FREEZE-THAW EFFECTS ON SOILS TREATED FOR WATER REPELLENCY

by

Dwayne H. Fink and Stanley T. Mitchell

INTRODUCTION

Water can be supplied to many arid areas by harvesting the precipitation that falls on artificially prepared, water-repellent soil catchments. Several repellents, including fuel oil (Hillel, et al., 1967), silicone (Myers and Frasier, 1969) and paraffin wax (Fink, Cooley and Frasier, 1973) have been used successfully for this purpose. However, the failure of a wax-treated water harvesting catchment in 1973 threatened to negate much of the earlier progress attained in developing all water-repellent treatments of soils for collecting precipitation. This reversal, which included an element of serendipity, led directly to these freeze-thaw cycle studies. The introduction presented here documents the sequence of events leading to this freeze-thaw study.

Limited field testing of paraffin wax was initiated in 1972 at the Granite Reef test facility. Early results (Fink, Cooley, and Frasier, 1973) from two wax-treated plots were very encouraging: for example, quality of water from the plots was good; vegetation was completely controlled; and (most important) runoff yields continued to be high (about 90 to 95 percent of annual precipitation) after 3 years of natural weathering.

Encouraged by the initial success, we installed several other paraffin wax treated catchments in 1973. Two of these new sites also show promise, even though they have not yet withstood one of the severest of tests -- the test of time. One site, however, failed shortly after installation, and that failure served to effectively check any inclination for indiscriminate recommendation of the treatment.

The unsuccessful catchment, Seneca, located north of Globe, Arizona, is 0.2 hectare in size, and was treated in June of 1973 by spraying the paraffin wax (128-130 AMP) on as a hot melt at a coverage rate slightly exceeding 0.5 kg/m^2. The catchment had been scraped several years previously, but its surface remained rather rough and sported considerable vegetative growth as compared to the two smooth, denuded Granite Reef wax-treated plots.

Figure 1 compares the 1973 runoff data of the paraffin wax-treated Seneca and Granite Reef sites. The Granite Reef data comes close to falling on the magical 100% runoff line. Only a little precipitation (0.5 mm) was retained on the Granite Reef site before runoff was initiated; then practically all of the remaining precipitation ran off. For 1973, 90% of the total precipitation ran off the two Granite Reef sites.

The Seneca data fell even further below the 100% runoff line (Figure 1). The initial retention was much higher (5.0 mm) which reflected the rough condition of the soil surface caused by the depressions and scattered vegetation. Also, the runoff vs. precipitation line did not parallel the 100% runoff line, which means that part of the water from each storm soaked into the soil; i.e., the treated soil was not even completely water repellent.

Two other observations of the Seneca data: (1) The first major storm after the wax treatment yielded poorly, which probably merely resulted from the loose, dry grass lying on the plot which had to be washed off; (2) The other observation is considerably more serious. Only 6 or 7 months after treatment, the runoff had dropped back to normal, or even below normal, which meant almost no runoff occurs at all, ever, except for a very occasional large, high intensity storm. Since this drastic decrease occurred in January and February, we naturally attributed the plot failure to the disruptive

---

Contribution from the Agricultural Research Service, U. S. Department of Agriculture. The authors are Soil Scientist and Physical Science Technician, respectively, at the U. S. Water Conservation Laboratory, 4331 East Broadway, Phoenix, Arizona 85040. Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U. S. Department of Agriculture.

effects of the freeze-thaw cycle. Freezing and thawing can tear a soil apart, whether it is treated with a stabilizer or not (Benoit, 1973; Leo, 1963, Willis, 1955). Furthermore, Hershfield (1974) showed that the frequency of the freeze-thaw cycle in the Seneca area was one of the highest in the nation, with possibly 100 or more cycles annually. Since freeze-thaw cycles occur to some degree throughout most of the United States, including most of the dry West where the potential for water harvesting is greatest, this failure threatened to negate much of the previous progress (Fink and Frasier, 1975) of using water repellents for water harvesting.

Thus, we decided that freeze-thaw cycling had to be incorporated into the laboratory tests to minimize the risk involved in installing large and expensive field sites, and to permit us to develop and test water-repellent soil treatments which could withstand the ravaging effects of freezing and thawing.

METHODS

This report is a summary of several separate laboratory experiments evaluating two of the more promising and most evaluated repellents, refined paraffin wax and a dust suppressant oil from Chevron Research Company, for water harvesting purposes. Since a number of experiments are represented here, not all treatments were tested on each soil. Also, since there was some gradual refinement of techniques for treating and evaluating the samples, not all samples received each of the tests.

The six soils discussed in this report include, of course, the surface (0-8 cm) and subsurface (8-16 cm) Seneca soil adjacent to the plot on which the supposed freeze-thaw damage occurred. Also included are the Granite Reef soil from the laboratory's major water harvesting test site near Mesa; and the Monument Tank #2 soil from a proposed water harvesting site which like Seneca is also near Globe, Arizona; and lastly, for comparative textural purposes, a silt and a fine sand -- both obtained from the Salt River bed in Phoenix. Several other soils have received some preliminary testing but are discussed only summarily here. All soils were screened to less than 2 mm and analyzed for texture (Table 1).

All laboratory testing reported here was done using small (9-cm diameter) petri dish samples. The soils were packed wet, air dried, then treated with materials to stabilize them and make them water repellent.

The wax was added to the soil in chipped form, then melted into the soil using a heat lamp. The dust suppressant was either brushed onto the soil surface, or else diluted with benzene and sprayed on.

Each sample underwent a battery of tests to judge its performance. The samples were first tested for degree of water repellency by measuring the maximum height (ℓ) of a large (approximately 3-cm diameter) water drop resting on the treated soil surface (Fink, 1970). This value was normalized by dividing it by the theoretical height (ℓ_n = 0.3855 cm) of a similar drop having a 90° contact angle when resting on a smooth, nonporous solid surface. Treatments with relative values of ℓ/ℓ_n equal to or greater than 1.30 were defined to be adequately water repellent.

Secondly, the treated samples were tested for long-term hydrating effects by simply noting what happened to the water drop of the previous repellency test, and the soil beneath it, over a 4-hour period. Passing, for this 4-hour-hydration test, denotes that the drop (slightly reduced in size due to evaporation) and the soil beneath it remained intact after this time period; failure denotes that the drop had either completely infiltrated the soil (low repellency or untreated areas), or that the soil under the drop had swelled sufficiently to destroy its stabilized structure. This is a severe test; samples that failed it were not even evaluated in the freeze-thaw chamber.

The third test subjected the treated soils to cyclical freezing and thawing. Samples that had passed the previous test were placed in a freeze-thaw chamber; a large (approximately 3-cm diameter) water drop was placed atop the treated soil near the center of the dish; and the chamber was then cycled between approximately -20 C and +20 C. Usually, after an indefinite number of cycles, the water drop completely infiltrated the soil. The sample was then air dried, tested for structural stability (by brushing the treated soil surface with a stiff brush), and then given another 4-hour-hydration test. If the sample passed these two checks it was again placed into the freeze-thaw chamber. This process was repeated until the sample permanently lost either repellency or structural stability.

RESULTS AND DISCUSSION

Treated samples were tested first for degree of water repellency. Table 2 summarizes the results: (+) denotes treated samples which met or exceeded repellency requirements ($\ell/\ell_n \geq 1.30$), while (-) denotes treatments which failed ($\ell/\ell_n < 1.30$). All soil application rate combinations tested for these two repellents passed this relative water repellency test which suggested that all treatment rates exceeded the optimal rate. However, while this test was useful for characterizing the relative repellency of different repellents, it was not definitive for judging adequate application rates.

The 4-hour-hydration test was more useful than the water repellency test for determining optimal application rates. Samples with inadequately treated surfaces may gradually wet and fail under prolonged hydrating conditions. Most samples treated with either paraffin wax or dust suppressant also passed the 4-hour-hydration test (Table 3) -- but not all. As in the previous relative repellency test, (+) denotes treatments which passed, while I denotes a failure from complete infiltration of the large water drop within the 4 hours, and an S denotes structural failure of the treated soil. Structural failure, when it occurs, normally is caused by swelling of the soil under the drop, with subsequent cracking upon drying. Also, after drying, such soils usually cannot withstand brushing with a stiff brush. This is a severe and definitive test for evaluating water-repellent treatments; samples which failed it were not advanced to the freeze-thaw cycle chamber. One sample failed because the drop infiltrated the soil. Evidently at the low application rate of 0.25 kg/m^2 of paraffin wax, we occasionally missed treating a spot or two. Other treatments (not reported here) receiving this low application rate of wax plus other additives showed a propensity for failure due to infiltration. Thus, for effective coverage, 0.5 kg/m^2 wax appeared to be approximately the low application rate limit.

Five samples failed this 4-hour-hydration test because of structural breakdown (Table 3). All structural failures occurred on only one soil; furthermore, all treatments tested on this soil failed. The recalcitrant soil happened to be the Seneca subsoil. Here then is the serendipitous element of our Seneca plot failure. While loss of repellency and associated structural breakdown initially were ascribed to the effects of freezing and thawing, it now appears that the plot failed primarily because of hydration and associated swelling of the subsoil phase exposed by the preparatory scraping. Of course, freezing and thawing may have both compounded and accelerated the breakdown.

Even though the freeze-thaw cycle may not have been primarily responsible for ruining the Seneca plot, our laboratory experimentation has shown that such cycling can quickly destroy most of those treatments which passed the two previous tests. Failure from freezing and thawing always involved a structure breakdown -- the treatment either gradually swelled under the influence of the cycling, then cracked upon drying, or just gradually pitted away until the underlying, untreated, nonrepellent soil was exposed. Failure always occurred directly under the water drop at the center of the petri dish, never in the dry soil area around the edge.

Table 4 shows the number of freeze-thaw cycles needed to destroy the structure of soils treated with three levels of the two repellents; both range and average values are given. An asterisk by the number means that the sample was still being tested. All the asterisked numbers are quite large, indicating months of testing in the freeze-thaw chamber. A zero (0) in the freeze-thaw columns means that the sample failed the previous 4-hour-hydration test, therefore was not subjected to cycling.

From Table 4 we can conclude: (1) Neither paraffin wax nor the dust suppressant worked successfully on the Seneca subsoil. (2) The Monument Tank #2 soil passed the 4-hour-hydration test, but the maximum number of freeze-thaw cycles it could withstand was only 12, which is probably not nearly enough to survive even one winter in the Globe, Arizona, area. (3) The paraffin-treated Granite Reef and Seneca surface soils were a little better than the previous two soils at withstanding freeze-thaw cycling -- but not much. Also, increasing the wax application rate generally slightly improved their structural stability. Of course, the Granite Reef field sites are not subjected to many freeze-thaw cycles, and furthermore, their surfaces are so smooth that practically no water is ever ponded on them.

Table 4 indicates some other obvious points. (1) The Arizona silt and the Arizona sand treated with paraffin wax withstood freeze-thaw cycling better than the other soils. Apparently, coarser-textured, water-repellent soils are less subject to freeze-thaw damage than those containing considerable clay. (2) The dust suppressant withstood freezing and thawing better than paraffin wax for

Granite Reef, Seneca surface, Arizona silt and Arizona sand. At rates equal to or exceeding 1 ℓ/m², the dust suppressant held up quite well on these four soils. One of the most interesting observations of the entire study was the extreme dichotomy contrasting the dust suppressant-treated Seneca surface and subsurface soils: the former withstanding as many as 1000 freeze-thaw cycles while the latter none.

We were very concerned about the large variability of the dust-suppressant-treated soils to withstand freeze-thaw cycling. This may have been due to product variability, since three separate batches of dust suppressants were used, or to differences in application procedure (undiluted versus diluted with benzene). Unfortunately, there were no obvious direct correlations with longevity. Unfortunately, also, a preliminary, small 10-m² field test plot at the Granite Reef test site treated with dust suppressant failed after only 6 months of weathering. More research is needed to resolve these discrepancies but the fact that some soils treated with dust suppressant plus other additives have now withstood over 1000 freeze-thaw cycles (almost an order of magnitude greater than anything else yet tested) makes the effort worthwhile.

We are testing other treatments to improve structural stability under the freeze-thaw cycle, such as clay removal, altering the exchangeable cations, adjusting soil pH, and incorporating other additives with the repellents. Some of these treatments show promise, but additional research still is needed.

CONCLUSIONS

These laboratory studies suggested that the wax-treated Seneca plot failed, not because of the freeze-thaw cycle as we originally supposed, but rather because of swelling and shrinking of the treated soil which caused complete structural breakdown and loss of repellency. This swelling and shrinking of the field plot was aggravated by a preparatory scrapping which exposed the high swelling, high clay content subsoil horizon, and by surface roughness and vegetation which ponded considerable amounts of precipitation which initiated the swelling.

Conclusions from the freeze-thaw laboratory studies, expressed here in terms of recommendations for installing water-repellent water-harvesting field catchments are: (1) the smoother the plot, the less chance there will be for freeze-thaw damage (where there is no ponded water there is no freeze-thaw damage); (2) generally, coarser-textured soils can withstand freeze-thaw cycling better than finer-textured soils; (3) soil properties, other than texture, may affect resistance to damage by freeze-thaw cycling (the Granite Reef, Seneca surface, and Monument Tank soils were all sandy loams, yet showed tremendous differences in their ability to withstand freezing and thawing; (4) increasing the repellent application rate may improve a soil's resistance to breakdown (optimal application rates of paraffin and dust suppressant on most soils were about 0.5 kg/m² and 1 ℓ/m², respectively).

In the laboratory tests, the dust suppressant-treated soils generally withstood the effects of freezing and thawing better than those treated with paraffin wax. In the field, weathering factors, other than the freeze-thaw cycle may be more significant in deteriorating the dust suppressant. Some of these factors are currently being investigated.

REFERENCES CITED

Benoit, G. R. 1973. Effect of freeze-thaw cycles on aggregate stability and hydraulic conductivity of three soil aggregate sizes. Soil Sci. Soc. Amer. Proc. 37:3-5.

Fink, D. H. 1970. Water repellency and infiltration resistance of organic-film-coated soils. Soil Sci. Soc. Amer. Proc. 34:189-194.

Fink, D. H., K. R. Cooley, and G. W. Frasier. 1973. Wax-treated soils for harvesting water. J. Range Management 26:396-398.

Fink, D. H., and G. W. Frasier. 1975. Water harvesting from watersheds treated for water repellency. In SSSA Special Publication No. 7, Chemical Soil Conditioners, Chapter 17.

Hershfield, D. M. 1974. The frequency of freeze-thaw cycles. J. Applied Meteorology 13:348-354.

Hillel, D., and Associates. 1967. Runoff inducement in arid lands. Final Technical Rept., USDA Project A10-SWC-36. 142 p.

Leo, Micah W. M. 1963. Effect of freezing and thawing on some physical properties of soils as related to tomato and barley plants. Soil Sci. 96:267-274.

Myers, L. E., and G. W. Frasier. 1969. Creating hydrophobic soil for water harvesting. J. Irrig. and Drain. Div., Amer. Soc. Civ. Engin. Proc. 94 (IR1):43-54.

Willis, W. O. 1955. Freezing and thawing, and wetting and drying in soils treated with organic chemicals. Soil Sci. Soc. Amer. Proc. 19:263-267.

Table 1. Soils and associated texture analyses.

SOIL	SAND	SILT	CLAY	CLASSIFICATION
		%		
GRANITE REEF	66	27	7	SANDY LOAM
SENECA (0-8 cm)	56	34	10	SANDY LOAM
SENECA (8-16 cm)	28	23	49	CLAY
MONUMENT TANK #2	62	24	14	SANDY LOAM
ARIZONA SILT	41	54	5	SILT LOAM
ARIZONA FINE SAND	80	18	2	LOAMY SAND

Table 2. Relative water repellency (ℓ/ℓ_n) of paraffin wax and dust-suppressant treated soils as a function of repellent application rate.

TREATMENT	RATE	NO. SOILS	NO. SAMPLES TESTED 1/	
PARAFFIN WAX (MELT)	kg/m^2		(+)	(-)
	0.25	6	8	0
	0.50	6	9	0
	0.75	7	13	0
TOTAL		8	30	0
DUST SUPPRESSANT	ℓ/m^2			
	0.50	8	14	0
	1.00	8	14	0
	1.50	4	4	0
	2.25	5	5	0
TOTAL		8	37	0

1/ (+) denotes $\ell/\ell_n \geq 1.30$; (-) denotes $\ell/\ell_n < 1.30$.

Table 3. Structural stability and sustained repellency of paraffin wax and dust-suppressant treated soils subjected to 4-hour-hydration test.

TREATMENT	RATE	NO. SOILS	NO. SAMPLES TESTED 1/		
	kg/m^2		(+)	(S)	(I)
PARAFFIN WAX (MELT)	0.25	6	7	0	1
	0.50	7	9	1	0
	0.75	9	14	1	0
TOTAL		9	30	2	1
DUST SUPPRESSANT	ℓ/m^2				
	0.50	9	17	1	0
	1.00	9	17	1	0
	1.50	6	7	1	
	2.25	5	5	0	0
TOTAL		9	46	3	0

1/ (+) denotes treatments which withstood the test; (S) denotes those which failed structurally; (I) denotes those which lost repellency.

Table 4. Number of freeze-thaw (F.T.) cycles to effect structural destruction of water-repellent treated soils.

SOIL	PARAFFIN WAX Rate	No. Samples Tested	F.T. Range	Avg.	DUST SUPPRESSANT Rate	No. Samples Tested	F.T. Range	Avg.
	kg/m^2		—cycles—		ℓ/m^2		—cycles—	
GRANITE REEF	0.25	2	11-17	14	0.5	4	34-164	75
	0.50	3	11-33	22	1.0	4	19-403	147
	0.75	4	11-33	24	1.5	2	426-655	540
SENECA (0-8 cm)	0.25	2	0-14	7	0.5	3	34-330	170
	0.50	2	16-22	19	1.0	3	813*-893	861*
	0.75	3	14-43	25	1.5	1	960*	960*
SENECA (8-16 cm)	0.25	0	--	--	0.5	1	0	0
	0.50	1	0	0	1.0	1	0	0
	0.75	1	0	0	1.5	1	0	0
MONUMENT TANK #2	0.25	1	6	6	0.5	3	2-7	5
	0.50	1	6	6	1.0	3	7-12	10
	0.75	2	6-11	8	1.5	1	7	7
ARIZONA SILT	0.25	1	56	56	0.5	3	14-877*	365*
	0.50	1	425	425	1.0	3	184-795*	396*
	0.75	1	123	123	1.5	2	772*-862*	817*
ARIZONA FINE SAND	0.25	1	43	43	0.5	2	219-682*	450
	0.50	1	101	101	1.0	2	74-951*	512*
	0.75	1	109	109	1.5	1	728*	728*

* still being tested

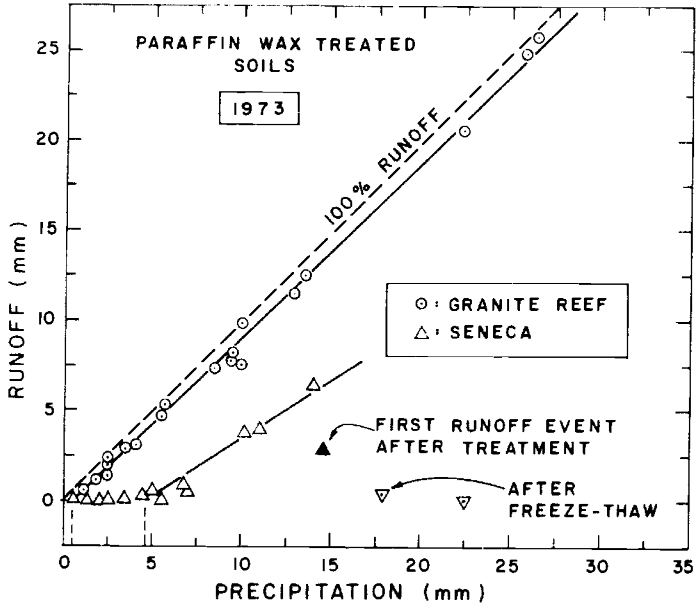

Figure 1. Runoff versus precipitation for Granite Reef and Seneca paraffin wax treated water harvesting sites.