

Solar Radiation Effects on Frost Action in Soils

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Engineers should be aware of solar radiation effects of frost action in soil foundations on the performance of surface structures. Damage to concrete canal drop structures and lining 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 shaded and sun-exposed sides of a small canal. Periodically, data on air temperatures, snow cover, and cloudiness 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 longwave, nighttime radiation, frost penetrated 28 percent more on the painted shaded side than on the unpainted shaded side. For the unpainted concrete, frost penetrated 9-13 percent less on sun-exposed than on shaded sides.

In the current emphasis to develop solar energy for many purposes, the possibility of its use to reduce frost action in soil foundations and 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; it is common knowledge that frost heave is often greater in shaded than in sun-exposed areas, other surface and climatic conditions being equal. For example, this has been observed along highways shaded by trees, bluffs, buildings, or overpasses where frost penetration has been deeper than in unshaded areas. Although there are many factors that 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 due to solar influences have also been apparent on concrete lining and other structures of irrigation canals. This paper will first mention three instances in which damage to concrete canal structures has been greater on shaded than on sun-exposed sides in areas where frost heave has been unusually high. The main part of the paper will describe a small field experiment where frost penetration was measured in the soil foundation beneath black-painted and unpainted concrete lining on shaded and unshaded canal side

slopes (2). The experiment was conducted adjacent to a site where previous research on polystyrene insulation for 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 in this instance no damage occurred and painting of canal linings as a general practice to control frost heave would not be practicable. However, the attention of engineers should be directed to potential problems and beneficial effects from solar action on soil foundations of structures. Besides the avoidance of problems, there are opportunities to devise new ways to use passive or active solar energy to control frost heave in soil foundations. Some research in this direction has been started with experiments such as those on earth heat pipes with solar augmentation to control preferential 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 concrete walls has been mostly on the south side where shading occurs in winter; the lateral force of soil frost action on the wall 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 to lower the water table. The sun-exposed wall is relatively undamaged although the drainage from weep holes shows the presence of groundwater. The reinforced concrete floor of the chute 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

Figure 1. Damage caused by frost action in soil on shaded south side of canal drop structure.



Figure 2. Wall deflected inward by frost pressures in soil.



Figure 3. Breakage during spring thawing period of concrete canal lining on south side of east-west oriented canal.



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 lining thickness. This canal is oriented east-west and the greatest damage by far is on the south-side slope, which is completely or partly shaded at times when the sun is low over the southern horizon in winter. The damage occurred mostly during a two-week period in March after a particularly cold winter. Apparently, during the winter, frost action in the soil subgrade heaved the concrete relatively uniformly without causing noticeable cracks. When thawing occurred in March, the soil under the north slope, exposed more or less directly to the sun, thawed faster than that on the 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 (Figure 4) offers a possible basis for explaining the slow uni-

Figure 4. Cross section of concrete lining and angle of sun on sun-exposed slope.

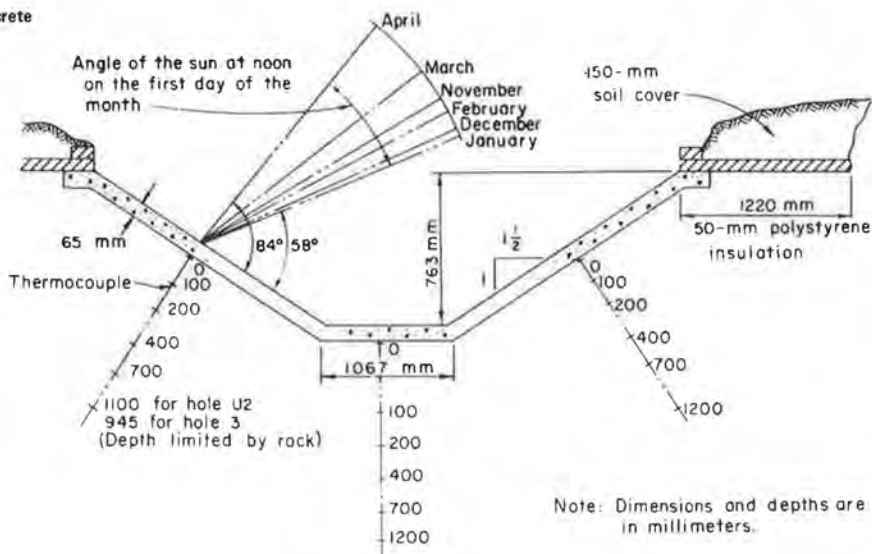
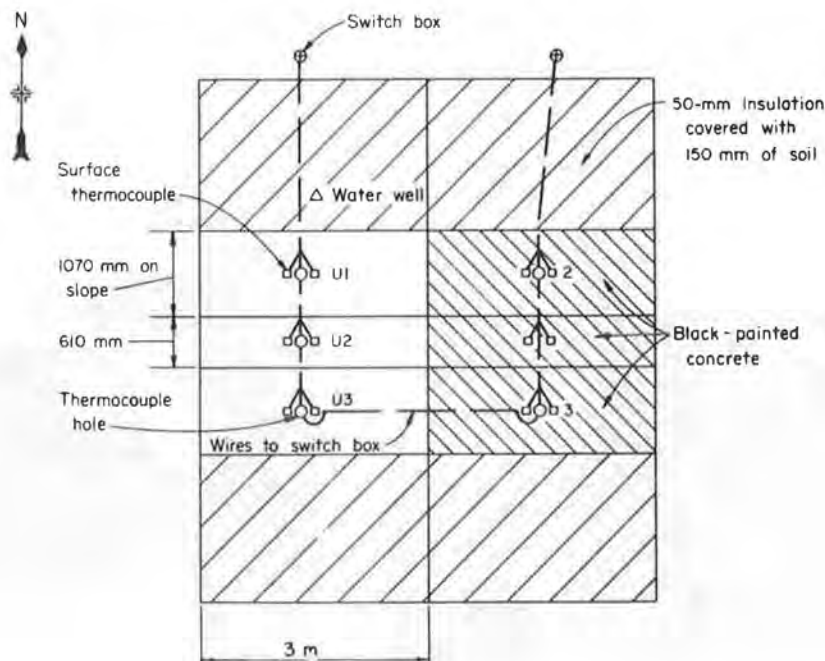


Figure 5. Plan of frost test section.



form 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. Subsequently, 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 noted above has led to improved design and construction practices to avoid damage. In one special instance, a chute 1950 m long replaced a series of drop structures located down 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 on each side were provided.

FROST INVESTIGATION

Test Program

This solar experiment was conducted during one winter. 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 investigation site was located on the Riverton Unit, Pick-Sloan Missouri River Basin Program, 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, p. 17).

The test section was oriented due east-west, which 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; the liquid limit was between 26 and 36 and the plasticity index between 12 and 20. The soil dry density was 1650-1675 kg/m³ and the relative mass density, 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 (Figure 5). Polystyrene insulation 50 mm in thickness with a 150-mm soil cover was placed on each side of the canal lining to prevent frost penetration from outside the lining.

After a thorough cleaning of the concrete surface, one section of lining was covered with one coat of primer and two coats of black vinyl acetate paint (Figure 6). Surface thermocouples were installed in pairs on the sides (Figure 7) and bottoms of the painted and unpainted test sections. The thermocouple tips were attached to the concrete with screws and black or clear silicone sealant.

A cross section of the lining with the location of thermocouples beneath the concrete is shown in

Figure 4. 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 to record 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.

Radiation Equipment

At the Midvale Irrigation District yard in Pavillion, a stationary radiometer was installed on top of a post. A digital readout of the total insolation for any period of time was provided by an ampere-hour meter. A separate meter on the radiometer indicated the instantaneous rate of insolation.

At the canal test site, incident radiation and radiation reflected from the concrete lining surfaces were measured by a small portable radiometer.

MEASUREMENTS AND OBSERVATIONS

About once a week and for one day each month at 2-h intervals between 6:00 a.m. and 6:00 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 and thin or heavy; and degree of cloud cover was estimated (clear, less than 0.3; partly cloudy, 0.4-0.7; and cloudy, greater than 0.8). Wind direction and speed were estimated and records of snow and ice in the canal made. About once a month, the groundwater level in a well beside the canal was measured.

Pavillion is located at 43°50' north latitude and 108°41' west longitude at an elevation of 1660 m. A cumulative degree-days curve, 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 Celsius degree-days; each degree-day is the algebraic difference between the average of maximum and minimum daily temperatures and 0°C. The freezing duration for the winter of 1977-1978 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
Dec. 9	0.3 cm snow, shaded side
Jan. 4	1 cm snow, shaded side
Jan. 13	Trace of snow, shaded side
Jan. 20	8 cm snow, test area
Jan. 25	2 cm snow, ground, and 15 cm drifted in lateral bottom
Feb. 2	15 cm snow, in bottom
Feb. 13	15 cm snow, test section
Feb. 17	15 cm snow, shaded side
Feb. 24	6 cm ice, on bottom
March 1	6 cm ice, on bottom

DISCUSSION OF RESULTS

Radiation

The radiation measurements and the cloud conditions are shown in Table 1. A comparison of radiation on the black and unpainted concrete sections 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.

The intensity of insolation on a plane surface depends on the angle of the sun's rays with the surface; the highest intensity is when the angle is 90°. A plot of sun angles on the sun-exposed north side of the canal lining is shown in Figure 4; these were computed from the angle of the side slope and with the latitude and the declination of the sun.

Temperature and Frost Penetration

Averages of all temperatures measured at each thermocouple beneath the concrete are plotted in Figure 9. The temperatures of both black-painted and un-

painted 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. Compared with the unpainted concrete, the higher average temperatures beneath black-painted concrete on the sun-exposed side and lower temperatures beneath this type of surface on the shaded side are also seen.

An example of a one-day record of concrete surface and soil subsurface temperatures is shown in Figures 10 and 11. On clear days or when clouds were not heavy, the plots of temperatures during the day show a wide variation between temperatures at

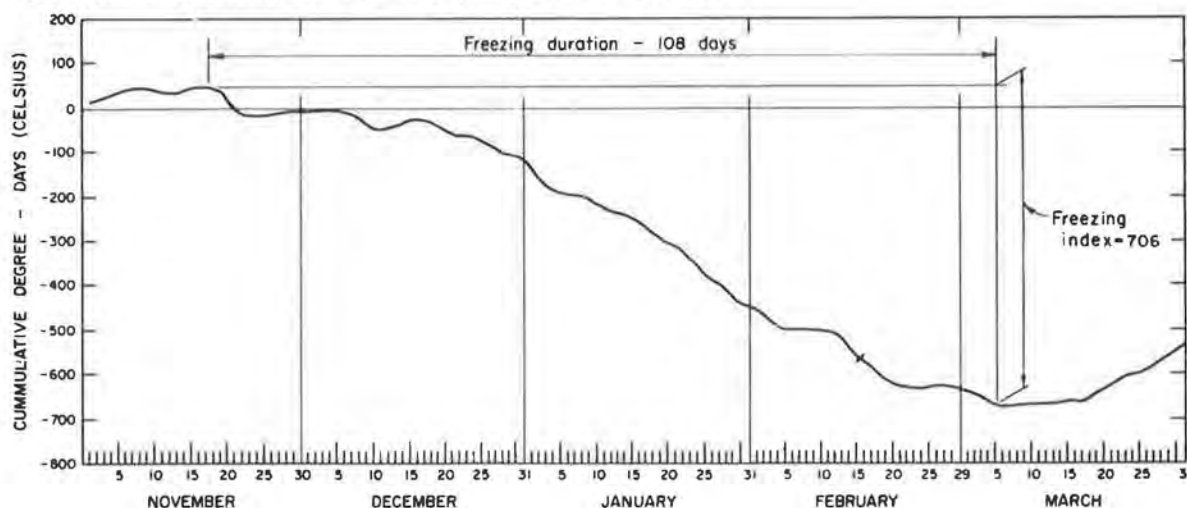
Figure 7. Thermocouples for measurement of surface temperatures on unpainted concrete lining.



Figure 6. Black-painted concrete lining with unpainted control section in foreground.



Figure 8. Cumulative degree-days curve for Pavillion, Wyoming, for winter of 1977-1978.



the surface and beneath the concrete on the sun-exposed side. As would be expected, this 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 that on 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; the difference was 13 percent.

Although there were no thermocouples 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 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, adjacent lining heaved a maximum of about 20 mm

Table 1. Solar radiation at Pavillion, Wyoming, and at concrete lining test site on lateral 15.1.

Date	Time	Pavillion Station Incident (W/m ²)		Incident (W/m ²)	Test Site Reflected (W/m ²)								Sky Condition
					Shaded				Unshaded				
		Instantaneous	Cumulative		Black		Unpainted		Black		Unpainted		
					Reading	Albedo	Reading	Albedo	Reading	Albedo	Reading	Albedo	
1977													
12/13	1200	279	103 689	439	31	7	47	11	47	11	98	22	Cloudy, thin, of medium height ^a
12/13	1400	265	103 758	-	31	-	31	-	77	-	126	-	Cloudy, thin, of medium height
12/13	1600	14	103 827	31	16	51	31	100	16	51	16	51	Cloudy, thin, of medium height
12/21	1300	349	105 711	300	31	10	62	21	77	26	77	26	Cloudy, high, thin ^b
									98	28	174	50	Clear, high, thin clouds
1978													
1/4	1330	397	110 383	349	62	18	62	18	126	33	174	46	Clear, no clouds
1/13	1330	384	112 544	377	62	17	47	13	174	40	223	51	Clear, high, thin clouds
1/25	1330 ^c	432	116 519	439	47	11	98	22	188	38	188	38	Clear, high, thin clouds
2/2	1330	474	121 330	502	62	12	112	22	488	97	502	100	Clear, high, thin clouds
2/13	1400	432	126 420	502	188	37	202	40	126	78	126	78	Clear, no clouds
2/17	0800	195	-	160	98	61	98	61	223	48	286	52	Clear, no clouds
2/17	1000	307	-	460	126	27	126	27	251	50	251	50	Clear, no clouds
2/17	1400	502	130 325	502	139	28	160	32	160	68	59	59	Clear, no clouds
2/17	1600	209	-	237	77	32	98	41	188	38	223	44	Cloudy, high, thin; varied cloud cover
2/24	1340	418	135 694	502	77	15	126	25	126	29	139	32	Cloudy, high, thin; varied cloud cover
3/1	1330	-	-	439	98	22	139	32	160	35	223	48	Clear, high, thin
3/8	1250	-	-	460	77	17	98	21	126	53	139	59	Clear, no clouds
3/15	0800	-	-	237	31	13	77	32	188	31	223	37	Clear, high, thin
3/15	1000	-	-	600	31	5	112	19	188	31	202	33	Cloudy, heavy, of medium height
3/15	1200	-	-	614	62	10	126	20	223	29	300	39	Cloudy, heavy, of medium height
3/15	1400	-	-	774	112	14	139	18	126	33	174	46	Clear, high, thin clouds
3/15	1600	-	-	377	49	13	98	26	62	25	98	39	Cloudy, heavy, of medium height
3/22	1300	-	-	251	49	19	77	31					

^aSun out more when instantaneous reading was taken.

^bSun covered with clouds part of time.

^cFresh snow; some ice on radiometer.

and settled back to 4 mm above the prewinter level without causing any noticeable cracking (5).

For any permanent installation of this sort to benefit from solar heat absorption, the surface would need to retain its capacity for absorption. A dark-surface concrete canal lining, whether painted or with pigment incorporated in the concrete, would no doubt lose much of its color and effectiveness

for this purpose because of weathering action and the sediment and other material that normally collects in a canal. Furthermore, any scheme for adapting active or passive solar systems to canals would need to be reliable when unattended in relatively remote areas and require a minimum of maintenance.

Figure 9. Averages of temperatures measured below concrete canal lining during winter of 1977-1978.

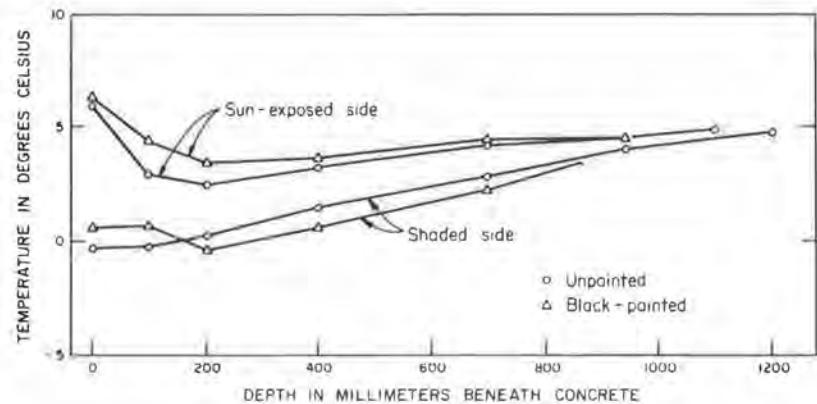


Figure 10. Temperatures on surfaces and in soil beneath (a) painted and (b) unpainted concrete canal lining, December 13, 1977.

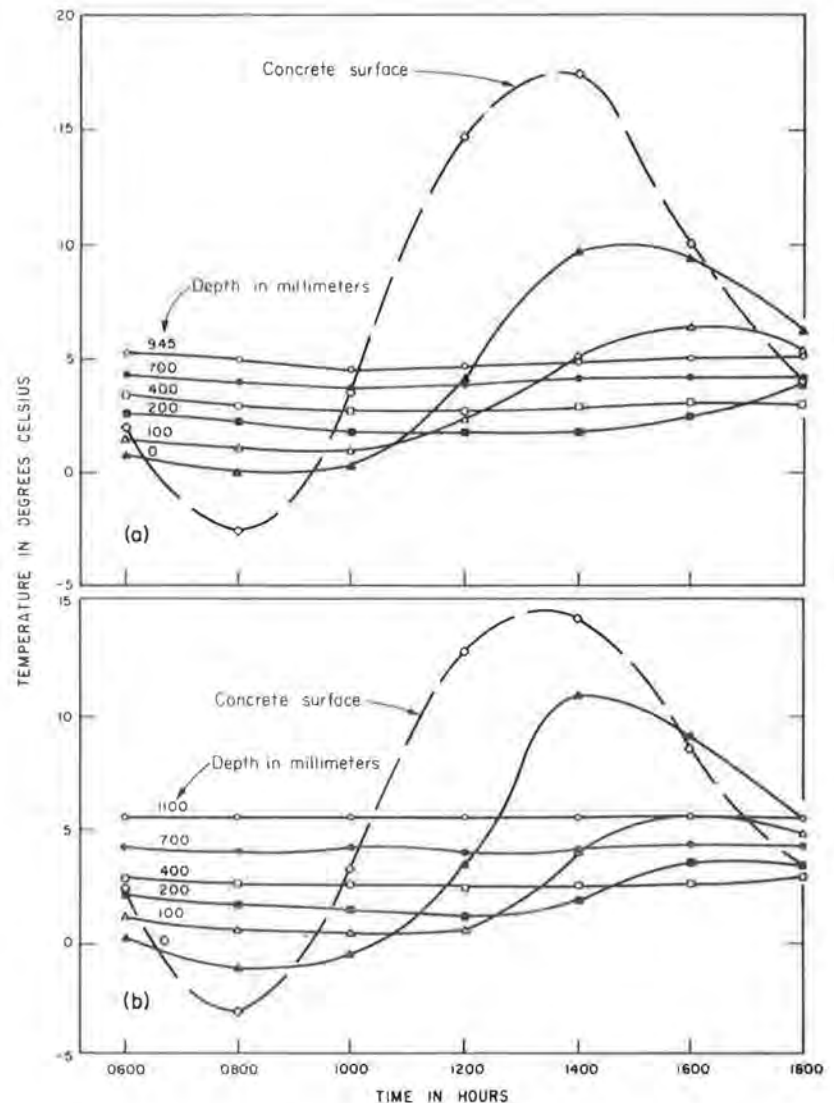


Figure 11. Temperatures on surfaces and in soil beneath painted and unpainted concrete canal lining on shaded sides and on unpainted bottom, December 13, 1977.

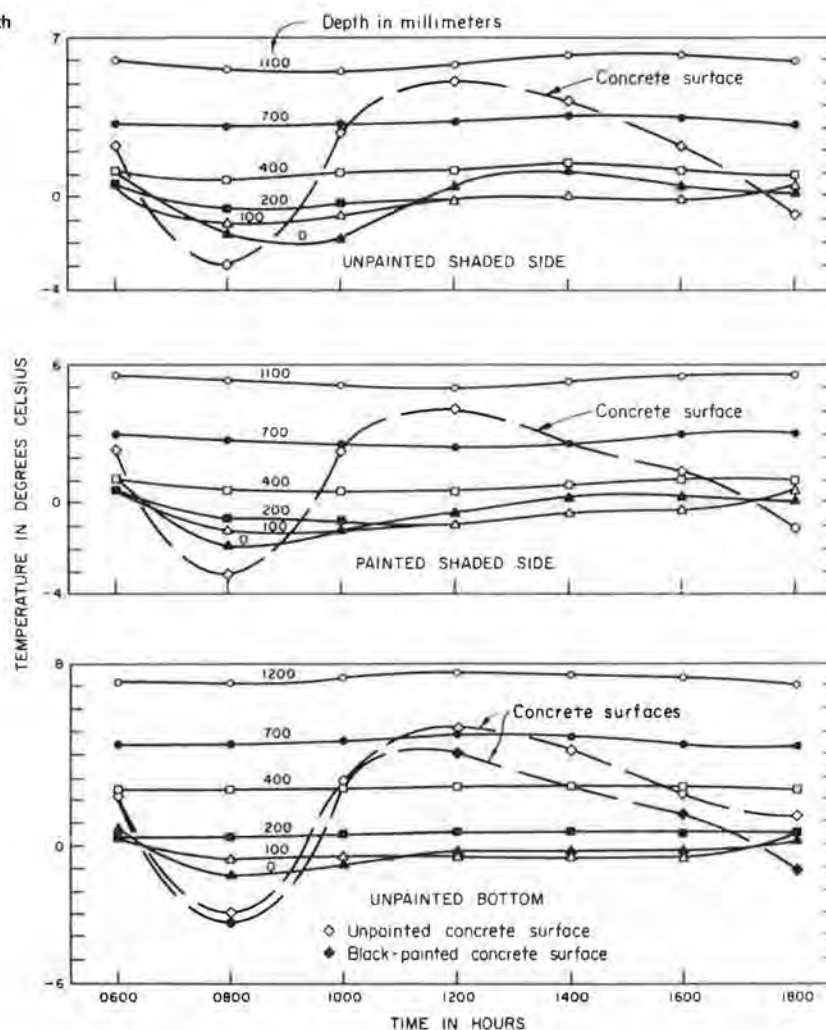
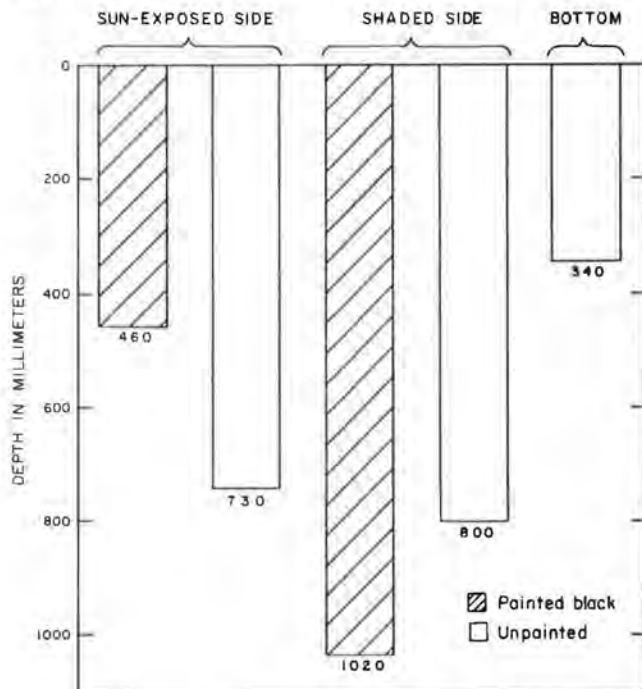


Figure 12. Maximum frost penetration beneath concrete canal lining.



SUMMARY AND CONCLUSIONS

Frost-heave damage to concrete canal structures can be significantly greater on shaded than on unshaded sides due to differences in solar effects on frost action in the soil foundation.

A field experiment was conducted during one winter to determine depth of frost penetration beneath black-painted and unpainted concrete canal lining on the north and south side slopes of an east-west oriented canal. The experiment showed that on the north sun-exposed slope, maximum frost penetration was 37 percent less beneath black-painted than unpainted concrete. On the shaded to partly shaded south side slope, frost penetration was 28 percent deeper beneath the black-painted concrete than for the unpainted concrete, which shows the effect of the long-wave, nighttime radiation. For the unpainted concrete during two successive winters, frost penetration was 13 and 9 percent less on the sun-exposed side than on the shaded side.

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Factors Affecting Coating of Aggregates with Portland Cement

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The Kuwaiti experience in applying the technique of cement coating the smoothly textured aggregates in the production of high-quality asphaltic mixtures has been that the success of the resulting cement treatment was not always certain. It was influenced rather by a number of material and processing variables. The effect of four such variables is investigated by preparing a number of cement-coated sand samples at different levels of treatment and under controlled laboratory conditions. Cement coats produced in these samples were then evaluated by analyzing and comparing the results from a close visual examination, a particle-size analysis, a specific-surface analysis, and a chemical analysis for cement content of the various fractions. The study indicated two extreme and identifiable states of coating within which successful treatments were attainable. At the lower levels of water and cement contents, the added cement failed to adhere permanently to the surface of particles, resulting in a poorly coated sand of a higher fines content. At the higher levels of water and cement, the finer fractions of the sand started forming weakly cemented lumps, thus effecting a coarser gradation that lacked the finer sizes. By applying certain limits on the amount of added cement to avoid arriving at these objectionable extremes, a practical relationship was developed expressing the amount of cement required for proper coating in terms of the specific surface of the sand intended for treatment.

Surface texture of aggregates is an important property influencing the behavior of asphalt pavements. It can be said in general that asphaltic mixtures made with rough-textured aggregates have better resistance to stripping (1), higher Marshall and Hveem stability values at optimum asphalt (2), and longer fatigue lives in stress-controlled tests (3,4).

In Kuwait, the technique of coating aggregates with portland cement to enhance surface texture is widely used at the present time in the production of high-quality asphaltic mixtures (5). Under the severe weather conditions of the region, these mixtures are believed to be superior in resisting such common types of failure as surface corrugations (developed particularly at traffic intersections), fatting up or bleeding, and premature distortion in the wheel tracks of heavy and channelized traffic. Experience in applying the cement-coating technique has indicated that the quality and effectiveness of the resulting treatment are not always satisfactory and depend on a number of material and processing variables. Among such variables are the type of aggregate, the amount of added cement, the quantity of water, the time of mixing, and the type of mixer used in the process.

Experience has also showed that the effect of the

above variables in coating fine aggregates is much greater than in coating coarse aggregates, where good results were readily obtainable. The large mass of individual particles in this case and consequently the higher-impact forces they produce in the mixer during the process of coating leave only a secondary role for the smaller forces due to surface tension, water viscosity, cohesion, etc., to play in distributing the added cement. With sand-size aggregates this latter role becomes more important and perhaps dominant. A knowledge of the levels at which the variables in the coating process would produce optimum results becomes highly necessary, since an arbitrary selection of these levels may produce inferior results.

A particular difficulty often encountered in the cement coating of sand is a significant and uncontrollable change in its gradation after treatment. Either an abundance of fines or severe deficiency may result, depending on the values selected for various parameters. In addition to reducing the effectiveness of the added cement, such extreme conditions often necessitate subsequent corrective measures to satisfy job-mix requirements for gradation.

The purpose of this paper is to investigate the effect of four factors on the quality of the cement coat obtained in the treatment of sand: the gradation of the sand, its initial surface characteristics, the amount of added cement, and the quantity of added water.

Guirguis, Daoud, and Hamdani (6) have dealt with the effect of coating the aggregates with cement on laboratory performance of asphaltic mixes.

METHODOLOGY

The approach adopted here was to prepare samples of cement-coated sand by several treatments and under controlled laboratory conditions. Each treatment represented a particular combination of the four variables adopted in the study. The cured samples were then analyzed by four methods, including granulometric and gravimetric measurements. Results from these analyses were compared and discussed, and the quality of the different cement treatments was appraised accordingly.