

# Solar Radiation Effects on Frost Action in Soils

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Engineers should be aware of the effects of solar radiation on frost action in soil foundations and the subsequent effect on the performance of surface structures. Damage to concrete canal drop structures and linings from frost heave on shaded sides in contrast to sun-exposed sides is described. To demonstrate passive solar effects on frost penetration, winter temperatures were measured on the concrete surfaces and in the soil subgrade beneath black-painted and unpainted concrete linings on both the shaded and sun-exposed sides of a small canal. Periodically data on air temperatures, snow cover, and cloud conditions were collected and incident radiation and radiation reflected from the different concrete surfaces were measured. Frost penetrated 37 percent less on the painted, sun-exposed side than on the unpainted, sun-exposed side. Because of long-wave, nighttime radiation, frost penetrated 28 percent more on the painted shaded side than on the unpainted shaded side. For the unpainted concrete, frost penetrated 9 to 13 percent less on sun-exposed than on shaded sides.

In the current emphasis on developing solar energy, the possibility of using it to reduce frost action in soil foundations and the consequent damage to overlying structures should not be overlooked. For frost-susceptible soils in cold climates, the effects of passive solar energy are often apparent. For example it is known that frost heave is often greater in shaded than in sun-exposed areas even though the surface and climatic conditions are the same for both. This has been observed along highways shaded by trees, bluffs, buildings, or overpasses where frost penetration has been deeper than in unshaded areas. Although many factors affect frost heave, a general correlation has been established between shadow zones beneath east-west oriented overpasses and the magnitude of frost heave; in extreme cases, differential pavement movement has presented a hazard to fast-moving traffic (1).

Differences in performance caused by solar influences have also been apparent on concrete linings and other structures of irrigation canals. Three instances are examined where damage to concrete canal structures has been greater on shaded than sun-exposed sides in areas where frost heave has been unusually high. This paper describes a small field experiment where frost penetration was measured in the soil foundation beneath a black-painted and an unpainted concrete lining on both the shaded and unshaded side slopes of a canal (2).

The experiment was conducted adjacent to a site where previous research on using polystyrene insulation as a lining had been completed and a major part of the temperature-measuring instrumentation was already in place. With a small amount of additional work, the test site provided an opportunity to demonstrate solar effects in soil under different surface and shading conditions.

Even though no damage occurred in this instance and the test results indicate that painting of canal linings to control frost heave would not be practicable as a general practice, the attention of engineers should be directed to potential problems and beneficial effects from solar action on the soil foundations of structures. In addition new ways to use passive or active solar energy to control frost heave in soil foundations should be investigated. Some research in this direction has been started with experiments such as using earth heat pipes with solar augmentation to control icing on highway pavements and bridges (3).

## EXAMPLES OF FROST DAMAGE

Figure 1 shows a rectangular inclined canal drop of

reinforced concrete affected by frost action. This canal runs east-west and the inward deflection of the concrete walls has been mostly on the south side where shading occurs in winter; the lateral force of soil frost action in the backfill is apparent from the bending of the 75-mm-diameter steel pipes added for support. Some of the wall backfill on the shaded side has been removed to relieve pressure, and weep holes have been drilled in the walls to lower the water table. The sun-exposed north wall is relatively undamaged although the drainage from weep holes shows the presence of ground water. The reinforced concrete inclined channel has also been damaged from differential frost heave; greater heave occurred in the south half than in the north half.

Frost damage on the outlet of a rectangular inclined drop of reinforced concrete is shown in Figure 2. Here the top of the south wall of the east-west oriented structure has tipped inward about 200 mm. As a maintenance procedure, a concrete cap superimposed with soil has been added to prevent possible collapse of the wall.

Figure 3 shows frost heave damage to a 65-mm-thick, slip-formed concrete lining in a small canal. At the crack in the side slope, the upper portion of the lining is offset upward an amount about equal to the 65 mm lining thickness. This canal is oriented east-west and the damaging crack is on the south side slope which is completely or partially shaded at times when the sun is low over the southern horizon in winter. The crack appeared mostly during a 2-week period in March, following a particularly cold winter. Apparently during the winter, frost action in the soil subgrade heaved the whole concrete-lined section relatively uniformly without causing noticeable cracks.

When thawing occurred in March, the soil under the lining on the north slope, exposed more or less directly to the sun, and under the bottom lining thawed faster than that on the partially shaded south side; and the concrete was broken by the differential settlement. Although other factors such as the insulating effects of snow may have been involved, a study of the angle of the sun on the lining in winter (see Figure 7) offers a possible basis for explaining the slow uniform heave and the faster differential settlement; in March the angle is greater than at any other time since significant freezing temperatures started at the onset of winter. Exploration at the end of March showed ice lenses still under the south slope. After complete thawing of the soil, the offset was reduced to about 25 mm. For north-south oriented canals, insolation is more even on both sides of the canal and damage from frost heave is usually much less.

Past damage such as that described above has led to improved design and construction practices. In one special instance a chute, 1950 m long, replaced a series of drop structures on a hillside where extensive damage to the drop structures had recurred. The base of the chute was located near the ground surface and shallow subsurface drains were provided on each side.

## FROST INVESTIGATION

### Test Program

The solar experiment described was conducted during

Figure 1. Damage caused by frost action in the soil on the shaded south wall and on the south side of the inclined channel.

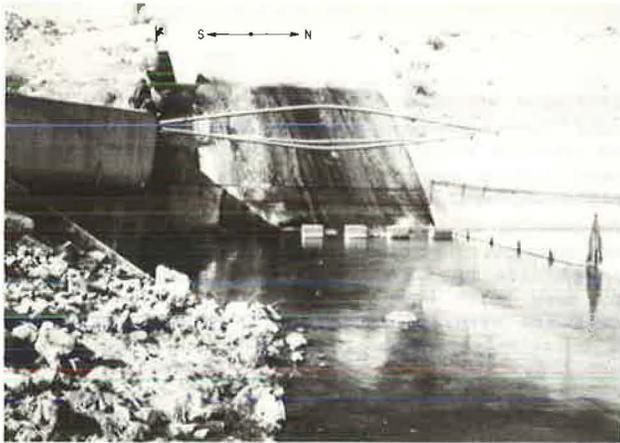
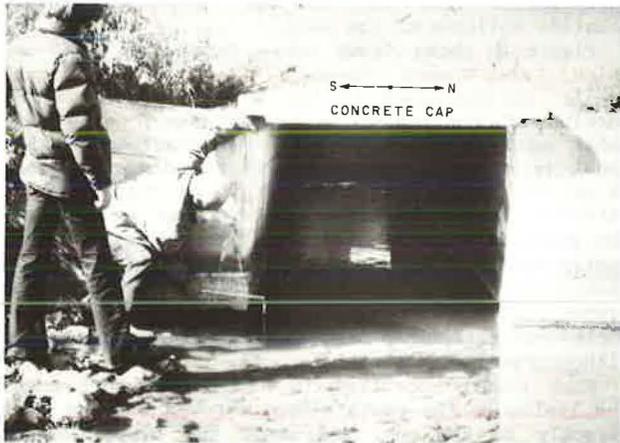


Figure 2. Inward deflection of south wall at the outlet of a chute is restrained by a concrete cap and additional soil.



the winter of 1977-1978. The purpose was to determine what effect radiation from the sun would have on frost penetration beneath a particular black-painted concrete canal lining with its soil conditions compared with penetration for an adjacent unpainted section. Incident radiation and radiation reflected from the concrete surfaces were measured. Temperatures were also measured on the concrete surfaces and at six depths in the soil beneath the lining to monitor the progress of frost. Climatic data were gathered and the groundwater level was recorded at intervals during the winter.

#### Test Site

The canal test site was located on the Riverton Irrigation Project, between stations 7+25.5 and 7+34.5 m on Lateral 15.1 about 1.5 km west of the town of Pavillion in west-central Wyoming. It was at one of two sites on the project where previous tests with polystyrene insulation had been made (4,5). The test section was oriented due east-west; this provided shaded south and unshaded north side slopes. The soil at the test site ranged from a silty or clayey sand to a lean clay. Its liquid limit was between 26 and 36 and its plasticity index was between 12 and 20. The dry density of the soil was

Figure 3. South side of concrete canal lining broken during spring thawing period.



1650 to 1675 kg/m<sup>3</sup> and the relative mass density was 2.67. The moisture content ranged from about 6 percent near the ground surface to 25 percent below the bottom of the canal where the groundwater table was encountered.

#### Test Installation

The test sections consisted of two adjacent sections of concrete lining each about 3 m in length (see Figure 4). Polystyrene insulation 50 mm in thickness with a 150-mm soil cover was placed on the ground at the edge of each side of the canal lining to prevent frost penetration from outside the lining (see Figure 7). After a thorough cleaning of the concrete surface, both the shaded and unshaded sides, one section of lining was covered with one coat of primer and two coats of black vinyl acetate paint (see Figure 5). Surface thermocouples were installed in pairs on the sides and bottoms of the painted and unpainted test sections (see Figures 4 and 6). The thermocouple tips were attached to the concrete with screws and black or clear silicone sealant.

Figure 7 shows a cross section of the lining with the location of thermocouples beneath the concrete. Thermocouples were installed by (a) coring a 100-mm hole through the concrete, (b) augering a hole in the soil below perpendicular to the concrete surface, (c) placing the thermocouples which were loosely attached at the desired spacing to a lath in the hole, (d) refilling the hole around the thermocouples with a soil-water slurry, and (e) filling the concrete hole with fresh concrete. The thermocouple wires were of the polyvinyl-coated, copper-constantan type. They were connected to multiple-position switches mounted on steel posts. A thermocouple for recording air temperature was located about 1 m from the ground surface in a specially constructed wooden box attached to one of the switchbox posts.

When temperatures were to be measured, a digital thermometer was connected to one of the switches, and the temperature at each thermocouple was read by switching from one to another. Before use in the field test, the accuracy of the digital thermometer was checked in a laboratory environmental chamber for the range of field temperatures.

#### Radiation Equipment

Radiation measurements were taken to provide back-

ground information for comparison with conditions in other areas where an application of the black surface for absorption of solar heat might be used. At the Midvale Irrigation District yard in Pavillion, a radiometer (Mark IV Sol-a-Meter) was installed on top of a post. This instrument uses four 20-mm<sup>2</sup> silicon cells to generate a current directly proportional to the incident solar radiation measured in cal/(cm<sup>2</sup>·min) [cal/(cm<sup>2</sup>·min) x 697.3 = W/m<sup>2</sup>]. The manufacturer states that it has a spectral response from 0.35 to 1.15 microns and an accuracy of +3 to +5 percent. A digital readout of the total insolation for any period of time is provided by an amperes per hour meter. A separate meter indicates the instantaneous rate of insolation.

At the test site, incident radiation and radiation reflected from the concrete lining surfaces were measured by a Mark VI Sol-a-Meter. The instrument measures radiation directly in British thermal units per square foot hour (multiply by 3.152 for watts per square meter) with an accuracy stated by the manufacturer to be ±2 percent. It was placed on top of one of the switchboxes, with the sensor pointed upward, to measure incident radiation. For

a measurement of radiation reflected from the concrete surface, it was held approximately 400 mm from the concrete.

**Measurements and Observations**

About once a week and for 1 day each month at 2-hr intervals between 6 a.m. and 6 p.m. project personnel measured (a) radiation in the general area and that reflected from the painted and unpainted concrete surfaces, (b) air temperatures, and (c) temperatures on the concrete surfaces and in the soil beneath. At the time of these measurements, clouds were described as high, medium, or low; thin or heavy; and degree of cloud cover was estimated (clear, less than 0.3; partly cloudy, 0.4 to 0.7; and cloudy, greater than 0.8). Wind direction and speed were estimated and records made of snow and ice in the canal. About once a month, the groundwater level in a well beside the canal was measured.

Figure 4. Frost test section showing black and unpainted concrete sections, insulated sides of the test area, and the thermocouple system.

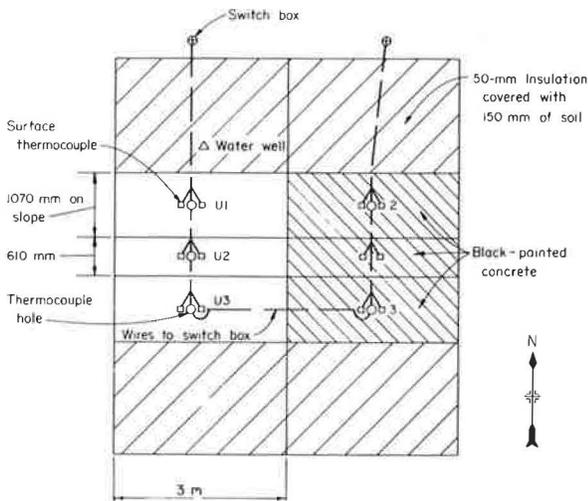


Figure 5. Black-painted concrete lining with unpainted control section in the foreground.



Figure 6. Thermocouples for measuring surface temperatures. Wires in PVC conduit lead to subsurface thermocouples.

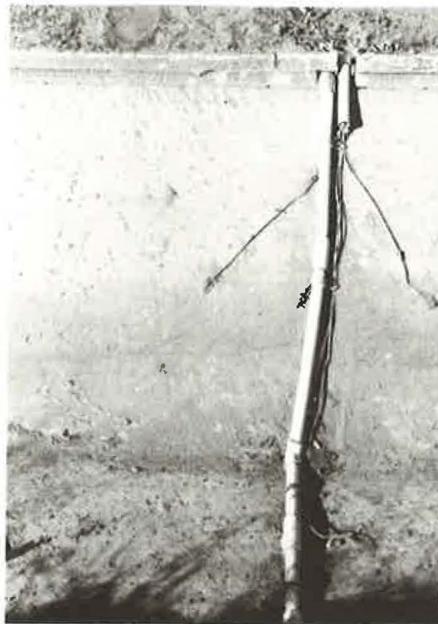


Figure 7. Cross section of concrete lining showing the locations of subsurface thermocouples and angles of the sun on the sun-exposed slope.

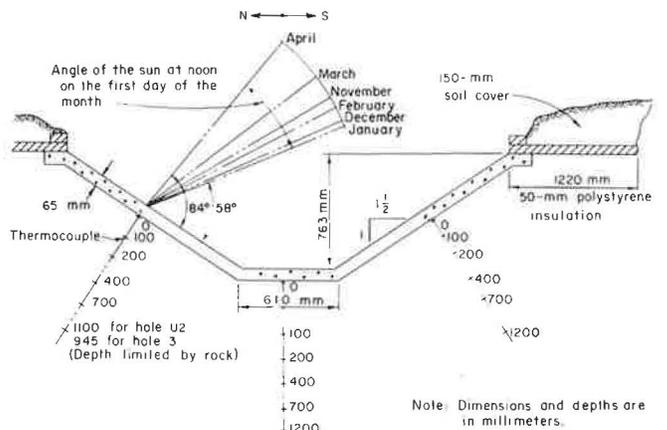


Figure 8. Cumulative degree-days for Pavillion, Wyoming—winter of 1977-78.

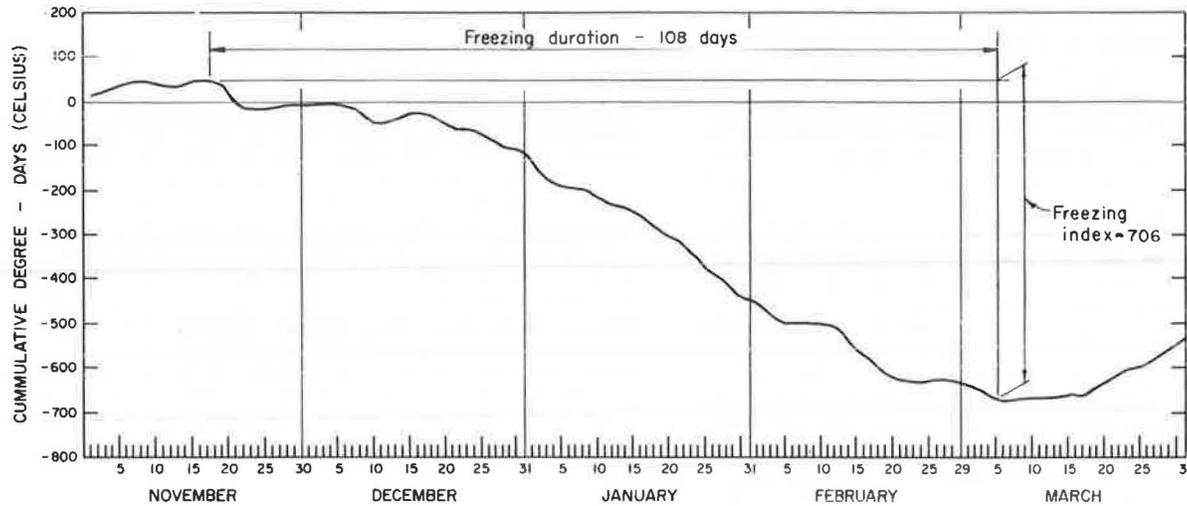


Table 1. Record of solar radiation (watts per square meter) at Pavillion, Wyoming, and at concrete lining test site on lateral 15.1.

Date	Time	Test Site												Cloud Conditions
		Pavillion Station Incident Radiation		Incident Radiation	Reflected Radiation									
		Instantaneous	Cumulative		Shaded				Unshaded					
					Reading	Albedo <sup>a</sup>	Reading	Albedo	Reading	Albedo	Reading	Albedo		
1977														
Dec. 13	1200	279	103,689	439	31	7	47	11	47	11	98	22	Cloudy, thin, of medium height <sup>b</sup>	
13	1400	265	103,758	-	31	-	31	-	77	-	126	-	Cloudy, thin, of medium height	
13	1600	14	103,827	31	16	51	31	100	16	51	16	51	Cloudy, thin, of medium height	
21	1300	349	105,711	300	31	10	62	21	77	26	77	26	Cloudy, high, thin <sup>c</sup>	
1978														
Jan. 4	1330	397	110,383	349	62	18	62	18	126	33	174	46	Clear, no clouds	
13	1330	384	112,544	377	62	17	47	13	174	40	223	51	Clear, high, thin clouds	
25	1330	432 <sup>d</sup>	116,519	439	47	11	98	22	188	38	188	38	Clear, high, thin clouds	
Feb. 2	1330	474	121,330	502	62	12	112	22	488	97	502	100	Clear, high, thin clouds	
13	1400	432	126,420	502	188	37	202	40	126	78	126	78	Clear, no clouds	
17	0800	195	-	160	98	61	98	61	223	48	286	52	Clear, no clouds	
17	1000	307	-	460	126	27	126	27	251	50	251	50	Clear, no clouds	
17	1400	502	130,325	502	139	28	160	32	160	68	59	59	Clear, no clouds	
17	1600	209	-	237	77	32	98	41	188	38	223	44	Cloudy, high, thin. Varied cloud cover	
24	1340	418	135,694	502	77	15	126	25	126	29	139	32	Cloudy, high, thin. Varied cloud cover	
Mar. 1	1330	-	-	439	98	22	139	32	160	35	223	48	Clear, high, thin clouds	
8	1250	-	-	460	77	17	98	21	126	53	139	59	Clear, no clouds	
15	0800	-	-	237	31	13	77	32	188	31	223	37	Clear, high, thin clouds	
15	1000	-	-	600	31	5	112	19	188	31	202	33	Cloudy, heavy, of medium height	
15	1200	-	-	614	62	10	126	20	223	29	300	39	Cloudy, heavy, of medium height	
15	1400	-	-	774	112	14	139	18	126	33	174	46	Clear, high, thin clouds	
15	1600	-	-	377	49	13	98	26	62	25	98	39	Cloudy, heavy, of medium height	
22	1300	-	-	251	49	19	77	31						

<sup>a</sup> Percentage of reflected radiation based on the incident or total incoming radiation.  
<sup>b</sup> Sun out more when instantaneous reading was taken.  
<sup>c</sup> Sun covered with clouds part of time.  
<sup>d</sup> Fresh snow. Some ice on radiometer.

The town of Pavillion is located at 43°50' north latitude and 108°41' west longitude at an elevation of 1660 m. A cumulative degree-days curve for the winter of 1977-1978, based on air temperatures recorded at Pavillion, is given in Figure 8; this type of curve is useful for comparing temperatures in different locations (6). This shows that the freezing index was 706 degree-days Celsius; each day's contribution in degree-days is the algebraic difference between the average of maximum and minimum daily temperatures and 0°C. The freezing duration for the winter was 108 days.

Snowfall during the winter of 1977-1978 was light. The following data on snow and ice in the canal at the test site were recorded:

Date	Snow and Ice Conditions
12-09	0.3 cm of snow on shaded side
01-04	1 cm of snow on shaded side
01-13	Trace of snow on shaded side
01-20	8 cm of snow on test area
01-25	2 cm of snow on ground and 15 cm drifted in the lateral bottom
02-02	15 cm of snow in the bottom
02-13	15 cm of snow on the test section
02-17	15 cm of snow on the shaded side
02-24	6 cm of ice on bottom
03-01	6 cm of ice on bottom

DISCUSSION OF RESULTS

Radiation

The radiation measurements and the record of cloud conditions, which were started about 2 months after the test installation was made, are shown in Table 1. A comparison of radiation on the black-painted and unpainted concrete section can be made from the albedo, which is the percentage of reflected radiation based on the incident or total incoming radiation. As expected, the black surface usually absorbed more daytime radiation than did the unpainted surface. Varying cloud conditions sometimes affected radiation readings within short time intervals.

Because the test was to simulate a field condition at the test site, no attempt was made to clean the concrete surfaces during the test period. Some dust accumulated on surfaces, particularly from an adjacent unpaved county road. Although snowfall was light, it would cover one side more than the other and melt faster on the north than the south side. These factors together with the particular reflective quality of the black paint used would result in absorptivity-emissivity values that may not be comparable with those of other investigators who have measured radiation under other conditions.

The intensity of insolation on a plane surface depends on the angle of the sun's rays with the surface; the highest intensity is at 90°. A plot of sun angles on the sun-exposed north side of the canal lining for the middle of each month during the test period is shown on Figure 7. These were computed from the angle of the side slope, the latitude, and the declination of the sun.

Temperature and Frost Penetration

Averages of all temperatures measured during the winter recording period at each thermocouple location beneath the concrete are plotted in Figure 9. The temperatures of both black-painted and unpainted concrete were higher on the sun-exposed side than on the shaded side by about 6°C at zero depth (bottom of the concrete) and less than 1°C at 1000 mm. It can also be seen that compared to the unpainted concrete, the average temperatures beneath black-painted concrete on the sun-exposed side are higher and temperatures beneath black-painted concrete on the shaded side are lower.

An example of a 1-day record of concrete surface and soil subsurface temperatures is shown in Figures 10 and 11; on that day there were thin clouds of medium height. On clear days or when clouds were not heavy, the plots of temperatures during the day show a wide variation between temperatures at the surface and those beneath the concrete on the sun-exposed side. As would be expected, the variation was much less on the shaded side.

A plot of maximum frost penetration is shown in Figure 12. Although the black surface generally absorbed more radiation than the unpainted concrete during the day, this was offset by the longer wave radiation from the black surface at night. Therefore, although the black surface reduced frost penetration 37 percent on the sun-exposed side, it caused an increase in penetration of 28 percent on the shaded side. For the unpainted section, frost penetration was 9 percent less on the sun-exposed side of the canal compared with the shaded side. During the preceding winter, temperatures on the same section indicated that frost penetration was about 700 mm on the sun-exposed side compared with 800 mm on the shaded side for a difference of 13 percent.

Although no thermocouples were installed beneath the painted concrete at the bottom of the canal, those installed under the unpainted bottom showed that frost had penetrated about 340 mm; during the previous winter the penetration at this location was 400 mm. This penetration was probably influenced by the presence of the water table and, at times, by snow and ice in the lateral. The depth of the water table below the lining ranged between 140 mm on

Figure 9. Average of temperatures measured below the slopes of concrete canal lining during winter of 1977-78.

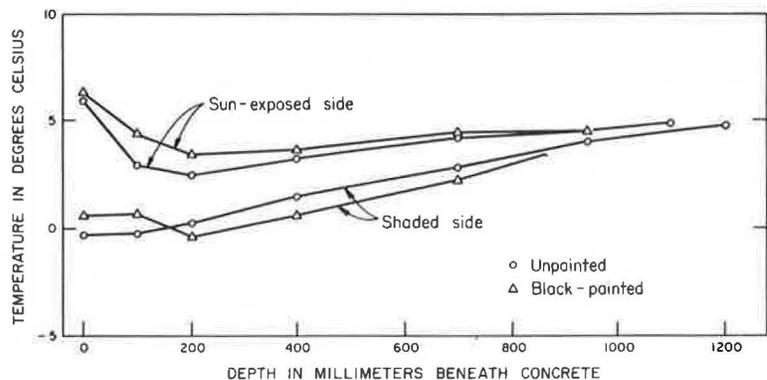
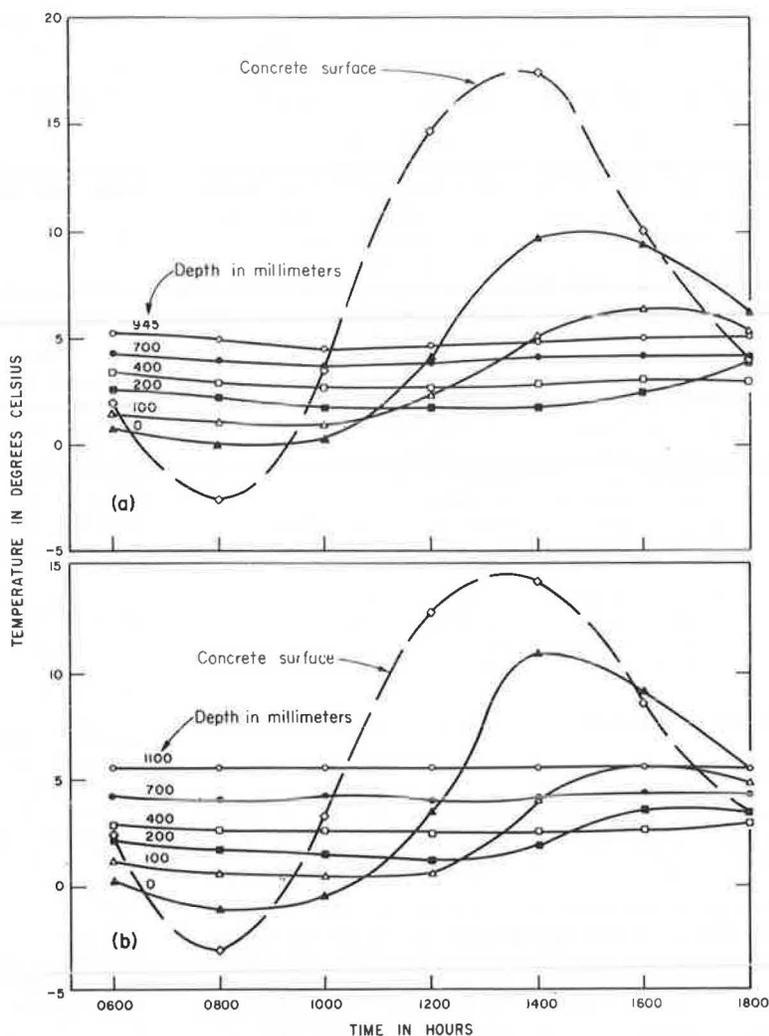


Figure 10. December 13, 1977: surface and subsurface temperatures for (a) painted and (b) unpainted concrete canal lining on sun-exposed side (thin clouds of medium height).



November 17, 1977, to 325 mm on March 8, 1978. Thus the frost penetrated to approximately the water table elevation.

Frost heave on the lining was not measured during this experiment. However, during the previous winter, the adjacent lining heaved a maximum of about 20 mm and settled back to 4 mm above the pre-winter level without causing any noticeable cracking (5).

#### CONCLUSIONS

Based on experiences with east-west oriented concrete canal structures damaged by frost action in soil foundations and backfill and the measurement of frost penetration beneath unpainted and black-painted concrete canal lining, the following conclusions about the effects of solar radiation are drawn:

1. Damage to walls and linings on south, shaded sides can be significantly greater than on north, sun-exposed sides. The damage can occur by differential settlement during uneven soil thawing as well as by frost heave.

2. For the unpainted concrete canal lining during two successive winters, frost penetration was 13 and 9 percent less on the sun-exposed side than on the shaded side.

3. On the north, sun-exposed side slope of the lining, maximum frost penetration was 37 percent less beneath black-painted than beneath unpainted concrete.

4. On the south, shaded side slope of the lining, frost penetration was 28 percent deeper beneath the black-painted concrete than for the unpainted concrete, showing the effect of the long-wave, nighttime radiation.

#### ACKNOWLEDGMENT

The frost investigation was conducted jointly by U.S. Bureau of Reclamation personnel from the Engineering and Research Center in Denver, Colorado, and from the Riverton Project, Riverton, Wyoming. Richard Berg of the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire, had visited the test site before a previous adjacent test of frost penetration when polystyrene insulation was used. He offered excellent suggestions, particularly on instrumentation, and supplied pertinent Corps of Engineers' literature on the subject. Funding for the investigation was from the Soil Mechanics and Open and Closed Conduit Systems items of the Water Resources Planning and Engineering Research Program.

Figure 11. December 13, 1977: surface and subsurface temperatures for painted and unpainted shaded side and on unpainted bottom.

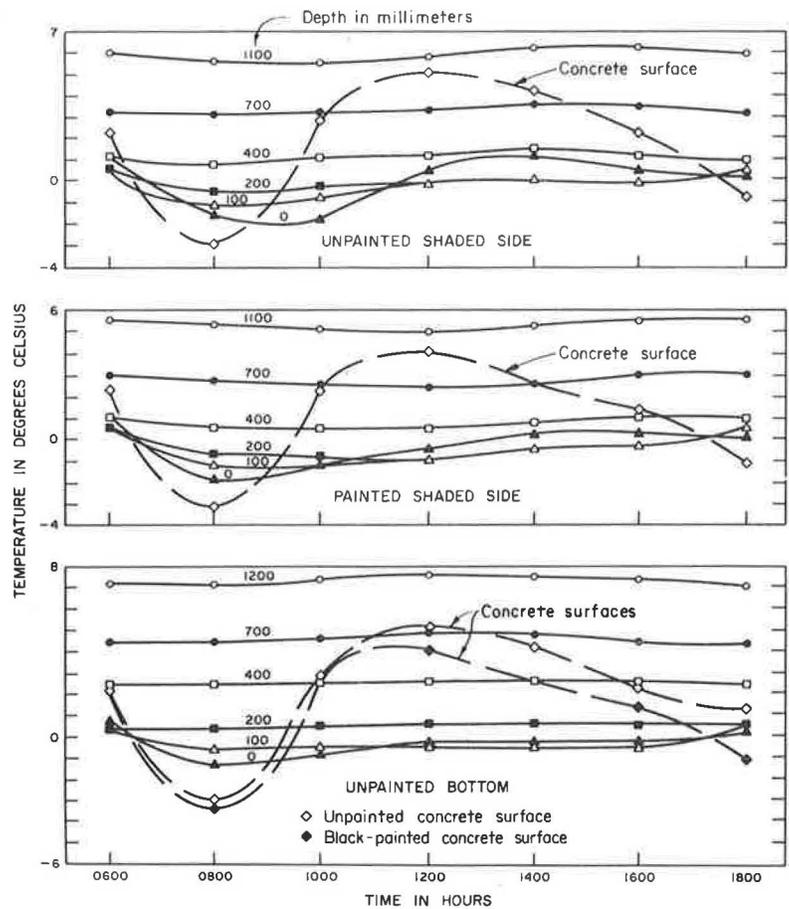
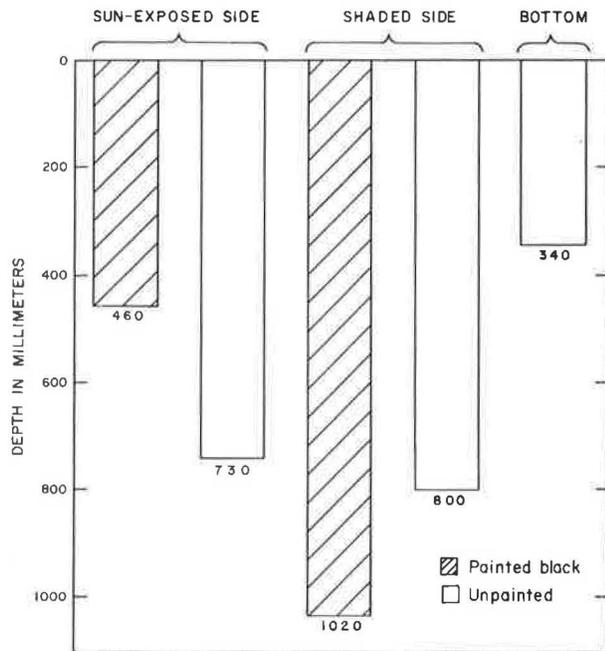


Figure 12. Maximum frost penetration beneath concrete canal lining.



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