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EFFECT OF TEMPERATURE AND MOISTURE ON THE STRENGTH OF SOIL-PAVEMENT SYSTEMS

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ABSTRACT

The physical phenomena that accompany and characterize the interaction of a soil-pavement system with its thermal and moisture environment are identified and discussed. Knowledge of the basic theories regarding the daily and seasonal temperature waves and their interaction with soil moisture is stipulated. The effect of temperature change at constant moisture (or liquid) content and of change of moisture (or liquid) content at constant temperature is illustrated by experimental data on different components of soil-pavement systems. The combined effect of moisture and temperature changes is shown for various sections of the AASHO test road. Reference is made to the fact that most component layers of a road cross section belong to the large class of collameritic systems and to the many practically important analogies deriving from this for apparently widely differing construction materials.

Effect of Temperature and Moisture on the Strength of Soil - Pavement Systems

by Hans F. Winterkorn[1] and H. Y. Fang[2]

INTRODUCTION

Ever since the great expansion of motorized traffic after World War I and the concomitant demand for more and better roads stimulated the search for more economical i.e. more rational road design and construction, the importance of the influence of climate on the quality and durability of soil-pavement systems has been realized and studied with increasing sophistication of theoretical and experimental tools. See Winterkorn(35,36,38,40), Winterkorn and Eyring(37), Fang(10,11), Highway Research Board(1,18,19,20), and other pertinent literature. Also, increasing use was made of the information and concepts developed in other scientific areas from the theoretical and experimental work of Quetelet (1796-1874) on the daily and seasonal temperature waves to that of R. Geiger(15) and his followers on soil microclimatology. Stipulating the availablilty of this large body of information and of established pertinent concepts on the moisture and temperature regime in soils and also in subgrade-base-pavement systems, the present paper will deal with selected aspects of the influence of temperature and moisture content on the mechanical resistance properties of structural components of such systems. Also,

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whenever indicated, an attempt will be made to elucidate certain fundamental aspects of soil-moisture-temperature interactions whose mechanisms are still in dispute.

Pertinent dynamic considerations - Although general acquaintance with the available theoretical infrastructure for the understanding of the temperature and moisture regime in a soil-pavement system has been stipulated, a few facts deserve to be especially remembered. These are:

1. A highway pavement system, being either in fill or cut, is much more complicated than a plane surface soil system of theoretically infinite lateral extent. This normally renders the theoretical treatment of thermal and moisture interaction of a soil-pavement system with its environment so complicated that it can be used only as a general guide while the actual physical parameters have to be determined by test.

2. Thermal and moisture conductivities and mechanical properties of polydisperse, multiphase systems, that are composed of solid, liquid and gaseous phases depend not only on their phase compositions but also on the dispersion of the phases and on the previous history of the system[13,40,41]; also, because of contribution from water movement in the vapor phase and the lightness of the water molecule,

the vertically upward thermal conductivity of a moist soil system may be considerably larger than the vertically downward one.

3. Since heat and moisture move together from higher to lower temperatures and the movement and concentration of either or both may greatly affect the service quality and durability of a road, safeguards must be built into a soil-pavement system against their undesirable effects. It is most important to avoid great differences in thermal and moisture transmission properties of the different constituent layers of a pavement system down to a depth at which there is still a marked amplitude of the daily and seasonal temperature waves; this will eliminate the formation of a potential water collector where it can do greatest damage.

THE EFFECT OF TEMPERATURE ON SOIL PROPERTIES

In assaying the effect of temperature on soils and similar systems and in any attempt to bring into harmony some apparently contradictory findings reported in the literature, it is necessary to understand how temperature affects each of the main components phases (solids, liquids, gas) separately and also their interaction with each other within the framework of the total system. Generally, more important than the increase in volume with increasing temperature (at constant pressure) is the decrease of the internal friction of the liquid phase and its increase in the gaseous phase. This is important when the liquid serves as a lubricant as in Proctor and similar compaction methods. However, this lubricant effect may be quite small especially if the soil possesses a granular bearing skeleton which determines the bulk volume of the system and whose intertices provide the space occupied by silt-clay and water phases. On the other hand, soils without such bearing skeletons have more surface area that must be lubricated in compaction and whose interaction with water is dependent on temperature. The existence of such interaction has been known for a long time, as has been the fact that it is a function of type and amount of mineral (especially clay) surfaces and of types and amounts of exchangeable ions, as well as of the electrolyte environment in the contacting aqueous phase. The effect of temperature on this interaction could be expected from pertinent physico-chemical considerations and was studied by Baver and Winterkorn[3] on extracted natural clays already in the early 1930's over a wide moisture range and a temperature range from 30° to 99°C. In order to explain the results of these and of correlated studies[33,44] they separated the total interaction (swelling) water at elevated moisture-content into (1) hydratation water whose binding is associated with a considerable amount of heat of wetting and (2) osmotic water, the relatively unrestrained water between the hydrated cations in what many call the diffuse double layer. Now, both types of water are intrinsically related to the dielectric constant of water[3,33,17]. Since the latter decreases with increasing temperature, and more rapidly than is the increase in kinetic energy of the exchange ions with temperature increase, a decrease in both the hydratation water and the osmotic water in a saturated soil system may be expected with increasing temperature. This means that, at constant total water content, increase in temperature decreases the portion that is bound or restrained and increases the portion that is free while also decreasing the viscosity of the latter.

While this temperature effect is quite straight forward in relatively pure clay-water systems within a limited range of temperature, it becomes more complicated even with these when high temperatures may cause marked dispersion or flocculation effects depending on clay mineral and exchange ion type. Even greater complexity obtains in the presence of non-clay minerals of silt and larger size. The basic phenomenon however is a decrease in interaction water with increasing temperature. This decrease will normally result in an increase in the coefficient of permeability with increasing temperature. However, in the presence of a strong dispersion effect, the permeability may actually decrease especially if the clay is contained within the interstices of a coarse-granular skeleton.

The facts and considerations just presented should impress on one's mind the great importance of visualizing all the geometric, granulometric and structural factors within a system that are either restraining or permitting the full expression of the mineral-water-temperature interaction. It is from such a perspective that the data reported in the literature should be assayed. A limited selection of such findings is given below.

Plastic and Liquid Limits

Casagrande[8] found no significant variation in values of liquid limit with variation in temperature between 7°C to 24°C. Youssef, et al[45] testing Egyptian soft to stiff, dark brown clays found that temperature changes caused a change in liquid and plastic limits proportional to the change with temperature of the viscosity of water. Chandrasekharan, et al[9] studying the effect of heat treatment on Indian black cotton soil found a moderate reduction of water affinity in the initial ranges of heat treatment between 25° and 200°C. The temperature effect on the consistency properties of laterite soil has been reported as not significant because of the relatively inert character of the clay minerals (kaolinite and oxides of iron and aluminum) present. Laguros[23] testing kaolinitic, illitic, montmorillonitic, and montmorillonitic-illitic clays found that their liquid and plastic limits decreased with increase in temperature, with a maximum effect in the case of the montmorillonitic clay.

Density-Moisture Relationships

Soil temperature has an effect on compaction particularly on soils high in clay content. Hogentogler[21] reported laboratory compaction tests on a clayey soil in which density was increased 3 pcf, and the optimum moisture content decreased 3% units when the temperature of the soil increased from 34°F to 115°F. In a similar study Woods[44] found that the difference in the maximum dry density at temperatures from 35°F to 75°F was 2% for a sandy clay.

Burmister[6] found the dry density of a particular soil compacted at the optimum moisture content at 65°F to be 104 pcf while it was only 90 pcf at 35°F. Laguros[23] obtained comparable results working with clay soils containing kaolinitic, illitic, montmorillonitic, and montmorillonitic-illitic clay minerals, respectively.

Compressibility

Gray[16] reported an increase in compressibility with increase in temperature, the greatest effects being observed in the range of secondary consolidation. Burmister[5] described temperature effects that he considered serious enough to render ordinary consolidation test results as useless. Finn[14] investigating the effect of temperature on the consolidation characteristics of remolded clays during primary compression, found that the coefficient of consolidation, C_c, increased radically between 40°F and 70°F but did not increase significantly between 70°F and 80"F. Lambe[24] reported decrease in soil volume with increase in temperature observed in tests run at constant pressure with the temperature being the only external variable. Lo[25] demonstrated that even relatively small changes in temperature can cause a marked change in compressibility in the secondary consolidation range. Similar conclusions on the temperature effect on secondary compression were drawn by Campanella and Mitchell[7] and by Schiffman, et al.[31]. Paaswell[28,29] found that temperature increases caused immediate volume changes, the magnitudes dependent upon the magnitude of the temperature change. The magnitude of the initial stress (excess-pore-pressure) was seen to have a secondary effect on the magnitude of the volume change. These volume changes are attributed to a transfer of stress between the pore fluid and the matrix, as increases in temperature increase the pore pressure but decrease the matrix strength. Plum and Esrig[30] found that the amount of temperature induced consolidation is related to soil compressibility; the higher the compressibility the greater the consolidation for a given temperature increase. A given increment in temperature at constant effective stress had an effect equivalent to some increment of pressure at constant temperature. He also showed the volumetric strain of an illite-water system as a function of overconsolidation ratio, for a temperature increase from 24 to 50°C.

Pore Water Pressure

Campanella and Mitchell[7] emphasize the role of pore water pressure changes accompanying temperature changes. Determinant factors under drained conditions appear to be the thermal expansion of the pore water, the compressibility of the soil structure, and the initial effective stress. Their experimental results show several clay-water systems in which each change in temperature by 1°F changed the pore water pressure by about 0.75 to 1.0% of the initial effective stress. For less compressible materials the pore-water pressure change was considerably greater.

Modulus and Shear Strength

Murayama[27] using a rheological model for analysis of the elastic modulus of clay-water systems showed that the modulus decreased as the temperature increased.

Mitchell[26] studied the relationship between initial stress and strain in stress relaxation tests at various temperatures. Considering the straight-line portions of the curves through the plotted data as representative of the elastic modulus of the soil, he concluded that the modulus decreased with increase in temperature. Similar conclusions on the temperature effect on shear strength were drawn by Campanella and Mitchell[7], Languros[23], Sherif and Burrous[32]. It must be kept in mind that with exception of the Atterberg limit and compaction tests, the effect of temperature on soil water systems was determined at constant water constent or at free accessibility to a water reservoir. If change in temperature is associated with a change in moisture content then the total effect is the sum, or the difference, as the case may be, of both temperature and moisture change effects. This, of course, is the reason why field plate load and CBR tests yield higher values for moduli and bearing values during the warmer months [2,10,11].

The general effect of temperature on the engineering properties of subgrade soils is summarized in Table 1. However, the information contained therein is to be used with caution because of the possible modifying or counteracting effects due to the previously mentioned geometric, granulometric, and soil structure factors.

THE EFFECT OF MOISTURE CONTENT AT CONSTANT TEMPERATURE ON THE STRENGTH OF SUBGRADE SOILS

It would be impossible within the frame of this paper to organize and analyze the large body of knowledge available on this subject. All that can be done is to point out the most important general relationships. These are concerned with the influence of particle size composition or granulometry, presence or absence of a granular bearing skeleton, secondary structure of silt-clay aggregations and the mechanical, thermal, and moisture history of the soil system especially if it is of a cohesive nature.

Noncohesive soils - sands, gravels, cobbles, and their mixtures derive their mechanical resistance properties from friction and interlocking which are affected to only a small degree if at all by the presence of water. They are members of the large class of macromeritic systems, and their mechanical properties are in full accordance with the laws established for such systems[43].

In the case of cohesive soils distinction must be made between those that in the compacted state possess a granular skeleton and those without. The former are defined by a combined volume of silt-clay plus associated maximum in situ water content that is smaller than the intergranular spaces left free by the skeleton. The maximum water content is geometrically defined. If it is exceeded e.g. by a pumping pavement, then the system becomes a macromeritic liquid. Cohesive soils with granular bearing skeletons are members of the large class of construction materials that have been designated as Collameritic Systems. See Table 2 taken from Winterkorn[39]. This table indicates the analogies which can be expected in the behavior of various building materials and which allow, among other things, to make "synthetic soils" of well defined bearing characteristics from sand-asphalt mixtures[42].

Of the soils without a granular bearing skeleton, the least desirable are the silts that change from a semi-solid to a liquid state at a small increase in moisture content. The greater the clay content and its water affinity of a soil the smaller is the change of its consistency with increase in water content. Of course, such soils also show excessive swelling and shrinkage, but except for soils of high alkali-montmorillonite content, excessive volume and consistency changes can be controlled by waterproofing stabilization.

The shear strength of cohesive soils while a function of phase composition (including water content) and temperature, is not uniquely controlled by these but depends also on the direction from which the water content has been reached. Higher shear strength at a particular water content and also higher thermal conductivities were obtained when the path was from the wet to the dry side[13].

EXPERIMENTAL DATA ON COLLAMERITIC SYSTEMS HAVING EITHER WATER OR ASPHALT AS THE LIQUID PHASE

In view of the wealth of data available on the effect of water on the shear strength of soils of various granulometric and mineral properties, it was thought of interest to present in Fig. 1 some recent data on the tensile strength of a silty clay compacted to different densities at different moisture contents[12]. At high moisture contents increase in density produced only a slight increase in tensile strength; however, at low moisture contents the tensile strength increased sharply with an increase in density. Higher tensile strength existed on the dry-side of the optimum moisture content.

The effect of temperature on tensile strength of bituminous concrete has been studied by Kennedy and Hudson[22], and Breen and Stephens[4]. Their findings indicate that tensile strength increases as temperature decreases (see Fig. 2). Breen and Stephens have also investigated the more important relationship of work to failure as a function of temperature and asphalt content for a given penetration grade. It is shown in Fig. 3 that the work required for failure always decreases with decreasing testing temperature. This is due to the change of the asphaltic cement from a viscous liquid at elevated temperatures to a brittle glass-like solid at low temperatures. At the lower temperatures the effect of asphalt content on work is less significant than at the higher temperatures.

Fig. 4 gives the CBR values of a sand of narrow size range mixed with 2% of 180-200 penetration A.C. as a function of the dry density of the sand, the test temperature, and the surcharge[42]. It is of special interest that the decrease of the viscosity of the asphaltic cement with increasing temperature loses its pertinency at high surcharge values. Fig. 5 documents seasonal variations (spring and fall) of pavement deflection observed on various types of bases at the AASHO Road Test[1]. The deflections are greater in the spring for all types of bases studied which obviously is caused by the high moisture content found in the subgrade soil-pavement system during this season. It is of general interest that greater variability in the deflection was observed when traffic loads were increased and base thickness decreased.

SUMMARY AND CONCLUSIONS

1. Physical phenomena that accompany and characterize the interaction of a soil-pavement system with its thermal and moisture environment are identified and discussed.

2. The general effect of temperature on the strength of subgrade soils is summarized in tabular form. The strength parameters are in terms of consistency, compressibility, permeability, and modulus. It is suggested that information contained therein is to be used with caution because of the possible modifying or counteracting effects due to geometric, granulometric, and soil-structure factors.

3. At constant moisture content, the strength of a soil-pavement system generally decreases as the temperature increases. If change in temperature is associated with a change in moisture content, then the total effect is the sum, or the difference, as the case may be, of both temperature and moisture change effects.

4. The important factors that govern the effect of moisture content at constant temperature on the strength of subgrade soils are pointed out. These factors include: particle size composition (granulometry), presence or absence of a granular bearing skeleton, secondary structure of silt-clay aggregations, and the mechanical, thermal, and moisture history of the soil system.

5. The mechanical resistance properties of noncohesive soils such as sands, gravels, cobbles, and their mixtures, can be analyzed protitably by use of the Winterkorn macromeritic liquids concept.

6. Since most component layers of a road cross section belong to the large class of collameritic (cemented particle) systems, there exist many practically useful analogies, regarding their mechanical resistance properties and their temperature and moisture susceptibilities, which aid in the understanding of their service behavior even though they may appear to be vastly different in type and character.

Table 1

General Effect of Temperature on the Engineering Properties of Subgrade Soils

Soil Properties	Temperature	
	Low	High
Water Retention	High	Low
Liquid Limit	High	Low
Plastic Limit	High	Low
Maximum Compacted Density	Decrease	Increase
Optimum Moisture Content	Increase	Decrease
Void Ratio at Constant Pressure in Open Saturated System	High	Low
Volume Change (conditions as above)	Swelling	Shrinkage
Coef. of Compressibility, a_v.	Decrease	Increase
Pore-Water Pressure	Decrease	Increase
Coef. of Permeability, K	Decrease	Increase
Shear Strength	High	Low
Modulus	High	Low

Table 2

COLLAMERITICS (Winterkorn, 1955)

The Science of Composition and Properties of Non-Metallic Construction Materials

Properties of the aggregates	based on Properties of Cementing Agents	Combination of Aggregates and Cementing Agents.
A Physical I Granulometry Laws of Arrangement and Packing as a function of 1) Size & gradation 2) Shape factors a) spherical b) cubic c) plate-like d) needles & fibers II Mechanical 1) Strength & toughness 2) Abrasion resistance B Physico-Chemical and Chemical I Reactivity and Bonding with cementing materials II Reactivity with deleterious substances	A Inorganic I Simple: Gypsum and lime Plasters. II Complex: Sorel and hydraulic cements. III Clay-water B Organic I Bituminous: asphalts, pitches, tars. II Natural and synthetic Resins, elastomers and related substances. III Gums and Glues	A Design of I Mortars with inorganic or organic cements. II Concretes: Portland Cement-, bituminous-resinous-, clay-, etc. III Plastics: Powder-, paper-and fiber-filled.

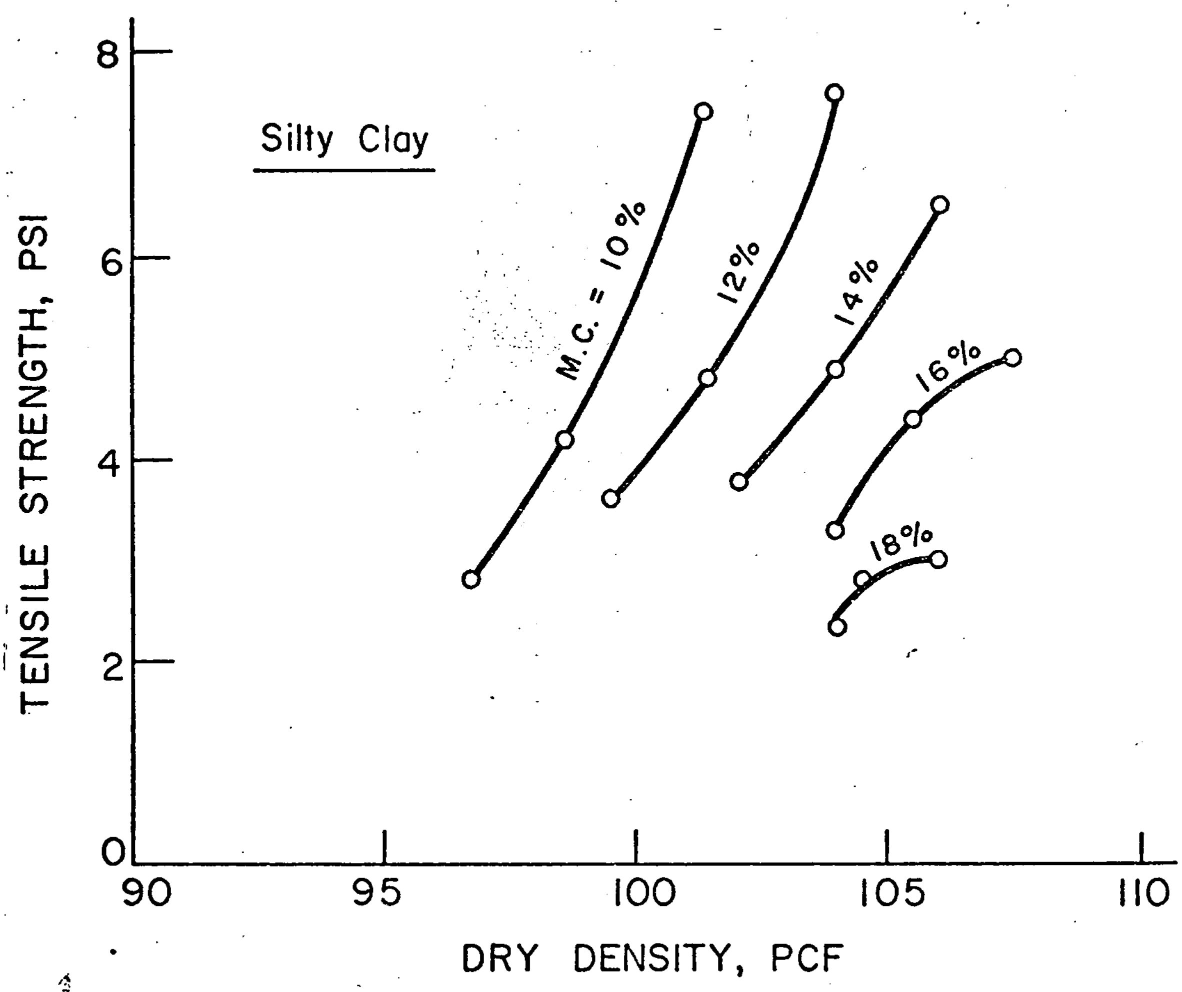

Fig. 1 Effect of Moisture Content and Dry Density on Tensile Strength (from Fang and Chen, 1971)

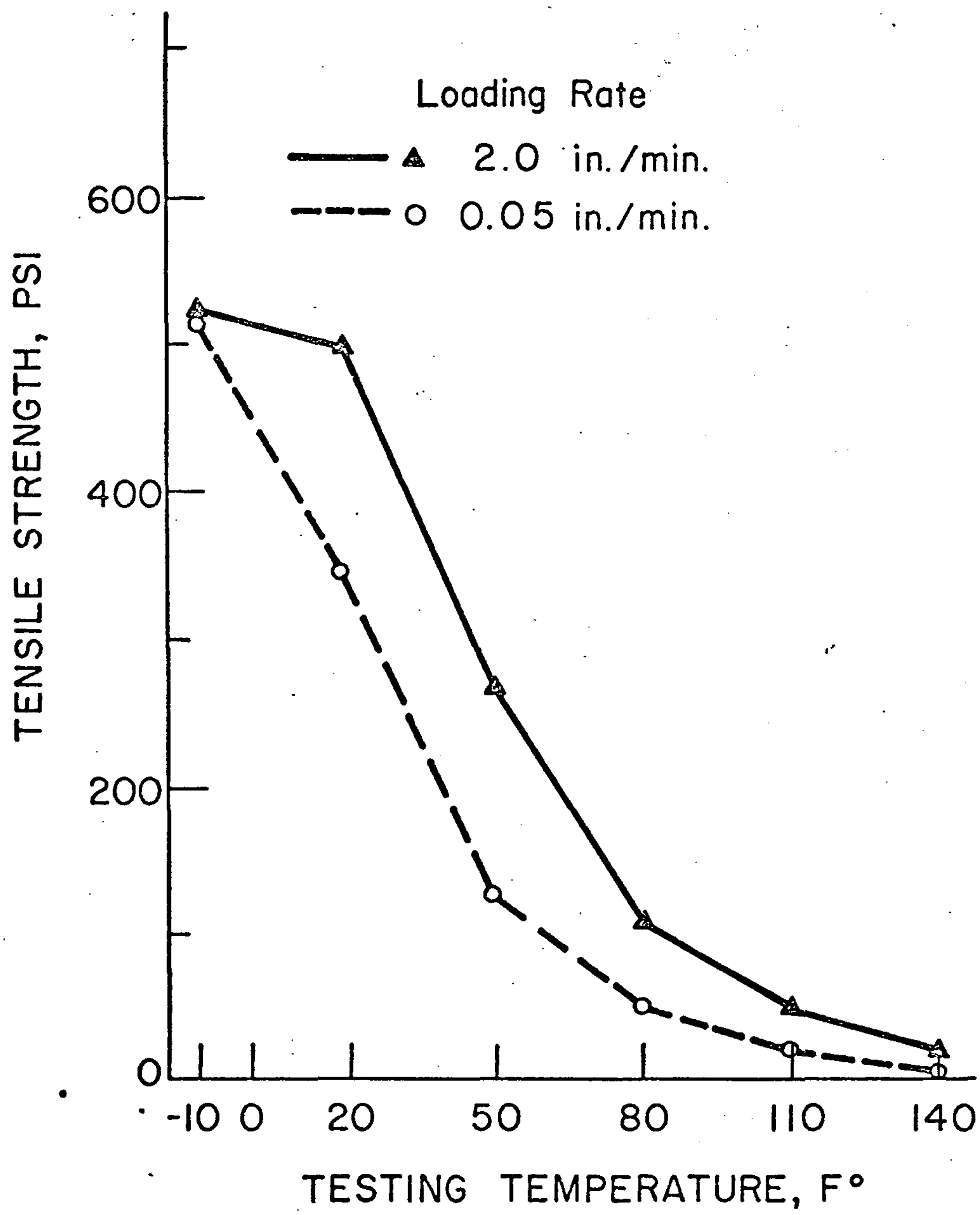

Fig. 2 Effect of Temperature on Tensile Strength of Bituminous Stabilized Materials (from Kennedy and Hudson, 1968)

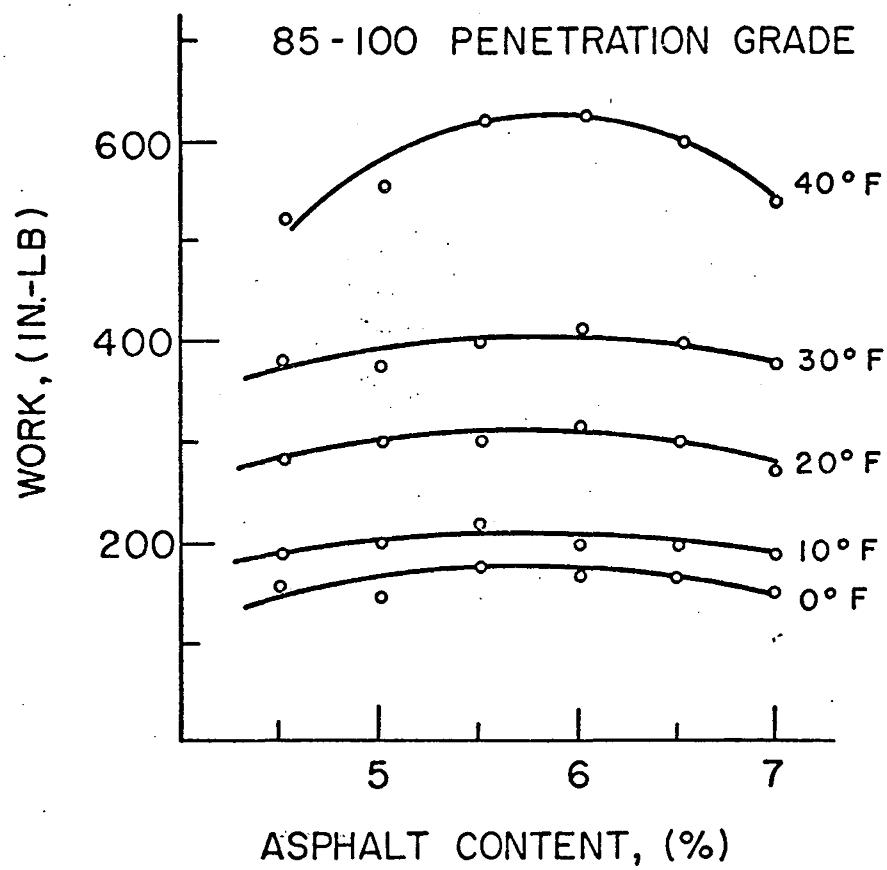

Fig. 3 Effect of Asphalt Content and Temperature on Work (from Breen and Stephens, 1966)

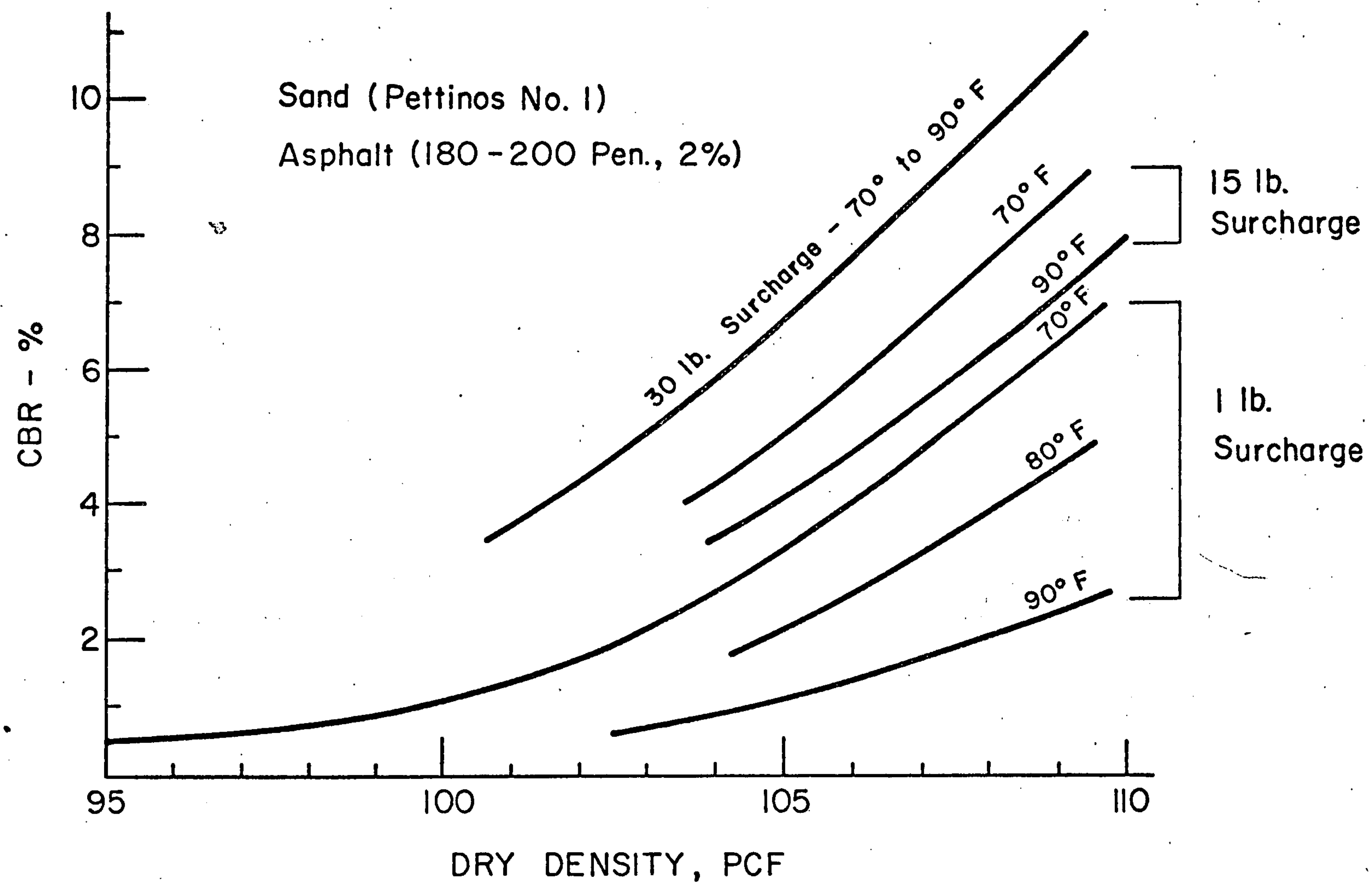

Fig. 4 Effect of Temperature and Surcharge on CBR of Sand-Asphalt Mixtures (from Winterkorn, 1968)

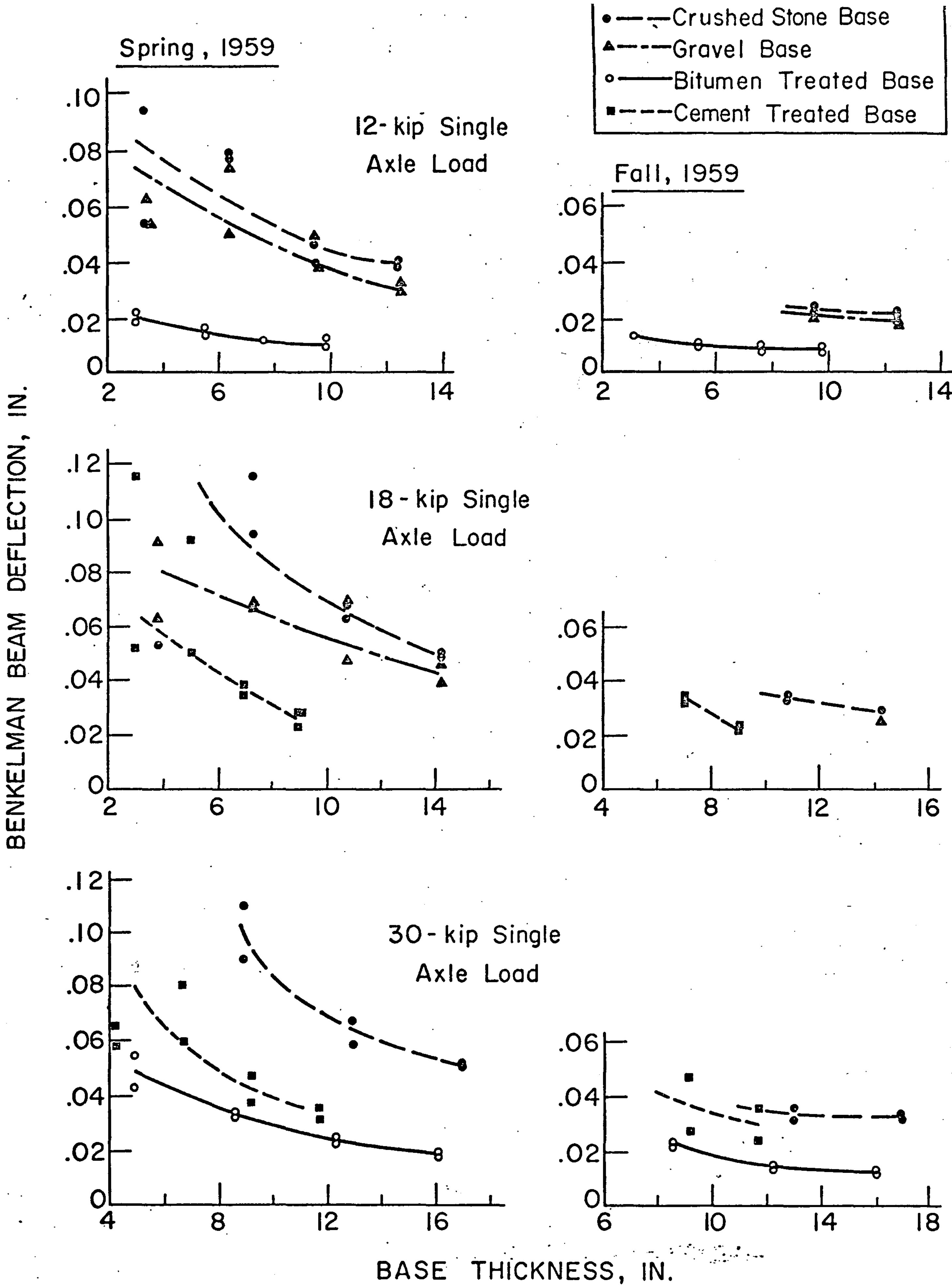

Fig. 5 Seasonal Effect on Surface Deflection with Various Base Types (from AASHO Road Test, 1962)

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