk Failure Study committee, there was minor evidence to indicate that undermining was developing. Following a suggestion of the Pavement Research Advisory Committee it was decided that removal of a few sidewalk slabs at some field test sites for visual inspection and evaluation would be financially justifiable.

On October 31 and November 1, 1977, sidewalk slabs were removed at 3 test sites to permit visual inspection of the subgrade. These were Test Area #2 (crushed gravel subbase with cut-off walls as shown in Figure 8), Test Area #4 25 mm (4") pipe underdrain placed along the high side of the sidewalk as shown in Figure 10), and Test Area #5 (polyethylene sheeting with 175 mm (7") plastic pipe and No. 8 stone underdrain system as shown in Figure 5). It should be pointed out that Test Area #5 was inspected when feasible during a rainstorm and the drain was always found to be carrying clear water. Thus this system has been extremely effective in preventing the reoccurrence of sidewalk undermining. In addition, a sidewalk slab was removed at a location where undermined sidewalk had been replaced with the combination curtain wall and 7" underdrain pipe (refer to Figure 4) and a slab was lifted enough for visual inspection at Test Area #3 (curtain wall poured monolithically and on the high side of the sidewalk as shown in Figure 9).

No definite undermining was found at any of the locations inspected, although at Test Area #2 there was some indication that undermining was in the very early stages of development. Other observations made during the field evaluations were as follows:

1. At Test Area #5 there were a lot of gray colored fine particles in the top 25 mm to 50 mm (1" to 2") of the No. 8 stone, although none were noticeable below this point; and

2. the subgrade soil at Test Area #4 did not appear to be the typical problem soil often encountered at undermined sidewalks.

The fines in the No. 8 stone are possibly due to cement mortar that infiltrated when the sidewalk was placed, but this section should be reinspected in the future for verification of this speculation.

The fact that no undermining was found at any of the sites should not be taken to mean that the operations tested are totally successful in preventing undermining. The site of Test Area #1 built under normal construction (i.e., with compaction of the subgrade and cut-off walls) has the most severe geometric conditions of all the test sites. When this site was inspected in May 1976 the only indication of undermining was that some soil particles were visible on the sidewalk. There was no noticeable distortion of the sidewalk at that time. But in November 1977, when this site was revisited, the evidence of undermining was overwhelming. There was a considerable amount of uplift of the sidewalk slabs at the lower part of the section as is shown in Figure 22. Additionally, some undermined slabs upgrade of the paint pictured had collapsed and had been filled in with bituminous material, and there were many holes along the edge of the sidewalk. Since this section represented the severest geometric conditions and took from 5 to 6 years for unmistakable undermining to develop, and since any procedure would logically delay sidewalk undermining a little, there is a strong possibility that in the case of the other test sections not enough time has elapsed for undermining to develop. Future inspections of the test sites will reveal the validity of this suspicion.

The one very important finding from the inspections was that the relatively thin and unreinforced sidewalk slabs can be handled with little or no damage. Thus, it is felt that the existing slabs can be used to economic advantage in repairing undermined sidewalks.

At the test location incorporating the so-called minimum pipe underdrain system no slabs were removed for visual inspection because of the newness of the test sections. However, it is felt that if a drainage system is to be utilized as the technique for preventing undermining, then the minimum pipe procedure would definitely be the most economical one that would perform effectively. It is conceivable that in extreme cases and under severe conditions a pipe would be necessary to remove the large volume of water encountered. A definite answer as to what conditions would dictate the use of a pipe is not now available; much research on the subject of subsurface drainage is needed.

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Figure 22. Uplift of sidewalk at lower end of section at Test Area #1 due to undermining upgrade of failure.

References 14 and 15 are cited in partial support of the contention that use of an open-graded aggregate alone can be as effective in draining water, if not more so, as an underdrain system utilizing pipe. The minimum pipe underdrain system should have the same general shape as the underdrain system currently used for maintenance replacement (refer to Figure 5), except that there should be a minimum of 100 mm (4") of No. 8 stone under the edges of the sidewalk and the depth of the stone under the center of the sidewalk could be reduced to 300 mm (12") or less.

CONCLUSIONS

The attempt to design a model sidewalk for testing various procedures for preventing the undermining of sidewalks was successful. The conclusions below are based upon the results of tests with this model, along with the evaluation and observation of field test sections and of other sites where sidewalk undermining exists.

1. Close to maximum compaction of the subgrade soil, either with or without the use of cut-off walls, does not prevent sidewalk undermining.

2. The use of No. 21-A stone compacted as a subbase for the sidewalk has good potential for preventing undermining, but measures should be taken to prohibit the transfer of undermining to another location.

3. The modification of the subgrade soil by the addition of 2% agricultural grade hydrated lime has excellent potential as a technique for preventing undermining and the transfer phenomenon by modifying the soil in the utility strip to the edge of the pavement.

4. A drainage system placed under the sidewalk to drain infiltrated water seems to be very effective in the prevention of sidewalk undermining and is the only potential solution that has been field tested.

5. The reuse of existing sidewalks slabs in the repair of undermined sidewalks is feasible and could result in financial benefit to the Department, if implemented as part of the maintenance replacement technique for sidewalk repairs.

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