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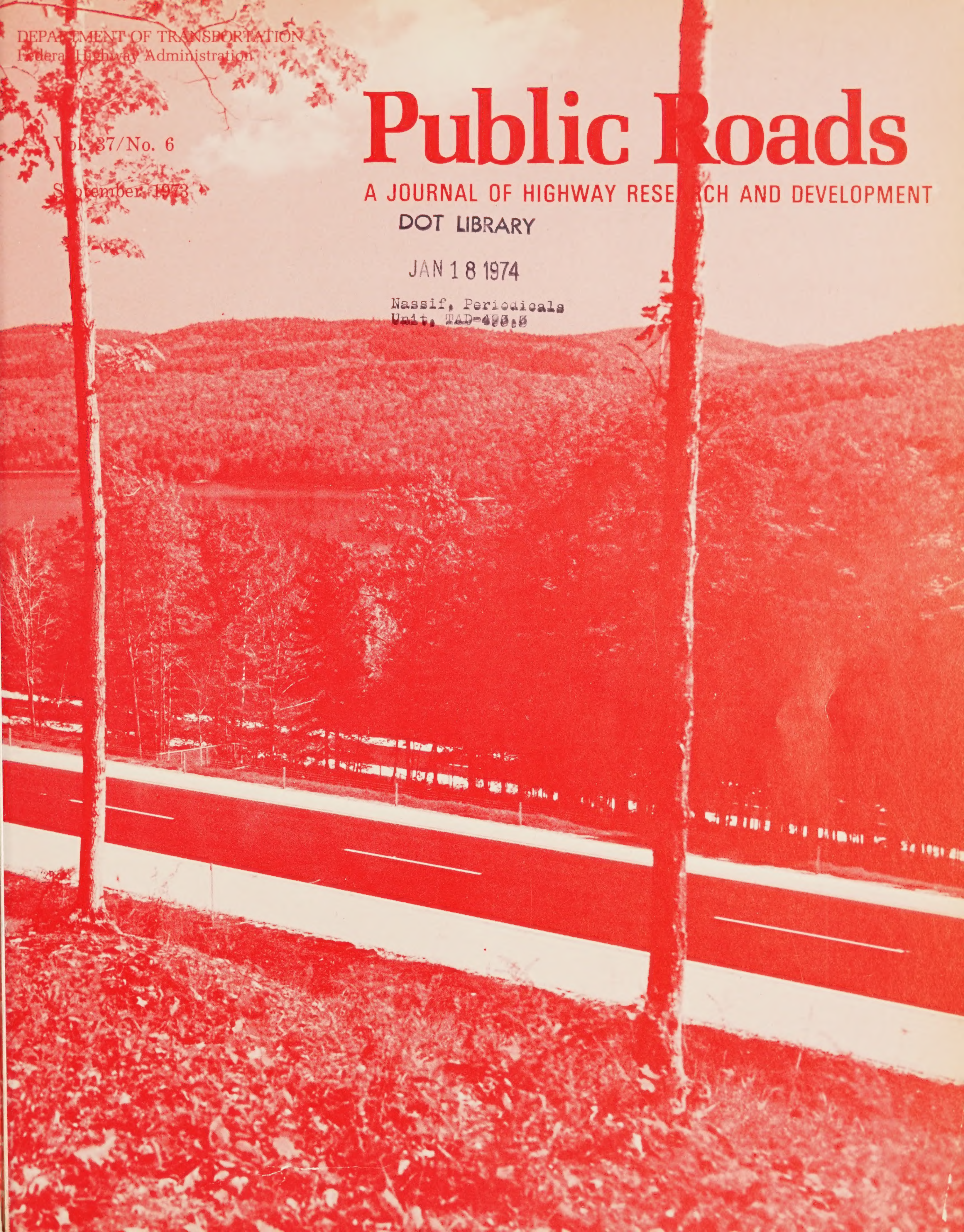

PUBLIC ROADS

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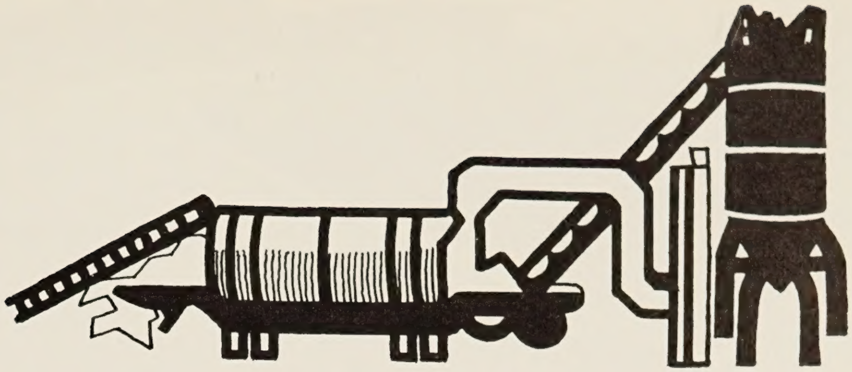
COVER

Interstate 87—the Adirondack Northway in Essex County, N.Y. (Photo courtesy of the New York State Department of Transportation.)

PROGRESS REPORT ON DRYER DRUM PROCESS FOR PRODUCING BITUMINOUS CONCRETE MIXES



by [1] Edwin C. Granley and Robert E. Olsen

Introduction

THE DRYER DRUM process has been used for a number of years to produce hot emulsion mixes. These were produced under a license from K. E. McConnaughay Company, Inc., who pioneered in promoting and developing this process. However, here and in Europe, the producers, including McConnaughay, have expanded this concept to include preparation of mixes using penetration grade asphalts. The earliest documented experimentation we are aware of was done by the Asheville Paving Company (*1*)[2] in 1959. They operated a plant in Asheville, N.C., for several months, but were unable to convince the State of its capabilities to produce a low cost mix. Therefore, the use of the process with penetration grade asphalts was essentially dormant until 1970, when plants in Iowa and Washington started operation.

The dryer drum mixing method of producing bituminous mixtures is a relatively simple process. Cold aggregates are blended on belts according to formula and fed into the dryer drum where penetration grade asphalt—with or without proprietary additives—is introduced. In the rotating drum, the aggregate is simultaneously heated, dried, and coated with asphalt. The mixture is discharged onto a conveyor and elevated to a hot storage bin and then to the hauling equipment. It is necessary for aggregates to be correctly blended at the cold feed source. This has been accomplished successfully with mechanical feeders and proper stockpiling techniques.

The dryer drum process eliminates many pieces of operating equipment normally associated with a conventional mixing plant such as the bucket elevator, the screening plant with dust covers, hot bins, weight hoppers, assorted controls, and the pugmill mixer. Another advantage is the reduction of fuel consumption since mixtures are usually produced at lower temperatures.

It is also possible that the control of dust emissions from the exhaust stack will be less of a problem than with a conventional plant. Currently, steps are being taken for the purchase of equipment and the training of personnel to make studies of stack emissions of a selected number of conventional and dryer drum plants. This should provide valuable data regarding the range of pollutants now being emitted from both types of operations.

The Federal Highway Administration (FHWA) became involved in evaluating the characteristics of this process in 1971 in the State of Washington. Mr. William L. Allen, Jr., Area Engineer in the FHWA Washington Division, instigated a study program of the operation of a Shearer-designed plant that was producing mix for private work. Test data gathered from this initial evaluation effort indicated that a satisfactory mix was being produced (*2,3*).

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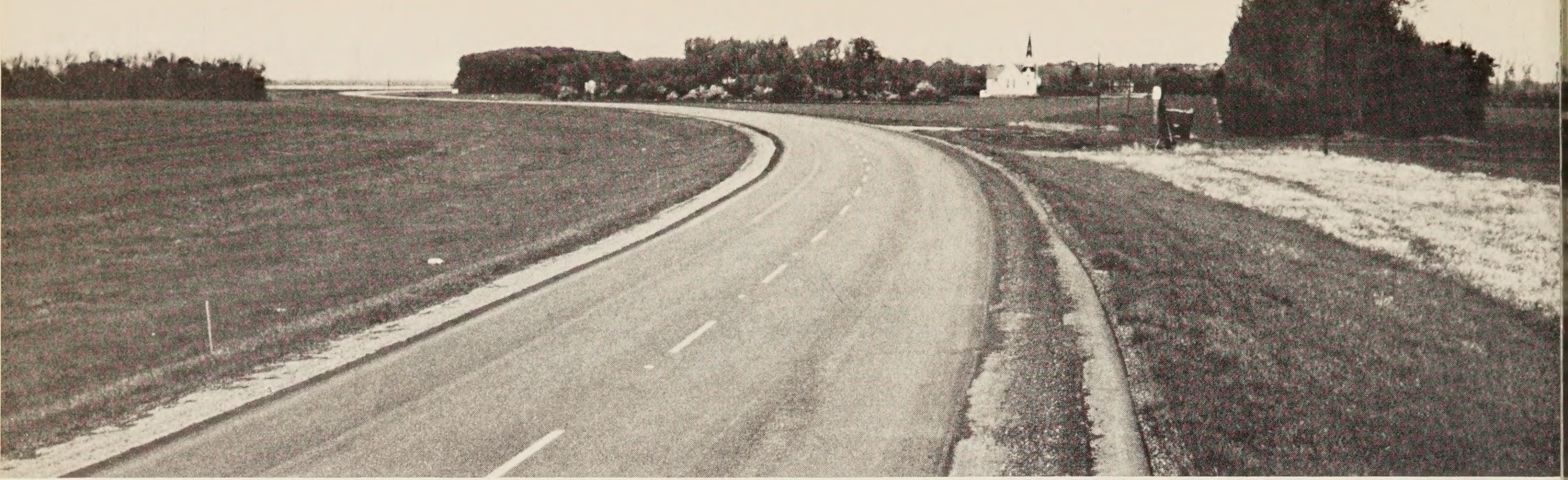
[1] Presented to the NAPA's (National Asphalt Pavement Association) 18th Annual Convention, Miami, Fla., Jan. 31, 1973, and AASHO's (American Association of State Highway Officials) 58th Annual Meeting, Phoenix, Ariz., Nov. 28, 1972.

[2] Italic numbers in parentheses refer to the references listed on page 210.



North Dakota State Highway 32 south of Edinburg.

A McConnaughay-designed turbulent mass plant also produced mixes for projects in Iowa during the 1970 and 1971 seasons. The results were reported in 1972 by James Ziegler (*4*) of Ronald Kenyon Construction Company at the 17th Annual NAPA Convention. Operations of this plant followed an operating procedure similar to that used in Washington except that a chemical agent was added to aid in coating.

Since it was evident that industry was becoming more interested in using this process, the evaluation scope widened in 1972 to include data on the quality of mixtures produced in plants operated in North Dakota, Iowa, and Minnesota.

The first study was conducted in North Dakota on the bituminous hot mix produced in a Shearer-designed dryer. This 10 by 40 ft. butane-propane-fired dryer was used to produce mixes for overlaying and widening an existing pavement on State Route 1 north from Lakota. The surfacing mixture consisted of 200/300 penetration grade asphalt and 5/8 in. maximum size dense-graded crushed-gravel aggregate. On two additional short sections, mixtures containing 85/100 and 120/150 penetration grade asphalt were laid to evaluate their performance. On each section, one-half of the mixes were produced at 200°–220° F and the other half at higher temperatures. Normal procedures were used for compacting these sections. Production rates varied from 240 to 400 tons per hour.

The second study, conducted in Iowa, was on a 9 by 36 ft. Cedarrapids turbulent mass process dryer. This unit was producing base material at 190° F and surfacing material at 260° F for an Emmet County project near Estherville. During the observation period, 5/8 in. maximum size crushed gravel and 120/150 penetration grade asphalt were used for the base mixture and 85/100 for the surfacing course. A butane-purpose mixture was used for fuel and a proprietary chemical agent was added to aid in coating the aggregate. Production varied from 275 to 340 tons per hour.

The third study was made on a 9 by 32 ft. fuel-oil-fired Barber–Greene dryer at Olivia, Minn. During the first phase of this study, the plant was used to produce an overlay material for city streets in Olivia. The mix was a blend of 3/8 in. maximum-size taconite aggregate and 120/150 penetration-grade asphalt and was mixed between 310° and 360° F. For the second phase, 5/8 in. maximum-size crushed gravel aggregate and 120/150 penetration-grade asphalt were used for surfacing Route 21 in Renville County. The temperature of the mix produced at the plant in this phase was 230° F. The production rate for both mixes was 200 tons per hour.

Testing Procedures

Evaluation of the dryer drum process was directed primarily toward obtaining answers to two questions concerning quality:

(1) Was the mixture being harmed by exposure to the direct flame in the dryer?

(2) Would the equipment consistently produce a uniform product?

Hardening of asphalt

Answers to the first question regarding possible harm to the mixture through exposure to heat in the dryer were obtained by determining the degree of hardening of asphalt through the various stages of the process. Tests were made in the following order:

(1) A penetration test value of the original asphalt was determined.

(2) Penetration tests were made on recovered asphalt from mixture samples obtained at the plant and at the paving site. These two sets of samples were placed in gallon cans containing solid carbon dioxide. The cans were immediately capped. Carbon dioxide gas replaced the air in the mixture and escaped through a pinpoint hole in the lid. The can lid and pinhole were sealed with solder when pressure buildup ceased. This procedure was designed to ensure that the mixture would be in an inert atmosphere during shipment and storage. The cans were shipped to the Federal Highway Administration Fairbank Highway Research Station at McLean, Va. There the samples were maintained at 0° F until scheduled for testing. Companion samples were obtained to determine moisture content of the mixtures.

(3) The standard thin film oven test, AASHO T–179, was made on the original asphalt samples obtained from delivery trucks. This test measures the effect of heat and air on semisolid asphalt materials. The results may be used as

a guide to the amount of hardening that may occur during the operation of a hot mix plant.

(4) Another simulation test was made in the laboratory on samples of asphalt and dried aggregates from the Iowa and North Dakota projects. These samples were combined in the same proportion as on the respective projects and mixed at 325° F for 2 minutes in the standard laboratory mixer. The mixture was molded at 255° F. The hot molded specimen was then crumbled and flattened on a pan and subjected to 325° heat for 20 minutes after which it was kept at 0° F until the recovery test was made. This nonstandard test was designed to duplicate expected hardening that would occur in conventional production samples obtained at the paving site.

Test results pertaining to asphalt hardening are shown in figures 1 through 5. All penetration tests on recovered asphalt were well above the counterpart thin film oven test value and also above those for simulated pugmill mixing tests on the orignal asphalt. This signifies that the asphalt in the mixes produced by dryer drum operations was not prematurely hardened. It should also be noted that recovered penetration values were not affected by extremes of mix temperatures.

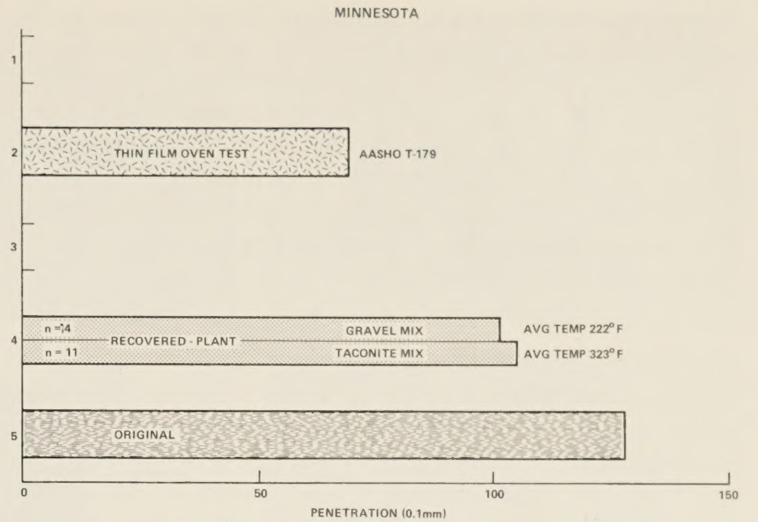


Figure 3.—Penetration at 77° F 120/150 grade asphalt.

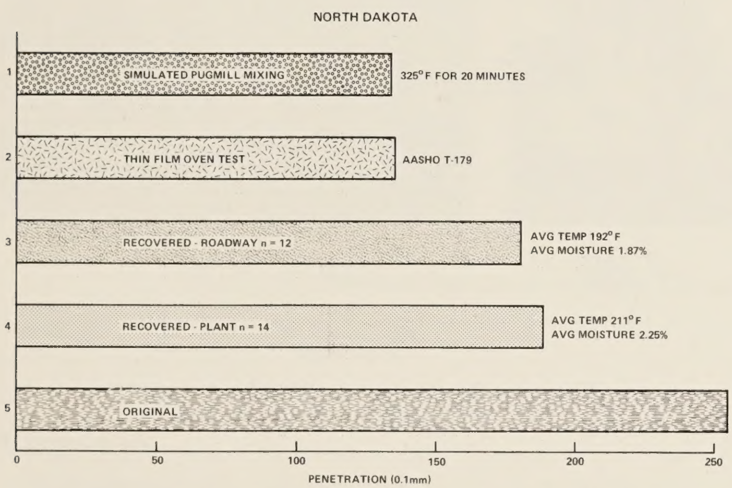


Figure 1.—Penetration at 77° F 200/300 grade asphalt.

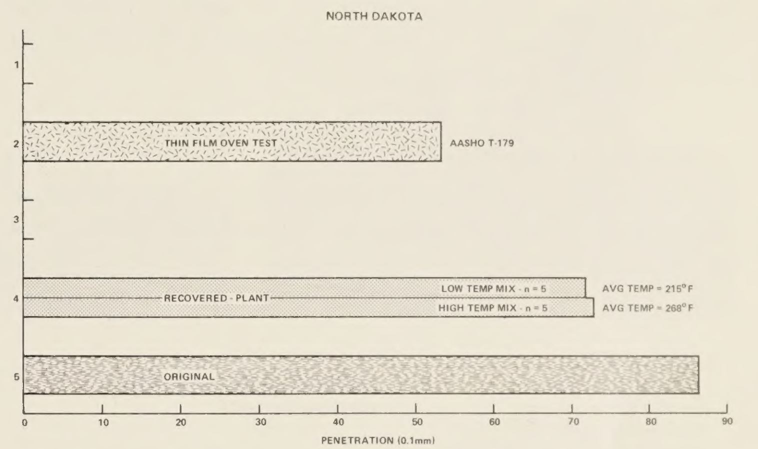


Figure 4.—Penetration at 77° F 85/100 grade asphalt.

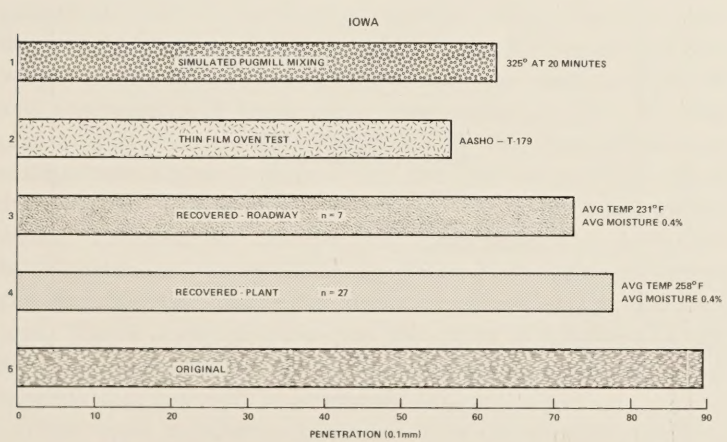


Figure 2.—Penetration at 77° F 85/100 grade asphalt.

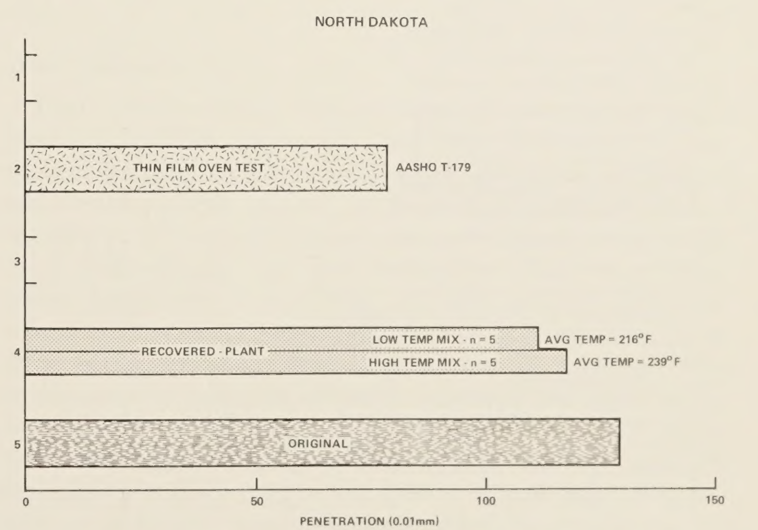


Figure 5.—Penetration at 77° F 120/150 grade asphalt.

Figure 3 shows that in the Minnesota project essentially the same penetration value from recovered asphalt was obtained even though the average temperature difference for the two mixes was 101° F. The same trend is evident in figures 4 and 5 for data from the North Dakota project although smaller average temperature differences were maintained.

The above tests were conducted under the direction of Edward R. Oglio, Highway Research Engineer, Materials Division, Office of Research, FHWA.

Uniformity of asphalt

The second question to be answered relates to the ability of the dryer drum process to produce a consistently uniform product relative to asphalt content and aggregate gradation. In the Iowa and North Dakota plants, changes in the rate of flow of asphalt were controlled automatically by the aggregate belt scale system to match variation in aggregate flow rates. The Minnesota plant was controlled manually. The standard deviations of extracted asphalt content for the plants investigated in this study were compared with standard deviations of 26 conventional batch plants (*5*) as shown in figure 6. The relative ranking shows that uniformity of asphalt content was comparable in quality to that maintained by the 26 plants which produced satisfactory mixtures.

Uniformity of aggregate gradation

Another quality factor is gradation control. The success of the dryer drum operation depends on good cold feed control which in turn depends on the uniformity of stockpiled materials. The stockpile aggregates in each State were, on the average, within the specified grading band limits. However, on the North Dakota project, some material in the stockpile exceeded the limits set forth for the No. 4 and No. 200 sieves (fig. 7). Additional screening would not have remedied this slight deviation since the trouble was in the gradation of the stockpile. In Iowa, the aggregate gradations met the requirements for the sieves shown, as indicated by the crosshatched area within the specified grading band limits in figure 8.

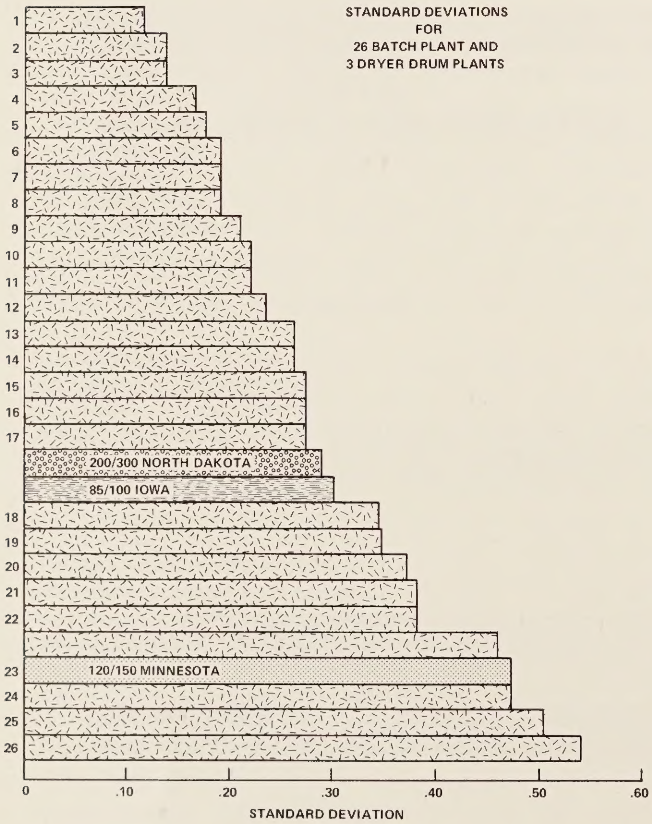


Figure 6.—Asphalt extraction testing.

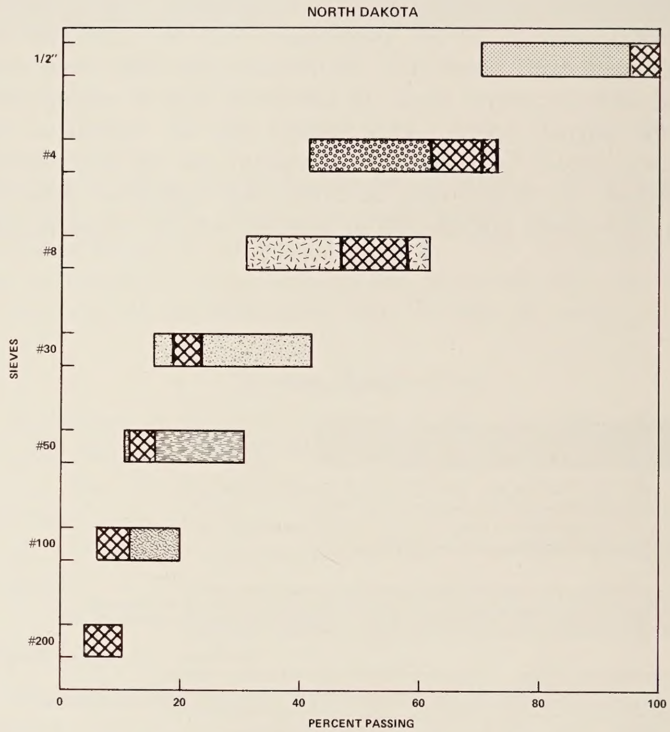


Figure 7.—Specified grading band and project (±) two standard deviation spread.

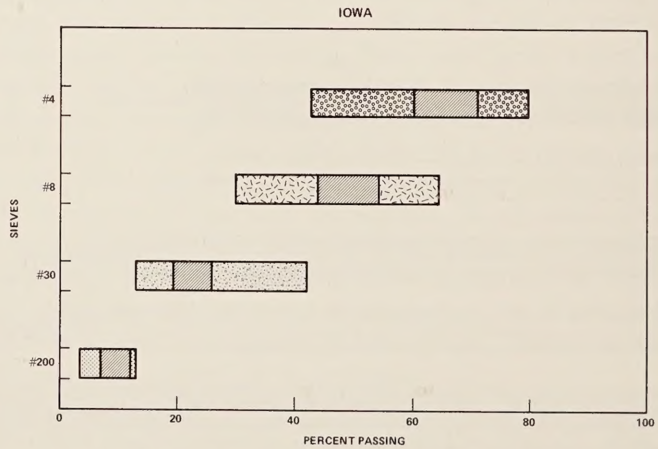
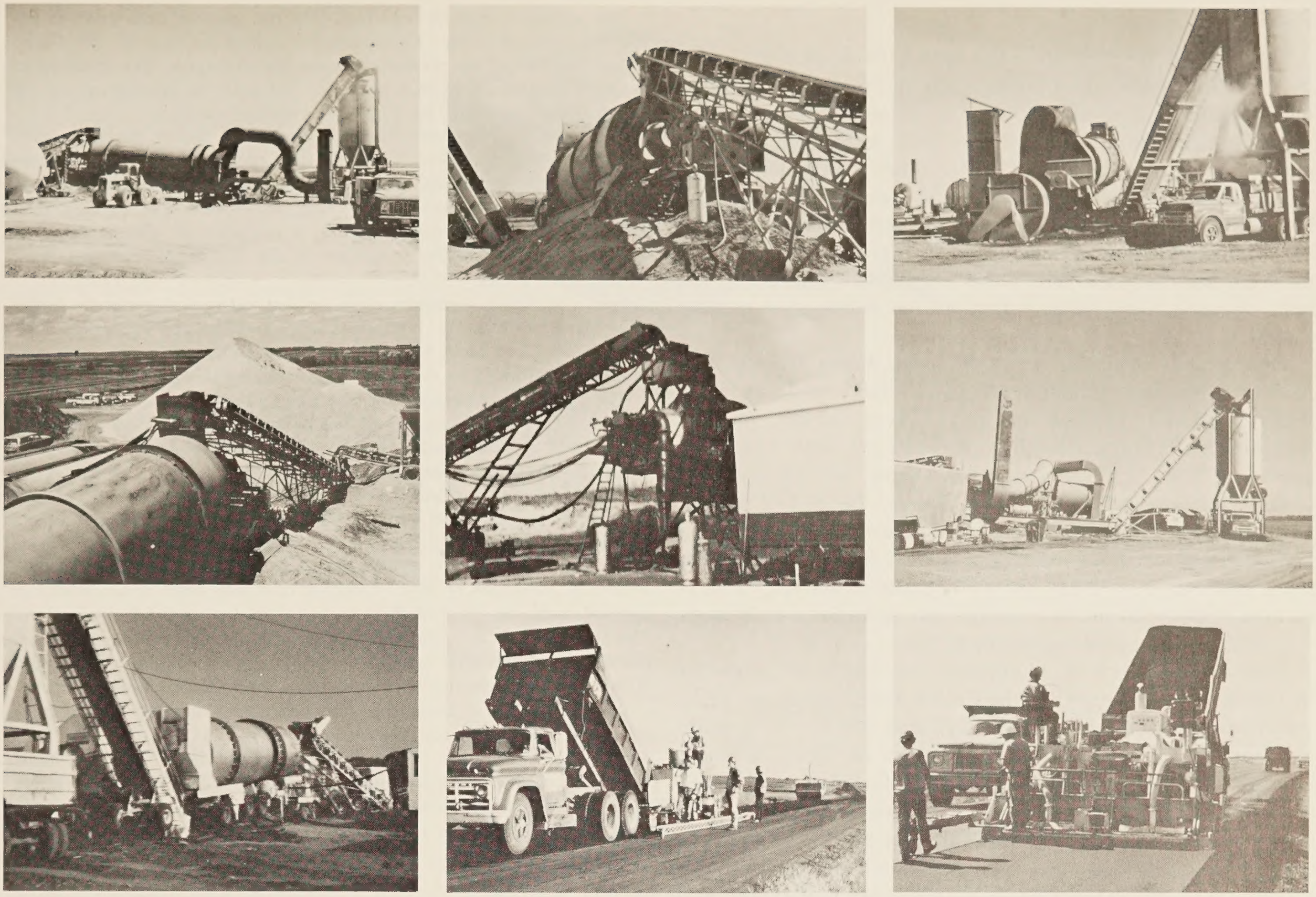


Figure 8.—Specified grading band and project (±) two standard deviation spread.



Scenes of dryer drum mixers in operation in North Dakota, Minnesota, and Iowa.

Compaction

Past research (*6*) has indicated that to achieve maximum density, breakdown rolling—both steel and pneumatic—should be completed before the pavement temperature drops below 220° F. Yet in North Dakota specified densities were obtained when the mix containing 2 percent moisture was compacted at 190° F by a single-vibrator roller—usually after five passes. An interesting correlation resulted when the unit weight from hot samples obtained from the plant at 210° F was compared with those made from mixes at 250° F. The unit weights were the same even though the moisture content varied from about 2 percent for the low temperature mixes downward to less than ½ percent for the higher temperature mixes. In Iowa, for example, the temperatures of the mixes were maintained from 230° to 250° F to achieve proper density. Moisture content at these temperatures was 0.4 percent. These examples show that the effect of water as an aid to compaction has not been fully explored or explained and suggests that research is needed in this area.

Until more experience is gained, it is not possible to forecast the effect of water in the mix at the time of compaction. The long-term benefits to be achieved by mixing at lower temperatures, resulting in less premature hardening, make this production procedure attractive.

Dust emission

Dust emissions from conventional bituminous hot mix plants have created much adverse attention. This dust can be trapped to meet emission standards only by the addition of an elaborate and costly collector system. Without such additional control equipment, the exhaust from the conventional dryer drum plant exits directly into the atmosphere. The dryer drum plants observed did not have any such control equipment, nevertheless, visual observations of their dust emission varied from being almost invisible to light gray in intensity. This would seem to be a major benefit; however, the need for future control cannot be properly evaluated until more operational experience is gained. Although it may not solve all emission problems, we believe—from visual appearances—that much simpler control equipment will be needed for the dryer drum process.

Production costs

Cost savings resulting from the use of the dryer drum process to produce bituminous hot mix was not within the scope of this evaluation. It would appear that investment in equipment would be less, since the dryer has been assigned the double duty of drying and mixing, thereby eliminating the need for the pugmill and its supporting units. Increased portability and possible lower mixing temperatures would also enter into the economic picture. Estimates of savings range from 30 to 60 cents per ton. The only valid and meaningful figures will have to come from industry through the competitive bidding system.

Observations made on plants in Iowa, North Dakota, and Minnesota showed variations of plant design and operation that can affect production and cost. These include: position and shielding of burner; length of flame; length, slope, rotational speed and flight configurations of the dryer; air velocity; rate of feed; stack temperature; and the position for adding bituminous materials. Each of these cited differences in plant design and operational characteristics can have an effect on production rates, efficiency of coating and mixing, and emissions. This is an area where refinements in design and operational techniques will result as more field experience is gained.

Over 800,000 tons of bituminous hot mix were produced by the dryer drum process in the United States during the 1972 construction season—10 times greater than that for the preceding year. Of this total, 425,000 tons were produced in North Dakota, 300,000 in Iowa, 135,000 in Minnesota, and lesser amounts in Oregon and Michigan. Trial use of this process has been approved for projects in several other States for the 1973 construction season.

This novel process reflects a technical advance which was not considered possible a few years ago. It has won acceptance in several States and is being watched with interest throughout the country. This is a healthy atmosphere for implementing a major technological breakthrough.

Conclusion

The Federal Highway Administration studies have shown conclusively that a quality mix can be produced by the dryer drum process that is at least equal to that being produced by conventional plants. Long term observations of completed projects will provide answers as to whether a more durable mix is being produced.

The North Dakota State Highway Department's special provision to the hot bituminous pavement specifications is one approach used to provide an option for the bidder. This provision is essentially as follows:

The contractor may elect to operate the hot mix plant without plant screens. The basic requirements of this method of operation are to remove all plant screens with the exception of the scalping screen. Permission to continue under this option may be rescinded upon failure to maintain production within the specified gradation limits. Under this option the following paragraphs will apply:

The aggregate shall be separated into two general sizes prior to being fed into the dryer. The material retained on the ½- by 1-inch slotted sieve shall be crushed to meet the maximum size specified in the contract and placed in a stockpile. The material passing the ½- by 1-inch slotted sieve shall be placed in a separate stockpile.

The engineer will determine after production begins, the percentage of material passing the No. 4 sieve in each respective pile. The engineer will determine when a sufficient volume of material has been produced so that the average percentage passing No. 4 sieve can be used as a target value to be maintained within a tolerance of plus or minus 5 percentage points for the remainder of the aggregrate produced from the aggregate source.

Each individual aggregate shall be fed through a separate feeder that has a positive feed and that can be easily and accurately calibrated. The feed shall be quick adjusting and shall maintain a constant and uniform flow throughout the range of its calibration.

The point of acceptance for the physical properties of the aggregates will be in the stockpiles at the plant site. Acceptance testing for aggregate gradation will be performed just prior to the addition of bituminous material to the mixture.

An approved dryer-drum mixing process will be permitted in lieu of pugmill mixing. The system shall provide positive weight control of the cold aggregate feed, by use of a belt scale or other device which will automatically regulate the feed gate and permit instant correction of variations in load. The cold feed flow shall be automatically coupled with the bitumin flow to maintain the required proportions. The system shall be equipped with automatic burner controls and shall provide for temperature sensing of the bituminous mixture at discharge. If the dryer-drum mixing process is used, the following applies:

(1) The moisture content of the bituminous mixture at discharge from the mixer shall not exceed 3 percent.

(2) The temperature of the bituminous mixture at discharge from the mixer shall not exceed 300° F. The actual mixing temperature shall be adjusted as directed by the Engineer, within the allowable limitations, to best suit construction conditions.

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(*1*) Charles B. Foster and Fred Kloiber, "Supplement to 'More on Drum Mixing,'" *Newsletter, NAPA,* Jan. 29, 1973.

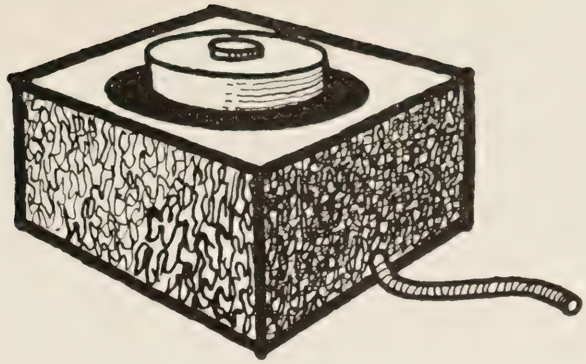
(*2*) William L. Allen, Jr., and John T. Price, "The Dryer-Drum Mixing Process for Producing Asphalt Concrete Mixtures in the State of Washington," *FHWA, Washington Division,* 51st Annual WASHO Meeting, Salt Lake City, Utah, June 5–9, 1972.

(*3*) Ronald L. Terrell and Emory S. Richardson, "Asphalt Paving Mixtures Produced by the Dryer-Drum Process," *University of Washington* and *FHWA,* Vancouver, Wash., August 1972.

(*4*) James Ziegler, "The Turbulent Mass Process," *Ronald Kenyon Construction Company,* West Des Moines, Iowa, 17th Annual Convention, NAPA, Jan. 4–14, 1972.

(*5*) Edwin C. Granley, "Quality Assurance in Highway Construction, Part 4—Variations of Bituminous Construction," *Public Roads,* vol. 35, No. 9, August 1969.

(*6*) M. J. Kilpatrick and R. G. McQuate, "Bituminous Pavement Construction," *U.S. Department of Transportation, FHWA, BPR,* June 1967.



FROST HEAVE AND THE RAPID FROST HEAVE TEST

by J. Harold Zoller

Use of an appropriate test method for determining the frost susceptibility of subbase and base course materials should permit the selection of materials that would prevent detrimental effects of frost action in the lower layers of a pavement system. Proper determination of the frost susceptibility of available local materials might permit the use of some granular materials that had, by previously used criteria, been considered unsatisfactory. Therefore, a reduction in construction and maintenance cost of pavements should result.

A rapid test to measure the frost susceptibility of materials for use in subbase and base courses of pavements is described in this article. A frost susceptibility classification, based on the heave rate of the tested material, is presented. The mechanics of frost heave and parameters affecting frost heave of soil materials are also discussed. Use of the test to select nonfrost-susceptible materials for subbase and base courses should reduce pavement maintenance costs.

The test method should be evaluated in other States, with local materials, to determine that the heave rates obtained in the laboratory test approximate those in the highway structure, and that the range in heave rates designated by New Hampshire for various frost susceptibility classes are appropriate.

Introduction

THE effects of frost action in foundations have constantly intrigued and frustrated designers of transportation facilities and buildings. Shifted and cracked buildings, warped and fragmented road surfaces, and tilted retaining walls bear mute testimony to the harshness of frost damage resulting from improper designs. Through experience, designs have been evolved (*1, 2, 3, 4*)[1] which minimize or eliminate these problems.

For buildings, the solution often is to construct the footings at a depth which is below the frost line. For streets and highways, the detrimental effects of frost action are frequently controlled by placing a nonfrost-susceptible base or subbase material to a depth equal to or greater than that of the anticipated frost penetration. However, high quality granular material is becoming scarce while demand for suitable materials seems to be increasing.

A further and increasingly urgent consideration stems from the concern of the ecologist that the environment remain undisturbed by all the activities of the road builder. Amid such constraints it is imperative that new construction techniques be evolved, new sources of materials be located, new standards of acceptability be adopted, and a means be found of beneficiating previously unsatisfactory materials.

The rapid freeze test described in this article was devised to provide a rapid, economical, and accurate measure of the frost susceptibility of granular materials for use above natural subgrades to prevent or control detrimental frost heave.

Investigation into the phenomenon of frost heaving of New Hampshire pavements and the practical solution of related problems which result from such action was initiated in 1965 by the civil engineering department of the University of New Hampshire (UNH) as the contracting agency in cooperation with the New Hampshire Department of Public Works and Highways and the U.S. Department

[1] Italic numbers in parentheses identify the references on page 220.

of Transportation, Federal Highway Administration. Currently these studies have delved into the question of why and how frost heaves occur, and what factors are best suited to predict frost potential of a granular base.

An attempt was made to relate various physical properties and characteristics of soils to the frost susceptibility of the materials. Tests included grain size and hydrometer analyses, specific gravity of fine and coarse fractions, moisture-density, capillarity, permeability, liquid limit and plastic limit. Soil samples were subjected to x-ray diffraction to identify mineral composition and were examined by the electron microscope to determine particle shape and structure. Effects of variations in density of soil and rates of freezing were investigated. Soil-gradation improvements, by washing to remove fines and adding coarse material, were tried. Moisture migrations in closed systems caused by thermal gradients at freezing temperatures were also studied.

When the variables just mentioned were combined into meaningful parameters and analyzed by computer in a regression analysis, it was found that predictions of an unknown soil's frost behavior were unacceptably inaccurate. Thereafter, no major attempt was made to correlate a soil's frost heave prediction with combinations of its normal test characteristics except in a broad sense. Rather, the thrust of the program recently has been to develop and perfect equipment and procedures for a rapid frost heave test and to gain as much experience with it as possible. Fifty-six soil samples from construction sites were submitted by the State of New Hampshire for analysis.

Equipment developed by the project has been turned over to the State and personnel have been trained so that the rapid frost heave tests are now being conducted by the State on questionable materials.

As a result of the frost heave testing program at UNH, materials that could not pass the specifications for base course construction in use 5 years ago are now being used by the New Hampshire Department of Public Works and Highways with assurance that no detrimental frost heaving will result.

Mechanics of Frost Heave

When water is converted to ice at atmospheric pressure it expands approximately 9 percent. The expansion of many natural soils upon freezing has been observed to be much greater than is explained by the mere expansion of the water within the voids of the soil.

Taber (*5*) and Beskow (*6*) point out that frost heaving results from the growth of ice crystals as influenced by pressure, the rate and direction of heat transfer, and soil stratification. Ice crystal growth under pavements is usually in a vertical direction and is dependent on a continuous supply of water. For a slow rate of frost penetration—0.25 inch per day—the rate of heave of a soil increases as the percentage of grains finer than 0.02 mm diameter increases (Linell and Kaplar) (*7*). Casagrande (*8*) states that considerable ice segregation should be expected in nonuniformly graded soils with more than 3 percent by weight finer than 0.02 mm size, and in uniformly graded soils with more than 10 percent finer than 0.02 mm size.

The Corps of Engineers (*9*) has classified frost-susceptible soils in the following manner:

- F1 materials, the least frost susceptible, are gravelly soils containing between 3 and 20 percent by weight finer than the 0.02 mm size.
- F2 materials include sands with 3 to 15 percent by weight finer than the 0.02 mm size.
- F3 materials include gravelly and sandy soils not in the F1 and F2 groups, and clay with plasticity index of more than 12 percent.
- F4 materials are the most frost susceptible of all soils and include all silts, silty sands, lean clays with plasticity index less than 12 percent, and most varved clays.

The Corps of Engineers also classifies soils quantitatively in terms of rate of heave of a specimen which has been prepared and frozen under standard test conditions (*10*). According to this criterion, the frost susceptibility of a soil is classified as negligible, very low, low, medium, high or very high, as the rate of heave varies on a scale from 0 to more than 8.0 mm per day.

Generally, the following conditions are necessary for detrimental frost action:

- The soil must be frost susceptible in terms of its grain size.
- A supply of free water must be available within the height of capillary rise of the soil.
- The soil must be sufficiently permeable to permit the rapid upward flow of water.
- A subfreezing temperature must be applied to the soil surface.

Soil Parameters in the Frost Heave Equation

The common soil parameters which influence the frost susceptibility of a material are thought to be permeability, capillarity, gradation, and density. In addition, surcharge, mineral type, and dissolved salts influence the amount and severity of detrimental frost action.

Permeability and capillarity

The permeability of a soil is a measure of its ability to permit the flow of water through it. The coefficient of permeability, *k*, is the average velocity of flow under a hydraulic gradient of unity, and is usually expressed in cm/sec (*11*). The velocity depends on both the area available for flow and the configuration of the path of flow. In general, fine-grained soils have smaller void spaces and more tortuous flow paths than do coarse-grained soils. Therefore, soil permeability generally decreases with increasing proportions of fines.

The capillary saturation developed in a soil is dependent on its saturation history. If the soil has been previously saturated or water is able to percolate downward through the soil, a higher degree of capillary saturation will be obtained than when the water is raised by capillarity from below. Water rising in a dry soil due to capillary pressure entraps air in the large voids, resulting in a lower degree of saturation. It is obvious that the percent saturation will affect the quantitative flow of water to the freezing zone.

Gradation and density

The gradation is the distribution of sizes of individual particles, usually in terms of proportions by weight of dry soil. Gradation has an effect on permeability and capillarity of the soil. For example, if a few coarse particles are added to a fine-grained soil, the permeability may be slightly reduced because total pore space is reduced, while the capillarity is relatively unchanged. However, if a large amount of coarse-grained material is added, the permeability will increase because there is an insufficient amount of fine-grained material to fill the voids created by the coarse-grained material (*4*). A decrease in capillarity would also result from the increase in pore sizes. Therefore, the rate at which water will move to a freezing zone in a soil is a function of the gradation.

The density of a soil is its weight per unit volume, and may refer to the soil mineral (dry density) only or to moist soil (wet density). As the density of the soil is increased, the pores become smaller and capillarity increases while permeability is reduced. Increasing the capillarity causes an increase in frost heave potential on the soil until a critical density is reached (*6, 12*). Beyond this point, an increase in density continues to cause an increase in capillarity; however, the steady decrease in permeability now becomes the major factor and the rate of upward flow of water is decreased. It has been reported that, since materials used in the construction of roads are usually compacted beyond the critical density, an increase in compactive effort will cause a slight decrease in frost heave potential (*12, 13*).

Thermal conductivity is also affected by density; an increase in density causes more and better points of contact between particles, which results in increased thermal conductivity.

The dry density of the soil depends on its porosity and gradation, the size and shape of the particles, the type and magnitude of compactive effort, and molding moisture content. A soil of uniform gradation is highly porous because the particles are the same size. A nonuniformly graded soil contains particles of varying sizes so that smaller grains are available to fill the pore spaces among the larger grains, resulting in higher density and smaller pore spaces than that of a uniformly graded soil. Therefore, a soil of uniform gradation is able to tolerate a comparatively higher percentage of fines without detrimental frost action than a nonuniformly graded soil, because it has more void space. Using the frost-susceptibility criterion of not more than 3 percent finer than the 0.02 mm size, therefore, may lead to the rejection of some non-frost-susceptible soils.

Surcharge

Surcharge in connection with frost action is the load which must be lifted by freezing ice lenses. An increase in the surcharge decreases the rate of heave. Linell and Kaplar (*7, 14*) report that, for the silts and granular soils tested with the Corps of Engineers method, the rate of heave for a soil with a 6 p.s.i. surcharge is only 10 percent of the rate of heave for the same soil with a 0.5 p.s.i. surcharge. The surcharge is lifted when water molecules move between the frozen ice lens and the soil particles. An increase in the surcharge decreases the ability of the water molecules to replace those which have been frozen.

Chemical properties

Chemical properties are important when dealing with clay soils. Adsorbed water in the surface of a clay mineral freezes at a lower temperature than does free water in the pores. Winterkorn (*15*) states that the zone of unfrozen water then acts as a channel through which water can move to the freezing areas. Grim (*16*), working with montmorillonite clay, states that water penetrates the individual molecular layers. This water consists of molecules in a definite pattern—similar to ice—and is not mobile. In general, whether water can move within montmorillonitic clay is dependent on the type of adsorbed ions (*17, 18*). Calcium, magnesium, and hydrogen adsorbed ions permit a higher degree of water mobility than do sodium ions. Kaolinitic clays consist of particles that are considerably larger than those of montmorillonitic clays. The smaller specific surface area of kaolinitic clays is responsible for a reduction of the adsorptive force and an increase in the mobility of the water.

The mineral composition of sands and gravels will affect their specific heat, thermal conductivity, and density (*18*). The mobility of water in sands and gravels is also affected by the presence of ions, but is primarily a function of gradation.

Dissolved salts

The addition of either sodium chloride or calcium chloride to a soil may reduce heaving (*19, 20*). Salts may be present in soil either from application during construction, or from infiltration as a result of salting the roads during the winter. Beskow (*6*) states that very weak concentrations of salt tend to increase the heave potential by making the layers of adsorbed water on the soil particles thicker, increasing the supply of water to the ice lens. Generally, however, a reduction in heave is believed to result from increases in salt concentration in a soil.

On the basis of evidence to date, it is impossible to predict quantitatively the effect of dissolved salts on frost heave. The performance of the salt concentration is dependent on the texture of the soil, its permeability, presence of an impervious cover, and the incidence of moisture. During leaching the salt concentration is reduced faster for coarse-grained soils than for fine-grained soils.

Movement of Moisture Through Freezing Soils

Although many theories have been advanced to explain the movement of moisture through soils under freezing conditions, no general agreement exists. Four hypotheses suggested in the literature are (1) capillary flow, (2) suction force, (3) thermodynamic theory and (4) vapor transfer.

Capillary flow theory

The phenomenon of capillary flow of moisture in soils is well documented (*6, 11, 21, 22*). As was described earlier, capillary tension acting at the interface between water and soil particles can provide sufficient force to lift water a substantial height above the free water table. Beskow (*6*) attributes the flow of water toward a zone of freezing in a soil to this force of capillarity.

Suction force theory

A soil particle is surrounded by a layer of adsorbed moisture held there by a comparatively large adsorptive (cohesive) force. When an ice crystal forms, water molecules from the adsorbed moisture film adhere to the crystal and freeze. Because the film of water on the soil particle is stressed by the adsorptive forces, the water molecules that have moved to the ice crystal are replaced from the moisture film surrounding adjacent soil particles. This process is continuous and results in a flow of moisture—in the liquid phase—to the ice crystal (*22*).

Thermodynamic theory

Soil has been found to be plastic at temperatures below 0° C (*23*). This phenomenon has led to the theory that a layer of water separates the ice from the soil (*24*). The ice front moves through the pores of the soil at some radius of curvature of the ice-water interface at a temperature below the natural freezing temperature of the water. This temperature depression, called supercooling, is inversely related to the radius of curvature. The radius of curvature, however, is dependent on the size of the soil pores. A soil with small pores has small radii of curvature and, therefore, requires a greater temperature depression to move the ice front through the pores (*23, 25*).

Chalmers et al. (*23*) state that the energy released as a result of the temperature depression "must do work to lift the surcharge and to pull water up from the ground water table."

Vapor transfer of moisture

Moist soils are never completely saturated but the air they contain is almost always completely saturated with moisture vapor. When a thermal gradient is imposed on a moist soil, the vapor pressure will decrease in the direction of decreasing temperature and moisture flow in vapor form will result. In his experiments, Jumikis (*26*) found the amount of water diffused in 1 day, through an area of 1 cm^2, at a temperature of 0° C and a temperature differential of 2° C over the air space, to be 0.0138 gram. He concluded that water transmission in vapor form is insignificant. However, Zoller (*27*) has reported the buildup of ½-inch-thick ice lenses in the parging between granite facing on buildings and porous concrete block backing which generated sufficient force to rupture the wire ties and threaten to dislodge entire blocks of granite. These ice lenses were attributed solely to moisture transmission in vapor form.

Frost Penetration

Rate and depth of frost penetration in a soil are governed by the thermal conductivity, specific heat, and latent heat of fusion of the soil mass, as well as the freezing index to which the soil has been subjected. The study of thermal characteristics of soils is difficult because it involves the solid, liquid, and gaseous states. The difficulty of the problem is increased with the formation of ice, which changes the thermal properties of the material.

The rate of frost penetration increases for soils which have high coefficients of thermal conductivity. The addition of water to the soil in turn increases the conductivity by establishing better thermal contacts between the soil grains. Shannon and Wells (*28*) found that thermal conductivity was dependent primarily on the moisture content and whether the soil was frozen. At high moisture content, frozen soil has a 50 percent higher thermal conductivity than unfrozen soil. Beskow (*6*) states that the thermal conductivity of ice is three or four times greater than that of water.

Rate of penetration vs. rate of heave

Beskow (*6*), in laboratory tests, used rates of frost penetration ranging from 8 to 24 cm per day. This is about 10 times the naturally occurring rate. The rate of heave of relatively permeable soils has been found to be reasonably independent of the rate of frost penetration at freezing rates in the order of 9 inches per day (*6, 23*). If the rate of frost penetration is slow, thick lenses will form, since more water has time to move to each lens. If the rate of penetration is increased, there is less time for water to move to a lens and thinner lenses are formed. However, the rate of water flow, and thus the heave rate, still remain fairly constant. If the rate of frost penetration is too rapid, the soil is frozen before water has time to move and form lenses, and the soil freezes homogeneously (*6, 12*).

If one imagines an approach to the limiting case of instantaneous freezing of a soil mass, the resulting heave—at a heave rate approaching infinity—would result entirely from freezing in situ water as no time would be available for moisture migration. Since detrimental frost heaving is a function of water drawn in from outside the freezing soil mass, a correction for freezing in situ water subtracted from the measured heave rate would result in rate of heave which was attributable solely to the freezing of moisture drawn in from outside. Such a correction was proposed by Kaplar (*7, 10*) and Biddiscombe (*29*). Reduced to equation form the correction, δ_c, in mm per day is:

$$\delta_c = 0.0231\, PS \left(\frac{G\,\gamma_w}{\gamma_s} - 1.0\right)$$

where: P = Rate of penetration of freezing surface in inches per day

S = Degree of saturation in percent

G = Specific gravity of soil particles

γ_w = Unit weight of water

γ_s = Unit weight of dry soil

For granular soils studied by this project, which were drained prior to testing and therefore only partially saturated, no correction for freezing of in situ water was applied. For comparison of fine-grained saturated soils with high void ratios, however, such a correction may be very helpful in accounting for differences in the rate of frost penetration during testing.

Total heave

The total amount of heave experienced will depend on the rate of heave and the length of time during which heaving occurs. The maximum depth of penetration has been reached when the rate of heat extraction is not sufficient to continue movement of the ice front through the soil pores. Therefore, if the rate of frost penetration down to a given depth is fast, the total amount of heave will be less than that produced by a slow rate of frost penetration to the same depth. Otis (*30*) states that some cold winters in New Hampshire have caused less heaving than mild ones. This could be due not only to less freezing and thawing taking place, but also to the faster rate of frost penetration and to surcharge effects.

Depth of Penetration

Several factors govern the depth to which frost will penetrate during a given winter. Internal factors include properties such as specific heat, thermal conductivity, water content, density, soluble salts, and surficial conditions such as evaporation of water, type and thickness of ground cover, and soil color. External factors are air temperature, incident solar radiation, wind, barometric pressure, snow cover, and precipitation (*18*).

New Hampshire has a range of freezing index values—cumulative degree days below 32° F—that varies from a mean of 300 near the coast to over 2,000 near the Canadian border (*9*). Average depths of frost penetration vary from 30 inches near the coast to 47 inches near the Canadian border (*18*). Extreme frost conditions may produce penetration depths of 60 to

75 inches (*18*). Sanger (*31*) has developed charts which correlate freezing index, surface conditions, soil, and frost penetration. For bare ground or pavement with no snow cover, the depth of penetration varied from 10 to 30 inches for a freezing index of 300 and from 41 to 82 inches for a freezing index of 2,000, depending on the type of soil.

Corps of Engineers Freeze Test

In brief, the Corps of Engineers standard freeze test as described by Kaplar (*10, 32*) is an exacting test in terms of equipment, time, and technical talent. Soil specimens are placed in 6-inch-diameter tapered molds and frozen from the top in freezing cabinets placed in a 40° F room at the rate of approximately ½ inch per day. Time requirements for sample preparation and testing approach 6 weeks.

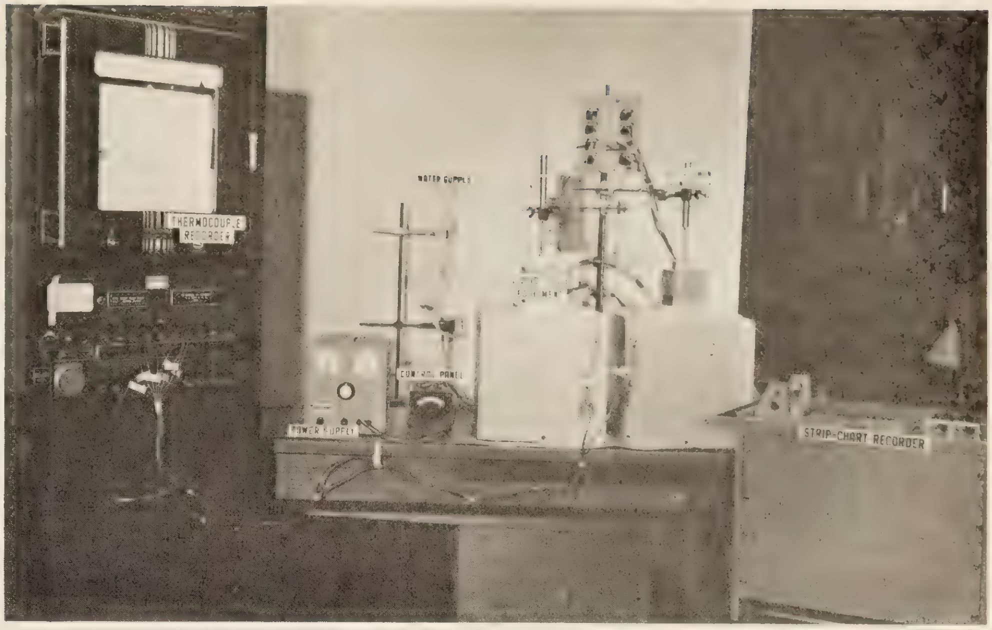


Figure 1.—Liquid-cooled equipment.

UNH Rapid Freeze Test

A primary objective of the UNH research project was the development of inexpensive freeze testing equipment and techniques which could be applied in a limited space in a conventional soils laboratory. A block of rigid foamed plastic was used to insulate the specimen from normal room temperatures and Peltier thermoelectric batteries were installed as freezing units. This relatively compact and inexpensive equipment eliminated the need for extensive cold room facilities and freezing cabinets. A reduction in the time duration per test was also desirable. The testing time was reduced by using an increased rate of freezing. By introducing a segmented specimen mold consisting of lucite rings, which resulted in relatively stable heave rates throughout the test, the testing time was reduced further. This meant that for a heave test involving a constant rate of frost penetration, no additional information could be obtained by freezing a specimen beyond the first few inches. Thus the testing time was halved again by freezing only 3 inches of the specimen instead of 6.

The air-cooled Peltier thermoelectric batteries specified by Biddiscombe (*29*) have a heat pumping capacity of approximately 300 BTU/hour when operating at maximum allowable input power of 4.5 amps and 12 volts d.c. The operating characteristics of these units are such that the actual heat pumped is a function of the temperature difference between the hot and cold plates as well as input current. When the temperature of the cold plate is 0° C (32° F) and the ambient or hot plate temperature is 25° C (77° F), the maximum heat pumping capacity of the battery is about 68 BTU per hour. The cold plate is a circular aluminum disc, 5⅜ inches in diameter. A 2-inch separation between hot and cold junctions is filled with rigid foamed plastic insulation. The hot plate is equipped with aluminum fins and a high-speed fan for rapid dissipation of heat.

Dependence of the air-cooled Peltier batteries on a relatively constant room temperature for constant output renders these units somewhat unreliable during periods of variable ambient temperature. Accordingly, a liquid-cooled Peltier battery was utilized for the rapid freeze test. In this battery an ethyl-glycol coolant is circulated through the "hot" side of the battery at a temperature which may be held constant at any value or controlled as a secondary means of regulating the rate of heat withdrawal from the soil samples. Liquid-cooled Peltier batteries have been most reliable and effective as a "heat sink" in the rapid freeze test. Apparatus is shown in figure 1.

Reasonably satisfactory results have also been obtained in the test with the circulation of a refrigerant, ethyl-glycol, in the cooling head itself, without using a Peltier battery. In general, a more rapid response and better control have been achieved with the liquid-cooled battery.

The specimen mold consists of seven lucite rings with a 5.46-inch internal diameter and a wall 0.25-inch thick. Five of the rings are 1.00 inch high and the remaining two are 0.50 inch high. The seven rings are stacked with one of the half-inch rings at the top and the other at the bottom. The top three 1-inch rings have holes drilled in the center for the insertion of thermocouples. Because the soil is compacted directly into the lucite, the multiring mold is placed inside a standard CBR mold for stability and support during compaction. The soil is then compacted in layers with a Marshall hammer to achieve the desired uniform density throughout the specimen. The sample is removed from the CBR mold, and thermocouples are inserted in the edge of the specimen at 1-inch intervals, from the top of the sample to a depth of 3 inches. The specimen is then ready to be placed in the freezing apparatus.

The freezing container is a 16 by 16 by 14 inch block, built from a solid block or sheets of rigid foamed polystyrene insulation. A 6¼-inch-diameter hole is cut in the center of the block to a depth of 7½ inches and lined with a waxed cardboard cylinder mold which has been cut to a height of 7½ inches. A constant-head water supply is attached to the bottom of the cylinder. A 5½-inch-diameter, ½-inch-thick porous stone is supported 1 inch from the bottom of the cylinder. The specimen, with ring mold intact, is placed on the porous stone.

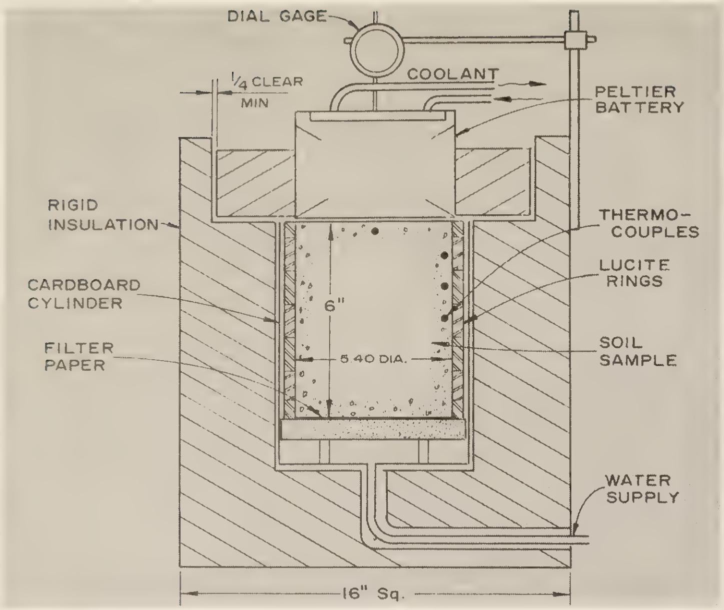


Figure 2.—UNH rapid freeze test equipment setup.

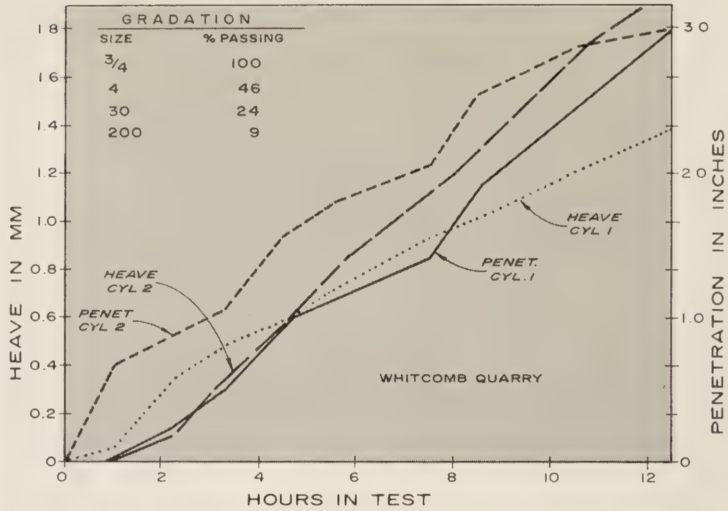


Figure 3.—Typical heave and penetration curves.

Filter paper is used to keep fine particles from infiltrating into the porous plate. The Peltier battery is placed atop the soil system with the cold plate in contact with a second filter paper on the top of the soil.

The thermocouple leads are connected, through a switch, to a millivolt potentiometer and another thermocouple which is immersed in an ice bath. The differential voltages set up between the ice bath thermocouple and the specimen thermocouples can be measured with the potentiometer and converted to differential temperatures. Temperature observations can thereby be made and the location of the 32° F isotherm can be determined by linear interpolation. A dial gage is mounted above the battery to permit the heave of the sample to be observed. The weight of the Peltier battery and connecting hoses approximates the 0.5 p.s.i. surcharge of the Corps of Engineers test. A schematic cross section of the freezing chamber is shown in figure 2.

After a specimen is prepared and placed in the freezing apparatus, it is saturated from the bottom by raising the level of the water table to the level of the top of the soil specimen where it is held constant for 16 hours. Current is applied to the Peltier battery during this period to cool the sample. In order to cool the sample and not allow freezing to occur, the input current is adjusted so that the heat pumped by the battery will be zero when the difference in temperature between the hot and cold plates equals the difference between ambient temperature or coolant temperature and the freezing temperature of water.

At the end of the 16-hour cooling period, the water table is lowered to ½ inch above the bottom of the specimen and the input current to the battery is increased to begin freezing the specimen. The input current applied to the battery is dependent upon the difference in temperature between the hot and cold plates and the desired amount of heat to be pumped. During a series of freezing tests in which the testing procedure was being established, it was found that for a temperature of 32° F at the top of the specimen, a heat pumping capacity of approximately 65 BTU per hour produced freezing rates generally between 3 and 7 inches per day. The temperature at the top of most of the tested soil specimens stabilized at approximately —4° C (25° F) during testing. At this cold-plate temperature, the heat pumping capacity required is approximately 34 BTU per hour. Calculations indicate that a maximum of about 5 to 6 BTU per hour may be leaking through the sides and bottom of the insulating container.

The input current is adjusted as necessary during the test to offset significant changes in the ambient temperature which would otherwise change the heat pumping rate or to compensate for variations in the soil undergoing test. Heave and thermocouple readings are taken hourly until the 32° F isotherm has reached a depth of 3 inches. Typical heave and penetration curves are shown in figure 3. It is sometimes necessary to disregard the heave rate in the first hour or two of freezing because it is frequently different during the remainder of the test.

To keep the rings in alinement during the compaction process they are usually taped together with masking tape in three lines at 120°. On several occasions the tape was inadvertently left in place during the freezing cycle with the result that almost no heaving of the sample occurred even when the soil was a high heaving material such as New Hampshire silt. This illustrates the effectiveness of the ring mold concept in reducing wall friction and the sensitivity of the soil to relatively minor surcharge effects.

Frost Susceptibility Classification

The original measure of frost heave potential proposed by Casagrande, and reported by Kaplar (*10*), was based on a constant rate of frost penetration test with rates of freezing between ¼ and ¾ inch per day. This scale has been adopted as a standard by the Corps of Engineers (table 1) and was used as a reference in the initial studies at UNH (*29, 33*).

As the UNH freeze test utilized stacked-ring molds and a rapid rate of cooling, the heave rates measured for granular materials in the UNH test tended to be much higher than the rates measured in the Corps of Engineers test. Only a few

Table 1.—Frost susceptibility classes by Corps of Engineers and UNH

Frost susceptibility classification	Corps of Engineers freeze test—average rate of heave	UNH freeze test—average rate of heave
	mm./day	*mm./day*
Negligible	0–0.5	0– 6.5
Very low	0.5–1.0	6.5– 8.0
Low	1.0–2.0	8.0–10.3
Medium	2.0–4.0	10.3–13.0
High	4.0–8.0	13.0–15.0
Very high	>8.0	>15.0

materials were subjected by Leary (*33*) to both the Corps of Engineers and UNH freezing test procedures. The curve of figure 4 plotting these duplicate tests indicates consistently greater heave rates with the UNH equipment. Based on this curve a modified frost susceptibility classification was adopted for the rapid UNH test, which reflects the greater heave rates experienced as shown in table 1. The modified scale is plotted on the vertical axis of figure 4.

Table 2 summarizes the results of the UNH rapid freeze test for several typical materials used in the project. The West Lebanon and Whitcomb materials failed to pass the New Hampshire gradation limitation for material passing the No. 200 sieve; however, both exhibited a negligible heave rate in the rapid freeze test. The Hudson and Thornburn pit materials also failed the New Hampshire gradation requirements, while the Paquette pit materials passed.

State of compaction

The results from a test series varying the percent compaction indicated that there is approximately a linear relationship between heave rate and percent compaction. In addition, the extrapolated zero percent compaction intercept is approximately the same heave rate value for all materials tested. Thus the calculated heave rate at a given percent compaction for any material is a simple function of its heave rate at any other compaction as expressed by the equation:

$$HR = S\,(PC) - 15.40$$

where:

HR = Heave Rate
PC = Percent Compaction
S = Slope of Percent Compaction — Heave Rate Line

Figure 5 is the working expression of this relationship. From this chart the proposed UNH frost susceptibility scale can be extended to any desired percent compaction. In New Hampshire, the percent compaction is normally based on the maximum dry density obtained in AASHO method T 99. As noted previously, soil materials are compacted in molds for the UNH rapid freeze test in layers using a Marshall hammer to

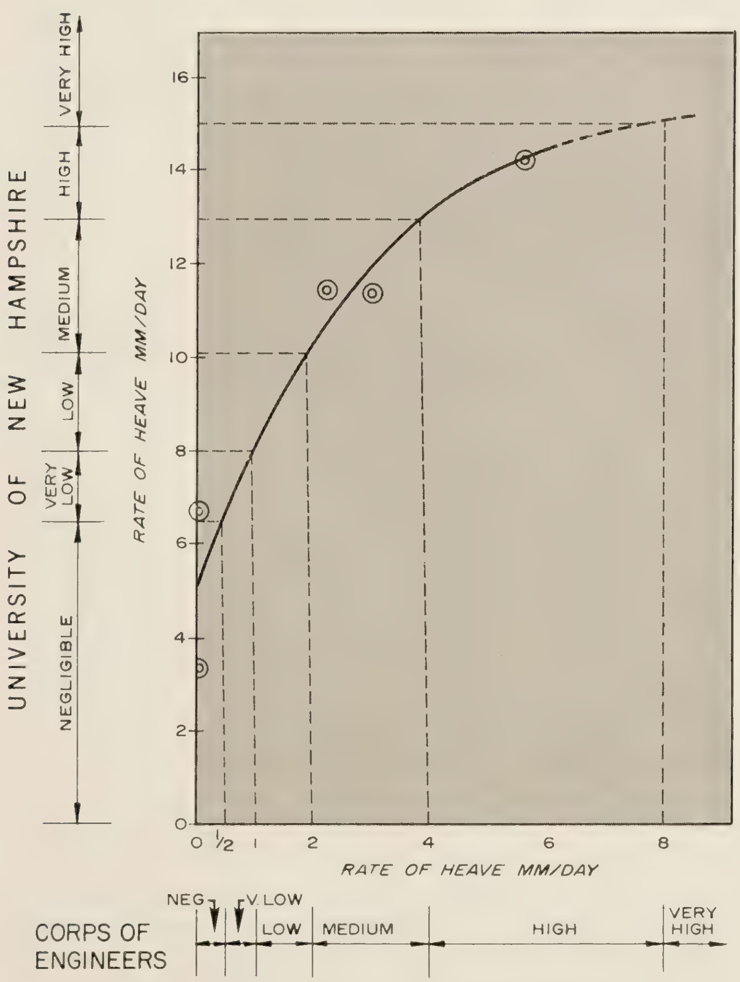


Figure 4.—Frost susceptibility classification.

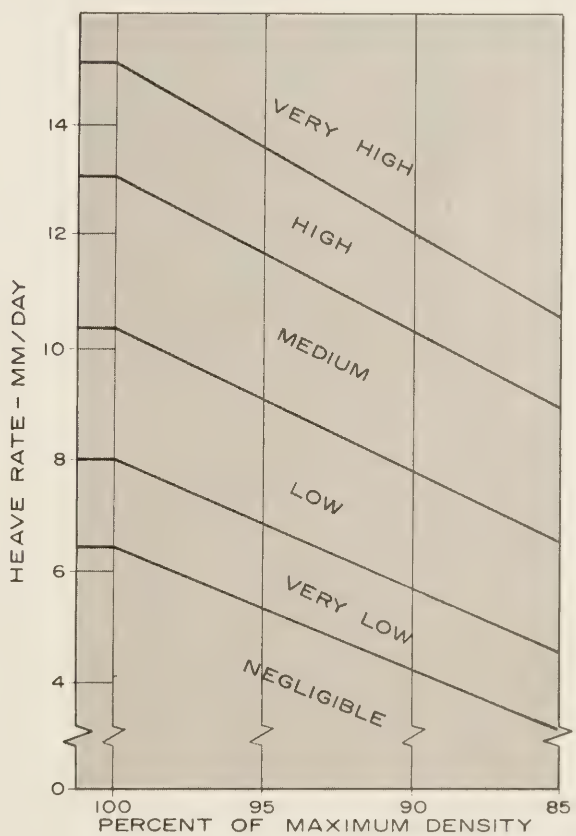


Figure 5.—Frost heave classification as affected by density.

achieve the desired density. If a field density of 95 to 100 percent is anticipated or specified for a material, the first cylinder would be compacted in 3 layers with 54 blows per layer and its computed density compared with the desired density. Modifications in the number of layers and blows would then be tried to obtain the desired density.

Material Modification and Additives

It has been shown (*29* and *33* through *39*) that the frost heaving characteristics of a soil may be altered by gradation modification and that, in general, increasing the amount of coarse aggregate or decreasing the amount of fine-grained material will produce a material which is less subject to frost heaving. It is recommended that, in materials where modification by such methods is being considered, specific modified samples be tested rather than attempting to establish modification guidelines for which many exceptions would be required.

The effect on frost heave of portland cement and asphaltic emulsion added to granular base materials was evaluated in this project. Nearly always the additives were effective in reducing the frost heave potential. Portland cement, however, generally had a pronounced effect on heave rate, while the effect of asphaltic emulsion in some materials was minimal (*38, 39*).

Field Investigation of Frost Heaving

The initial field investigation procedure adopted in 1965 involved the selection and extensive instrumentation of a few field sites to monitor depth of frost penetration and resulting heave throughout the freezing period. Sites selected were on a secondary road in Farmington, N.H., and two sites on the Durham bypass, Route 4, which were built to relatively frost-free standards. After several years of monitoring the results from these stations, it became apparent that each year was a rerun of the previous year and that no significant data would be forthcoming from the annual accumulation of test information from these sites.

Measurements taken over several winters have shown that measurable heaving occurs on even the highest type of pavement sections. For example, in 1969 the two test sections in Durham on Route 4 heaved 0.12 inch and 0.14 inch, respectively, while at the Farmington site —in conditions more conducive to maximum heave—the heave was 1.6 inches in 1967, 1.7 inches in 1968, and 1.62 inches in 1969.

In 1969, a section of Interstate 95 in Seabrook, N.H., on an approach to a rest area, was selected for surveillance. A network of points was laid out with 9 points at 50-foot intervals. It was noted that the heaves were, in general, less than ¼ inch; however, at one point a maximum heave of nearly an inch was recorded. Heaving of these higher types of pavements is generally not objectionable because it is of relatively small magnitude; it is uniform; and it does not appear to weaken the surface appreciably when thaw occurs.

To validate the UNH rapid freeze test it will be necessary to sample field locations where significant heaves have been recorded and compare the results of the freeze test on such samples with the severity of heaves experienced in the field. Unfortunately, the funds available in the past were not sufficient to permit such a field testing program. In addition, the New Hampshire Department of Public Works has been understandably reluctant to authorize a sampling program which would require cutting into the pavement and base structure on primary and secondary highways.

Factors Influencing Magnitude of Frost Heaving

Experience has shown that maximum heaving occurs when the subgrade is a silt soil with the water table well within

Table 2.—Material properties and freeze test results

Material	Liquid limit	Plastic limit	Soil classification Unified[1]	AASHO[2]	Sample No.	Molded moisture content	Dry unit weight	Percent of maximum density	Heave rate	UNH frost susceptibility
						percent	*p.c.f.*		*mm/day*	
W. Lebanon I	....	Nonplastic	GM	A–1	1	4.51	135.46	93.42	1.04	Negligible
					2	5.23	131.38	90.61	0.96	Do.
					3	4.54	143.68	99.09	0.99	Do.
					4	4.47	129.37	89.22	0.81	Do.
					5	3.87	138.99	95.86	1.28	Do.
Whitcomb quarry	....	.... do	SM	A–1	1	5.95	140.02	94.74	2.43	Negligible
					2	5.50	143.60	97.16	4.38	Do.
Bank run gravel, Hudson Sand & Gravel	16.3	.... do	SM–SP	A–1	1	5.41	132.20	98.88	10.74	Medium
					2	6.13	132.40	98.95	8.24	Low
					3	6.52	130.21	97.32	8.64	Low
					4	6.00	130.21	97.32	10.11	Medium
Gravel, Paquette pit (Pittsburg)	20.5	.... do	SP	A–1	1	7.81	121.25	88.76	4.59	Very low
					2	7.66	123.17	90.17	4.95	Do.
Gravel, Paquette pit (Clarksville)	17.8	.... do	SP	A–1	1	8.20	126.06	93.38	5.31	Very low
					2	8.55	124.87	92.50	5.31	Do.
New Hampshire silt	24.1	.... do	ML	A–4	1	15.88	104.06	96.26	20.20	Very high
					2	15.73	103.31	95.57	31.00	Do.
					3	17.63	102.03	94.38	42.00	Do.
					4	15.97	102.53	94.85	44.00	Do.
Thornburn pit, Haverhill	25.3	.... do	SP–SM	A–3	1	19.30	100.50	96.03	24.40	Very high
					2	21.20	98.70	94.29	16.20	Do.

[1] Based on information in the *Unified Classification System*, Technical Memorandum No. 3-357, vols. 1, 2, and 3, Waterways Experiment Station, U.S. Corps of Engineers. 1953.

[2] Based on Standard Specifications for Highways, Materials and Methods of Sampling and Testing (Part 1, 10th ed.), the Classification of Soils and Soil Aggregate Mixtures for Highway Construction Purposes, *AASHO* Designation: M 145-66.

the zone of capillary rise. As soils become more granular, the height of the capillary rise decreases and the ability of a soil to expand against a fixed overburden pressure decreases. As soils range into the clay sizes, their potential for heaving tends to increase as well as the lifting pressures they are capable of developing. Actual field heaving, however, decreases since the permeability is reduced for such soils. In general, clay and silt soils are not suitable for use in pavement systems since their bearing capacities are inadequate to support wheel loads, particularly under thaw conditions.

The total heave which may potentially occur at a given point on a highway is usually considered to be a function of depth to water table, as well as soil characteristics mentioned earlier. If it is assumed that the maximum elevation of the free water table occurs at the original ground level in fill sections, then it is reasonable to suppose that the total recorded heave should decrease as the depth of fill increases because of increased overburdened pressures and a reduced period of freezing zone–capillary zone contact. If many points were to be surveyed, it was anticipated that a plot of heave versus fill depth should have an envelope curve which would define the limiting conditions for detrimental frost heaving. Points on or near the envelope identify those field locations where soil characteristics and water table elevation are most conducive to frost action.

Numerous points on local primary and secondary highways were observed over a period of three winters. Observations included total heave, variations from a 10-foot straight edge as a measure of detrimental heave, and calculated cut or fill at the point. Results are plotted on figure 6. It will be noted that maximum heave tends to decrease with increasing depth of fill although significant heaves were recorded even on fills as high as 25 feet.

Furthermore, as the depth of fill increased the detrimental frost heave decreased. Severely detrimental frost heaving was limited to those areas which were in a cross section of nearly zero fill or in cut sections. The author believes that the detrimental heaves resulted primarily from nonuniformity in the subgrade, either from poor drainage or the presence of boulders or pockets of nonheaving material near the surface. The author believes also that the actual value of maximum heave is relatively unimportant as long as the riding quality is not adversely affected. In other words, fairly large heaves are permissible as long as maximum variations from a plane surface are held to those of normal paving tolerance. In the deeper fill sections heaving is probably due to the migration and freezing of moisture within the wet soil mass below the impervious pavement layer and is not dependent upon a free water table within the capillary zone.

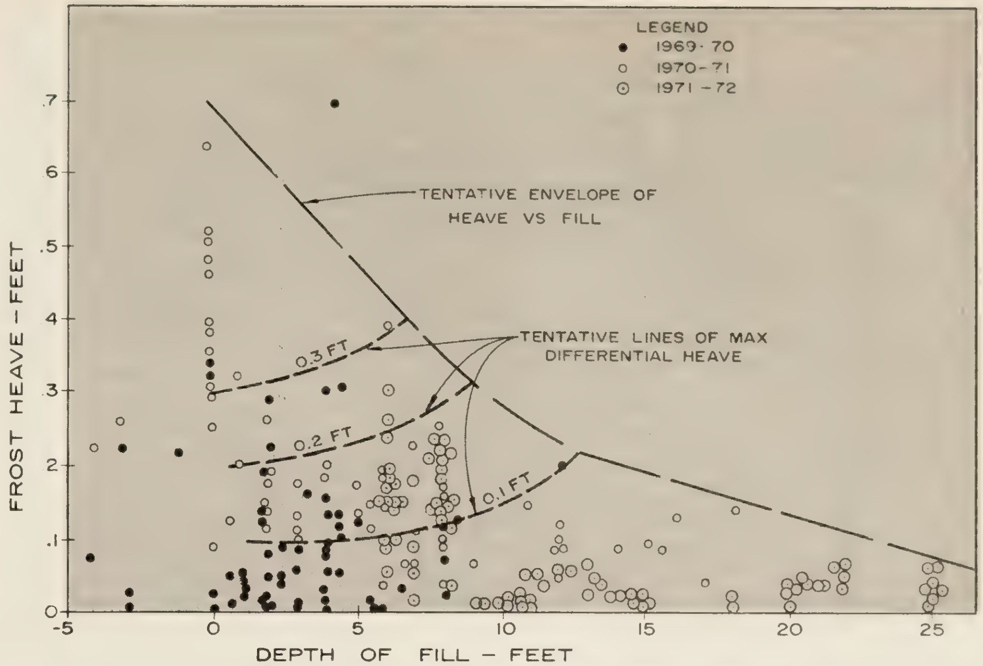


Figure 6.—Measured frost heave vs. depth of fill.

Summary

It is hoped that the UNH rapid freeze test will be applied experimentally by many States as a means of differentiating between frost-susceptible and nonfrost-susceptible soils for use in subbase and base course construction. As reported, many New Hampshire base course materials were tested during the project life. No instances have been reported to the author in which materials classified as low or nonfrost-susceptible by the UNH rapid freeze test have subsequently produced detrimental heaves in the field. Such correlations of laboratory testing with field experience must be carried out on a broad scale under a complete spectrum of field conditions before the rapid freeze test and its associated use classification can be regarded as a completely reliable indicator of probable field performance. In the meantime, it is offered as an experimental tool of potential value to fill a current need in many areas of the United States.

ACKNOWLEDGMENTS

The guidance and assistance of the New Hampshire Department of Public Works and Highways is acknowledged with gratitude. The close cooperation and advice of Paul S. Otis, formerly Materials and Research Engineer, Philip E. McIntyre, Materials and Research Engineer, and Dennis Hamilton, Soils Engineer, have been particularly helpful. The counsel and encouragement of Lawrence E. Yearke, Assistant Division Engineer, and of Herbert E. Hodgdon, Planning and Research Engineer, New Hampshire Division, Federal Highway Administration, are also appreciated.

The contributions of the students who provided the muscle, the ingenuity and many of the ideas which led to the successful conclusion of the project are recognized.

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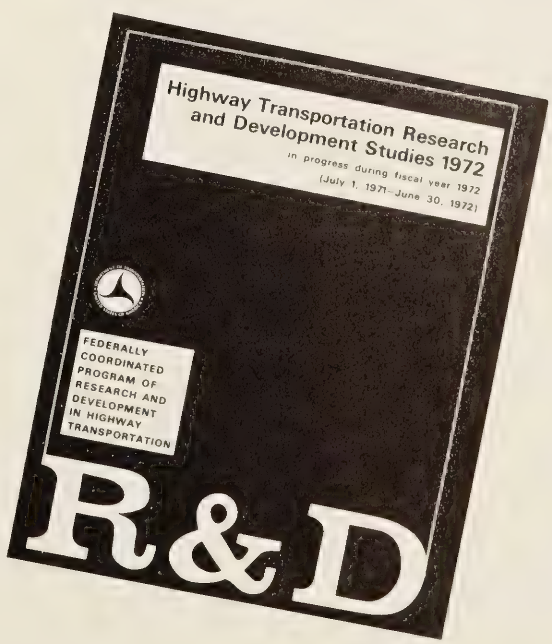
NEW PUBLICATIONS

The information presented in **Highway Transportation Research and Development Studies 1972** represents a complete inventory of the research and development studies approved, in progress, or completed during fiscal year 1972. The report contains individual vignettes for all research and development studies that are supported and aided by the Federal Highway Administration's Offices of Research and Development, Bureau of Motor Carrier Safety, and selected planning research studies from the Offices of Planning.



This publication is intended primarily for the information and guidance of Federal and State personnel concerned with highway-related research, particularly those in the Federal Highway Administration (FHWA) and other agencies within the U.S. Department of Transportation (DOT), and those in State highway departments or departments of transportation. It will be useful also to other Federal and local government personnel, to highway-oriented and vehicle-oriented trade, professional, and research organizations, and to members of the general public interested in or concerned with research in highway transportation.

A new easier-to-read format has been used for this issuance of the annual series. In addition, the publication has been organized in accordance with FHWA's recently introduced Federally Coordinated Program of Research and Development in Highway Transportation (FCP).

Implementation/User Package "how-to-do-it"

The principal tool for implementing research and development is the implementation/user package which provides "how-to-do-it" information to the potential user. The package converts research findings into practical tools. The packaging requirement is accomplished between the identification and promotion stages of implementation.

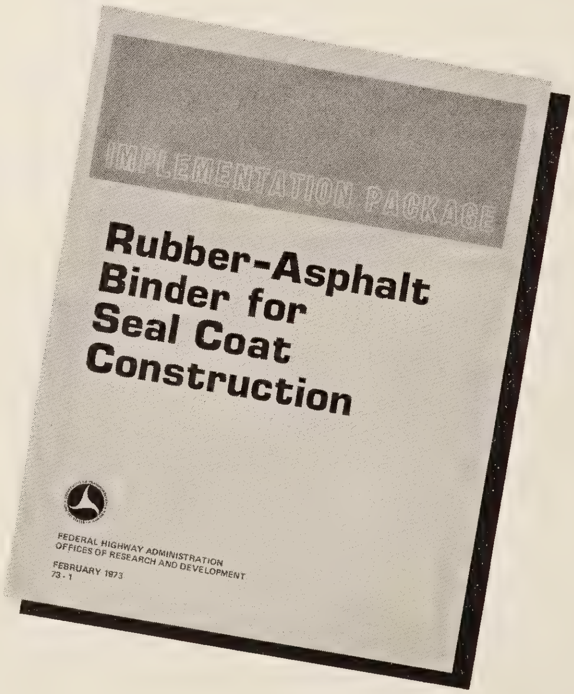
The following items are brief descriptions of selected packages which are actively being developed, or have been recently completed, by State and Federal highway units in cooperation with the Implementation Division, Offices of Research and Development, Federal Highway Administration (FHWA). All completed packages will be placed in the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Va. 22151.

Packages Completed

by FHWA Implementation Division

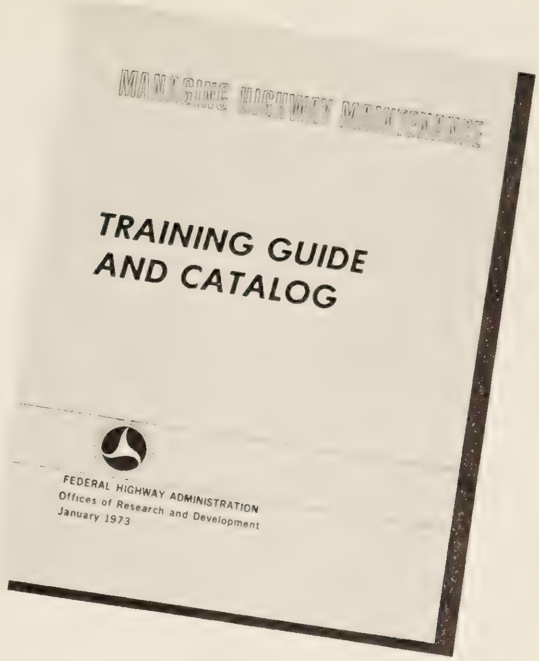
Rubber–Asphalt Binder for Seal Coat Construction

The package presents background information, construction details and suggested specifications for rubber-asphalt seal coat construction which has been successfully applied in Arizona to inhibit the formation and propagation of cracks that generally render seal coats ineffective. The powdered rubber used in the binder is reclaimed from discarded automobile tires which have become a major waste disposal problem. The package is in a form that can serve as a user manual for construction engineers. Distribution has been made to States and FHWA field offices. (NTIS PB 219012).



Managing Highway Maintenance Training Guide and Catalog

Research has shown that the efficiency and effectiveness of highway maintenance operations can be significantly improved by applying modern management principles. In recognition of the need to train field engineers, superintendents and foremen who manage highway maintenance, a comprehensive management training curriculum has been developed and is now completed. Requests for the Training Guide and Catalog and sets of the curriculum should be sent to the National Highway Institute, Federal Highway Administration, Washington, D.C. 20590.

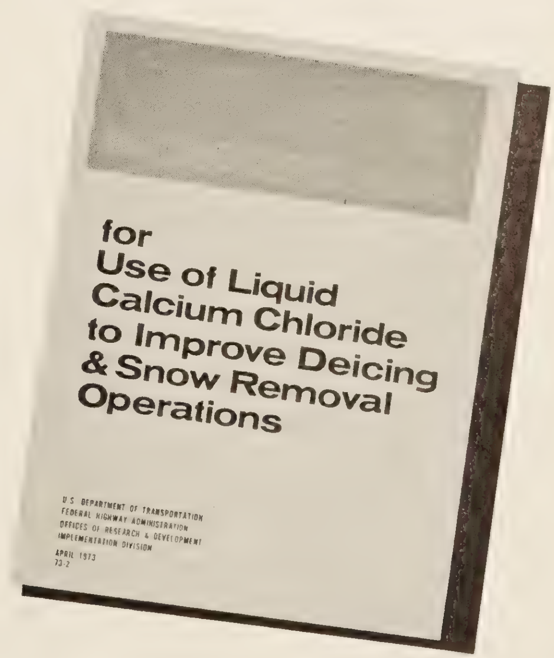


Slotted Corrugated Metal Pipe for Surface Water Drainage

The package illustrates design details and construction installation techniques for slotted corrugated metal pipe drains which have been developed and refined over a period of years by the California Division of Highways. The concept has proven effective in the areas of safety, economy, hydraulic efficiency, maintenance, and esthetics. Distribution has been made to the States and FHWA field offices.

Use of Liquid Calcium Chloride to Improve Deicing and Snow Removal Operations

The package outlines the method developed by the Iowa State Highway Commission for prewetting rock salt with a solution of calcium chloride to speed up and increase the effectiveness of pavement deicing operations. Using a liquid chloride applicator kit installed on existing salt spreading trucks has reduced cost of salting, produced effective melting action at temperatures below 20° F, reduced roadside pollution potential due to salt, and reduced overtime labor costs. The package includes current State practice, a description of the applicator kit, specifications and operating guidelines. Distribution has been made to the States, counties, and FHWA field offices.



Packages in Preparation

Project Management System Utilizing the Critical Path Method

by FHWA Implementation Division

An extremely useful computer program for scheduling emergency relief projects that must be put into service in a minimum time is being finalized for implementation. The system was successfully used in Pennsylvania in scheduling construction to replace a bridge destroyed by hurricane Agnes. The refined user manual for the system will combine methods of networking, critical path computations, and project management techniques.

Open Graded Bituminous Mixtures for Pavements

by FHWA Region 10, Portland, Oreg.

For several years the U.S. Forest Service has successfully used open graded emulsified asphalt mixtures for pavement construction. These open graded mixes have been low in cost and have demonstrated good stability and internal drainage qualities. The package being developed will cite background and experience, construction features, cost data, and guide specifications. The Forest Service cold mix procedure outlined in the report is relatively pollution free.

Prestressed Concrete Panels for Highway Bridge Decking

by Texas Highway Department

The Texas Transportation Institute and the University of Texas have recently completed a joint research study to develop a composite segmental bridge deck comprised of 3¼-inch-thick prestressed concrete panels which are used as permanent forms for a subsequent topping of 3½ inches of cast-in-place concrete. The State has recently constructed two bridge decks utilizing this new concept. The current implementation plan includes the preparation of a user-oriented manual for bridge designers in other States. FHWA Region 6 personnel located in Fort Worth, Tex., will assist the Texas Highway Department in preparing this manual.

Computerized Roadway Design System

by Texas Highway Department

The Roadway Design System (RDS) is an automation tool that assists the highway design engineer by greatly expanding productivity and flexibility in the design process. The preliminary system has been tested in FHWA and State highway offices and work is underway to refine the system and make it more applicable on a widespread basis. The updated package will include system refinements, training materials, and documents for operating and maintaining the computer programs.

Slotted Underdrains for Pavement System Drainage

by FHWA Region 8, Denver, Colo.

A package being developed will describe the use of the slotted underdrain system which results in greater efficiency in the performance of drainage layers, filter layers, and drainage pipe. The package will include a comparison of current State designs, design procedures, and promotional visual aids.

Concrete Delamination Detector for Inspecting Bridge Decks

by FHWA Implementation Division

A delamination detector has been developed which acoustically senses and records the location of voids and disbonded concrete—a major bridge deck deterioration problem. Commercial models of the devices will be available in the near future. The user package being developed includes operating and calibrating procedures, instructions on interpretation of data, and maintenance requirements for the device. Audiovisual materials will be included.

Computerized Bridge Rating System

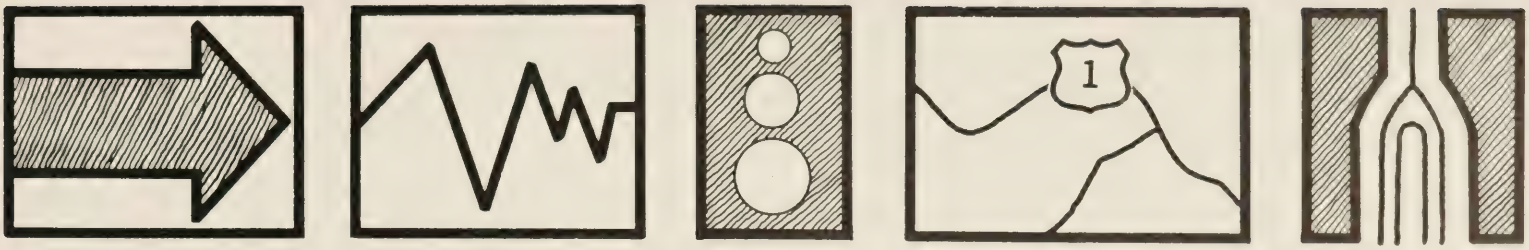
by Wyoming Highway Department

A system developed by the State of Wyoming for bridge design has been modified to materially assist State highway departments in accomplishing the structural rating requirements of the national bridge inspection standards. A series of workshops around the country have explained the system to highway personnel. A preliminary version is in use and trial experience will be used to evaluate and refine a complete implementation package.

Texas Crash Cushions

by FHWA Region 6, Fort Worth, Tex.
and Texas Highway Department

This implementation activity will be concerned with the application to practice of an adaptation of the Texas Crash Cushion. The Texas Crash Cushion, consisting of a number of 55-gallon steel drums, has been adapted to provide highway maintenance vehicles with protection from rear-end collisions by errant vehicles. Wheels and a trailer hitch have been added to the Texas Crash Cushion so that it can be attached to a maintenance vehicle such as a dump truck to provide such needed protection to the truck and maintenance personnel. The implementation activity will include the development of a how-to-do-it manual on the process of designing the portable or mobile trailer system to protect slowly moving or stopped maintenance vehicles working on highways. The manual will also include the appropriate procedure for attaching the protective system to the highway maintenance vehicle. The implementation package is being prepared by the Texas Transportation Institute, Texas A&M University, in cooperation with the Texas Highway Department and FHWA.



NEW RESEARCH IN PROGRESS

The following items identify new research studies that have been reported by FHWA's Offices of Research and Development. These studies are sponsored in whole or in part with Federal highway funds. For further details, please contact the following: Staff and Contract Research—Editor; Highway Planning and Research (HP&R Research)—Performing State Highway Department; National Cooperative Highway Research Program (NCHRP)—Program Director, National Cooperative Highway Research Program, Highway Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

FCP Category 1—Improved Highway Design and Operation for Safety

FCP Project 1B: Remedial Driving Techniques for Freeways and Interchanges.

Title: Effectiveness of Traffic Safety Material in Influencing Driving Performance of the General Driving Population. (FCP No. 41B5012)

Objective: (1) To develop new traffic safety materials, (2) to determine if such materials influence drivers by reducing accidents and convictions, (3) to determine if effectiveness of materials is a function of age and/or sex of the driver.

Performing Organization: Division of Highways, Sacramento, Calif. 95807

Expected Completion Date: April 1975

Estimated Cost: $71,000 (HP&R)

FCP Project 1H: Skid Accident Reduction.

Title: Measurement Systems Development, Validation, and Analysis of Road Roughness. (FCP No. 31H3112)

Objective: Instrument a multiple-beam seismic system and a passenger car conduct pavement profile and vehicle tests. Develop roadway roughness criteria and an analytic pavement profile for simulation studies.

Performing Organization: Purdue Research Foundation, Lafayette, Ind. 47907

Expected Completion Date: May 1975

Estimated Cost: $68,000 (FHWA Administrative Contract)

Title: Development of Noncontact Profiling System. (FCP No. 31H3132)

Objective: A method of profiling pavement surfaces that will operate at traffic speeds is required.

Performing Organization: IIT Research Institute, Chicago, Ill. 60616

Expected Completion Date: June 1974

Estimated Cost: $96,000 (FHWA Administrative Contract)

FCP Project 1I: Traffic Lane Delineation Systems for Adequate Visibility and Durability.

Title: Grooved Stripe for Plow-Resistant Wet-Night Lane Delineation. (FCP No. 31I1083)

Objective: To test and evaluate the effectiveness of grooved pavement stripes, as a supplement to ordinary striping, which will be capable of providing adequate lane delineation at night under wet pavement conditions, and capable of withstanding the destructive action of steel-bladed snowplows.

Performing Organization: New York Department of Transportation, Albany, N.Y. 12226

Expected Completion Date: October 1975

Estimated Cost: $99,000 (FHWA Administrative Contract)

FCP Project 1L: Improving Traffic Operations During Adverse Environmental Conditions.

Title: Fixed Illumination for Pedestrian Protection. (FCP No. 31L2042)

Objective: To develop an understanding of the critical parameters involved in pedestrian crossing behavior at night on city streets and how the design and installation of specialized fixed source illumination may be employed to increase the pedestrian's safety when crossing both illuminated and nonilluminated streets.

Performing Organization: Franklin Institute Research Laboratory, Philadelphia, Pa. 19103

Expected Completion Date: September 1975

Estimated Cost: $290,000 (FHWA Administrative Contract)

Title: Improved Warrants for Fixed Illumination on City Streets. (FCP No. 31L2082)

Objective: To develop and refine definitive standards for design and installation of fixed-source illumination on city streets based on an understanding of the relationship between the visibility level achieved and driver performance.

Performing Organization: Franklin Institute Research Laboratory, Philadelphia, Pa. 19103

Expected Completion Date: January 1975

Estimated Cost: $153,000 (FHWA Administrative Contract)

FCP Project 1O: Aids to Surveillance and Control.

Title: Analysis of Railroad Grade Crossing Accident and Inventory Data. (FCP No. 31O1012)

Objective: To review and edit grade crossing accident and inventory data; update data base and assist in analyzing data to develop accident prediction equations and accident severity prediction equation for train involved and non-train involved accidents at grade crossings.

Performing Organization: National Bureau of Standards, Washington, D.C. 20590

Expected Completion Date: June 1974

Estimated Cost: $95,000 (FHWA Administrative Contract)

FCP Category 2—Reduction of Traffic Congestion, and Improved Operational Efficiency

FCP Project 2C: Requirements for Alternate Routing to Distribute Traffic Between and Around Cities—Single Diversion Point.

Title: Highway Advisory Information Radio. (FCP No. 32C2253)

Objective: To determine technical requirements, design, fabricate and field test an engineering model of an in-vehicular automatic radio receiver, associated roadside transmitter, and encoding electronics to provide audio signing messages to motorists.

Performing Organization: Atlantic Research Corporation, Alexandria, Va. 22314

Expected Completion Date: July 1974

Estimated Cost: $162,000 (FHWA Administrative Contract)

FCP Category 3—Environmental Considerations in Highway Design, Location, Construction, and Operation

FCP Project 3A: Engineering Economic Evaluation of Vehicle Use and Traffic Control.

Title: Design and Analysis for Bus and Truck Road Systems in Urban Areas and Restrictions on Truck Traffic. (FCP No. 33A2052)

Objective: Detailed engineering economic evaluation of selected bus and truck oriented measures which will reduce traffic congestion in urban areas.

Performing Organization: Wilbur Smith and Associates, Columbia, S.C. 29202

Expected Completion Date: February 1975

Estimated Cost: $323,000 (FHWA Administrative Contract)

FCP Project 3F: Pollution Reduction and Visual Enhancement.

Title: Controlling Erosion Along Highways with Vegetation and Other Protective Cover. (FCP No. 43F1542)

Objective: To determine the effects of grading methods (cut and fill slopes) or soil/water movements and speed of establishing permanent vegetation; to test species for more effective "off-season seedings"; to examine further new methods for establishing legumes and woody groundcover.

Performing Organization: Virginia Polytechnic Institute, Blacksburg, Va. 24061

Expected Completion Date: April 1976

Estimated Cost: $105,000 (HP&R)

Title: Causes and Control of Decline in Woody Plants along Roadsides. (FCP No. 43F2534)

Objective: To identify and measure the causes for the decline of roadside plantings and to examine the effect of various practices as they relate to the deterioration of woody plants.

Performing Organization: University of Illinois, Urbana, Ill. 61801

Expected Completion Date: March 1978

Estimated Cost: $125,000 (HP&R)

FCP Category 4—Improved Materials Utilization and Durability

FCP Project 4D: Remedial Treatment of Soil Materials for Earth Structures and Foundations.

Title: Determination of Strength Equivalency Factors for the Design of Lime-Stabilized Roadways. (FCP No. 44D3122)

Objective: To develop an improved procedure for assigning appropriate gravel factors for design of lime-stabilized roadways and to verify the relationship between strengths after accelerated curing and long term field curing.

Performing Organization: Division of Highways, Sacramento, Calif. 95807

Expected Completion Date: June 1977

Estimated Cost: $81,000 (HP&R)

FCP Project 4F: Develop More Significant and Rapid Test Procedures for Quality Assurance.

Title: Basic Variable in Consolidation Testing and Design. (FCP No. 44F1184)

Objective: To improve the accuracy of predicting settlement behavior by comparing accuracies of different consolidation test methods, and to establish standards for testing and guidelines for interpreting test data.

Performing Organization: Department of Transportation, Albany, N.Y. 12226

Expected Completion Date: March 1977

Estimated Cost: $396,000 (HP&R)

FCP Category 5—Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

FCP Project 5A: Improved Protection Against Natural Hazards of Earthquake and Wind.

Title: Aerodynamic Investigation of Cable-Stayed Bridge Models. (FCP No. 25A1022)

Objective: Determine flutter velocities of cable-stay bridges by means of wind tunnel test on scaled section models subjected to both laminar flow and scaled turbulence conditions.

Performing Organization: Federal Highway Administration, Washington, D.C. 20590

Expected Completion Date: June 1975

Estimated Cost: $50,000 (FHWA Staff Research)

FCP Project 5B: Tunneling Technology for Future Highways.

Title: Determination of the In situ State of Stress in Soils. (FCP No. 35B2052)

Objective: A review of the state-of-the-art for the determination of the state of stress in soils including the analysis of techniques for determining principal stress directions, the magnitude of normal and shear stresses on arbitrary planes, and the stress history of soils. The feasibility of the development of potential new ideas will be studied.

Performing Organization: IIT Research Institute, Chicago, Ill. 60616

Expected Completion Date: June 1974

Estimated Cost: $89,000 (FHWA Administrative Contract)

FCP Project 5D: Structural Rehabilitation of Pavement Systems.

Title: Evaluation of Serviceability of Flexible Pavements. (FCP No. 45D1083)

Objective: To establish criteria for determining when to overlay existing flexible pavements for long term economic benefits by using California's current or a modified maintenance rating system.

Performing Organization: Division of Highways, Sacramento, Calif. 95807

Expected Completion Date: April 1978

Estimated Cost: $92,000 (HP&R)

FCP Project 5F: Bridge Safety Inspection.

Title: Welding of Intermediate Strength Steels. (FCP No. 45F2142)

Objective: To evaluate welding processes and procedures and to determine the effect of welding situations on the possibility of inducing cracks.

Performing Organization: Division of Highways, Sacramento, Calif. 95807

Expected Completion Date: June 1976

Estimated Cost: $50,000 (HP&R)

Non-FCP Category 0—Other New Studies

Title: Balanced Quality Assurance and Control. (Non—FCP 40F1184)

Objective: To determine the respective levels of contractor's quality control and the highway department's quality assurance of highway materials. Develop and implement procedures that will effectively assure the quality of highway construction materials.

Performing Organization: Division of Highways, Sacramento, Calif. 95807

Expected Completion Date: June 1978

Estimated Cost: $114,000 (HP&R)

Highway Research and Development Reports Available From the National Technical Information Service

The following highway research and development reports are for sale by the National Technical Information Service, Sills Building, 5285 Port Royal Road, Springfield, Va. 22151.

Other highway research and development reports available from the National Technical Information Service will be announced in future issues.

STRUCTURES

Stock No.	
PB 215617	Analysis of Foundation with Widely Spaced Batter Piles.
PB 218355	Rigid Pavement Investigations—Growth Characteristics and Blowups and Performance of Transverse Joints and Joint Sealing Materials. Interim Report.
PB 218433	Pavement Deflection Measurement—Dynamic Phase III, WSU Impulse Index Computer, Section I (Suitcase).
PB 218821	Investigation of Slab Differential and Movement on I–83 Baltimore–Harrisburg Expressway.
PB 218922	Effect of Broom Texture on Motorcycle Rideability.
PB 218988	The Effect of Pavement Roughness on Safe Vehicle Handling Characteristics.
PB 219023	Application of Slab Analysis Methods to Rigid Pavement Problems.
PB 219058	Repeated Load Test Evaluation of Base Course Materials.
PB 219080	Performance of Transverse Joint Supports in Rigid Pavements.
PB 219108	"K" Value Correlation Study.
PB 219109	Flexible Pavement System Computer Program Documentation.
PB 219120	Pavement Deflection Measurement—Dynamic Phase III, Section II (Vehicle).
PB 219122	Reflection Cracking of Bituminous Overlays on Rigid Pavement.
PB 219199	In Service Behavior of Preformed Neoprene Joint Seals.
PB 219202	An Empirical Equation for Calculating Deflections on the Surface of a Two-Layer Elastic System.
PB 219231	A Discrete-Element Method of Analysis for Orthogonal Slab and Grid Bridge Floor Systems.
PB 219232	Evaluation of Combination Insert and Sealant for Concrete Pavements.
PB 219233	Cold Asphalt Concrete Overlay.
PB 219405	Construction and Long-Term Behavior of ⅛th Scale Prestressed Concrete Bridge Components.
PB 219796	Investigation of Slab Differential and Movement on I–83, Baltimore–Harrisburg Expressway.
PB 219832	Effect of Welding on Fatigue Life of High-Strength Reinforcing Steel Used on Continuously Reinforced Concrete Pavements.
PB 220021	Satellite Tests on the Northeastern Expressway I–95 (John F. Kennedy Memorial Highway).
PB 220022	Vol. II—Appendices.
PB 220043	Camber and Deflection Behavior of Prestressed Concrete Beams Made with Hawaiian Aggregates.
PB 220047	Slab Behavior of a Prestressed Concrete I-Beam Bridge—Lehighton Bridge.
PB 220054	Prestressing the Negative Moment Region of Composite Beams.
PB 220065	Variables Affecting the Negative Moment Behavior of Composite Beams.
PB 220069	Investigation of Traffic Induced Vibrations and Their Effects on the Concrete Decks of Highways.
PB 220088	Pavement Roughness and Serviceability.
PB 220106	Dynamic Tests of the California Type 15 Bridge Barrier Rail Series XXV.
PB 220112	Comprehensive Settlement Study of the Interstate Fill Across the James River.

MATERIALS

Stock No.	
PB 218390	Permeance as a Mix Design Criterion for Asphaltic Concrete Pavements.
PB 218434	Construction, Protection, and Maintenance of Concrete Bridge Decks.
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