LABORATORY STUDY OF EFFECTS OF ENVIRONMENT AND CONSTRUCTION PROCEDURES ON CONCRETE PAVEMENT SURFACES

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***Quality of Portland Cement Concrete Pavement
As Related to Environmental Factors and
Handling Practices During Construction***

Research Study 2-8-70-141

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FOREWORD

The information contained herein was developed on Research Study 2-8-70-141 titled "Quality of Portland Cement Concrete Pavement as Related to Environmental Factors and Handling Practices During Construction," in a cooperative research program with the Texas Highway Department and the Federal Highway Administration. The primary purpose of this study is to develop methods whereby the handling of portland cement concrete paving mixtures during construction could be improved.

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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

ABSTRACT

The quality of the riding surface is the element of construction which the traveling public generally uses to judge the quality of any pavement. However, those who are in the highway construction field want more than a good-riding pavement. The finished pavement must not only be smooth-riding but must also be durable, structurally sound, and safe (provide ample skid resistance). To this end, a study was conducted to develop improved construction practices related to the consolidation, finishing, and curing of Continuously Reinforced Concrete Pavements (CRCP).

A total of 56 sidewalk size slabs were cast in controlled environmental rooms. Parameters investigated included type of subbase, method of consolidation (vibration), type of finish, type of curing method, and curing environment. Also, the slabs were utilized to determine the effects of wind on the evaporation rate of water from the surface of the slabs. This was accomplished by generating wind over the surface of the slabs.

After a 28-day curing period the slabs were removed from their curing environment and a minimum of three cores were taken from each. These cores were then subjected to diagnostic analyses. At the conclusion of the tests, the data taken from the cores along with the water loss measurements were reduced, tabulated, analyzed, and curves plotted to illustrate the results obtained.

Some of the major conclusions reached were:

1. All of the methods of consolidation investigated produced adequate strengths.

2. Mechanical vibration of concrete slabs, whether internal or surface, improved the surface properties of the concrete.

3. Concrete slabs made with a mixture of rounded siliceous gravel and crushed limestone resulted in higher strengths than concrete made with either rounded or crushed coarse aggregate and a single fine aggregate.

4. Neither the type nor the texture of the subbases investigated adversely affected the strength of the concrete slabs.

5. Placing fresh concrete on a dry subbase (even at 140°F) did not adversely affect the strength of the concrete slabs. However, there may be other benefits from wetting the subbase.

6. In all cases (73°, 100°, and 140°F curing temperatures) adequate strengths were obtained. But, curing temperatures in excess of 100°F resulted in a significant reduction in the strength of the top portion of all concrete slabs, even though adequate curing methods were used. With the simulated wind conditions of 8-10 mph and 18-20 mph, this reduction in strength was even more pronounced. Conversely, high curing temperatures and the wind conditions did not significantly affect the strength of the bottom portion of the concrete slabs.

7. At temperatures in excess of 100°F, the surfaces cured with the combination monomolecular film (one application before final finish) followed by white pigmented compound (MMF + WPC) showed a high abrasion loss as compared to the surfaces cured with either water soluble linseed oil (LO) or white pigmented compound (WPC) by itself. Thus, there appeared to be no surface strength benefits from the one application of the MMF before finishing.

8. Evaporation of water from the surface of the slabs was significantly retarded with the use of any of the curing compounds (MMF + WPC, LO, and WPC). LO and WPC tended to retard the evaporation more than MMF + WPC. Thus, the laboratory results do not show any advantage to the particular way in which MMF was used as an evaporation retarder. Conversely, the use of an adequate curing compound was shown to be advantageous.

9. Evaporation rates measured experimentally in this study did not agree with the values predicted by the PCA chart, especially those where wind was present.

Key words: Concrete, Concrete Pavements, Concrete Construction, Concrete Finishing, Concrete Curing, Consolidation, Evaporation, Wind Effects, Curing Compounds.

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1.1 General Remarks

The construction procedures for Continuously Reinforced Concrete Pavements (CRCP) have continued to change during the past ten years of extensive use. These changes have come about through field experience and research and have resulted in better pavements. However, costly failures still occasionally occur, even though the state-of-the-art has continued to be improved. A concrete pavement must (a) provide a smooth ride for the traveling public; (b) be durable when subjected to natural weathering and to chemicals used for snow and ice control, and (c) be capable of sustaining the traffic it was intended to carry.

Proper consolidation, proper finishing, and proper curing are of particular importance in the production of this high quality concrete. Today, considerable research efforts are being applied to the problems of improper consolidation, finishing, and curing of CRCP. This research study has been devoted to determining the effects of variations in surface finishing, curing method and environment, materials, and vibration of CRCP. This report summarizes the results of the laboratory examination of construction practices related to this research study.

1.2 Purpose of the Investigation

This study was initiated to develop methods whereby the handling practices of portland cement concrete pavements during construction could be improved through a laboratory examination of construction practices related to the consolidation, finishing, and curing.

1.3 Scope

The scope of this laboratory investigation included:

1. A determination of the effects of vibration on concrete properties by varying the method of vibration, coarse aggregate type, and subbase type.

2. A determination of the effects of surface finish on the surface properties of concrete by varying the type of surface finish.

3. A determination of the combined effects of wind velocity, air temperature and relative humidity, concrete temperature and type of curing compound on surface properties of concrete.

1.4 Conclusions

The following conclusions were reached after laboratory evaluations were made on high quality, low slump concrete.

1. All of the methods of consolidation investigated produced adequate strength.

2. Mechanical vibration of concrete slabs, whether internal or surface, improved the surface properties of the concrete.

3. Concrete slabs made with a mixture of rounded siliceous gravel and crushed limestone resulted in higher strengths than concrete made with either rounded or crushed coarse aggregate and a single fine aggregate.

4. Neither the type nor the texture of the subbases investigated adversely affected the strength of the concrete slabs.

5. Placing fresh concrete on a dry subbase (even at 140°F) did not adversely affect the strength of the concrete slabs. However, there may be other benefits from wetting the subbase.

6. In all cases (73°, 100°, and 140°F curing temperatures) adequate strengths were obtained. But, curing temperatures in excess of 100°F resulted in a significant reduction in the strength of the top portion of all concrete slabs, even though adequate curing methods were used. With the simulated wind conditions of 8-10 mph and 18-20 mph, this reduction in strength was even more pronounced. Conversely, high curing temperatures and the wind conditions did not significantly affect the strength of the bottom portion of the concrete slabs.

7. At temperatures in excess of 100°F, the surfaces cured with the combination monomolecular film (one application before final finish) followed by white pigmented compound (MMF + WPC) showed a high abrasion loss as compared to the surfaces cured with either water soluble linseed oil (LO) or white pigmented compound (WPC) by itself. Thus, there appeared to be no surface strength benefits from the one application of the MMF before finishing.

8. Evaporation of water from the surface of the slabs was significantly retarded with the use of any of the curing compounds (MMF + WPC, LO, and WPC). LO and WPC tended to retard the evaporation more than MMF + WPC. Thus, the laboratory results do not show any advantage to the particular way in which MMF was used as an evaporation retarder. Conversely, the use of an adequate curing compounded was shown to be advantageous.

9. Evaporation rates measured experimentally in this study did not agree with the values predicted by the PCA chart, especially those where wind was present.

1.5 Recommendations

Based on the results of the laboratory phase of this study, the following recommendations are made:

1. Extend the scope of the laboratory study by initiating full scale field tests to verify the conclusions reached in this laboratory study.

2. Conduct a laboratory investigation under low temperatures (50°F) and compare these results with the results obtained from this research.

3. The water soluble linseed oil curing compound should be checked against current Highway Department

specifications and utilized in a full scale field test to verify its value.

1.6 Implementation Statement

As a result of this study, the present Texas Highway Department specifications and/or the Construction Manual include requirements for (1) minimum vibration frequency, (2) maximum internal vibrator spacing, and (3) the use of evaporation retarders to prevent the pavement from drying too rapidly during equipment breakdown or other emergencies.

Additional implementation is not recommended until these laboratory results are verified under field conditions.

The above statement represents the combined opinions of the study contact representative and the authors and should not be construed as departmental policy.

2. Background

2.1 Consolidation

Though the available literature contains many references on the consolidation of concrete, most of these are related to beams, columns, floor slabs, and dams.[1-7*] Reports in the areas of concrete pavement consolidation are somewhat limited in number.

When concrete was first adopted by the construction industry, the practice was to place it in relatively shallow lifts, or layers, with a consistency resembling that of a moist-earth.[7] It was compacted with heavy tampers and rammed at the expense of much hand labor.

With the introduction of reinforced concrete came thinner sections and the need for concrete of plastic consistency. The original moist-earth mixes were too difficult to place in narrow forms containing reinforcing steel, and wet mixes of plastic consistency became the vogue.[7] Ease of placement of these wet mixes was recognized but with loss in strength. Nevertheless, low-slump, dry mixes, which tests had proved would produce better concrete, were not completely favored because of the extra effort and expense required to thoroughly consolidate them.

Then it was discovered that fresh concrete, even though dry and harsh, acquired entirely different rheological properties when shaken or subjected to high frequency vibratory impulses.[7] It became plastic and semifluid. Under violent agitation, the force of gravity caused the mix to subside and seek its greatest density. When the vibrations stopped, friction again immobilized the concrete. Vibration itself imparts no new properties to concrete, but the benefits derived result from the ability to handle concrete of lower water content.[8]

Consolidation by vibration occurs in two stages.[4,9,10] The concrete mix is a mass of separate particles surrounded by mortar and held in this condition by the arching action of the larger particles. The particles are prevented from falling to a lower level by static friction and adhesion. The arching action results in a large volume of air-filled voids. This state of apparent equilibrium is not stable and as soon as the static conditions change to dynamic through the action of vibration, the system collapses under the combined action of gravity and vibration acceleration. Results show that the particle size of the aggregates affects an optimum frequency of vibration for which maximum strength of the concrete may be obtained.[3] The end of this stage is characterized by the closure of the surface, the formation of a continuous matrix of mortar enclosing the coarse aggregate and the entrapped air bubbles. At this stage, the concrete has all the characteristics of a heavy viscous fluid, and the surface of the concrete has become smooth.[4]

At the end of this first stage there is approximately five percent entrapped air (mainly along the sides of the form.) This air is removed during the second stage of compaction. At this stage, the air content is low enough that the concrete behaves like a dense liquid and transmits the vibration waves more effectively than during the first stage. If the vibration waves are sufficient to move the coarse aggregate particles, the entrapped air would require an unreasonably long vibrating time and during this time such problems as segregation would occur. Thus, some entrapped air will not be removed for reasonable periods of vibration. Unfortunately, it is not possible to accurately judge when the second stage of consolidation has reached the desired level. Usually the second stage is considered to be completed when air is no longer observed escaping from the surface. This stage is sometimes called de-aeration.[10]

The immersion type of concrete vibrator has an oscillating movement which is described by its frequency and amplitude. The frequency is the number of oscillations or cycles per unit of time, and the amplitude is the maximum deviation from the position of rest. The waves generated by the oscillating movement of the vibrator immersed in the fresh concrete dampen rapidly as the distance from the vibrator increases. The distance from the center line of the vibrator to the fartherest point at which the concrete is effectively compacted is the radius of action.[4,9] Many factors influence the attenuation of the waves and hence the radius of influence. Air voids in the concrete mix dampen the waves and decrease the radius of influence, but as the vibration continues the air is expelled from the fresh concrete mass which allows the radius of influence to increase. Also, the dampening appears to increase with the increase in the frequency of the vibration. If this is true, there is an upper limit to the frequency that can be used. Some quantitative results to demonstrate those concepts are shown in Figure 2-1.[11] Finally, the consistency and composition of the concrete influences the radius of action. As a result of these factors, it is not possible to give a simple rule for determining the compacting capacity of a given vibrator.[9]

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*Superscript Arabic numbers refer to corresponding items in the list of references (Sec. 5.8).

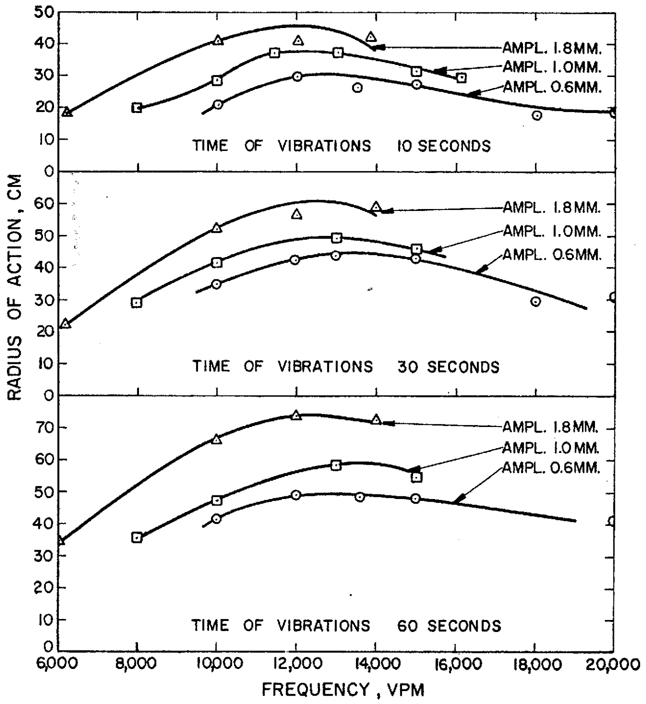


Figure 2-1. Relation Between the Radius of Action, Frequency, and Amplitude During Different Times of Vibration.[11]

There are three types of consolidating equipment generally used in concrete pavement construction. Each type is designed to accomplish specific purposes. However, difficulties in producing machines that will endure and give good service while operating at high speeds, impose practical limits on the frequencies to be employed. The type of equipment used include:[7]

1. Immersion vibrators, to be immersed directly into the concrete, with recommended minimum frequencies in concrete between 6000 and 9000 vpm (vibrations per minute)—(depending upon application).

2. Form vibrators, to be attached to the forms or molds, with a recommended minimum frequency on the form of 3600 vpm.

3. Vibrating screeds or pans, to be applied to the surface of concrete with a recommended minimum frequency in concrete of 3000 vpm.

The advantage of consolidating by vibration include: lowered cost of concrete through ease of placement and by reduced cement content, greater density and homogenity in the concrete, greater strength, improved bond with reinforcement, greater bond at construction joints, greater durability, and reduced volume change or shrinkage.[7]

One of the earliest field studies was made on the U.S. Government work at Davenport, Iowa. It was possible to make direct comparisons between hand placing and vibration. Their tests showed that, by appropriate changes in consistency and design of the mixture, it was possible to reduce the water content of the concrete more than a gallon per sack of cement; or it was possible to produce concrete of a given water-cement ratio with fully a sack of cement per cubic yard less than that required when placing by hand.[8] The changes in mixture composition consisted essentially in reducing the proportion of sand and increasing the coarse aggregate. Figure 2-2 may be taken as representative of the advantage to be derived from vibrations. This figure gives the relationship between compressive strength and cement content as based on this study. As can be seen, an increase in compressive strength is gained by the introduction of vibration together with the water content reduction. This reduction in water content will also have effects on the shrinkage of the concrete.

The Texas Highway Department has experienced problems with improperly consolidated concrete.[12] One location which has caused a considerable problem (for CRCP) is the concrete adjacent to construction joints. The concrete adjacent to this joint may be badly cracked or honeycombed in the bottom layer of the pavement indicative of improper consolidation. Other problems resulting from improper consolidation have occurred randomly in isolated, small locations on several projects. They occur frequently enough to be of concern. A third major problem not always associated with improper consolidation is manifested in closely spaced transverse cracks, or random longitudinal cracks, or transverse cracks joining together in the center area of the pavement.

To combat these problems, more effective construction control over vibration of CRCP could be accomplished by:[12]

1. "Requiring a tachometer to measure vibration frequency at regular intervals on all projects,

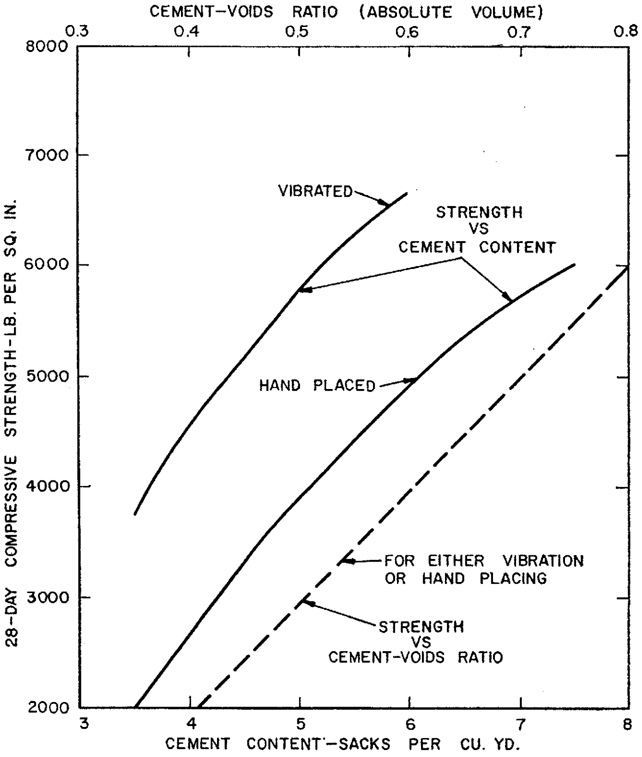


Figure 2-2. Relationship Between Compressive Strength and Cement Content.[8]

2. Utilizing concrete coring or some nondestructive technique to inspect consolidation in addition to thickness determinations,

3. Making inspectors more aware of the potential problems in consolidation, especially adjacent to transverse construction joints, and,

4. Requiring a visual indication on equipment to indicate whether or not internal vibrators are operating."

Also, the introduction of selected changes to current practices has been suggested.

The state of Colorado is presently studying the effects of vibration on the durability of concrete pavement.[13] A noticeable difference in durability of concrete pavements in Colorado seems to be associated with differences in consolidation and void content of the concrete. Where very little attention was given to consolidation of the fresh concrete, the ensuing years of heavy loads, studded tire use, and freezing weather have left the surface badly abraided. Field tests have been conducted utilizing an 8 in. pavement to determine if an extra effort to consolidate concrete pavements during construction consistently increases pavement durability, and what realistic densification effort should be specified to acquire durable pavements. Results from this study will be obtained over a several year period. However, much information about consolidation has already come to light. Concrete has developed almost the same flexure strength with the surface vibration as it has with a combination of surface and internal vibration. Also noted was that it takes a great deal of vibration to cause segregation of particles in an 8-in. layer of concrete having only a 1¼-in. slump. There was no visual indication of segregation of particles in any of the vibrated concrete that was placed.

One concrete problem affected by surface properties of the concrete is a "weak" concrete surface. There is evidence to indicate that differential settlement resulting from bleeding is one major contribution to a "weak" concrete surface.[14,15,16] The weakening of the surface may cause scaling, which has been defined "as local flaking or peeling away of the surface mortar portion of the concrete."[17] With the immediate placing of fresh concrete, the solid particles settle toward the bottom at a constant rate dependent upon gravity, the viscous resistance of the water, and the dimensions of the water-filled spaces in the concrete. The bleeding of a particular concrete can be considerably altered by vibration of the surface during the bleeding period. This vibration of the surface, together with the gravitational forces, increases the settlement. In addition, fines are worked to the surface. As a result, the surface region becomes more consolidated than the region immediately underneath, and, when the vibration ceases, the surface region will settle at a slower rate than the region immediately underneath. Should setting of the concrete interrupt the bleeding process before the surface zone reaches the underlying matter, a zone or plane of weakness may result.[15] An investigation of a bridge deck finished with conventional equipment exhibited a severe surface deterioration in the form of flaking. This flaking was due to the formation of a weak plane immediately below the surface of the concrete and was closely-connected with the bleeding characteristics of the mix.[16]

2.2 Finishing

The placement and finishing of concrete are two operations which have an extremely important effect on the final quality of portland cement concrete.[18] The method and type of finish have a pronounced effect on the durability of concrete as well as supplying the proper texture for skid resistance.

The initial placement of fresh concrete should be well consolidated, so the final finishing may be delayed as long as is practicable. The concrete should be such that it will be fairly uniform on the grade and in such quantity that a slight excess is carried ahead of the following screed. After the mechanical finishing (screeding) is completed, but while the concrete is still plastic, minor irregularities and open-textured areas on the surface should be removed. Normally, long-handled metal floats are used for this purpose. If these irregularities persist, it is well to check the aggregate grading, mix design, and method of placing the concrete, because a properly proportioned mix should not require hand floating if the preceding mechanical equipment is in proper adjustment.

When most of the water sheen has disappeared, but before the concrete becomes non-plastic, the final texture should be applied. The final finish is generally accomplished with a broom, belt, or by use of a burlap drag which leaves the surface with a gritty, coarse texture.

Where burlap is used, it should be of sufficient width and length to cover the slab so that the entire slab can be textured in one operation. At least 1 foot of the burlap should be in contact with the pavement surface.[19] Normally, two to four passes of the drag are required to obtain the proper texture. Caution should be taken to keep the burlap clean and moist.

"Belting is accomplished by the use of a narrow canvas or rubber belt which is moved longitudinally along the surface with a slight traverse back-and-forth motion; two men can handle the belt, one on either side of the slab."[20] However, the belt finish is not extensively used at the present time.

Coarse bristle brooms are usually made from steel or other materials.[20] The best textures are obtained when the broom is inclined away from the motion rather than vertically.

If the texture is formed while the concrete is too plastic, or after it has started to harden, the resulting texture will not have the desired gritty uniformity. Finishes become a problem because moisture loss is seldom uniform over an area of concrete pavement. Therefore, the finishing operation often must be delayed until the wetter spots have dried enough to hold the texture. By this time hydration may have begun and the drier spots are often too dry for texturing. The time of both the curing and finishing operations can make a great difference in the type texture which the pavement will maintain.

The addition of water to the surface to facilitate the action of pipe and diagonal wood floats and the finishing operation will increase the water-cement ratio of the surface, thus lowering the strength and durability of the pavement surface.

Concerning skid resistance, highway engineers have been studying the vehicle skidding problem, particularly resistance to skidding offered by pavement surfaces, for several decades. This problem was not considered critical with low traffic volumes and speeds. But with the increasing traffic volumes and speeds, the skidding problem has gained in significance. The shorter the distance required to stop a vehicle in emergency situations, and the higher the force to provide adequate cornering the better the resultant chance to avoid or reduce the severity of accidents. And, as stopping distance and cornering capability are directly functions of friction coefficient, a high value of friction coefficient is becoming more and more important.[20] Studies covering all phases of this problem are being made in many states.

Research indicates four factors which are the main contributors to friction properties of concrete pavements.[20] They are type of surface finish, type of fine aggregate, mix proportions, and construction practices.

The surface finish or texture may be divided into two categories: macrotexture and microtexture. Macrotexture refers to the large scale texture which results from the type surface finish the pavement receives as well as the timing of operation, curing methods, admixtures which are used, and the aggregates. The surface finish is the most important factor in macrotexture. The macrotexture is extremely important in providing friction for high speed traffic under wet pavement conditions as well as providing the primary drainage of surface water from flooded pavements.

Microtexture is that roughness inherent in the aggregate itself which determines whether it will remain rough or become slick (polish) with wear. The Texas Transportation Institute has been conducting research in skid resistance of pavement surfaces for a number of years and several significant advances to the state-of-the-art have been made.[21,22,23]

On concrete pavements, the microtexture is generally provided by the fine aggregate and accounts for most of the skid resistance in the dry or moderately wet condition.[24] This microtexture is very important in maintaining good adhesion-friction properties on pavement surfaces while they are dry or only moderately wet. This texture provides an aid in puncturing the thin water film; thus providing for essentially dry contact between the tire and pavement which allows for the high adhesion-friction component.

Proper mixture proportions, construction practices, and finishing techniques have been found to have a bearing on the friction properties that the pavement will possess. They must be employed to insure that a reasonable balance between macrotexture and microtexture level is actually built into the pavement surface, and that the surface will maintain a reasonable level of skid resistance throughout its service life.

2.3 *Curing*

The effectiveness of curing has been found to influence the durability and wear resistance of a concrete pavement surface.[25] If the cure is not applied immediately after the disappearance of the water sheen following texturing, much of the curing process may be lost; hence, affecting durability and wear resistance. Therefore, proper use of curing methods is beneficial and essential in acquiring durability and wear resistance in concrete pavements.

The surface properties of portland cement concrete are greatly affected by the combined effects of wind velocity, air temperature and relative humidity, concrete temperature and type of curing compound.

Properties of concrete such as resistance to freezing and thawing, strength, water tightness, wear resistance, and volume stability improve with age as long as conditions are favorable for continued hydration of the cement. For continued improvement in quality, there must be a presence of moisture and a favorable temperature.[26] Hydration virtually ceases when concrete dries below a relative vapor pressure (relative humidity) of about 0.80.[27] At this pressure the water-filled capillaries begin to empty. Since hydration occurs only in these water-filled spaces, hydration ceases when the capillaries begin to empty; therefore, the effective curing time is confined to that period during which the relative humidity in concrete remains above 80 percent. If saturated concrete is placed in saturated air, it will not lose weight, but if it is placed in air in which the vapor pressure is even slightly below that of saturated air, the concrete will lose water by evaporation. When the vapor pressure of the atmosphere changes, the moisture content of the concrete changes also; it rises with a rise in humidity, and vice-versa. Concrete sealed against evaporation must initially contain more than about 0.5 gm of water per gm of cement to insure full hydration, since self-desiccation progressively reduces the space available for hydration products.[27] Membrane cure used as a sealant will not assure full hydration but may be adequate and give adequate results.

Temperature has a significant influence on the rate of cement reaction. The curing temperature can influence the sequence in which the chemical products are formed as well as affect the final structure of the crystalline-gel mass. Hence the strength of the concrete will be affected. It has been concluded that there is a temperature during the early life of concrete which may be considered optimum with regard to strength at later ages.[28] Results, Figure 2-3, show that 1, 3, and 7 day strengths increase with an increase in initial and curing

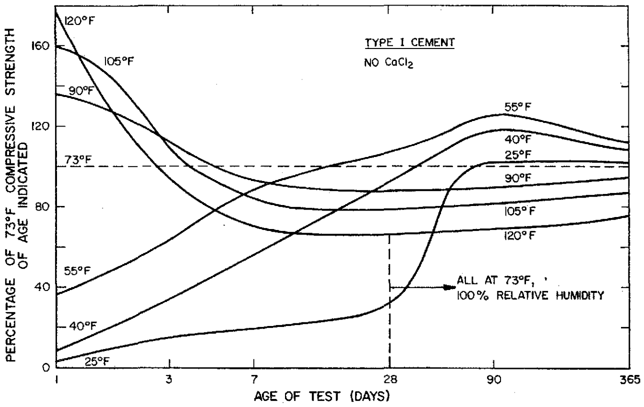


Figure 2-3. Effect of Temperature on the Compressive Strength of Type I Cement; Air Content, 4 ± ½ Percent; Cement Content, 5½ Sacks Per Cubic Yard.[28]

temperature; however, lower strengths resulted at 3 months and 1 year. On the other hand, concrete placed and cured at lower temperatures (as low as 25° F) while showing lower strengths at early stages, show greater strengths at later ages. (No data were available for strengths beyond the 1-year period.)

Because of increased labor costs and rapid construction pace, an increasing number of concrete highway pavements are being cured with membrane-forming curing compounds. Although it is recognized that moist-curing methods (ponding, sprinkling, wet coverings) best insure continued cement hydration, membrane-cured concretes have given creditable performance.[29] Engineers have expressed concern over nonuniform applications of curing compounds which primarily result from variations in speed at which mechanical sprayers apply the compound.

The object of membrane curing is to seal the exposed surface with an impervious membrane in order to prevent the evaporation of the water which is necessary for the hydration of the cement. In addition, the membrane may have a white or light color so it will reflect a considerable amount of heat from the sun which keeps the concrete surface at a cooler and more favorable curing temperature.

Field and laboratory tests have been conducted to evaluate several combinations of curing and protective treatments for concrete. A study conducted by the Virginia Highway Research Council evaluated concrete panels cured with white pigmented liquid membrane and white polyethylene, both with and without subsequent treatments using linseed oil.[30] On some concrete panels a monomolecular film was used to reduce evaporation prior to regular curing. Results showed that linseed oil (in mineral spirits) continued to be the most satisfactory of the several alternatives practically available for improved durability. Application of the linseed oil following curing with a white pigmented resin based compound of the type specified by the Virginia Department of Highways was again shown to be satisfactory. Finally, procedures for the use of monomolecular film was initiated on days with high evaporation potential, when there was delayed application of curing, or when equipment breakdowns occurred.

Reports by Pennsylvania Department of Highways and Kansas State University have also found during their evaluation of concrete protective sealants and curing compounds that linseed oil proved superior to all other products as a concrete protective material.[31,32] The Pennsylvania study found that linseed oil (in mineral spirits) protected concrete against surface scaling (local flaking or peeling away of the surface mortar portion of the concrete); in fact, no scaling occurred on either inner or outer surfaces of the linseed-treated slabs. The Kansas report substantiated the Pennsylvania findings. Results showed that "linseed oil (in mineral spirits) applied to hardened, air entrained, reinforced concrete and water soluble linseed oil applied to fresh, air entrained, reinforced concrete are both effective in impeding the progress of freeze-thaw damage in the presence of sodium chloride."[32] Linseed oil appears to act as a perma-selective membrane in that it permits the penetration of water into hardened cement paste at a reduced rate, but prevents the penetration of salts and other chemicals.

Field and laboratory tests conducted at Utah State University have demonstrated that a monomolecular film will serve as a suitable evaporation retarder on the surface of the concrete. A typical material which will serve as a suitable evaporation retarder is composed of molecules having a long hydrocarbon chain, which is hydrophobic, attached to a hydrophillic alcohol terminal group. The long hydrophobic chain orients itself vertically above the surface of the bleed water as illustrated in Figure 2-4.[33] If sufficient molecules are present, they form a tightly compressed, effective film. Water molecules may not possess sufficient energy to escape through this long chain film; hence, the evaporation is significantly retarded.

Besides the use of liquid membrane curing compound as a seal to prevent evaporation of moisture, the Portland Cement Association (PCA) states that there are precautions which can be taken when planning a concrete construction job to minimize the possibility of plastic shrinkage cracking.[26] They are not in any particular order:

1. Dampen the subgrade and forms,
2. Dampen the aggregates if they are dry and absorptive,
3. Erect windbreaks to reduce wind velocity over the concrete surface,
4. Erect sunshades to reduce concrete surface temperatures,
5. Avoid overheating the fresh concrete during cold weather,
6. Protect the concrete with temporary wet coverings during any application delay between placing and finishing,
7. Reduce time between placing and start of curing by improved construction procedures,

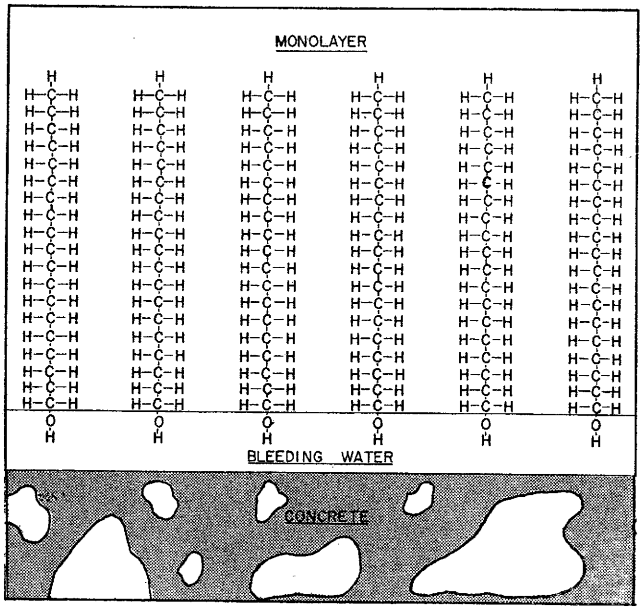


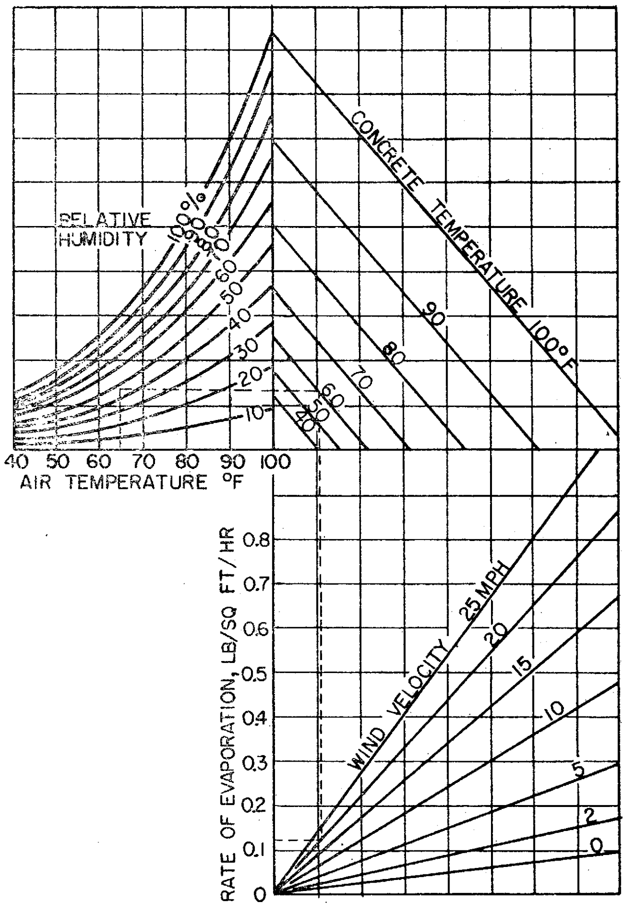
Figure 2-4. Film Forming Molecules Properly Oriented on the Surface of Bleeding Water.[33]

8. Protect the concrete during the first few hours after placing and finish to minimize evaporation. This is most important to avoid cracking. Application of moisture to the surface, using a fog spray nozzle, is an effective means of preventing evaporation from the concrete until a suitable curing material such as a curing compound wet burlap, or curing paper can be applied.

2.4 Plastic Shrinkage Cracking

A concrete problem that is affected by surface properties of the concrete involves plastic shrinkage. Plastic shrinkage cracking is usually associated with hot weather concreting and may develop whenever the rate of evaporation is greater than the rate at which water rises to the surface of the recently placed concrete (bleeding).[34] While plastic shrinkage cracking is normally associated with hot weather concreting, experience in Virginia has shown that spring and fall are more critical periods because of the occurrence of higher winds and lower humidities than are common in the summer.[35] This evaporation causes the concrete to shrink, thus creating tensile stresses at the drying surface. Liquid-membrane curing compounds are utilized to retard or prevent evaporation of moisture from the concrete. Without the application of these curing compounds, stresses will develop before the concrete has attained adequate strength, and surface cracking may result.[26,33,36,] Plastic shrinkage cracks vary in length from a few inches (2 to 3) to a few feet (3 to 7) and are often almost straight, without any definite pattern.[37] As regards to their depth, the term "surface cracks" is misleading; in fact widespread plastic cracking in pavement, extending to a depth of 4 in., has been observed.[36] Therefore, unless the cracks are quite shallow and narrow, they can weaken the pavement, permit penetration of moisture and render the reinforcement vulnerable to corrosion.[38]

If the rate of evaporation exceeds the rate at which bleeding water rises to the surface, then plastic shrinkage and plastic shrinkage cracking are likely to occur. This has been shown experimentally.[38] However, field investigations have shown that characteristics of the concrete do not have a major influence on plastic shrinkage or plastic shrinkage cracking.[36] This has led to the preparation (by the Portland Cement Association (PCA)) of a chart indicating the interrelationship between air temperature, relative humidity, concrete temperature, wind velocity, and rate of evaporation of surface moisture.[26] This chart, Figure 2-5, is based on a table of evaporation rates as a result of wind velocity, concrete and air temperature, relative humidity, which are based on data obtained by Menzel.[36] PCA states that evaporation rates above about 0.2 lbs/ft^2/hr may increase the possibility of plastic shrinkage cracking and that at rates below 0.1 plastic shrinkage cracking will probably not occur.[26]



TO USE THIS CHART

1. ENTER WITH AIR TEMPERATURE, MOVE UP TO RELATIVE HUMIDITY.
2. MOVE RIGHT TO CONCRETE TEMPERATURE.
3. MOVE DOWN TO WIND VELOCITY.
4. MOVE LEFT; READ APPROX. RATE OF EVAPORATION.

Figure 2-5. Effect of Concrete and Air Temperature, Relative Humidity, and Wind Velocity on the Rate of Evaporation of Surface Moisture from Concrete.[26]

It is generally accepted that the moisture drying rate is the most important factor affecting shrinkage and cracking of cement paste, mortar, and concrete. Presumably, air flow past drying specimens influences to some extent the amount that they shrink, but recent contributions appear to dispute this premise.[39,40] However, a review of this work shows that the research was conducted using hardened concrete specimens where the specimens were cured at least 3 days prior to placement in the wind. Therefore the findings do not apply to the effects of wind on fresh concrete.

3. Experimental Methods and Procedures

3.1 Parameters

The data obtained for this research were taken from 56 sidewalk sized test slabs that conformed to the dimensions given in Figure 3-1. Variables investigated included coarse aggregate, subbase, vibration, finishing, wind velocity, curing environment, and curing method (Table 3-1). Complete descriptions of all variables are given in the appendix in Sec. 5.1.

Constants included the mix design, fine aggregate, curing time, and mixing procedure.

3.2 Strength Tests

For control purposes, flexural strength tests were performed on two 6 x 6 x 36 in. beams from each batch of concrete (ASTM C78-64). The specimens were moist cured prior to testing. Also, compressive strength tests were made on two 6 x 12 in. cylinders from each batch (ASTM C39-64).

3.3 Data Collection From Cores

After 28 days of curing, a minimum of three cores (4 in. diameter x 8 in.) were taken from each slab and subjected to diagnostic analyses including:

1. Dynamic modulus of elasticity (ASTM C215-60). The torsional sonic modulus was determined for each use.
2. Impact Hammer readings of the cores as a measure of hardness (Section 5.3).
3. Bulk density by absolute volume of the top 3 in. and bottom 3 in. of each core (ASTM D1188-68).
4. Abrasion coefficient of the finished surface of the cores (ASTM C418-68).
5. Splitting tensile strengths on the top 3 in. and bottom 3 in. of each core (ASTM C496-66).

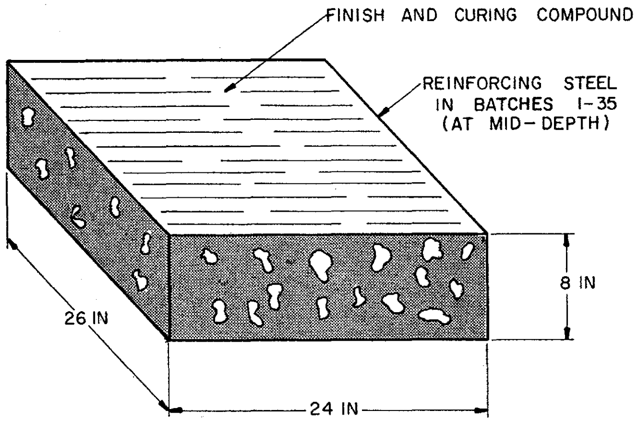


Figure 3-1. Dimensions for the Test Slabs.

3.4 Evaporation Rate Data

Batches 1 through 36 were subjected to zero wind velocity, while batches 37 through 56 were subjected to various wind velocities in order to investigate moisture evaporation from the surface of the test slabs. The steel forms (72 x 26 x 8 in.) for the slabs had two wooden dividers to separate the concrete into three slabs. These three slabs were in turn each subdivided into halves, one-half being covered with a curing compound, and the other half without curing compound. In each of these halves, as illustrated in Figure 3-2, there was a smaller metal box (6 x 4 x 4 in.) which was inside a wooden box. These smaller metal boxes were designed to be lifted out and weighed periodically on a 10,000 gm. balance. Concrete was placed in the forms in three layers, vibrated in place, finished, and the proper cure applied to the surface. To simulate outdoor conditions, wind was generated over the surface of the concrete slabs at 8-10 mph or 18-20 mph. Wind velocity remained constant along the slab setup as one ft high side forms were used to prevent the air path from spreading. The wind

TABLE 3-1. PARAMETERS AND SLAB CODE DESIGNATIONS

Parameter		Code Symbol
Coarse Aggregate	Siliceous Gravel	G
	Crushed Limestone	S
	Mixed Gravel and Limestone	M
Subbase	Coarse Textured Cement Treated Base	C_C
	Fine Textured Cement Treated Base	C_F
	Coarse Textured Black Base	B_C
	Fine Textured Black Base	B_F
	No Prepared Subbase (Wood)	N
Vibration	None	V_0
	Internal	V_1
	Surface (Pan Type)	V_2
	Combination (Internal and Surface)	V_3
Finishing	Burlap Drag	F_1
	Brush	F_2
	Tines	F_3
Wind	0 mph	W_1
	8-10 mph	W_2
	18-20 mph	W_3
Curing Environment	50° F—25% Relative Humidity (RH)	E_1
	73° F—25% RH	E_2
	73° F—50% RH	E_3
	100° F—30% RH	E_4
	100° F—50% RH	E_5
	140° F—25% RH	E_6
Curing Method	Polythylene Sheet (Poly)	1
	White Pigmented Curing Compound—resin based (WPC)	2
	Monomolecular Film Plus White Pigmented Curing Compound (MMF + WPC)	3
	Water Soluble Linseed Oil (LO)	4
	No Curing Compound	5

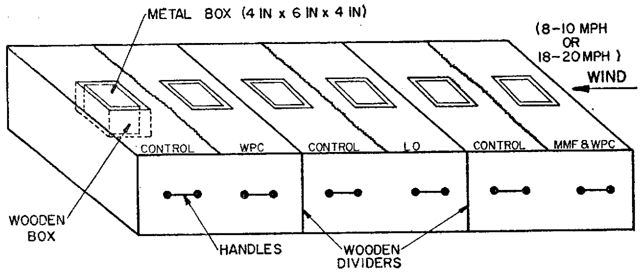


Figure 3-2. Concrete slab setup.

generator was turned on prior to the placement of the third layer and turned off only during the application of the curing compounds. The weighings of the boxes continued until the water loss became negligible, which was normally after 50 hours exposure to wind. As a method of control, weighings were taken from identical boxes under steady conditions (0 mph). The procedural details and all data are given in Section 5.2. As a check to insure that the relative humidity did not vary along the slabs' lengths, three control sections were monitored along each slab. Evaporation data from each control section were virtually identical.

4. *Results and Discussion*

4.1 General

The data which follow were obtained basically from six sources (see Table 5-7). The coarse aggregate type, subbase type, method of vibration, finishes, curing method, curing environment, and wind were varied while other parameters were held as constant as practical. The effects of selected variables are analyzed and compared in the following sections. Due to the large number of variables involved in this study, some grouping of the data was necessary, even though the grouping resulted in some data scatter. Where possible, the data scatter is illustrated and referenced. It must be remembered that only high quality concrete (slump 1 in. ± ½ in.) with no discernible bleeding was used in this research. The major results are summarized in the following sections. A complete discussion of each variable is given in the appendix.

4.2 Control Tests

Table 4-1 contains data obtained from the statistical analyses of the control specimens (complete data given in Table 5-6). As can be seen all strength values were considered to be adequate and the data scatter was considered reasonable as evidenced by the acceptable coefficients of variation.

4.3 Effect of Vibration on Concrete Properties

Examination of the pertinent data contained in Table 5-7 reveals that all types of vibration (surface-pan type, internal, and combination of surface and internal) produced high quality, uniform, strong, and dense concrete; as evidenced by the excellent splitting tensile strengths, densities, and dynamic modulus data obtained from the cores taken from the test slabs. In addition, it should be noted that even those slabs receiving no vibration were of adequate quality. It must be pointed out that a vibratory screed was used to level the surface prior to finishing which did impart some vibration into the test slabs. A comparison of Batch 36 results (which had no vibration of any type) with the slabs placed with no internal or surface vibration (V_0) showed that the screed did impart significant vibration and thereby affected the surface strength and abrasion resistance of the slabs.

The presence of steel (at mid depth) did not inhibit adequate consolidation. However, it must be pointed out that an excellent quality concrete was used, which may or may not be indicative of actual field conditions.

Concerning the surface properties of the slabs, it was found that the vibrated surfaces exhibited better abrasion (or wear) resistant surfaces. The slabs made with the gravel aggregate produced better results than either slabs made with the stone aggregate or mixed aggregate. This may indicate a need for considering the aggregate type as a parameter when studying surface properties. A complete discussion of this parameter, including data and appropriate figures, is given in Section 5.5.

4.4 Effect of Subbase Type on the Concrete Properties of the Slab

A study of these results shows that the type of subbase did not adversely affect the strength of the slab (see Section 5.6 for details). Even when the concrete was placed with the bases dry to create the most severe conditions, no adverse effect was observed due to subbase type. This indicates that the only reason to dampen

TABLE 4-1. CONCRETE FLEXURAL STRENGTH RESULTS

Control Test	Batch Code and Number of Values	Average (psi)	Standard Deviation	Coefficient of Variation (percent)	Remarks
Flexural	1-16[a]	788	80	10.2	28 day strength
	17-35[a]	822	87	10.6	7 day strength
	37-55[b]	805	46	5.7	7 day strength

[a] Three different coarse aggregate types were used.

[b] No beams for Batches 49 and 56.

the subbase prior to placing the concrete may be to reduce dust.

4.5 Effect of Surface Finish on the Surface Properties of Concrete

The type of surface finish produced on the laboratory slabs did influence the surface properties of the concrete (see Section 5.7 for details). A comparison of the abrasion coefficient of the various finishes (brush, burlap, and tines) reveals that the brush surface was weaker than the burlap drag, and the tines surface was the weakest of the three. However, all three produced satisfactory surfaces. With this laboratory finding, it is well to suspect that the burlap finish should provide a stronger surface, more resistant to wear for a longer period of time than either the brush or tines finish. However, most laboratory test methods are, at best, poor indicators of concrete performance in service and many different factors are at work on a given pavement surface. And, as every effort was made in the laboratory to make high quality surfaces, the effects of these three finishes on more realistic surfaces (such as would be made in the field under normal construction practices) might well be different.

4.6 Effect of Curing Media on the Rate of Evaporation From the Surface of the Slabs

As discussed (Section 3.4), measurements of water loss from the surface of the test slabs were recorded by the periodic weighing of boxes during the initial curing period (first 50 hours). Four types of curing methods were considered—monomolecular film followed by white pigmented curing compound (MMF + WPC), water soluble linseed oil curing compound (LO), white pigmented curing compound (WPC), and for comparison purposes, no cure.

Figures 4-1 through 4-6 were obtained from data contained in Table 5-8 with the water loss measurements being plotted against log time. The figures are representative of each compound's ability to retain water when exposed to various temperatures and wind velocities. By comparison, it is clearly shown that the portion of the slabs without any curing compound (no cure), exhibits considerably higher water loss than any of those slabs with a curing compound. At the early stages of concrete curing, all curing compounds appear to retard water evaporation at nearly the same rate, but a noticeable difference is seen in the later stages of curing. Further comparison of the six figures shows that it is clearly evident that *no significant* benefits were obtained by adding monomolecular film (MMF), in the particular manner employed in this research, before the white pigmented

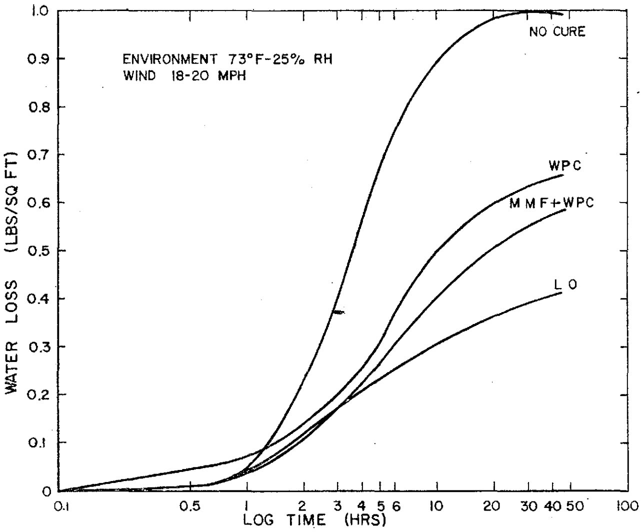


Figure 4-2. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 73°F and Wind Velocity of 18-20 mph.

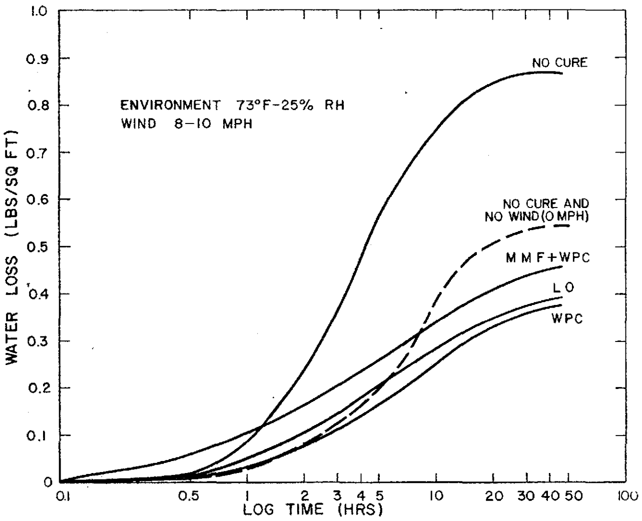


Figure 4-1. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 73°F and Wind Velocity of 8-10 mph.

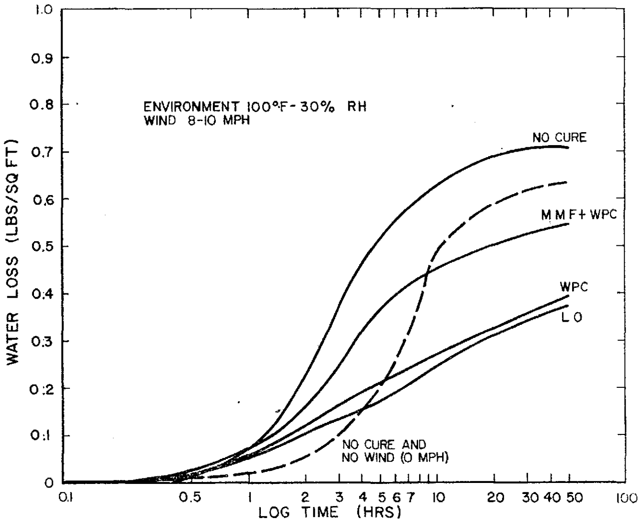


Figure 4-3. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 100°F and Wind Velocity of 8-10 mph.

curing compound (WPC). Though this statement seems inconsistent with other reports, it should be noted that a single application was used, at the highest rate recommended by the manufacturer. Perhaps two or more applications would produce better results, as it is hypothesized that insufficient film was present to form an effective barrier. Consistently, the water soluble linseed oil (LO) and white pigmented curing compound (WPC) retarded the rate of evaporation better than MMF + WPC (except at 73°F and 18-20 mph). In fact, at least a 15 percent reduction in water loss was noted with the use of LO and WPC over MMF + WPC at 73°F and 8-10 mph (Figure 4-1), and this reduction was 30 percent at 140°F and 8-10 mph (Figure 4-5). Therefore, on the type of concrete used in this study these laboratory results do *not* show any merit in using a single application of MMF prior to finishing as an evaporation retarder.

There is another interesting finding relating to the effects of wind. In Figures 4-1, 4-3, and 4-5 the evaporation rates for specimens cured without any compound (no cure) at the specified temperature—BUT WITHOUT WIND—are shown by dashed lines. Note the effect of wind when compared with no wind in the same environment. Without wind the evaporation during the first several hours is considerably reduced, and with wind none of the curing compounds reduced the evaporation rate to that experienced without cure at zero mph (note especially Figure 4-5). This dramatizes the strong influence of wind on evaporation.

As discussed in Section 2.4., there is a chart that has been prepared by the Portland Cement Association (PCA) indicating the interrelationship between air temperature, relative humidity, concrete temperature, wind velocity, and rate of evaporation of surface moisture (Figure 2-5). Values were obtained from the chart for the conditions employed in this study. A comparison of those values with the experimental values determined in this research are given in Table 4-2. (The experimental rate data were obtained from Figures 5-2 through 5-8). As can be seen, the values determined from this research are not quite as high as the values obtained from the PCA chart (except at 140°F). The values at

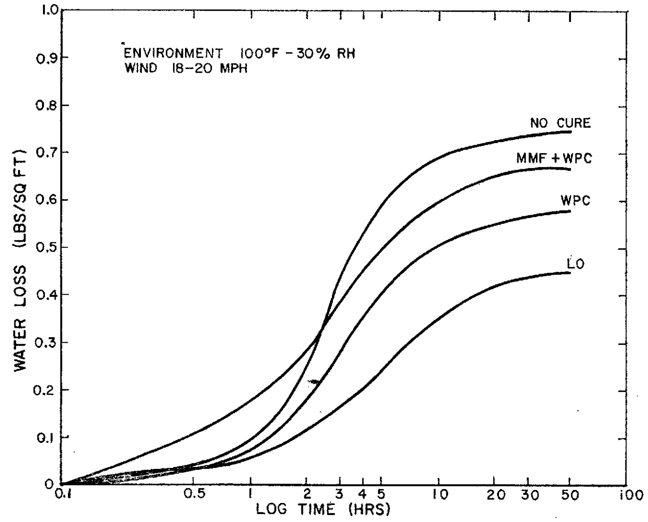


Figure 4-4. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 100°F and Wind Velocity of 18-20 mph.

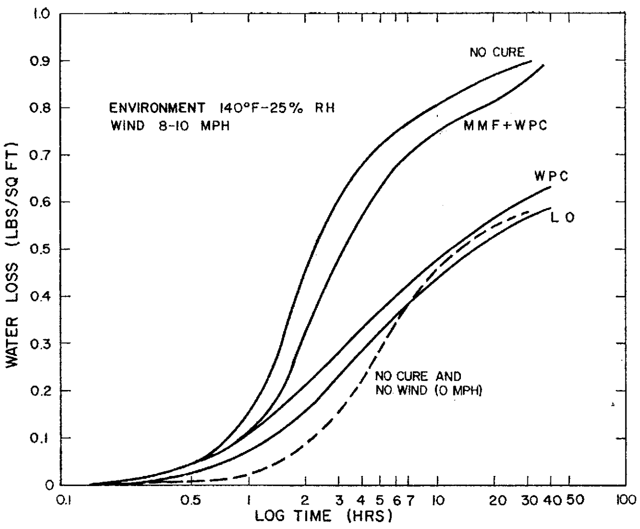


Figure 4-5. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 140°F and Wind Velocity of 8-10 mph.

TABLE 4-2. COMPARISON OF EVAPORATION RATES

Temperature (°F)	Wind Velocity (mph)	Curing Compound	Evaporation Rate (lbs/ft²/hr) Experimental	PCA[a]
73	0	None	.047	.040
73	10	None	.158	.22
		MMF + WPC	.058	——
		WPC	.031	——
		LO	.044	——
73	20	None	.186	.38
		MMF + WPC	.062	——
		WPC	.058	——
		LO	.029	——
100	0	None	.037	.03
100	10	None	.136	.14
		MMF + WPC	.085	——
		WPC	.065	——
		LO	.045	——
100	20	None	.182	.24
		MMF + WPC	.111	——
		WPC	.107	——
		LO	.057	——
140	0	None	.054	(.00)[b]
140	10	None	.206	(.00)[b]
		MMF + WPC	.198	——
		WPC	.099	——
		LO	.085	——
140	20	None	.235	(.00)[b]
		MMF + WPC	.128	——
		WPC	.031	——
		LO	.048	——

[a] From Fig. 2-5.
[b] Extrapolated values.

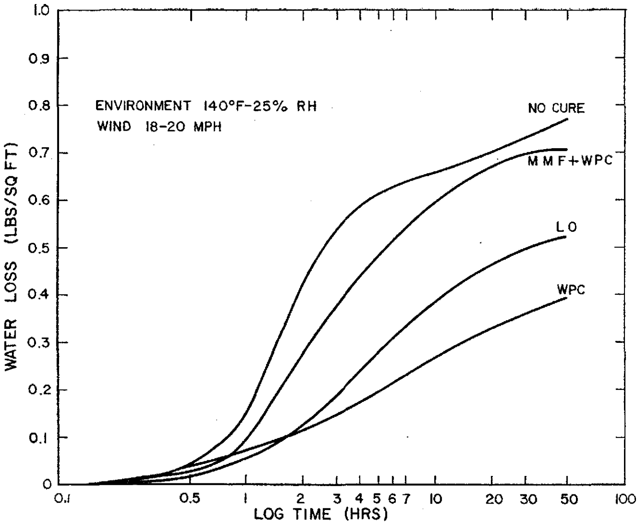


Figure 4-6. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 140°F and Wind Velocity of 18-20 mph.

140°F from the PCA chart had to be extrapolated so no real comparison could be made here. Note that the values obtained from the PCA chart for steady conditions (0 mph) are nearly the same as obtained experimentally in this study. However, significant differences were found at increased wind velocities, which casts doubt on the validity of that portion of the PCA chart.

4.7 Effect of Curing Temperature and Curing Method on Concrete Properties

The same indicators of concrete strength, as with previous analyses, were used to analyze the effects of curing temperature and curing method. Considered first will be the effects of steady conditions (no wind).

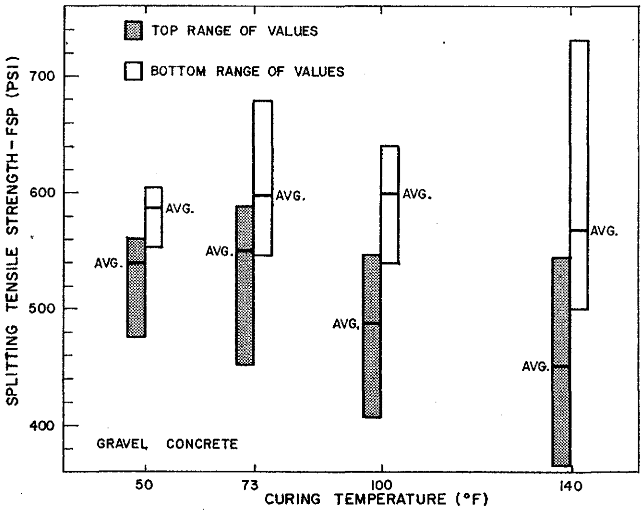


Figure 4-7. Effect of Curing Temperature on the Splitting Tensile Strength of the Top and Bottom of Concrete Cores at Steady Conditions (0 mph).

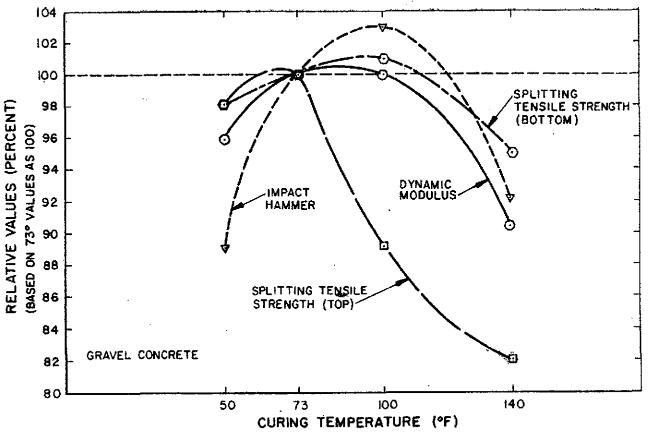


Figure 4-8. Effect of Curing Temperatures on Relative Values of Selected Concrete Properties.

Steady Conditions (No Wind). The effect of curing temperatures on the splitting tensile strength of the top and bottom portions of cores taken from the CRCP slabs are portrayed in Figure 4-7 (see Table 5-12). The range and averages are shown. Although there was considerable data scatter, definitive trends were established. First, as expected the top of the slab was influenced by curing temperature more than the bottom. Second, although higher temperature resulted in lower strengths, in almost all cases sufficient strength was obtained to make suitable concrete pavement. To verify and amplify the splitting tensile values, the dynamic modulus (torsional) of each core was determined along with the Impact Hammer readings of the CRCP slab. Both of these tests are indicators of strength, and it seems reasonable to expect a good correlation between the surface impact readings and the splitting tensile strength of the top portion of the slab. This was not observed in these tests, which indicates that the Impact Hammer readings were poor indicators of actual strength. Average values from these strength tests reveal similar trends to the splitting tensile strengths (Figure 4-8). It should be emphasized that all values contained data scatter, some of which were due

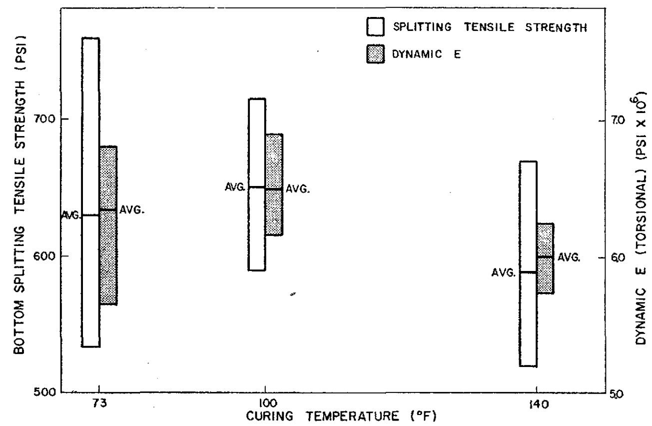


Figure 4-9. Effect of Curing Temperature on the Splitting Tensile Strength and Dynamic Modulus of the Bottom Portion of the Cores at the Wind Conditions of 8-10 and 18-20 mph.

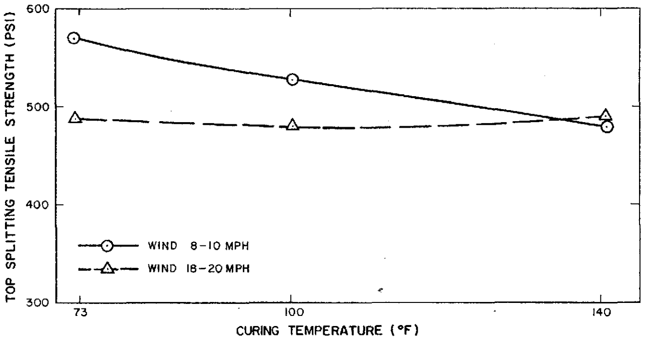


Figure 4-10. Effects of Wind on the Splitting Tensile Strength of Concrete.

to the effects of other variables being investigated (vibration, finish, cure method, type of base). However, it is believed that the trends depicted by Figure 4-8 are valid, and that a loss in concrete compressive strength of from 5 to 15 percent can be expected if curing temperatures in excess of 100°F are encountered.

Effects of Wind. As discussed in Section 3.4, wind was generated over the surface of the slabs. The effect of curing temperature on the splitting tensile strength and dynamic modulus of the *bottom* portion of the cores are portrayed in Figure 4-9 (see Table 5-9). As shown, only a slight loss in strength was noted at the increased curing temperature (140°F) which follow the results obtained under steady conditions.

The effects of wind on the curing of the *top* of the concrete is shown in Figure 4-10 (Table 5-9). Top splitting tensile strength is plotted against curing temperature for the four curing methods, MMF + WPC, WPC, water soluble linseed oil (LO), and No Cure. These four methods were grouped at each particular wind velocity because statistically, no distinguishable difference was established by any of the curing methods. As a review of the strength data (Table 4-1) indicates, the concretes used were of similar strengths, it is concluded that wind apparently affects the strength of the concrete 73°—25% RH. The increased wind (18-20 mph) must reduce the available water (evaporation from the surface) so as not to allow the concrete to obtain as high a surface strength (compared to 8-10 mph conditions).

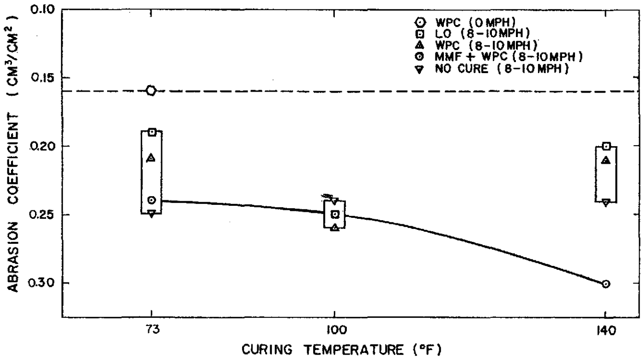


Figure 4-11. Effect of Curing Temperature and Curing Compounds on the Abrasion Coefficient at the Wind Conditions of 0 and 8-10 mph.

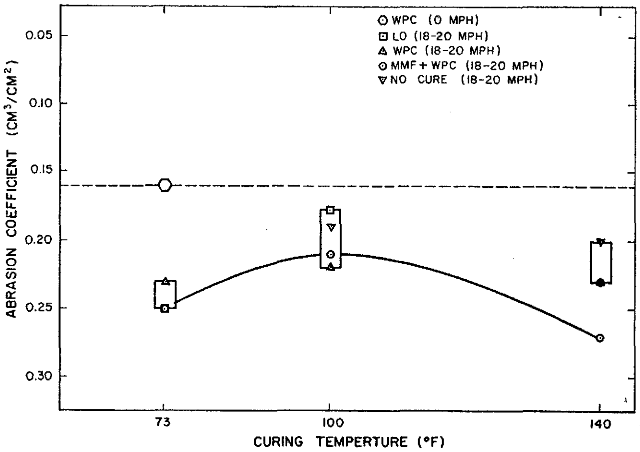


Figure 4-12. Effect of Curing Temperature and Curing Compounds on the Abrasion Coefficient at the Wind Conditions of 0 and 18-20 mph.

Figures 4-11 (8-10 mph) and 4-12 (18-20 mph) compare the abrasion loss with temperature under wind conditions. Data are contained in Table 5-9. As can be seen, an increase in abrasion loss is noted with increased wind conditions. Also, no apparent abrasion benefit is obtained with the use of these curing compounds as the "no cure" specimens had essentially the same losses as the "cured" specimens. A comparison of the four methods of cure (MMF + WPC, WPC, LO, and No Cure) indicates that at 140°F, MMF + WPC statistically exhibited a significantly larger abrasion loss. This statistical approach is based on a previous study.[41] Apparently, the MMF + WPC curing compound did not seal the surface against water loss as well as the other methods at this elevated temperature and wind condition. There must be sufficient water loss to cause a loss in

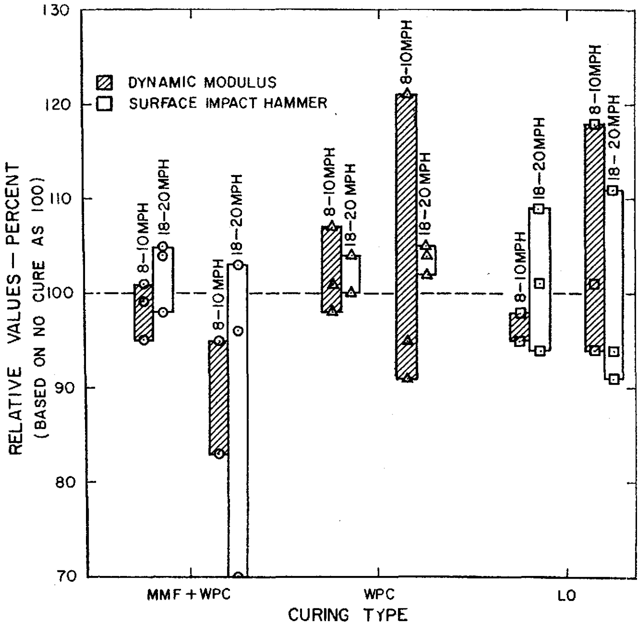


Figure 4-13. Comparison of Curing Method Using the Dynamic Modulus (Torsional) and Surface Impact Hammer.

surface strength; hence an increase in abrasion loss. (This point was discussed and verified in Sec. 4.6).

Figure 4-13 gives a comparison of the relative values of dynamic modulus and surface Impact Hammer (based on No Cure as 100 percent) as a function of curing method (see Table 5-10). The results follow the findings in the previous figures. In general, there was little strength benefit gained with the use of these curing methods at elevated temperatures and under these simulated wind conditions. It is interesting to note that the surface Impact Hammer readings follow the results obtained from abrasion loss data. It should be noted that all the slabs used in the wind study had a similar finish texture, which may account for the more uniform Impact Hammer readings. It was found that the surface cured with the MMF + WPC suffered more abrasion loss than surfaces cured with LO and WPC at the curing temperature of 140°F (Figures 4-11 and 4-12). The surface Impact Hammer readings, used as a measurement of strength, show the surface of the MMF + WPC slabs to have a reduced strength as compared to the slabs cured with LO and WPC (Figure 4-13). Again, excess water loss from the surface by evaporation of the slabs apparently does not allow the concrete to gain sufficient strength under these curing conditions.

In conclusion, the three types of curing compounds did not substantially increase the strength of the core specimens under the wind conditions studied; in some cases a loss in strength was noted. As found in the previous Section (4.6), the three compounds did retard the water evaporation from the surface of the slabs, which is very important in the concrete curing process. Apparently, precaution should be taken as to the amount to be applied to the surface. Curing compounds are needed, but the quantity applied to the surface must be held to a minimum to guard against a possible reduction in the ability of the concrete to resist wear and possible flaking or scaling of the surface.

5. Appendix

5.1 Discussion of Parameters

Aggregates. The concrete test slabs used in performing these tests were made utilizing three coarse aggregate types; a siliceous gravel (G), also referred to as Hearne aggregate, obtained from northwest of Bryan, Texas; a crushed limestone (S) obtained from San Antonio, Texas; and a combination or mixture (M) of the siliceous gravel and crushed limestone in equal proportions by weight. One fine aggregate was used; a siliceous river run sand (SF) obtained near Eagle Lake, Texas.

The physical properties of the aggregates are shown in Table 5-1 and their gradations are given in Table 5-2.

Subbase. Five different subbases were utilized: black base fine textured (B_F), black base coarse textured (B_C), cement treated fine textured (C_F), cement treated coarse textured (C_C), and a wood subbase (N). The five subbases are described in Table 5-3.

Vibration. Three methods of vibration were employed: internal (V_1), surface-pan type (V_2), and a combination of both internal and surface (V_3). Also, several slabs were placed with no internal or surface vibration (V_0). The concrete for the first 35 slabs was placed in the forms in two lifts and in the remaining 21 slabs in three lifts. Then, the proper method of vibration was applied to each slab. Two electric powered 1⅜ in. square-head, speed-type concrete vibrators were used at a constant speed of 8000 vpm (in air) regulated by a speed control unit. The test slabs were then struck-off flush with a vibratory screed in order to facilitate the finishing operation which followed.

TABLE 5-1. AGGREGATE PROPERTIES

Aggregate Type	SSD Unit Weight (pcf)	Absorption (Percent Dry Wt.)	Specific Gravity (SSD)
G[a]	110	0.8	2.66
S[b]	89	1.4	2.65
M[c]	99	1.1	2.66
SF[d]	107	0.5	2.66

[a] G—Siliceous Gravel
[b] S—Crushed Limestone
[c] M—Mixed (G and S)
[d] SF—Siliceous Fine Aggregate

Surface Finishes. After the slabs were struck off with the vibratory screed, one of three finishes was applied to the surface: burlap drag (F_1), brush (F_2), or tines (F_3). The surface finishes are described in Table 5-4.

Curing Method. After the appropriate surface finish was applied, one of five curing methods was begun. The five methods are described in Table 5-5. Where curing compounds were used the manufacturers recommendations for application were followed as nearly as practical.

Curing Environment. The environmental rooms utilized were located in the McNew Laboratory at Texas

TABLE 5-2. AGGREGATE GRADATIONS

Sieve Size	Cumulative Percent Retained			
	G[a]	S[b]	M[c]	SF[d]
1½ in.	0	0	0	
¾ in.	30	38	35	
⅜ in.	70	73	73	0
No. 4	100	100	100	1
No. 8				11
No. 16				25
No. 30				58
No. 50				93
No. 100				99

[a] G—Siliceous Gravel
[b] S—Crushed Limestone
[c] M—Mixed (G and S)
[d] SF—Siliceous Fine Aggregate

A&M University. The slabs were cured in one of six environments as prescribed in Table 3-1. The specified conditions were accurately maintained and monitored during the testing periods.

Wind. Batches 37 through 56 were concerned with water evaporation from the surface of the test slabs. To simulate outdoor conditions, the slabs were subjected to steady conditions (0 mph) - (W_1) and wind velocities of 8-10 mph (W_2) and 18-20 mph (W_3). The wind was generated through the use of a fan (blower) run by an electric motor. This generated wind was tunneled down through duct work to the required wind velocity. To assure that the required wind velocity was attained throughout the moisture loss measurements, an anemometer was used to periodically check the wind velocity. The blower remained on as long as measurements were being recorded (normally 50 hours).

Design Mixes. The mixes were designed using the absolute volume method with a specified cement factor and air entrainment admixture.[42] All batches were designed to produce similar strengths based on a cement factor of 5 sacks of cement per cubic yard of concrete,

TABLE 5-3. SUBBASE TYPE

Designation	Subbase Type	Description
B_F	Black Base Fine Textured	A Type D asphalt treated base produced from well graded aggregates (max. size ½ in.). The mixture contained 7.3 percent asphalt.
B_C	Black Base Coarse Textured	An asphalt treated base produced from a gap graded aggregate with a max. size of 1 in. and with 52 percent retained on a No. 10 screen. The mixture contained 4.3 percent asphalt.
C_F	Cement Treated Fine Textured	Essentially the same concrete as used in making the slabs except only the vibrating screed was used in placement. Water cement ratio (W/C) was 0.5.
C_C	Cement Treated Coarse Textured	Same materials as C_F except W/C = 0.7.[a]
N	Wood Subbase	Plywood Base.

[a] It is generally agreed that permeability increased with increasing W/C ratio and for these tests the higher permeability was assumed to have the coarser texture.

TABLE 5-4. SURFACE FINISHES

Designation	Finish Type	Description
F_1	Burlap	A burlap drag accomplished by passing a wet burlap cloth, with approximately two feet in contact with the surface until the desired texture is obtained.
F_2	Brush	Accomplished by passing a plastic-bristle brush over the slab surface slightly grooving the concrete. The brush is inclined at an angle of approximately 30 degrees to the surface. Usually two passes were required to obtain the desired uniform texture.
F_3	Tines	Accomplished by passing a series of thin metal strips (tines), ⅛ in. wide, over the slab surface, producing grooves of approximately ⅛ in. depth in the concrete. One pass was sufficient to obtain the desired texture. The tines spacing used was ¼ in. center-to-center.

TABLE 5-5. CURING METHODS

Designation	Curing Type	Description
1	Polyethylene Sheet (Poly)	Immediately after finishing, the test slabs were covered over completely with a sheet of polyethylene plastic for the 28 day curing period.
2	White Pigmented Curing	A white pigmented curing compound was sprayed on the test slabs after finishing and after the water sheen had disappeared from the surface (180 sq ft/gal).
3	Monomolecular film with a White Pigmented Curing Compound (MMF + WPC)	A monomolecular film was sprayed on the surface of the test slabs prior to finishing (200 sq ft/gal). After finishing, as soon as the water sheen had disappeared from the surface, the same white pigmented curing compound as used in curing method 2 was sprayed on the surface.
4	Water Soluble Linseed Oil (LO)	A water soluble linseed oil applied to the surface upon completion of the finishing operation (200 sq ft/gal).
5	No Cure (Control)	The slab surface was allowed to cure without application of any curing compound and/or compounds.

a coarse aggregate factor (CAF) of 0.78, a water-cement ratio (W/C) of 0.5, an air content of 3 percent, and a slump of 1 in. ± ½ in. (Table 5-6).

Due to the presence of free moisture in the aggregates used, the mixing water had to be altered slightly in some cases to maintain the desired slump. The time lapse between the introduction of cement to the mix and the final placement of the concrete into the forms was held as constant as practicable for all test slabs.

Curing Time. All test slabs were allowed to cure for 28 days in their particular curing environment. After 28 days, a minimum of three cores were taken from each slab section and subjected to diagnostic analyses. Due to the limited availability and mechanical problems of the coring machine, it was necessary for some of the slabs to be placed in the freezing room (−8°F) until cores could be taken. In the frozen state, it is generally accepted that the test specimen would neither gain nor lose any strength.

TABLE 5-6. CONCRETE MIX DATA

Batch Code	Aggregate		Percent Absolute Volume					Slump (in.)	Initial Unit Weight (pcf)	Flexural Strength (psi)[a]	
	Coarse	Fine	Cement	Water	F.A.	C.A.	Air			Third Point	Center Point
1	G	SF	8.7	13.8	22.3	51.2	4.0	1.5	149	640	755
2	G	SF	8.7	13.8	22.3	51.2	4.0	1.0	149	626	739
3	G	SF	8.7	13.8	22.3	51.2	4.0	1.8	148	679	801
4	G	SF	8.7	13.8	22.3	51.2	4.0	1.8	149	615	726
5	G	SF	8.7	13.8	22.3	51.2	4.0	0.8	149	629	742
6	G	SF	8.7	13.8	22.2	50.8	4.5	1.8	147	622	734
7	G	SF	8.8	13.9	22.4	51.4	3.5	1.5	148	602	710
8	G	SF	8.7	13.8	22.3	51.2	4.0	2.0	147	610	719
9	G	SF	8.8	13.9	22.3	51.2	3.8	1.3	150	740	873
10	G	SF	8.9	13.9	22.5	51.7	3.0	1.0	150	668	788
11	G	SF	8.8	13.9	22.3	51.2	3.8	1.0	150	734	866
12	G	SF	8.7	13.8	22.3	51.2	4.0	1.3	150	756	892
13	G	SF	8.9	14.1	22.6	51.9	2.5	1.0	148	780	920
14	G	SF	8.8	14.0	22.6	51.8	2.8	1.0	148	787	929
15	G	SF	8.8	13.9	22.4	51.4	3.5	1.5	150	604	713
16	G	SF	8.7	13.8	22.3	51.2	4.0	0.8	148	598	706
17	G	SF	8.8	13.9	22.4	51.4	3.5	1.0	128	607	716
18	G	SF	8.7	13.8	22.3	51.2	4.0	1.3	146	750	885
19	G	SF	8.7	13.8	22.3	51.2	4.0	1.3	145	575	679
20	G	SF	8.9	14.1	22.6	51.9	2.5	0.8	148	735	867
21	G	SF	8.8	13.9	22.4	51.5	3.4	1.3	149	627	740
22	G	SF	8.8	13.9	22.3	51.2	3.8	1.8	147	573	676
23	G	SF	8.8	13.9	22.3	51.2	3.8	1.8	148	698	824
24	G	SF	8.8	13.9	22.4	51.4	3.5	1.5	148	724	854
25	G	SF	8.7	13.8	22.3	51.2	4.0	1.5	147	650	767
26	G	SF	8.8	13.9	22.3	51.2	3.8	1.8	148	822	970
27	G	SF	8.7	13.8	22.3	51.2	4.0	1.0	147	708	835
28	S	SF	8.8	13.9	32.3	41.5	3.5	0.8	145	728	859
29	S	SF	8.8	13.9	32.3	41.4	3.6	1.0	146	713	841
30	S	SF	8.7	13.9	32.2	41.2	4.0	1.0	145	765	902
31	S	SF	8.8	13.9	32.2	41.3	3.8	0.8	146	770	909
32	M	SF	8.8	13.9	27.4	46.4	3.5	1.0	149	754	890
33	M	SF	8.8	13.9	27.4	46.4	3.5	0.6	149	708	835
34	M	SF	8.8	14.0	27.4	46.5	3.3	1.0	150	708	835
35	M	SF	8.8	13.9	27.4	46.5	3.4	0.5	150	776	916
36	G	SF	8.9	13.9	22.5	51.7	3.0	0.8	150	546	644
37	G	SF	8.8	13.9	22.3	51.3	3.7	0.8	144	674	746
38	G	SF	8.8	13.9	22.3	51.3	3.7	0.4	144	674	746
39	G	SF	8.8	13.9	22.3	51.3	3.7	1.4	144	674	746
40	G	SF	8.8	14.0	22.6	51.8	2.8	1.3	148	645	773
41	G	SF	8.8	14.0	22.6	51.8	2.8	1.0	148	645	773
42	G	SF	8.8	14.0	22.6	51.8	2.8	1.5	148	645	773
43	G	SF	8.8	14.0	22.4	51.5	3.3	1.0	148	679	837
44	G	SF	8.8	14.0	22.4	51.5	3.3	1.0	148	679	837
45	G	SF	8.8	14.0	22.4	51.5	3.3	2.0	148	679	837
46	G	SF	8.8	14.0	22.4	51.6	3.2	0.9	147	701	799
47	G	SF	8.8	14.0	22.4	51.6	3.2	1.8	147	701	799
48	G	SF	8.8	14.0	22.4	51.6	3.2	1.8	147	701	799
49[b]	G	SF	8.8	13.9	22.4	51.4	3.5	1.5	149	—	—
50	G	SF	8.9	13.9	22.5	51.7	3.0	2.8	148	663	833
51	G	SF	8.9	13.9	22.5	51.7	3.0	1.1	148	663	833
52	G	SF	8.9	13.9	22.5	51.7	3.0	1.4	148	663	833
53	G	SF	8.9	13.9	22.5	51.7	3.0	0.8	148	646	790
54	G	SF	8.9	13.9	22.5	51.7	3.0	1.3	148	646	790
55	G	SF	8.9	13.9	22.5	51.7	3.0	2.3	148	646	790
56[b]	G	SF	8.8	14.0	22.6	51.8	2.8	1.6	147	—	—

[a] For Batches 1-35, center point data were calculated from third point data by the use of the formula: R_c (center point) = 1.18 R_3 (third point).

[b] Only cylinders made for these batches.

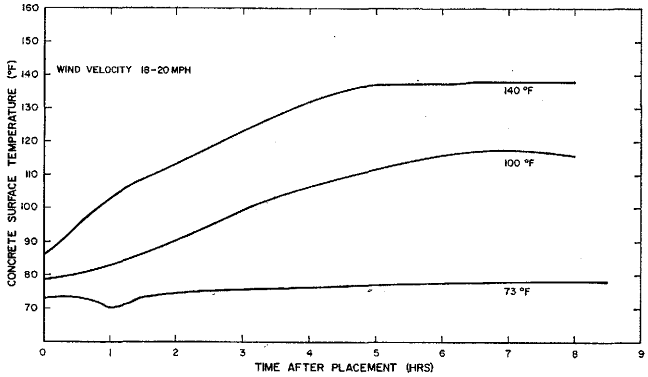


Figure 5-1. Concrete Surface Temperature vs. Time After Placement.

Impact Hammer readings[43,44] were taken on a few test slabs before placing them in the freezing room (−8°F). Just prior to the coring operation, Impact Hammer readings were again taken with no appreciable change in readings being observed. This indicated that, in the frozen state, the slabs remained approximately inert. Therefore, for testing purposes, all test specimens were considered to be at a 28-day strength.

5.2 Laboratory Procedures

The concrete for all batches was mixed in a 6 cu. ft. portable rotary-drum mixer at the concrete laboratory. Materials were stored inside the laboratory so as to maintain a constant batch temperature (80 ± 3°F). Prior to batching, a small "butter batch" consisting of identical materials as the batch, was placed in the mixer. This compensated for the materials which would normally stick in the mixer. The coarse aggregate and part of the mixing water containing the air entrainment admixture was added initially. After approximately one minute of mixing, the cement and fine aggregate were added. The remaining mixing water was then added until the desired slump was obtained. The mixing continued for approximately five minutes after the cement was added.

After the mixing was completed, the slump test (ASTM C143-66), unit weight (ASTM C139-63), and air content (ASTM C231-68) were determined and recorded. At the completion of these control tests, the concrete was then taken by wheel barrel to the appropriate environmental rooms and placed in specially built steel forms. Batches 1-35 were placed in two layers while Batches 37-56 in three layers. The steel forms have two wooden dividers to separate the slab into three test slabs. As soon as the concrete was placed, it was vibrated and screeded. Batches 37-56 had wind generated over their surfaces to simulate outdoor conditions. On selected slabs one coat of MMF was then immediately applied. All slabs were then finished with the appropriate finishing procedure. On selected slabs the LO was then immediately applied. Other slabs were allowed to dry for approximately 30 minutes (until the surface sheen disappeared) after which time they, as well as the slabs treated with MMF, were coated with WPC. After a period of time ranging from 22 to 72 hours, the forms were removed and the test slabs then labeled and allowed to remain in their curing environment for the 28-day curing period. Wind velocities were maintained for a period of approximately 50 hours.

Concrete temperatures were monitored in the middle and top of the slabs for several hours after placement. The slab top temperatures, for concretes placed in the 73, 100, and 140° rooms under an 18-20 mph wind velocity are plotted in Figure 5-1.

Following the curing period, the slabs were removed and cores taken from each. In some cases, it was necessary to place some of the slabs in the freezing room (−8°F) until cores could be taken. Upon removal of the cores they were labeled and the appropriate tests conducted.

5.3 Impact Hammer

The Impact Hammer was developed in 1948 by Ernst Schmidt, a Swiss engineer. The tool utilizes a constant spring force to propel a hammer against a steel plunger in contact with a concrete surface and then measures the rebound of the hammer. The softer the surface of the concrete, the farther the plunger will be embedded, more energy from the blow being absorbed and leaving less energy to rebound the hammer. On the hammer, a scale is marked off from zero to one hundred, and the percent of rebound is measured by a slider pushed along the scale by the rebounding mass.

A number of readings should be taken in one general locality with the longitudinal axis of the hammer perpendicular to the surface of the concrete, and the average of these readings used.

Besides the Impact Hammer being used to check the rate of strength gain for a given concrete, it is often used as a hardness tester.[45] The hammer is used in this research to measure the hardness of the cores taken from each test slab.

5.4 Tabulated and Plotted Test Results

Tables 5-7, 5-8, 5-9, and 5-10 contain the results of this research program. Figures 5-2 through 5-8 presents a plot of the evaporation rates during the initial

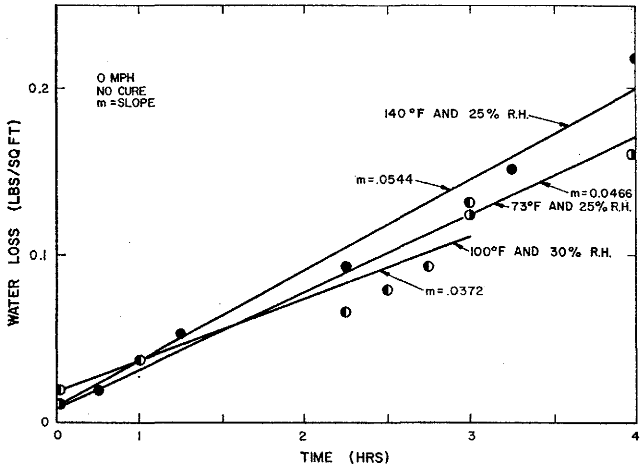


Figure 5-2. Determination of Evaporation Rate for Specimens Without Any Curing Compounds (No Cure) at Steady Wind Conditions (0 mph).

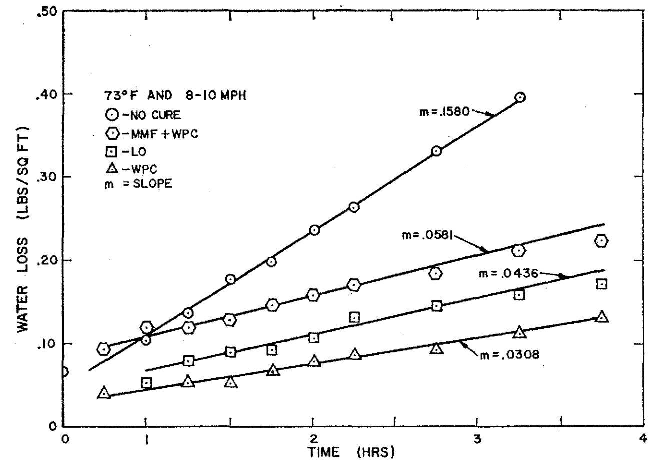


Figure 5-3. Determination of Evaporation Rate at the Curing Temperature of 73°F and Wind Conditions of 8-10 mph.

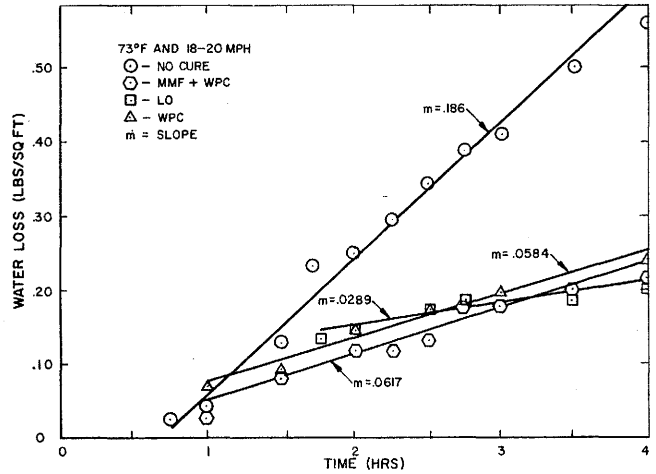


Figure 5-4. Determination of Evaporation Rate at the Curing Temperature of 73°F and Wind Conditions of 18-20 mph.

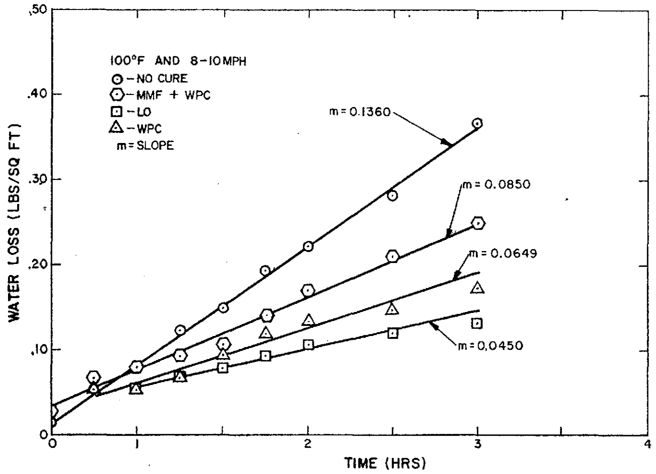


Figure 5-5. Determination of the Evaporation Rate at the Curing Temperature of 100°F and Wind Conditions of 8-10 mph.

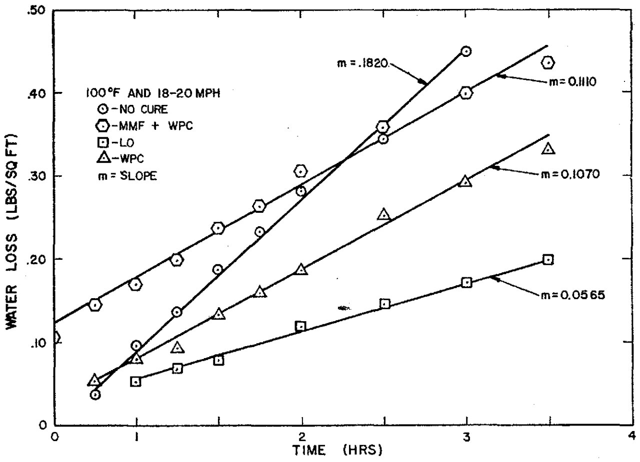


Figure 5-6. Determination of the Evaporation Rate at the Curing Temperature of 100°F and Wind Conditions of 18-20 mph.

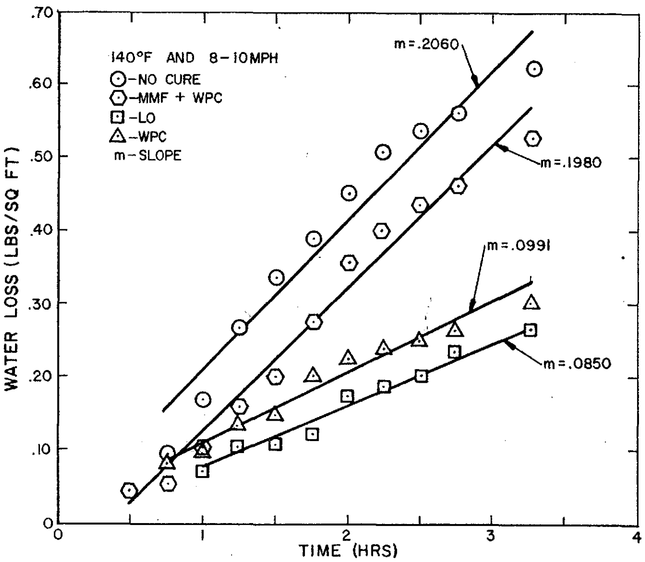


Figure 5-7. Determination of the Evaporation Rate at the Curing Temperature of 140°F and Wind Conditions of 8-10 mph.

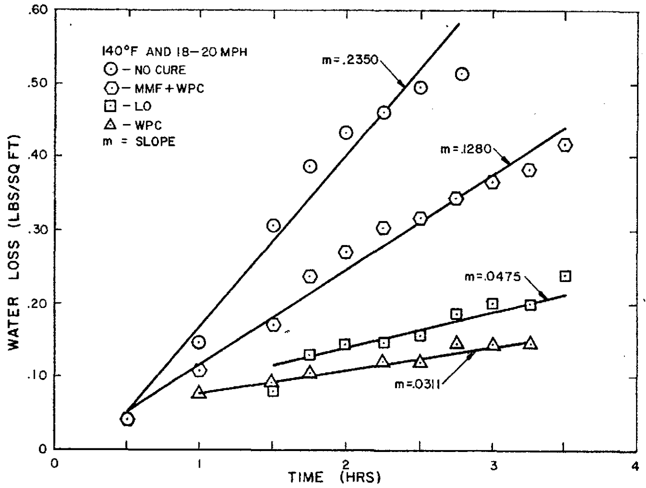


Figure 5-8. Determination of the Evaporation Rate at the Curing Temperature of 140°F and Wind Conditions of 18-20 mph.

hours of the curing process (from Table 5-8). The data were corrected for the change in weight due to application of the curing compound. For complete curves see Figues 4-1 through 4-6.

5.5 Vibration

The data used for this comparison of these variables are tabulated in Table 5-11. These data were selected

TABLE 5-7. CONCRETE PROPERTIES[a] OF CONTINUOUSLY REINFORCED CONCRETE PAVEMENT TEST SLABS

Batch Code	Slab Code[b]	Splitting Tensile Strength on Cores[c] Top (psi)	Bottom (psi)	Dynamic E of Cores[d] (psi x 10^6)	Abrasion Coefficient[e] (cm^3/cm^2)	Surface Impact Hammer[f]	Density of Cores[g] Top (pcf)	Bottom (pcf)
1	$GV_1F_1N\ E_21$	579	587	6.47	0.19	26	150	148
2	$GV_1F_1N\ E_22$	537	613	6.73	0.24	23	148	146
3	$GV_1F_2N\ E_23$	533	611	6.88	0.23	26	143	148
4	$GV_1F_1N\ E_31$	588	679	6.78	0.18	30	148	146
5	$GV_1F_2N\ E_33$	559	600	7.19	0.26	28	149	149
6	$GV_1F_2N\ E_51$	406	540	6.00	0.22	31	148	147
7	$GV_1F_2N\ E_53$	433	625	6.16	0.24	29	147	147
8	$GV_1F_1N\ E_61$	401	500	5.89	0.19	27	148	146
9	$GV_1F_2N\ E_63$	495[h]	501	5.95	0.21	24	147	147
10	$GV_2F_2C_CE_32$	542	546	6.93	0.14	27	149	149
11	$GV_3F_2C_CE_32$	565	593	5.89	0.19	28	149	148
12	$GV_1F_1C_CE_32$	499	574	5.54	0.16	28	148	147
13	$GV_1F_1C_CE_52$	537	584	6.72[h]	0.24	27	150	151
14	$GV_1F_2C_FE_52$	538	622	6.75	0.24	28	151	151
15	$GV_1F_2C_CE_62$	499	545	5.93	0.27	24	147	148
16	$GV_1F_3C_FE_62$		510	5.71[i]	0.24	25	146	147
17	$GV_1F_1N\ E_11$	476	583	5.91	0.20	—	148	149
18	$GV_1F_2N\ E_13$	549	588	6.23[i]	0.23	—	148	147
19	$GV_1F_3C_CE_12$	550	601	6.04[i]	0.23	26	149	149
20	$GV_1F_1C_FE_12$	553	553	6.88[h]	0.23	22	151	149
21	$GV_0F_1C_CE_32$	580[h]	570	5.60	0.18	26	150	148
22	$GV_1F_1B_FE_52$	470	586	6.53[h]	0.29	24	147	147
23	$GV_1F_3B_FE_12$	560	605	5.57[h]	0.17	26	148	146[h]
24	$GV_1F_3B_CE_52$	547	640	6.47	0.23	28	149	149[h]
25	$GV_1F_2B_CE_12$	541	585	6.41[h]	0.21	22	148[h]	148
26	$GV_1F_1B_CE_62$	477	729	5.97	—	24	149	149
27	$GV_1F_2B_FE_62$	543	624	5.28	0.22	24	148	148
28	$SV_0F_2B_FE_32$	551	648	5.68	0.27	22	145	145
29	$SV_2F_3B_FE_32$	577	673	5.83	0.30	22	146	146
30	$SV_1F_2B_FE_32$	516	570	5.73	0.26	24	148	149
31	$SV_3F_3B_FE_32$	582	665	5.92	0.32	24	145	145
32	$MV_1F_3B_CE_32$	609	598	6.29	0.21	21	148	146
33	$MV_2F_1B_CE_32$	616	763	6.52	0.16	24	149	150
34	$MV_3F_1B_CE_32$	643	662	6.50	0.18	23	149	150
35	$MV_0F_3B_CE_32$	584	580	6.18	0.29	17	146	146
36[j]	$GF_1N\ E_22$	522	564	—	0.56	—	149	150
37	$GV_1F_1W_3E_23$	536	628	6.33	0.25	20	148	150
38	$GV_1F_1W_3E_24$	498	598	5.65	0.25	23	149	149
39	$GV_1F_1W_3E_22$	440	698	6.23	0.23	22	140	148
40	$GV_1F_1W_2E_23$	558	596	6.80	0.24	21	148	148
41	$GV_1F_1W_2E_24$	581	759	6.40	0.19	24	149	147
42	$GV_1F_1W_2E_22$	556	563	6.59	0.21	23	148	150
43	$GV_1F_1W_2E_63$	467	557	5.77	0.30	18	146	148
44	$GV_1F_1W_2E_64$	457	625	5.74	0.20	22	148	149
45	$GV_1F_1W_2E_62$	502	528	6.27	0.21	20	150	148
46	$GV_1F_1W_3E_63$	394	521	5.88	0.27	25	146	148
47	$GV_1F_1W_3E_64$	488	634	6.12	0.23	22	148	149
48	$GV_1F_1W_3E_62$	524	670	6.02	0.23	24	147	147
50	$GV_1F_1W_3E_43$	438	612	6.54	0.21	16	146	149
51	$GV_1F_1W_3E_44$	504	590	6.88	0.18	21	148	149
52	$GV_1F_1W_3E_42$	461	716	6.55	0.22	24	148	150
53	$GV_1F_1W_2E_43$	516	649	6.17	0.25	19	148	151
54	$GV_1F_1W_2E_44$	530	591	6.37	0.25	24	148	151
55	$GV_1F_1W_2E_42$	545	689	6.61	0.26	25	150	149

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[a] All numbers were obtained by taking the average of three specimens in Batches 1-35 and two specimens in Batches 37-36 except where otherwise noted.

[b] For slab code designations, see Table 5-5.

[c] ASTM C496-66.

[d] ASTM C215-60 (Torsional).

[e] ASTM C418-68.

[f] Impact readings taken on the slab surface by a concrete test hammer, Model CT-320.

[g] ASTM D1188-68.

[h] Only two specimen results were averaged to obtain this number.

[i] Four specimen results were averaged to obtain this number.

[j] No vibration of any type used in placement of this slab.

TABLE 5-8. EVAPORATION RATES IN LBS PER SQ FT.

Batch Code[a] and Cure	Time In Hours[b] ½	1	1½	2	2½	3	4	6	10	24	45
37-3	—	.0264	.0792	.1188	.1320	.1716	.2112	.3036	.3828	.5280	.5808
38-4	—	—	.0792	.1452	.1716	.1848	.1980	.2178	.2772	.3828	.4224
39-2	—	.0660	.0924	.1452	.1716	.1980	.2376	.3564	.4620	.6072	.6600
37,38,39,-5[c]	—	.0396	.1276	.2464	.3388	.4092	.5588	.7568	.8932	.9768	.9878
40-3	.0660	.1188	.1254	.1584	.1848	.2112	.2442	.2838	.3300	.4356	.4488
41-4	—	.0528	.0858	.1056	.1452	.1584	.1914	.2112	.2508	.3564	.3960
42-2	—	.0528	.0528	.0792	.0924	.1122	.1584	.1848	.2376	.3432	.3696
40,41,42,-5[c]	.1056	.1012	.1782	.2376	.3322	.3960	.5060	.6292	.7392	.8426	.8690
43-3	.0396	.1056	.1980	.3564	.4356	.5280	.5544	.6600	.7392	.8316	.8844
44-4	—	.0660	.1056	.1716	.1980	.2640	.3432	.3564	.4488	.5280	.5808
45-2	—	.0924	.1452	.2244	.2508	.3036	.3564	.3828	.4752	.5544	.6204
43,44,45,-5[c]	—	.1672	.3036	.4532	.5368	.6292	.6996	.7260	.7786	.8492	.8976
46-3	.0396	.1056	.1716	.2772	.3168	.3696	.4488	.5412	.5544	.6600	.7128
47-4	—	—	.0792	.1452	.1584	.1980	.2640	.3432	.3564	.4488	.5412
48-2	—	.0792	.0924	.1188	.1188	.1452	.1716	.2376	.2508	.3300	.4092
46,47,48,-5[c]	.0396	.1452	.3080	.4356	.4928	.5280	.5720	.6292	.6644	.7128	.7744
49A-5	.0132	.0264	.0396	.0926	.0926	.1322	.1584	.2312	.4099	.5148	.5412
49B-5	.0132	.0198	.0528	.0926	.0926	.1518	.2180	.3696	.4752	.5544	.6215
50-3	.1056	.1584	.2376	.3036	.3564	.3960	.4488	.5412	.6072	.6600	.6732
51-4	—	.0528	.0792	.1188	.1452	.1716	.1980	.2772	.3696	.4224	.4488
52-2	—	.0792	.1320	.1848	.2508	.2904	.3432	.4356	.5016	.5544	.5808
50,51,52,-5[c]	.0529	.0969	.1894	.2820	.3436	.4494	.5243	.6212	.6828	.7405	.7446
53-3	.0264	.0792	.1056	.1716	.2112	.2508	.3036	.4356	.4488	.5148	.5544
54-4	—	.0528	.0743	.1058	.1190	.1322	.1455	.2248	.2513	.3306	.3702
55-2	—	.0529	.0926	.1321	.1455	.1719	.1851	.2248	.2777	.3570	.3967
53,54,55,-5[c]	.0132	.0793	.1498	.2202	.2821	.3656	.4583	.6035	.6167	.6784	.7060
56-5	.0198	.0396	—	—	.0793	.1256	.1716	.2777	.4884	.5940	.6276

[a] For Cure Code Designations, see Table 3-1.
Wind Conditions of 18-20 mph for Batches 37-39, 46-48, and 50-52; 8-10 mph for Batches 40-45 and 53-55; 0 mph for Batches 49 and 50.
Environmental Conditions of 73° F-25% RH for Batches 37-42 and 49A; 140° F-25% RH for Batches 43-48 and 49B; 100° F-30% RH for Batches 50-66.

[b] No evaporation rates taken at the times noted by the dash (-).

[c] No Cure was applied to half of each slab.

in order to compare the effects of vibration type on the splitting tensile strength, density, dynamic modulus of elasticity (torsional) and surface properties.

Figure 5-9 illustrates the splitting tensile strength of concrete cores as a function of vibration type and aggregate type. The average values are shown and though there appears to be significant difference in the results from internal and surface vibration, the scatter is too great to quantify this difference. As expected and

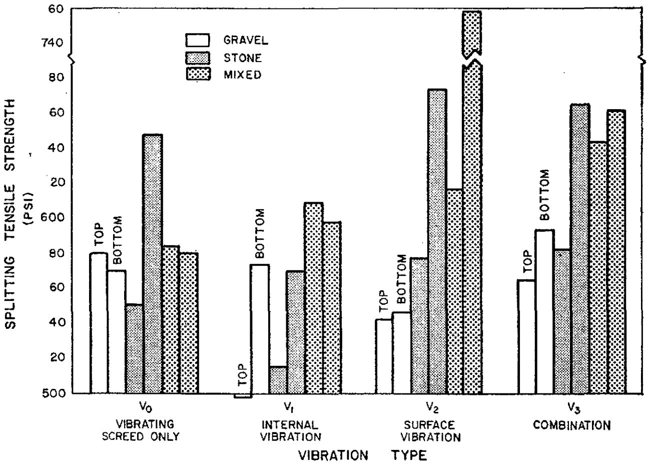

Figure 5-9. Effect of Vibration Type on Splitting Tensile Strength.

TABLE 5-9. CONCRETE PROPERTIES OF SLABS[a]

Batch Code	Slab Code	Splitting Tensile Strength of Cores Top-psi	Bottom-psi	Dynamic E of Cores psi x 10^6	Abrasion Coefficient cm^3/cm^2
12	$W_1E_3$2	499	574	5.54	0.16
40	$W_2E_2$3	558	596	6.80	0.24
41	$W_2E_2$4	581	759	6.40	0.19
42	$W_2E_2$2	557	563	6.59	0.21
40,41,42	$W_2E_2$5	583	657	6.72	0.25
53	$W_2E_4$3	517	649	6.17	0.30
54	$W_2E_4$4	530	591	6.37	0.20
55	$W_2E_4$2	454	689	6.61	0.21
53,54,55	$W_2E_4$5	523	695	6.56	0.24
43	$W_2E_6$3	467	557	5.77	0.25
44	$W_2E_6$4	457	625	5.74	0.25
45	$W_2E_6$2	502	529	6.27	0.26
43,44,45	$W_2E_6$5	502	571	5.83	0.24
37	$W_3E_2$3	536	628	6.33	0.25
38	$W_3E_2$4	498	599	5.65	0.25
39	$W_3E_2$2	440	699	6.23	0.23
37,38,39	$W_3E_2$5	478	537	6.01	0.23
50	$W_3E_4$3	438	613	6.54	0.27
51	$W_3E_4$4	505	590	6.88	0.23
52	$W_3E_4$2	461	716	6.55	0.23
50,51,52	$W_3E_4$5	515	667	6.29	0.20
46	$W_3E_6$3	394	521	5.88	0.21
47	$W_3E_6$4	489	634	6.02	0.18
48	$W_3E_6$2	525	671	6.02	0.22
46,47,48	$W_3E_6$5	547	600	6.03	0.19

[a] Selected slabs from Table 5-7.

TABLE 5-10. CONCRETE PROPERTIES AND RELATIVE PROPERTIES BASED ON NO CURE AS 100[a]

Batch Code	Slab Code	Dynamic E of Cores psi x 10^6	Dynamic E of Cores Rel.	Surface Impact Hammer Reading	Surface Impact Hammer Rel.
40,41,42	W_2E_25	6.72	100	25.2	100
40	W_2E_23	6.80	101	20.8	83
41	W_2E_24	6.40	95	23.8	94
42	W_2E_22	6.59	98	22.9	91
53,54,55	W_2E_45	6.52	100	20.4	100
53	W_2E_43	6.17	95	19.4	95
54	W_2E_44	6.37	98	24.0	118
55	W_2E_42	6.61	101	24.7	121
43,44,45	W_2E_65	5.83	100	21.2	100
43	W_2E_63	5.77	99	17.7	83
44	W_2E_64	5.74	98	21.5	101
45	W_2E_62	6.27	107	20.2	95
37,38,39	W_3E_25	6.01	100	20.9	100
37	W_3E_23	6.33	105	20.0	96
38	W_3E_24	5.65	94	23.1	111
39	W_3E_22	6.23	104	21.9	105
50,51,52	W_3E_45	6.29	100	22.7	100
50	W_3E_43	6.54	104	15.8	70
51	W_3E_44	6.88	109	21.3	94
52	W_3E_42	6.55	104	23.7	104
46,47,48	W_3E_65	6.03	100	23.9	100
46	W_3E_63	5.88	98	24.5	103
47	W_3E_64	6.12	101	21.7	91
48	W_3E_62	6.02	100	24.4	102

[a] Selected slabs from Table 5-7.

reported by others, the bottom portions of the cores exhibited generally higher splitting tensile strengths than the top portions. This is generally attributed to the more favorable curing conditions in the bottom sections.

However, it should be noted that when surface vibration was used, the stone aggregate and mixed aggregate slabs had higher splitting tensile strengths than did the gravel slabs. This difference on the average was greater than 10 percent. In these tests, though, all methods of vibration produced concrete of adequate strengths.

As anticipated (since the unvibrated strengths were as great as the vibrated strengths), no significant difference in density due to the use of vibration techniques was found.

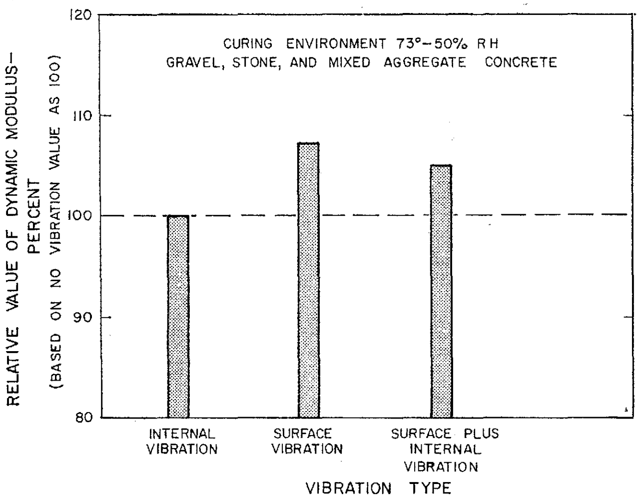

Figure 5-10. Effect of Vibration Type on Dynamic Modulus of Concrete.

The dynamic modulus of elasticity as a function of vibration type is shown in Figure 5-10, using the average values obtained for no vibration as 100 percent (see Table 5-11). Concretes made with gravel, stone, and mixed coarse aggregates were averaged together. A slight increase in modulus occurred when surface vibration was employed. However, there was insufficient information to fully verify this increase.

Using the values obtained from the slabs made from gravel aggregate and receiving no vibration as 100 percent, the Impact Hammer readings and the abrasion coefficients are illustrated in Figure 5-11 as a function of vibration type and aggregate (see Table 5-11). Of the nine vibrated slabs only two exhibited greater abrasion losses than the companion unvibrated slabs. The vibrated surfaces exhibited a more abrasion or wear resistant surface. This was also verified by the Impact Hammer readings of the surface. It should be noted that the gravel aggregate produced better results in most

TABLE 5-11. CONCRETE PROPERTIES AND RELATIVE PROPERTIES BASED ON NO VIBRATION AS 100[a]

Batch Code	Slab Code[b]	Splitting Tensile Strength of Cores Top psi	Splitting Tensile Strength of Cores Top Rel.	Splitting Tensile Strength of Cores Bottom psi	Splitting Tensile Strength of Cores Bottom Rel.	Dynamic E psi x 10^6	Dynamic E Rel.	Abrasion Coefficient cm^3/cm^2	Abrasion Coefficient Rel.	Surface Impact Hammer Reading	Surface Impact Hammer Rel.	Density of Cores Top pcf	Density of Cores Top Rel.	Density of Cores Bottom pcf	Density of Cores Bottom Rel.
21	F_1GV_0	580	100	570	100	5.60	100	.18	100	26	100	150	100	148	100
12	F_1GV_1	580	86	574	101	5.54	99	.16	112	28	108	148	99	147	99
10	F_2GV_2	542	93	546	96	6.28	112	.14	129	27	105	149	99	149	101
11	F_2GV_3	565	97	593	104	5.89	105	.19	95	28	106	149	99	148	100
28	F_2SV_0	551	100	648	100	5.68	100	.27	100	22	100	145	100	145	100
30	G_2SV_1	516	94	570	88	5.73	101	.26	104	24	113	148	102	149	103
29	F_3SV_2	577	105	673	104	5.88	104	.30	90	22	103	146	101	146	101
31	F_3SV_3	582	106	665	103	5.92	104	.32	84	24	110	145	100	145	100
35	F_3MV_0	584	100	580	100	6.18	100	.29	100	17	100	146	100	146	100
32	F_3MV_1	609	104	598	103	6.20	100	.21	138	21	120	148	101	146	100
33	F_1MV_2	616	105	763	132	6.52	105	.16	181	24	142	149	102	150	103
34	F_1MV_3	643	110	662	114	6.50	105	.18	161	23	134	149	102	150	103

[a] Selected slabs from Table 5-7.
[b] See Table 3-1.

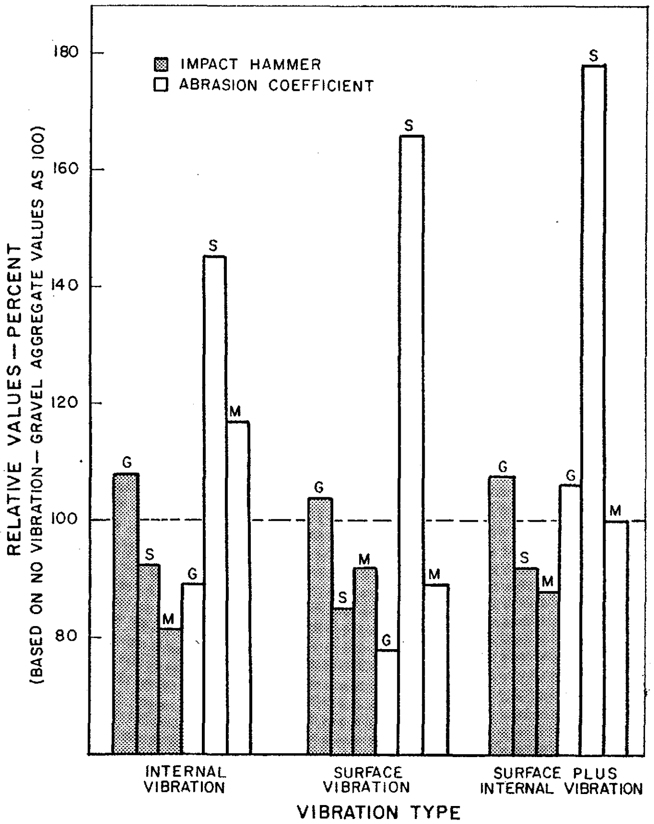

Figure 5-11. Effect of Vibration Type on Impact Hammer Readings and Abrasion Coefficient of Concrete Based on Gravel Aggregate.

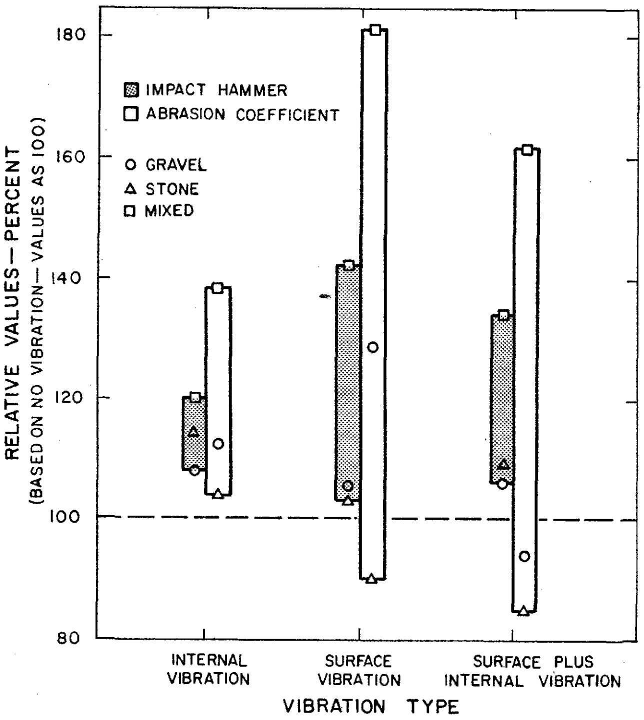

Figure 5-12. Effect of Vibration Type of Impact Hammer Readings and Abrasion Coefficient of Concrete.

cases for these two surface properties, and that the stone had consistently poorer values than the gravel or mixed aggregate concretes. Mechanical vibration improved the abrasive properties of the mixed aggregates more than the gravel or the stone (see Figure 5-12). Though the information is insufficient for quantitative conclusions, these data do indicate the need for considering aggregate type as a parameter when studying surface properties.

5.6 Subbase Type

It is reasonable to assume that if the subbase affects the concrete slab, it will more adversely affect the bottom portion of the slab due to the direct interface. For clarity, Table 5-12 contains the results as excerpted from

TABLE 5-12. CONCRETE PROPERTIES OF SELECTED SLABS[a]

Batch Code	Slab Code[b]	Splitting Tensile Strength on Cores Top (psi)	Splitting Tensile Strength on Cores Bottom (psi)	Density of Cores Top (pcf)	Density of Cores Bottom (pcf)	Dynamic Modulus (psi x 10^6)
13	$GV_1F_1C_CE_52$	537	584	150	151	6.72
15	$GV_1F_2C_CE_62$	499	545	147	148	5.93
19	$GV_1F_3C_CE_12$	550	601	149	149	6.04
14	$GV_1F_2C_FE_52$	538	622	151	151	6.75
16	$GV_1F_3C_FE_62$	423	510	146	147	5.71
20	$GV_1F_1C_FE_12$	555	553	151	149	6.88
24	$GV_1F_3B_CE_52$	547	640	149	149	6.47
25	$GV_1F_2B_CE_12$	541	585	148	148	6.41
26	$GV_1F_1B_CE_42$	477	729	149	149	5.97
22	$GV_1F_1B_FE_52$	470	586	147	147	6.53
23	$GV_1F_3B_FE_12$	560	605	148	146	5.57
27	$GV_1F_2B_FE_62$	543	624	148	148	5.28
6	$GV_1F_2N\ E_51$	406	540	148	147	6.08
7	$GV_1F_2N\ E_53$	433	625	147	147	6.16
8	$GV_1F_1N\ E_61$	401	397	148	146	5.89
9	$GV_1F_2N\ E_63$	495	501	147	147	5.95
17	$GV_1F_1N\ E_11$	476	588	148	149	5.91
18	$GV_1F_2N\ E_13$	513	588	148	147	6.23

[a] Selected slabs from Table 5-7. All values were obtained by taking the average of 3 specimens.
[b] See Table 3-1.

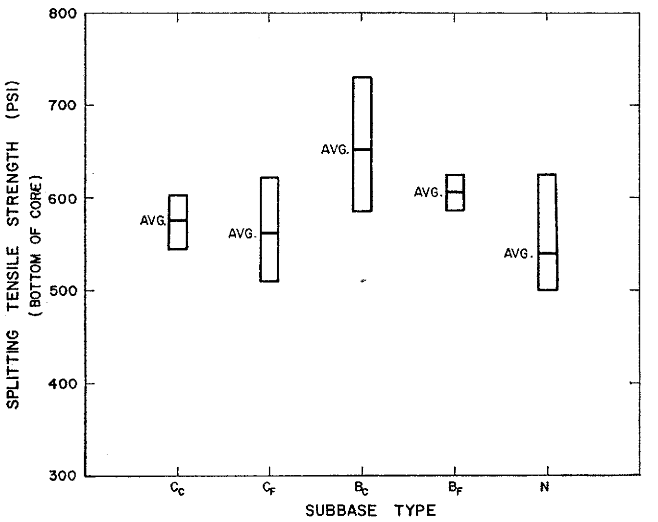

Figure 5-13. Effect of Subbase Type on Concrete Strength.

Table 5-7. A study of the results, Figure 5-13, reveals that in these tests the type of subbase did *not* adversely affect the strength of the slab (since the strengths of the bottom sections were in general higher than the strengths of the top sections), regardless of the environment. The texture of the bases in these tests did not adversely affect either the strength or density of the lower portions of the slab. It should be noted that the slabs in these tests were placed with the bases dry to create the most severe conditions. Still no adverse effect was observed due to subbase type.

5.7 Surface Finish

Relative values are shown in Figure 5-14, based on the burlap drag finish values as 100. It is evident that of the three finishes (brush, burlap, and tines), the burlap drag finish had the lowest abrasion loss and the tines finish the highest. Impact Hammer readings were taken and a good correlation with the abrasion coefficient was found. With a high abrasion loss (as found with the tines finish), the Impact Hammer readings, used as a measure of strength, were low.

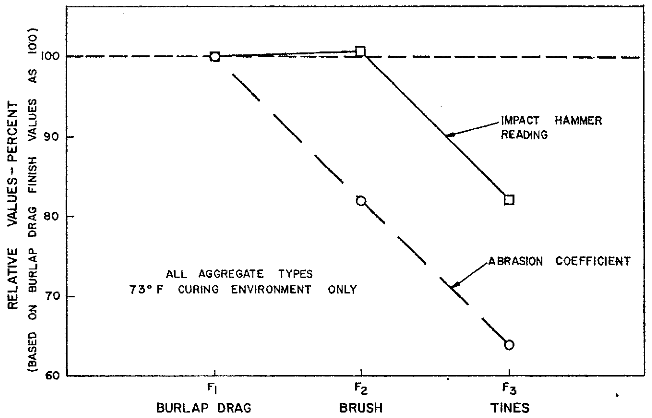

Figure 5-14. Effect of Surface Finish on Surface Properties of Concrete.

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