LABORATORY STUDIES OF THE ERODIBILITY OF COHESIVE MATERIALS 1/

by

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INTRODUCTION

Research Needs Statement C3-9 of the Highway Research Board (2)2/ is "Research on the Effect of Physico-Chemical Factors on the Erosion of Soil." The Problem Area of this statement concludes with, "Further, there exists at present no engineering test which is universally acceptable and which can be used to predict the erodibility of soils in the field." Part of this problem originates in the complex process of the erosion of cohesive materials. This paper is a progress report concerned with one specific segment of this problem, i.e., the influence of time and water content variables on the erodibility of cohesive materials.

METHODS AND MATERIALS

Data presented herein illustrate the influence of various parameters on laboratory determined erosion rates. Selected physical properties of the samples, together with general locations, are listed in table 1.

Soil samples were air dried, mixed, split to appropriate weight, rolled in a ball mill for 2 hours to reduce aggregation, and stored in plastic bags. Individual samples were sprayed to the packing water content,3/ stored overnight, and packed to predetermined bulk densities. Packing water content was 10% unless otherwise noted. Each sample was packed so the exposed surface was flush with the surface of the mold. The molds were 5.05 cm wide, 12.50 cm long, and 1.95 cm deep. Stainless-steel filters were used as the bottom of each mold. These filters permitted water sorption by the samples following compaction. Time required for this water sorption ranged from several minutes to several hours. By this procedure, sample water content prior to flume testing could be increased over packing water content without altering sample fabric. The sample water content prior to flume testing, termed antecedent water

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1/ Contribution from the USDA Sedimentation Laboratory, Soil and Water Conservation Research Division, Agricultural Research Service, United States Department of Agriculture, Oxford, Mississippi, in cooperation with the University of Mississippi and the Mississippi Agricultural Experiment Station.

2/ Italic numbers in parentheses refer to Literature Cited.

3/ Water content at compaction determined sample fabric, i.e., the orientation in space of the compositional elements (1).

TABLE 1.--Selected physical properties of the samples

Sample	Source location	Reference	Particle size			Dispersion ratio[1/]	Atterberg constants			Particle density
			> 63μ	63-2μ	<2μ		Liquid limit	Plastic limit	Plasticity index	
			---------Percent--------			--Percent--	--------------Percent---------------			$G./cm.^3$
Stock Soil-1	Marshall Co., Miss.	Figs. 1, 3, 5, 6, Table 2, 3	6	74	20	10	31	20	11	2.65
WC-2	--------do--------	Figs. 1, 6	34	55	11	7	21	17	4	2.64
C-8	--------do--------	Fig. 2	4	71	25	9	34	22	12	----
C-2	--------do--------	-------do--------	2	74	24	9	34	22	12	----
C-4	--------do--------	-------do-------	3	74	23	6	33	23	10	----
WC-1	--------do--------	-------do-------	8	70	22	5	30	20	10	----
C-5	--------do--------	-------do-------	3	77	20	21	28	20	8	----
H-S	--------do--------	Fig. 4	11	67	22	16	30	18	12	----
385-1B	York Co., Nebr.	Fig. 7	34	38	28	27	35	17	18	2.64
WA	Washington	Fig. 8	2	71	27	20	30	23	7	2.42
331-1H	Pawnee Co., Nebr.	Fig. 9	40	30	30	36	40	16	24	2.67
Stock Soil-2	Marshall Co., Miss.	Fig. 10	3	68	29	8	44	20	24	2.70
303-2E	Douglas Co., Nebr.	Fig. 10	1	73	26	22	38	18	20	2.64

1/ Percent <2μ undispersed divided by percent <2μ dispersed.

content, was determined by sampling a portion of the formed sample which would not be subsequently exposed to the erosive water flow during flume testing. All water contents are expressed as weight of water per weight of oven-dry soil. Prior to flume testing, the samples were covered to prevent evaporation and aged for predetermined times. Aging time was the time interval between completion of water sorption and initiation of flume testing.

The molded samples were eroded in a small flume. The flume bed was essentially horizontal and 5 cm wide. Flow velocity was 55 cm/sec (1.8 ft/sec), and the depth of flow was 2.0 cm. Water temperature was 40°C unless otherwise noted. Although flow velocity and depth were constant, the actual erosive force exerted on a sample undoubtedly changed as the sample eroded and the sample surface assumed a new configuration. The test material in the mold was mounted on the outside of an abrupt 5° turn, becoming a part of the side wall of the flume. Approximately two-thirds of the surface of the sample was exposed to the erosive test. These tests usually lasted several minutes. Highly erodible materials were tested for shorter periods of time so that the base filter would not be exposed. Material remaining in the mold after the test period was transferred to a pan, oven dried, and weighed. Eroded material was determined by difference in dry weight. Variations in this general procedure are noted where appropriate in the following discussion.

RESULTS AND DISCUSSION

The samples represented in figures 1, 2A, 3, and 4 were aged at the indicated antecedent water content for 4 hours before the erosive test. Water content at packing was the same as antecedent water for those samples containing up to 10% antecedent water. The influences on erosion rates of antecedent water contents of less than 10% are thus confounded with variable fabric (1). Samples containing 10% or more antecedent water were packed at 10% water. The samples represented in figure 2B were packed at 10% water, wet to approximate saturation, and aged the indicated time.

The two curves of figure 1 illustrate the dependence of erosion rate on antecedent water content. Both samples exhibited a peak erosion rate at an antecedent water content less than saturation. The peak rate occurred at a smaller antecedent water content for the relatively coarser textured WC-2 sample (34% > 63μ) than for the stock soil-1 sample (6% > 63μ). The increased erosion rate for stock soil-1 at antecedent water contents approaching saturation was associated with sample swelling during the test period.

The relation between antecedent water content and erosion rate for materials of similar texture is illustrated in figure 2A. For these five samples, the peak erosion rate was higher, the greater the antecedent water content at which it occurred. The most erodible sample, C-5, exhibited no peak erosion rate; rather the rate increased to a plateau as the antecedent water approached saturation. This shift of peak erosion rate was not due to textural differences as was the case for the samples shown in figure 1. The five samples represented in figure 2A have similar textures, and the shift was probably associated with soil chemical and/or mineralogical properties.

The erosion rate for samples at or approaching saturation was dependent upon wet aging time. This influence of aging time is illustrated in figure 2B, for the same samples shown in figure 2A. The erosion rate decreased as aging time increased for all but the most erodible samples or unless limited by the experimental conditions as in the case of sample C-8.

For a particular sample, the influence of antecedent water was not constant, but varied with water temperature and sample bulk density. Peak erosion rates occurred at the same antecedent water content for samples eroded at two water temperatures (figure 3),[4/] and the peak rates were much less with the lower water temperature. No swelling was observed for the samples eroded at 25°C, and samples eroded at this lower temperature were stable at antecedent water contents approaching saturation. Figure 4 illustrates the influence of bulk density. The samples packed to 1.6 g/cm^3 bulk density were more stable at antecedent water contents approaching saturation than were comparable samples packed to 1.4 g/cm^3 bulk density. Maximum peak erosion rates for these two bulk densities are approximately the same, suggesting less influence of aging time on samples at low antecedent water content than on samples at antecedent water contents approaching saturation. Similar results are indicated by the data in table 2. These results are, however, also confounded by the influence of variable fabric.

TABLE 2--Influence of aging time on erosion rate for stock soil-1 samples
[All samples compacted to 1.2 bulk density. Antecedent water content was the same as the water content during aging.]

Aging time (Hours)	Erosion rate[1/]	
	Aged at 5% [2/] water content	Aged at [3/] near-saturation water content
	G./min.	G./min.
1	29	36
4	30	19
8	31	17
24	29	16

1/ Mean of at least 3 values.

2/ Packed at 5% water.

3/ Packed at 10% water.

4/ The curve for the stock soil-1 sample tested at 40°C was previously presented in figure 1.

The preceding data are not suitable for evaluating the influences of compositional properties on stability. The antecedent water versus rate of erosion curves in many instances are valid only for specified conditions, i.e., bulk density, aging time, the bulk density-aging time interaction, etc. Aging time versus rate of erosion curves are simpler but are again valid only for specified conditions. These latter curves also exhibit considerable scatter. As an alternative, the influence of sample water content change was investigated.

The samples[5/] represented by the two curves in figure 5 were treated identically throughout the 4-hour aging period. Before being positioned in the flume, one set of samples was saturated by slow wetting through the base filter, whereas the other set was maintained at the same water content as that during aging. Sample water content change during the flume test was thus minimized for the presaturated samples. The presaturated samples exhibited no peak erosion rate; instead, the erosion rate increased as the water content during aging decreased below 10%. The reduced stability of these presaturated samples (samples aged at less than 10% water and then saturated) with decreasing water content during aging cannot be singularly attributed to the aging-time water content. These samples were formed at different water contents, and the influence of sample fabric confounds the results.[3/] The initial stability of samples aged and eroded at small antecedent water contents was determined primarily by limited water entry into samples during the short test period, and peak erosion rates resulted from variations in sample water content change.

Table 3 also illustrates the dependency of erosion rate on water content change. For these data, water content change was the difference between antecedent water content and sample water content following flume testing. Various samples at low antecedent water content were treated with wax such that the sample to air interfaces (the surfaces not exposed to water flow) were impermeable to air. These samples were paired with comparable, standard samples and tested. Sealing the sample to air interface inhibited water entry, and the sealed samples were more stable. Air entrapment apparently was not significant.

The influence of time of wetting is further illustrated in figure 6[6/]. For this and subsequent illustrations, the samples were packed, wet to approximate saturation, aged, sampled for antecedent water content, and eroded. Time of wetting was the time interval between exposure of the sample to water (through the base filter) and the observable complete wetting of the sample surface. For these samples (figure 6), stability increased as the time of wetting increased. This dependence of erosion rate on time of wetting is thought to be the source of scatter observed for aging time curves. The influence of water change per time of wetting on rate of erosion is illustrated in figure 7A. Water change was the

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5/ These stock soil-1 samples have stabilities different from other stock soil-1 samples. They were stored over summer in a relatively hot area, and this storage condition presumedly affected their stability.

6/ For each of the samples in figure 6, compaction at different water contents results in markedly different stabilities (See Footnote 3).

difference between antecedent water content and packing water content. In general, the rate of erosion increased as the rate of water change increased for each of the three bulk densities tested at 0 and 4 hours aging. These results suggest that water entry into a cohesive material is an internal stress-producing process.

TABLE 3--Rate of erosion and water content change values for normal and sealed sample pairs. (Water content change noted as Δ water)

Normal		Sealed		Difference[1/]	
Erosion rate [2/]	Δ water[2/]	Erosion rate [2/]	Δ water[2/]	Erosion rate [2/]	Δ water[2/]
G./min.	Percent	G./min.	Percent	G./min.	Percent
6.0	15.5	5.9	14.2	0.1	1.3
10.4	20.2	9.1	18.3	1.3	1.9
14.7	13.6	14.3	11.5	.4	2.1
14.8	25.9	10.8	21.9	4.0	4.0
14.8	19.6	12.3	17.2	2.5	2.4
15.0	16.6	14.1	15.0	.9	1.6
17.5	11.8	17.6	10.2	-.1	1.6
20.0	17.2	17.8	15.6	2.2	1.6
22.5	11.3	21.0	10.3	1.5	1.0
23.4	23.2	19.8	21.1	3.6	2.1
25.5	15.7	22.4	15.4	3.1	.3
28.5	25.6	22.9	20.1	5.6	5.5
Mean difference				2.1	2.1

1/ Normal minus sealed values.

2/ Mean of 3 values.

An empirical relation between rate of erosion and p ln(ΔWATER/TIME) is presented in figure 7B where "p" is the sample porosity, i.e., void volume/total volume. The two curves in this figure are counterparts to the curves in figure 7A. As presented in figure 7B, the relation is linear through the range of bulk densities tested for each aging time, and the samples aged 4 hours were more stable than similar but unaged samples. This decreased erosion rate with increased aging time is attributed to the development of cohesive forces during aging. Decay of the internal strain, i.e., the strain produced by water entry, may also be involved. Similar results are presented in figures 8-10 for a variety of cohesive materials. All regression and correlation coefficients are significant except the intercept coefficient for WA sample aged 0 hours. Studies attempting to relate these regression coefficients to soil properties are in progress.

CONCLUSIONS

Many channel materials are subjected to periodic wetting as determined by their hydrologic environment. Such materials encompass bed and bank materials for ephemeral streams and those bank materials which are positioned above base flow for perennial flow streams. Laboratory studies were conducted to evaluate the influences of soil water variables on stability of such materials.

In general, measured erosion rates varied directly with rates of water change in the samples. These results indicate that water entry into a cohesive material is an internal stress-producing process, and should be considered in conjunction with other erosive forces in stability studies. Antecedent water content and water temperature, to the degree that they influence water content change in the sample, indirectly influence stability. Sample composition, thus, has a dual role: 1) a direct influence on stability by determining the development of cohesive forces, and 2) an indirect influence on stability by determining the pertinent hydrologic properties of the sample.

The measured erosion rates varied inversely with aging time. This increased stability with increased aging time is attributed to the development of cohesive forces during the aging time. Decay of the internal strain, i.e., the strain produced by water sorption, may also be involved.

An empirical relation between the measured erosion rates and the rates of water change in the samples has been found to be statistically significant for many samples. These samples, from Nebraska, Washington, and Mississippi, illustrate the various influences of aging times and rates of water sorption. Current studies involve the attempt to relate soil properties with parameters from this empirical relation. The results will be used in a study of the influences of soil properties on critical boundary stress.

LITERATURE CITED

(1) Grissinger, E. H.
1966. Resistance of selected clay systems to erosion by water. Water Resources Res. 2(1):131-138.

(2) Hwy. Res. Board, Com. on Res. Needs, D. L. Lacey, Chrmn.
1970. Supplementary research needs statements. Hwy. Res. Cir. 111, 11 pp.

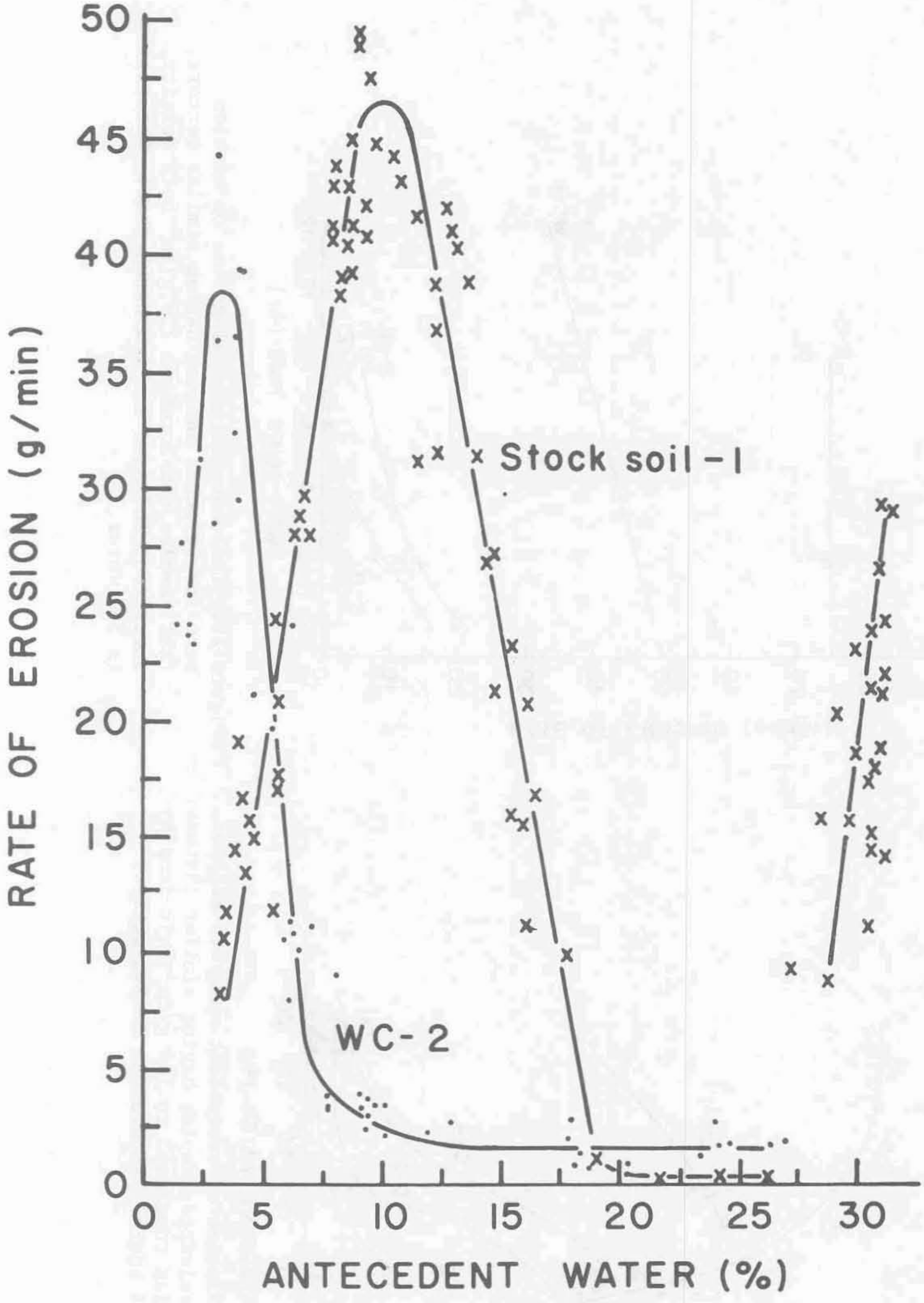

Figure 1.--Influence of antecedent water on erosion rate for samples of different texture. (Both samples compacted to 1.4 g/cm^3 bulk density and aged 4 hours. Saturation is 34% water.)

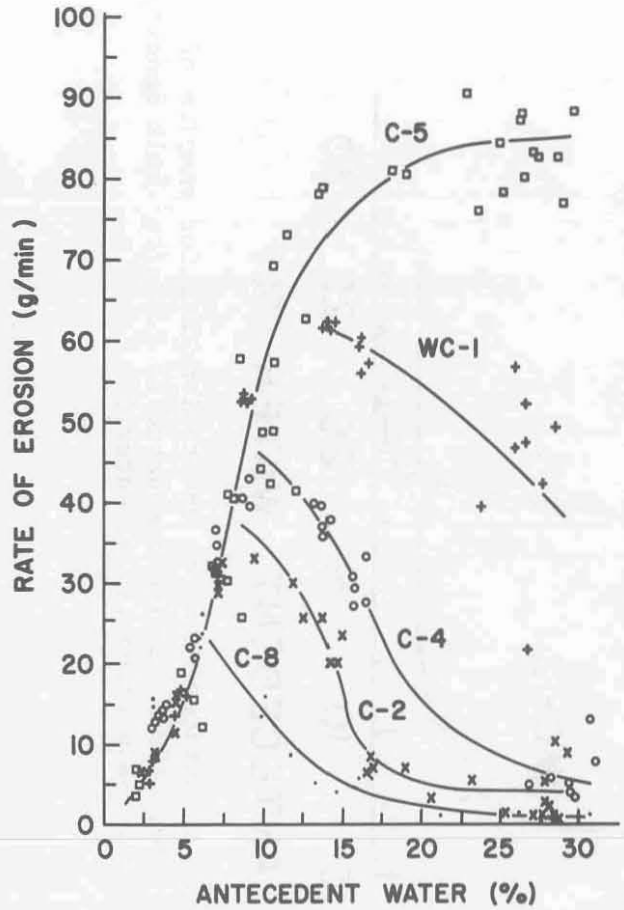

Figure 2A.--Influence of antecedent water on erosion rate for selected samples having similar texture. (All samples compacted to 1.4 g/cm^3 bulk density and aged 4 hours. Saturation is 34% water.)

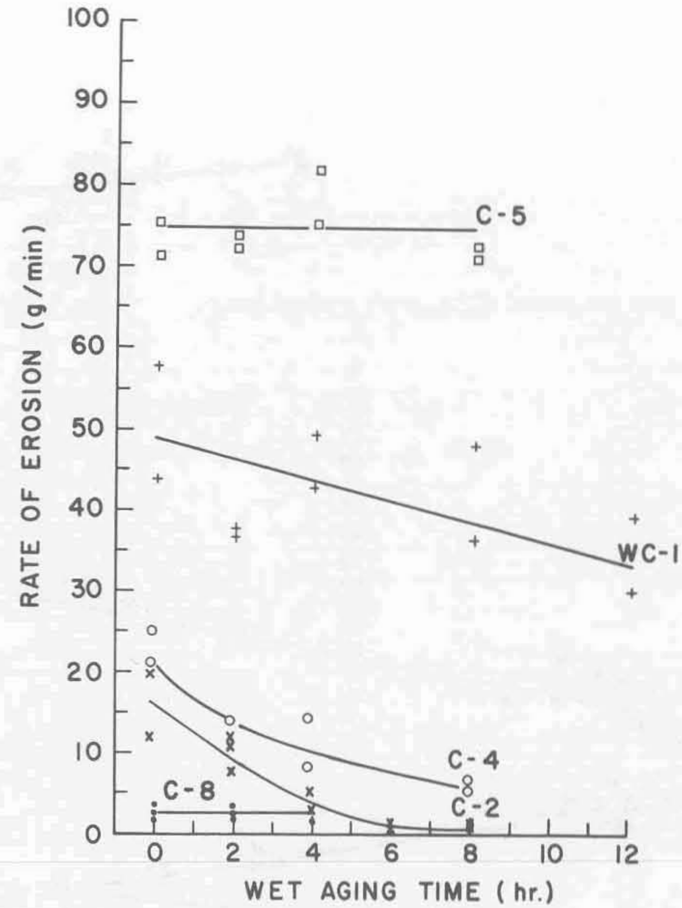

Figure 2B.--Influence of wet aging time on erosion rate for selected samples having similar texture. (All samples compacted to 1.4 g/cm^3 bulk density, saturated, and aged the indicated time. Saturation is 34% water.)

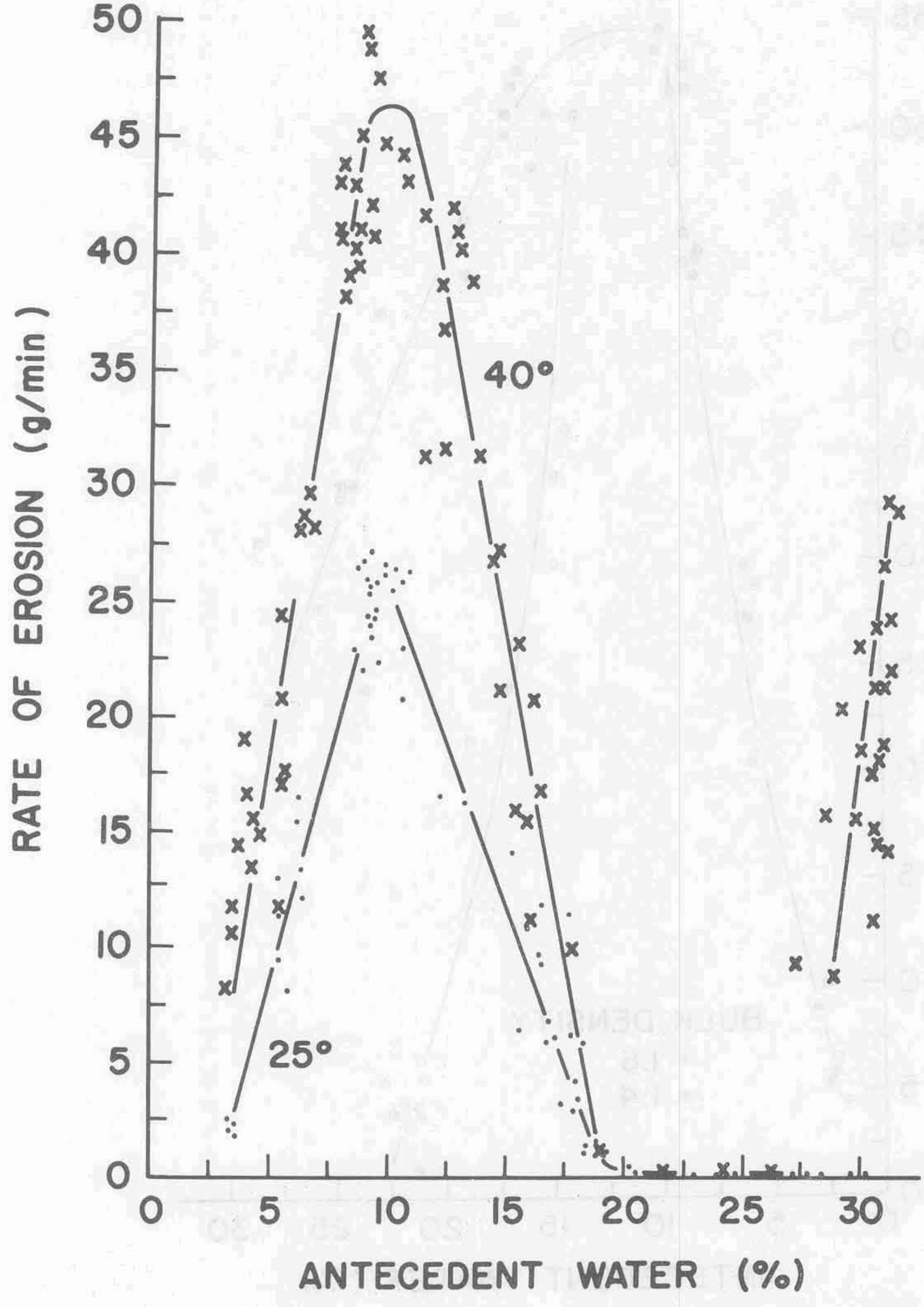

Figure 3.--Influence of antecedent water on erosion rate for stock soil-1 samples tested at different water temperatures. (Both samples compacted to 1.4 g/cm^3 bulk density and aged 4 hours. Saturation is 34% water.)

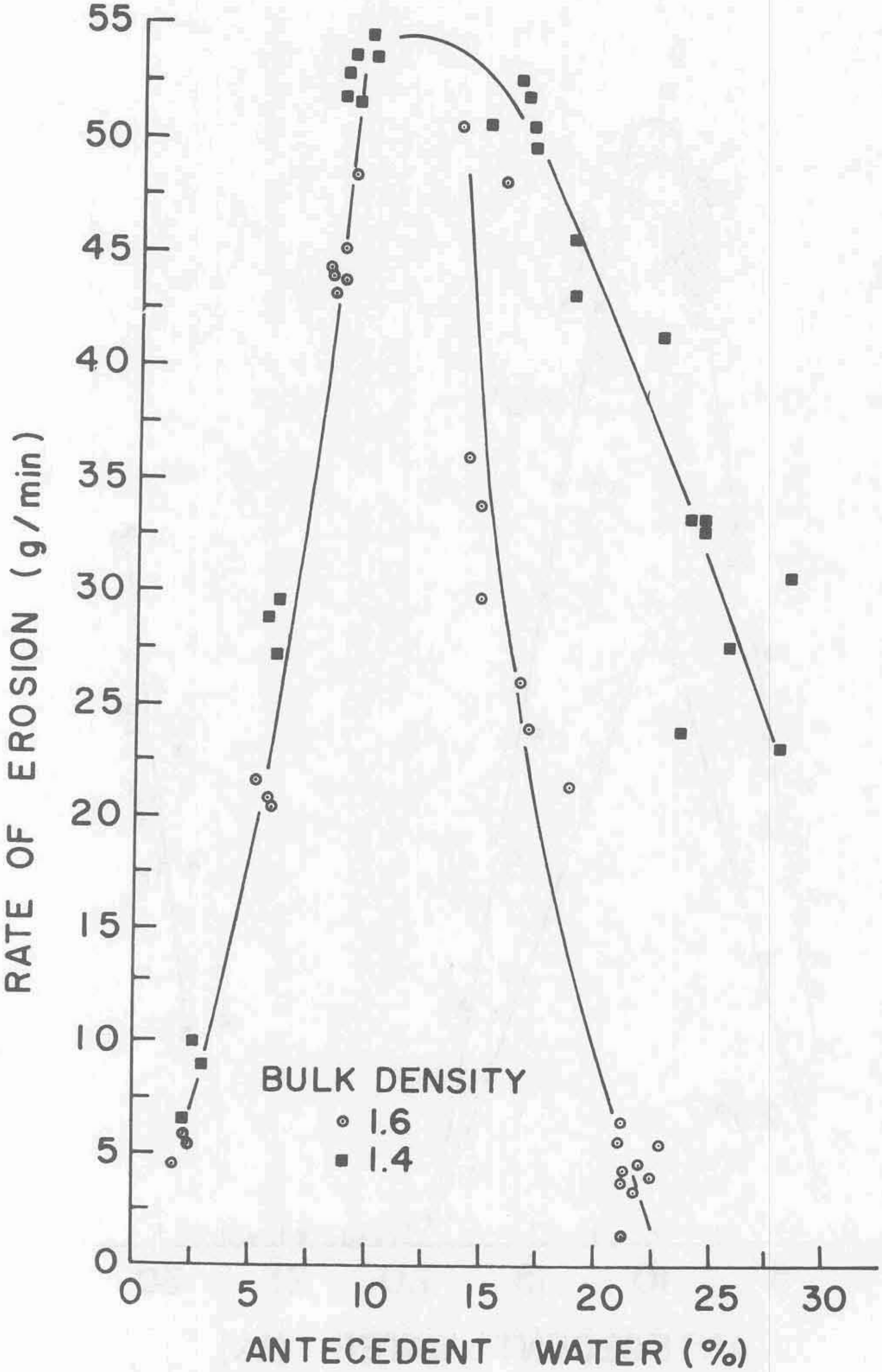

Figure 4.--Influence of antecedent water on erosion rate for H-S samples packed to two bulk densities. (Samples were aged 4 hours. Saturation is 34% water for the 1.4 g/cm^3 bulk density sample and 25% water for the 1.6 g/cm^3 bulk density sample.)

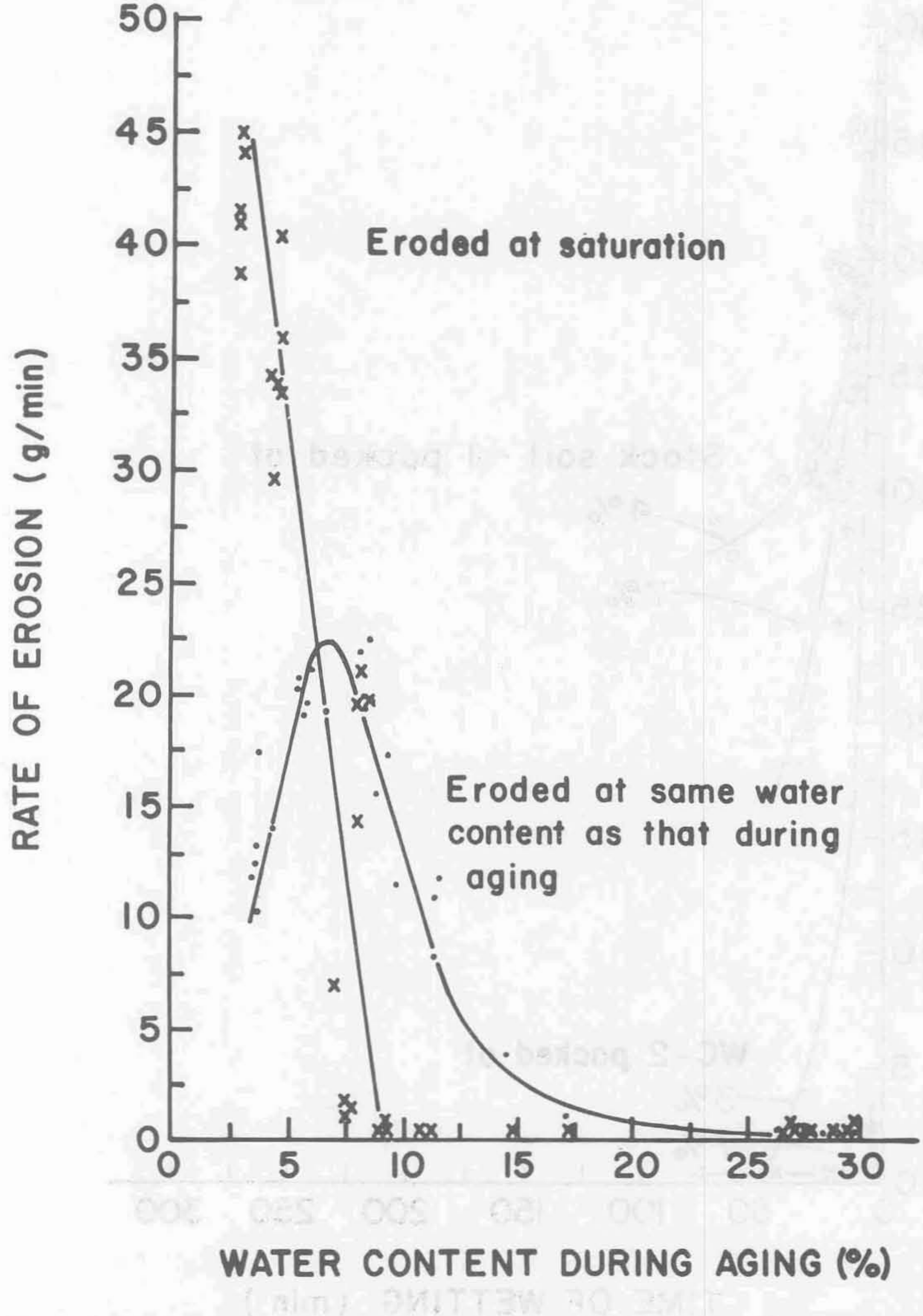

Figure 5.--Influences of water content during aging and antecedent water content on erosion rate for a stock soil-1 sample. (Both samples compacted to 1.4 g/cm^3 bulk density and aged 4 hours. Saturation is 34% water.)

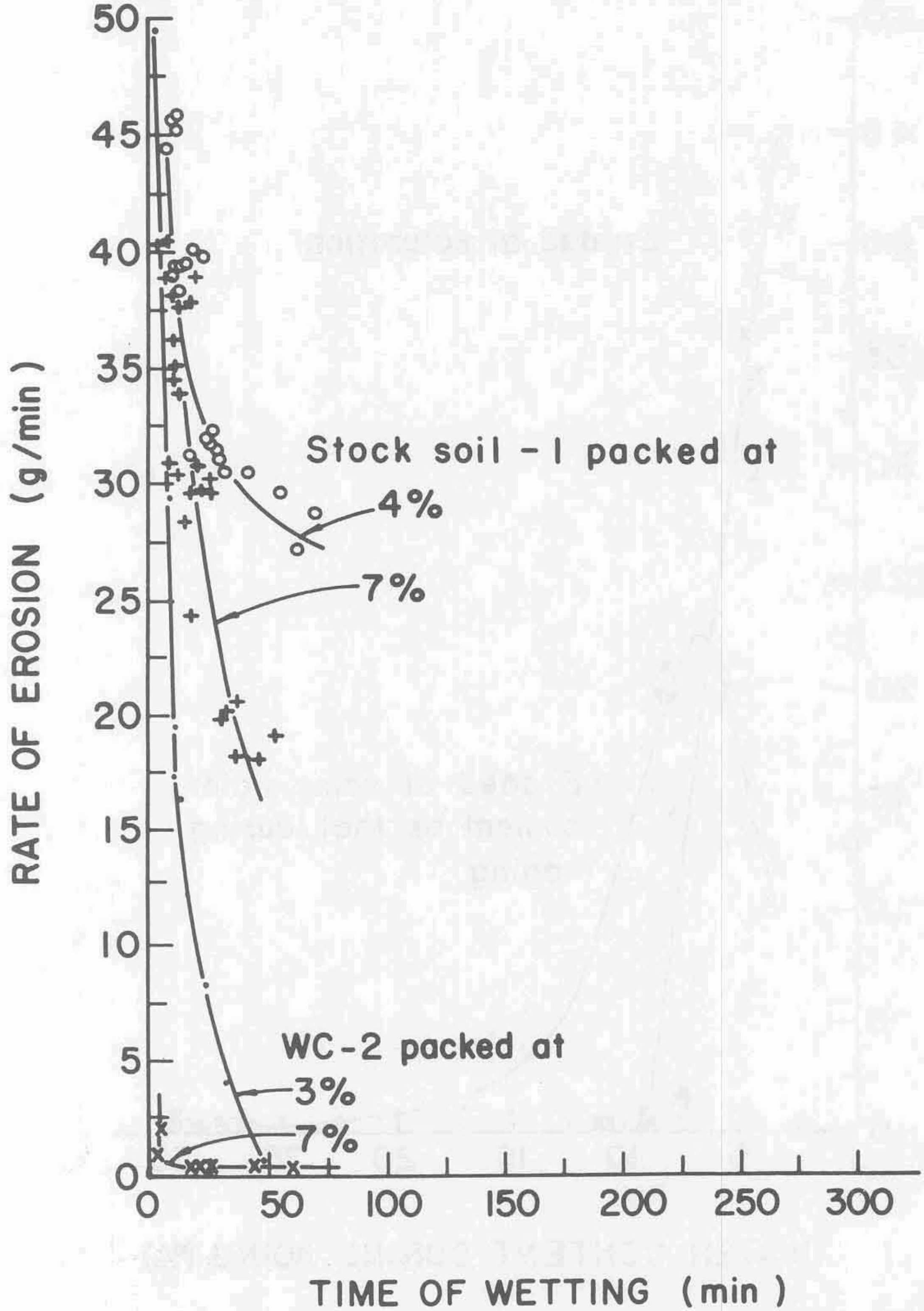

Figure 6.--Influence of time of wetting on erosion rate for materials packed at different water contents. (All samples compacted to 1.4 g/cm^3 bulk density, wet to saturation, and aged 4 hours.)

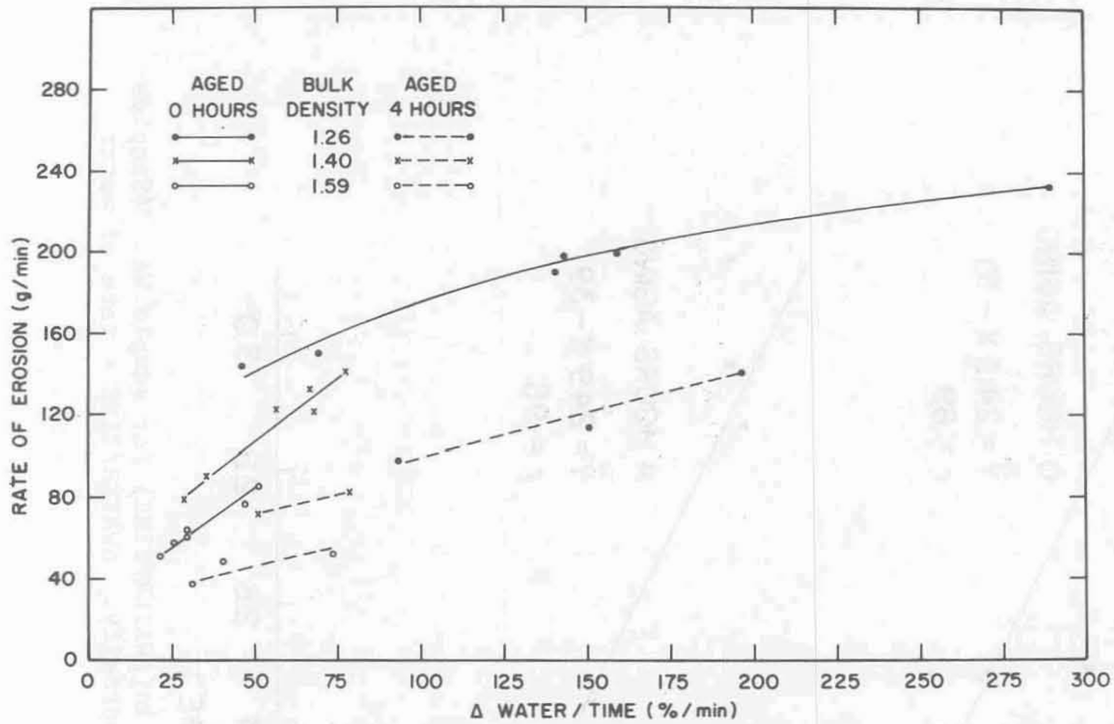

Figure 7A.--Influence of rate of water content change on rate of erosion for sample 385-1B.

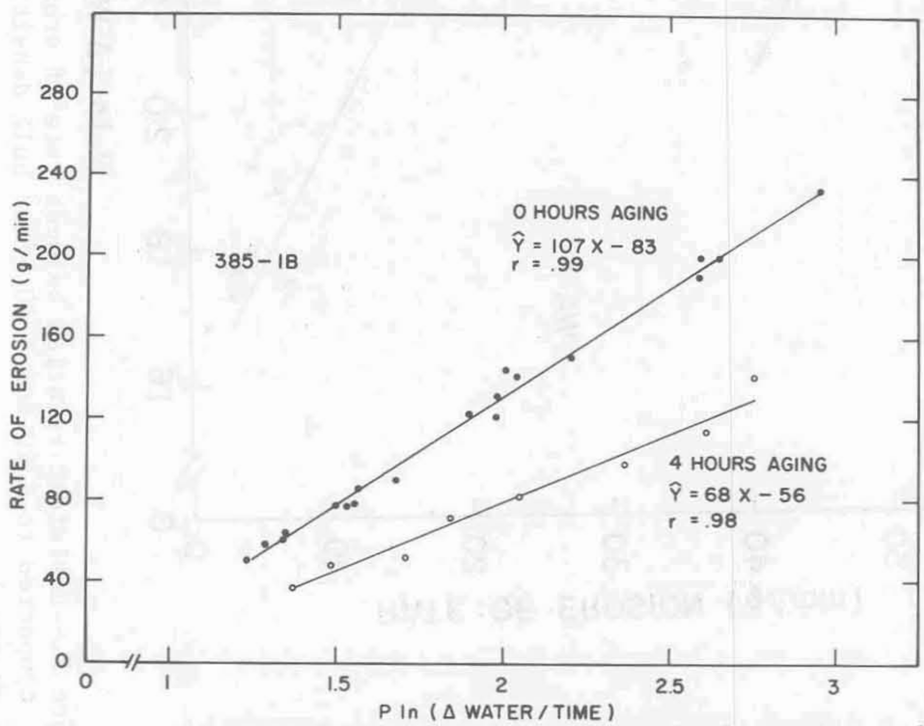

Figure 7B.--Empirical relation between rate of erosion and p ln(ΔWATER/TIME) for sample 385-1B. (Samples compacted to 1.26, 1.40, and 1.59 g/cm^3 bulk densities. p = porosity. ΔWATER/TIME = rate of water change.)

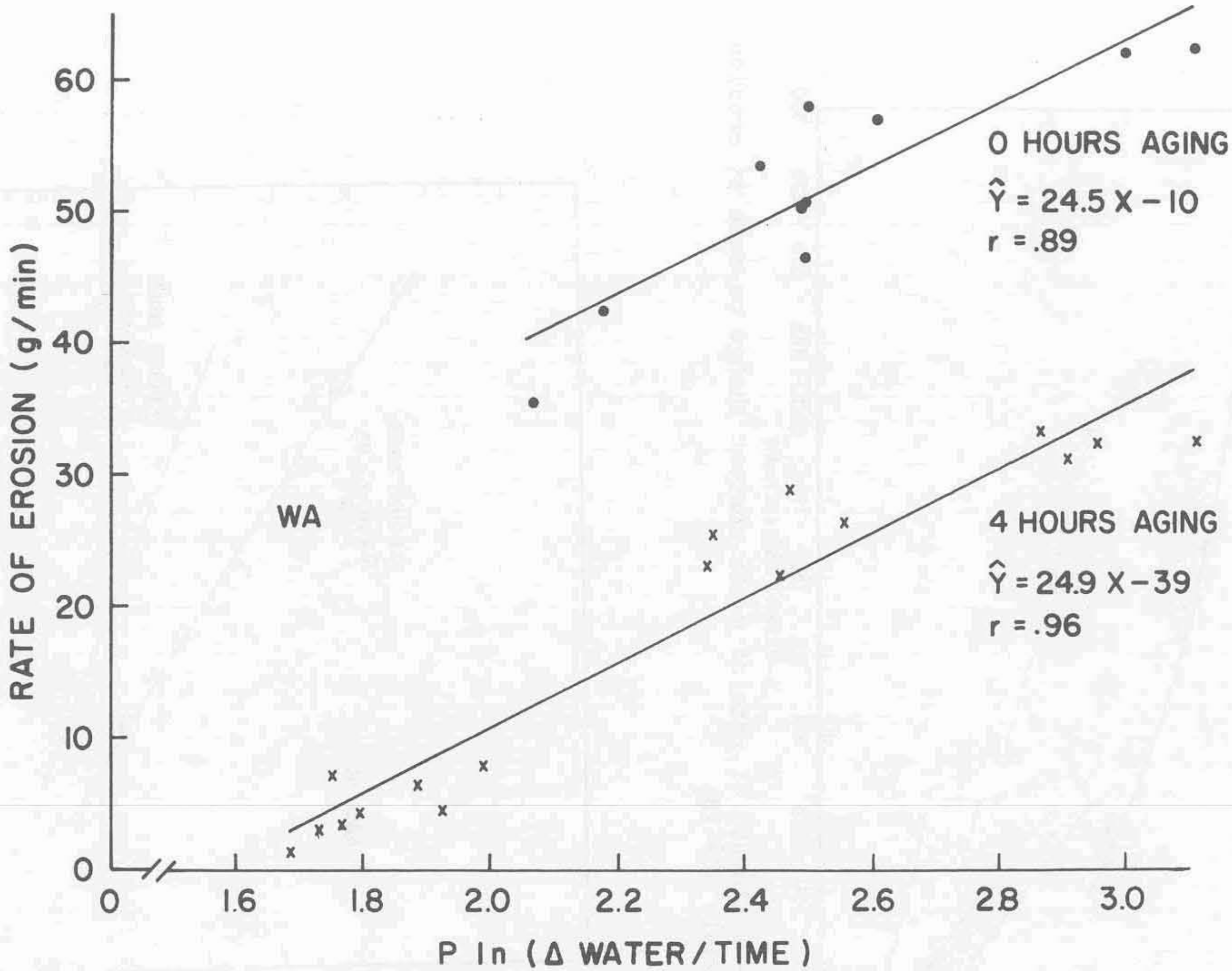

Figure 8.--Empirical relation between rate of erosion and p ln(ΔWATER/TIME) for sample WA. (Samples compacted to 1.20 and 1.40 g/cm^3 bulk densities. p = porosity. ΔWATER/TIME = rate of water change.)

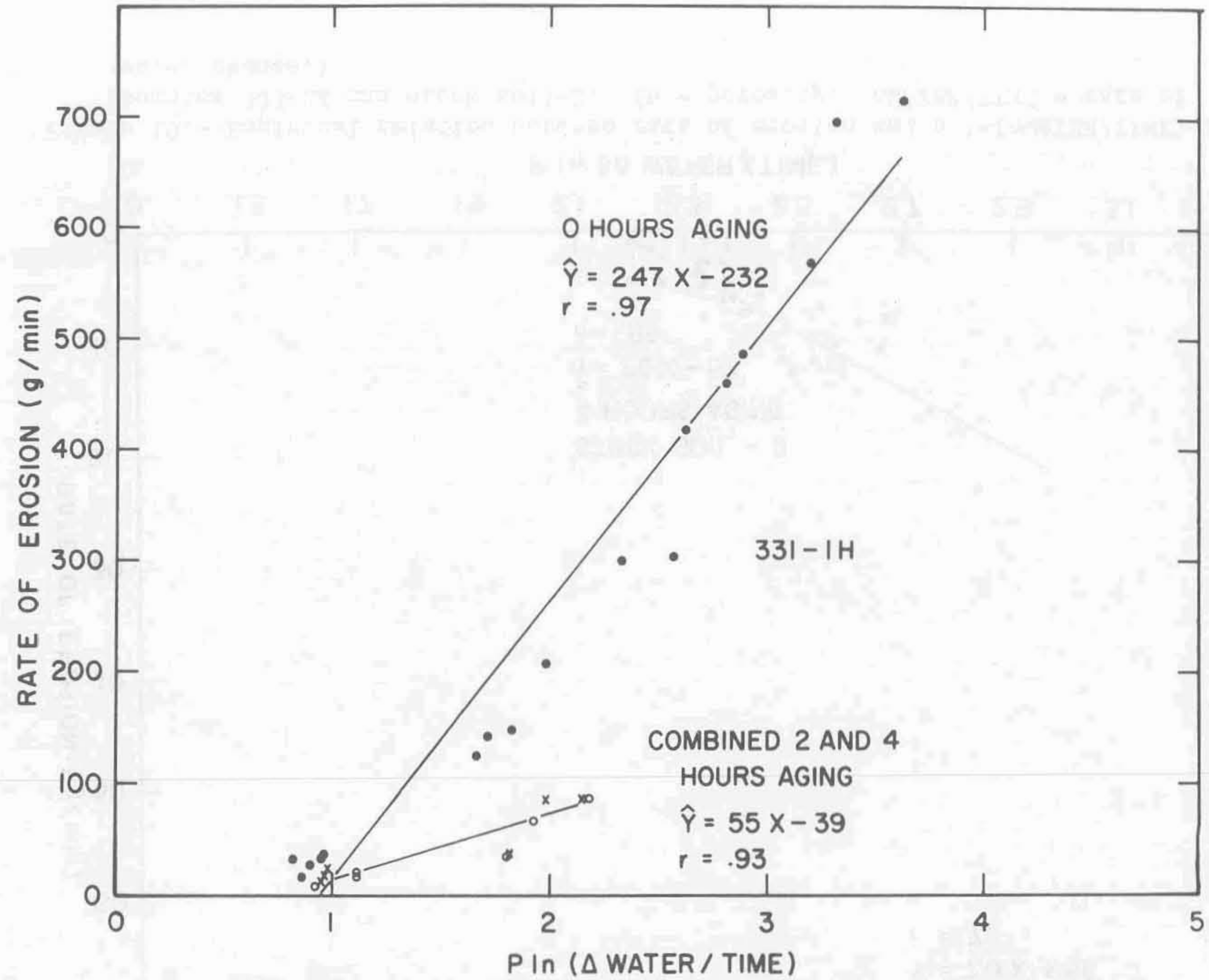

Figure 9.--Empirical relation between rate of erosion and p ln(ΔWATER/TIME) for sample 331-1H. (Samples compacted to 1.25, 1.40, and 1.77 g/cm^3 bulk densities. p = porosity. ΔWATER/TIME = rate of water change.)

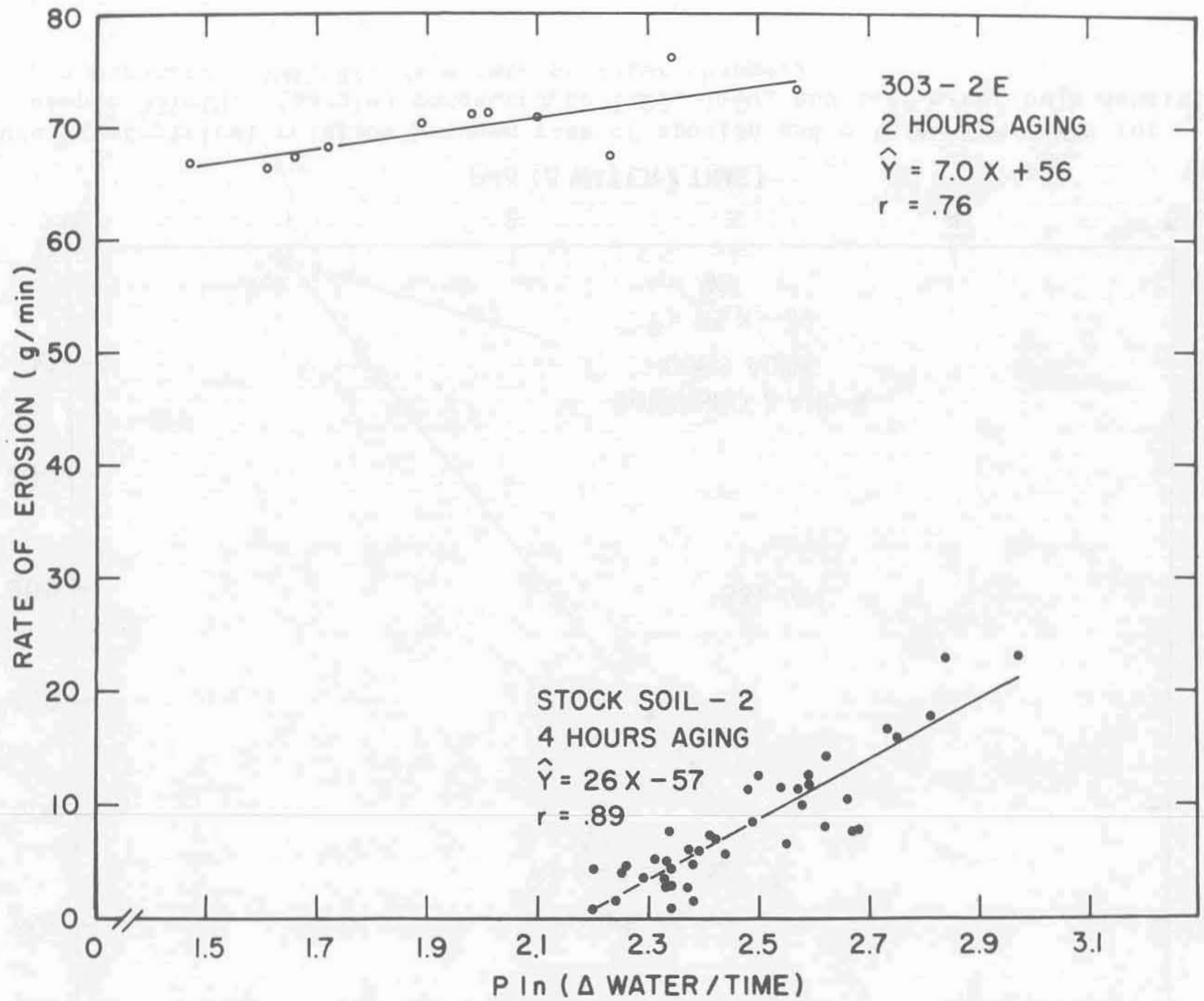

Figure 10.--Empirical relation between rate of erosion and p ln(ΔWATER/TIME) for samples 303-2E and stock soil-2. (p = porosity. ΔWATER/TIME = rate of water change.)