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# Effects of Environmental Factors on Construction of Soil-Cement Pavement Layers

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## KEY WORDS

Compaction delay, construction, laboratory tests, nomographs, relative compaction, relative humidity, relative strength, soil-cement, temperature, wind speed.

## ABSTRACT

The objectives of this research were to quantify the effects of certain environmental factors on the relative strength loss of soil-cement subjected to compaction delay and to develop a numerical tool engineers and contractors can easily use to determine a maximum compaction delay time for a given project. These objectives were addressed through extensive laboratory work and statistical analyses, including testing an aggregate base material and a subgrade soil each treated with two levels of cement. Environmental factors considered were wind speed, temperature, and relative humidity; three levels of each were evaluated in combination with three compaction delay times. The primary response variables were relative compaction and relative strength.

Within the ranges investigated in this research, relative strength is sensitive to variability among the selected independent variables, while relative compaction is not. Inferring relative strength from relative density is therefore not a reliable approach on soil-cement projects. Consistent with theory, higher wind speed, higher air temperature, lower relative humidity, and higher compaction delay time generally result in lower relative strength.

With the nomographs developed in this research, the maximum delay time permitted for compaction of a base or subgrade material similar to those tested in this research can be calculated.

## REFERENCE

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# Effects of Environmental Factors on Construction of Soil-Cement Pavement Layers

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## INTRODUCTION

### Problem Statement

For decades, portland cement has been used as an additive to improve the strength and durability of soils and aggregates used in highway construction. In the construction process, the cement is first blended with the soil or aggregate, then water is added, and finally the mixture is compacted to create a soil-cement product. Cement hydration begins as soon as water is introduced to the soil-cement mixture. The water and cement form a paste that ultimately bonds the soil and aggregate particles together, thus enhancing the strength and durability of the layer.

Initially, while the cement is just beginning to hydrate, the soil-cement remains workable and can be easily compacted. However, as the cement continues to hydrate, the bonds between soil and/or aggregate particles resist densification, and construction crews may be unable to compact the hydrating soil-cement to the required density; subsequently, a weaker final product results. Therefore, because soil-cement materials achieve their highest strengths when they are fully compacted, minimizing compaction delay is an important aspect of quality soil-cement construction.

On this topic, the majority of industry personnel agree that after 2 hours of hydration, a cement-treated material not yet compacted to its target density will exhibit reduced strength (Arman 1972, Arman and Saifan 1965, Ferguson 1993). Indeed, the decrease in strength and durability due to compaction delay may be of such magnitude that the benefit of adding cement to the native soil may be diminished or become negated altogether (Arman and Saifan 1965). As a result, a maximum of 2 hours between mixing and compaction has been widely adopted as the industry standard for soil-cement projects (NDOT 2001, GDOT 2003). This standard, however, does not incorporate the impact of site-specific environmental conditions on the actual time frame in which the soil-cement needs to be compacted.

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The premise of this research is that the allowable delay time between mixing of a soil-cement mixture and completion of compaction may be shorter or longer than 2 hours, depending upon environmental factors. Accordingly, the specific objectives of this research were to quantify the effects of certain environmental factors on the relative strength loss of soil-cement subjected to compaction delay and to develop a numerical tool that can be easily used by engineers and contractors for determining an acceptable compaction delay time for individual projects based on environmental conditions at the respective sites. Knowing in advance how much time is available for working the soil-cement will help contractors schedule their activities more appropriately and ultimately produce higher quality roads.

## Scope

The objectives of this research were addressed through extensive laboratory work and statistical analyses. All specimen conditioning was performed in a computer-controlled environmental chamber in the Brigham Young University (BYU) Highway Materials Laboratory to ensure accurate and repeatable testing. The laboratory work involved testing of two different materials, an aggregate base material and a subgrade soil, each treated with two levels of cement. Environmental factors included in the experimentation were wind speed, temperature, and relative humidity, and three levels of each were evaluated in combination with varying compaction delay times. The primary response variables in this research were dry density and 7-day unconfined compressive strength (UCS), and moisture profiles were also prepared for a few specimens. In all of the testing performed in this research, two replicate specimens were prepared for each unique condition.

## Outline of Report

This report contains five sections. This section presents the problem statement and scope of the research. The background section provides information concerning cement hydration and environmental effects, as well as soil-cement construction and properties. Descriptions of the experimental plan, laboratory testing procedures, and data analysis methods are given in the experimental methodology section. The results section explains the research findings, and the conclusion section summarizes the procedures, research findings, and recommendations.

# BACKGROUND

## Overview

The following sections discuss cement hydration and environmental effects, as well as soil-cement construction and properties.

## Cement Hydration and Environmental Effects

Soil-cement has a variety of applications including strength enhancement, erosion control, and slope stabilization (ACI 1990). In particular, portland cement is increasingly used for stabilization of soils and aggregates in pavement construction because the addition of small amounts of cement can improve both the strength and durability of the treated materials. Introducing cement to these materials can also reduce construction costs by decreasing both the amount of excavation required and the amount of hauling in of new materials suitable for the given project. In pavement construction, the first scientifically controlled soil stabilization project was in 1935 (PCA 1992); since that time, thousands of lane miles have been constructed using a variety of methods (PCA 2001).

Although numerous cementitious materials have been used for thousands of years in construction, the portland cement that is used today did not exist until Isaac Johnson developed a technique in 1845 that involved heating raw ingredients to extremely high temperatures (Mindess 2003). The raw ingredients clay, sand, and limestone are mixed to particular concentrations, partially melted together to form new chemical bonds, and then pulverized to produce a fine powder containing primarily calcium silicates (PCA 2008). Based on the relative concentrations of the resulting compounds, modern cement is classified by ASTM International (ASTM) C150 (Standard Specification for Portland Cement) into five major categories. Type I is most commonly used for general purposes, and Types II, III, IV, and V are used to obtain moderate sulfate resistance, early strength gain, low heat of hydration, and high sulfate resistance, respectively (Mindess 2003). Types I and II are most commonly used for soil-cement projects (ACI 1990).

Cement hydration occurs when calcium silicates, such as tricalcium silicate ($C_3S$), react with water to produce the cementitious product calcium silicate hydrate (C-S-H) (Mindess 2003). Soil-cement obtains strength as C-S-H forms around cement particles and continues to grow outward, forming bonds between surrounding cement, soil, and/or aggregate particles (Mindess 2003). In soil-cement construction, the rate at which C-S-H forms for a given cement content depends on environmental factors such as wind speed, air temperature, and relative humidity, as these factors affect the rate of water evaporation from soil-cement layers and alter the chemical kinetics of the cement hydration reaction (Mindess 2003). Although the effects of these factors on soil-cement have not been previously quantified, which is the purpose of the current research, their effects on water evaporation, which is positively correlated to workability loss, from concrete have been documented as shown in Figure 1 (Mindess 2003). Higher wind speed and air temperature and lower relative humidity are associated with higher rates of water evaporation from freshly placed concrete.

While high wind speeds cause high rates of water evaporation, they also present construction challenges related to personnel comfort and dust control on soil-cement projects. As cement is most often distributed from a spreader in the form of a dry powder, excessive wind can lead to loss of cement and poor air quality in the vicinity of the construction project. The Extended Land Beaufort Scale, presented in Table 1, depicts relationships between wind speeds in miles per hour and the corresponding qualitative effects of wind on people; the wind speeds shown in the scale are measured at

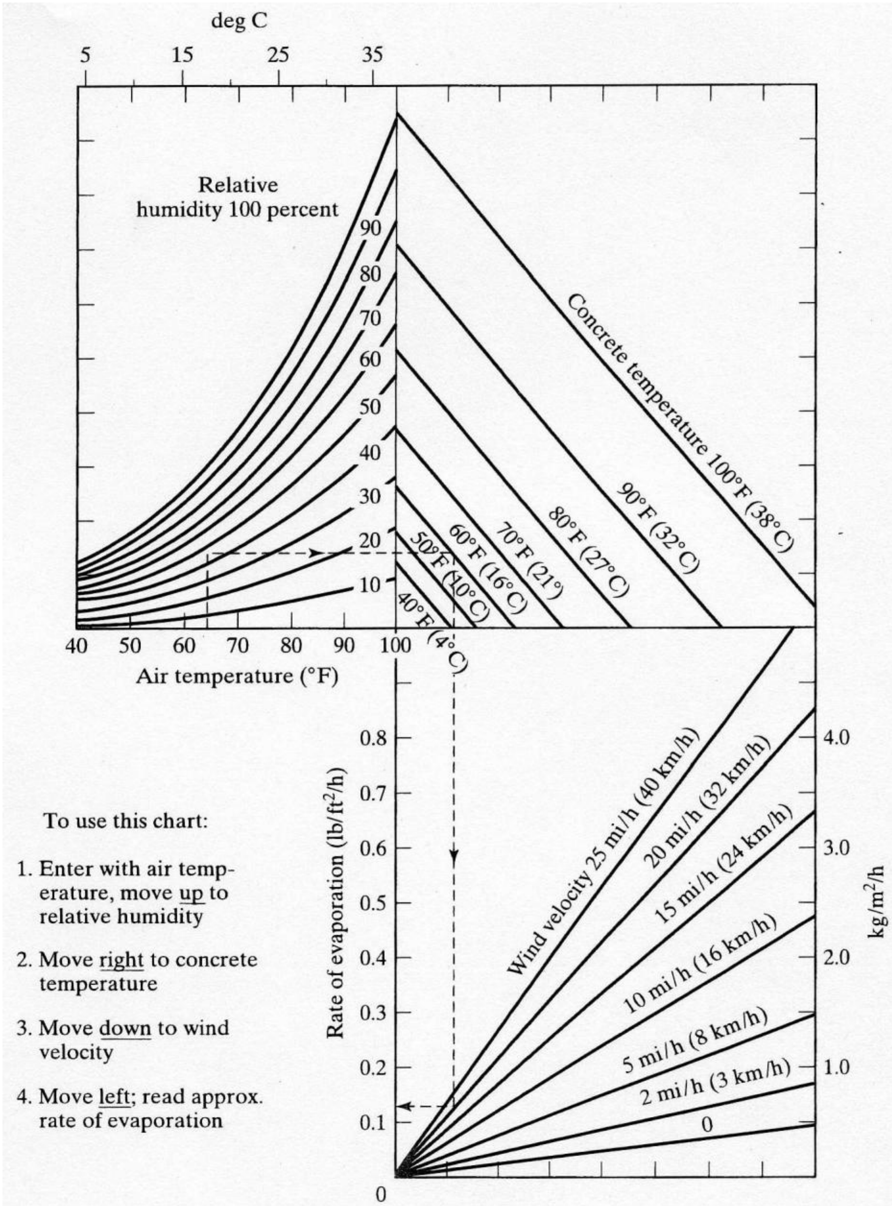


**Figure 1. Nomograph for estimating water evaporation rate from fresh concrete (Mindess 2003).**

a pedestrian height of 5.74 ft and are averaged over 10-minute periods (Blocken and Carmeliet 2004). The scale suggests that wind speeds associated with a Beaufort number of 4 or higher would be problematic for soil-cement construction due to difficulty in personnel mobility and dust-raising. A Beaufort number of 4 is also representative of the average wind speed for the first four geographical locations listed in Table 2; only the Western Long-Term Pavement Performance (LTPP) Program Region, including Utah, has a lower average wind speed, which is characteristic of a Beaufort number of 3. This table was developed from wind speed data that were collected at weather stations on United States Air Force bases throughout the nation (NRCS 2007). An overall average was calculated from the years that the bases recorded data, which ranged from 1931 to 2000.

**Table 1. Extended Land Beaufort Scale (Blocken and Carmeliet 2004)**

| Beaufort Number | Description | Wind Speed at 5.74 ft Height (mph) | Effect |
|---|---|---|---|
| 0 | Calm | 0.0-0.2 | No wind |
| 1 | Light air | 0.4-2.2 | No noticeable wind |
| 2 | Light breeze | 2.5-5.1 | Wind felt on face |
| 3 | Gentle breeze | 5.4-8.5 | Hair disturbed, clothing flaps, newspaper difficult to read |
| 4 | Moderate breeze | 8.7-12.3 | Raises dust and loose paper, hair disarranged |
| 5 | Fresh breeze | 12.5-16.8 | Force of wind felt on body, danger of stumbling when entering a windy zone |
| 6 | Strong breeze | 17.0-21.7 | Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, sideways wind force about equal to forwards walking force, wind noise on ears unpleasant |
| 7 | Near gale | 21.9-26.8 | Inconvenience felt when walking |
| 8 | Gale | 27.1-32.4 | Generally impedes progress, great difficulty with balance in gusts |
| 9 | Strong gale | 32.7-38.3 | People blown over |

**Table 2. National, LTPP Region, and State of Utah Wind Speeds**

| Geographical Region | Average Wind Speed (mph) |
|---|---|
| National | 9.1 |
| North Atlantic | 8.7 |
| North Central | 10.7 |
| Southern | 9.0 |
| Western | 8.1 |
| Utah | 6.2 |

In this research, air temperature and relative humidity data were obtained from the National Climatic Data Center (NOAA 2002, NOAA 2004). Table 3 displays average values for the nation, LTPP program regions (Mantravadi 2000, LTPP 2008), and the state of Utah. Daily air temperatures are reported as monthly averages. The monthly state air temperature data for each geographical region were downloaded and averaged over the presumed soil-cement construction months of March to October for the years in the afternoon for various cities throughout the nation. These values were downloaded and also averaged together by month. The monthly relative humidity data were then averaged over the lifetime of each city's weather station, which ranged from 6 to 72 years. Finally, all data were organized and reported according to geographical regions.

In addition to public climatological databases, research records prepared by BYU personnel during visits to various soil-cement construction projects nationwide were searched for environmental data relevant to this study. A project on Interstate 84 in Utah

**Table 3. National, LTPP Region, and State of Utah Temperatures and Relative Humidities**

| Geographical Region | Air Temperature (ºF) | Relative Humidity (%) |
|---|---|---|
| National | 61 | 68 |
| North Atlantic | 58 | 72 |
| North Central | 58 | 69 |
| Southern | 70 | 71 |
| Western | 57 | 59 |
| Utah | 58 | 55 |

during the months of June and July experienced ranges in humidity and temperature from 12 to 60 percent and 57 to 89ºF. Similarly, a construction site on United States Highway 91 (US-91) in Utah experienced ranges in humidity and temperature from 21 to 82 percent and 41 to 83ºF. Outside of Utah, BYU researchers have recorded data from the Southern and Western LTPP Program Regions. In the states of Idaho, Georgia, and Texas, recorded temperature and relative humidity values on soil-cement projects range from 22 to 70 percent and 68 to 93ºF; 41 to 83 percent and 75 to 100ºF; and 42 to 97 percent and 73 to 101ºF, respectively. Because these data were collected at just one or two projects in each of the listed states during a 1- or 2-day period in each case, the variability in values reflects the magnitudes of changes in environmental conditions that are possible during the construction hours of the day at a specific location. To the extent that such environmental changes affect soil-cement construction projects, contractors must be prepared to alter construction procedures as needed to ensure high-quality work.

## Soil-Cement Construction and Properties

The Portland Cement Association (PCA) has developed a set of guidelines, as outlined in the experimental methodology section, that engineers can use to determine the optimum cement content for a given soil or aggregate. When an appropriate amount of cement is added, stabilized materials typically exhibit one of two different structures once compacted. In fine-grained materials, individual grains are cemented together by a fairly uniform matrix of paste connecting all the particles (Arman and Saifan 1965). However, in coarse-grained materials such as aggregates, the particles are generally cemented together only at the points of contact within the matrix (Arman and Saifan 1965, Mackiewicz and Ferguson 2005, Ferguson 1993). Because coarse-grained materials generally have lower specific surface areas than fine-grained materials, coarse-grained materials usually require less cement than fine-grained soils to produce a stabilized material and may achieve higher strengths (Arman and Saifan 1965, PCA 1992). Current guidelines for determining typical strengths of soil-cement for different American Association of State Highway and Transportation Officials (AASHTO) soil types are given in Table 4.

Because density is commonly assumed to be an appropriate surrogate measure for strength, the nuclear density gauge is often used by transportation agencies for quality assurance testing of soil-cement (ACI 1990). Accordingly, subgrade soil and aggregate

**Table 4. Typical UCS Values of Soil-Cement by AASHTO Soil Type (ACI 1990)**

| Soil Type | 7-day Soaked Compressive Strength (psi) |
|---|---|
| Sandy and Gravelly Soils:<br>AASHTO Groups A-1, A-2, A-3<br>Unified Groups GW, GC, GP, GM, SW, SC, SP, SM | 300-600 |
| Silty Soils:<br>AASHTO Groups A-4 and A-5<br>Unified Groups ML and CL | 250-500 |
| Clayed Soils:<br>AASHTO Groups A-6 and A-7<br>Unified Groups MH and CH | 200-400 |

base materials are ideally compacted at optimum moisture content (OMC) to ensure that maximum dry density (MDD) is obtained. The use of cement as a stabilizer typically increases the amount of water required to reach the maximum density; enough water needs to be present in the soil-cement to wet the additional surface area of the cement particles and provide for cement hydration (Senol et al. 2002). Therefore, calculation of the amount of water needed to achieve these results is required prior to the commencement of construction. Even though the calculated moisture content may be difficult to obtain exactly at the construction site, compaction within the range of slightly below the OMC up to 2 percent above the OMC should be strictly enforced (Sebesta 2005, PCA 2001), as the required densities should still be attainable with appropriate compaction effort. On the other hand, compaction of soil-cement at a moisture content significantly above or below OMC will produce material with a comparatively low dry density.

Current construction guidelines attempt to facilitate adequate compaction of soil-cement layers by mandating that a newly mixed soil-cement material cannot be left undisturbed for more than 30 minutes and that it must be compacted within 2 hours and shaped within 3 hours (Ferguson 1993, ACI 1990). However, even though contractors may follow these guidelines precisely, problems can still arise due to fluctuations in environmental conditions at construction sites. For example, on the aforementioned soil-cement project on US-91 in Utah, compaction delays, moisture contents, and dry densities were measured at 30 different sites along the project. The average delay time for this project was calculated to be just 15.0 minutes, yet the average relative compaction was only 93 percent of MDD despite the fact that the average water content was within 0.5 percent of OMC. The compaction delay time in this case was the length of time between the mixing of water and cement into the base material and the commencement of compaction. Although this measure of compaction delay does not provide information about the total time delay that occurred between mixing and final compaction, which is the focus of the current research, BYU research personnel involved in the US-91 project remember the contractor finishing compaction within the recommended 2-hour period (Personal communication, M. A. Rogers, August 22, 2008). Thus, while the project utilized just 2 percent cement, the comparatively high temperatures and low relative humidity characteristic of Utah summers would have required faster compaction for achievement of 95 percent or greater relative compaction. Therefore, consideration of the effects of factors such as wind speed, air temperature, and relative humidity on the strength of soil-cement comprised of different soil or aggregate types prepared with different cement contents and compacted at varying delay times is important.

The properties of soil-cement become uncertain once compaction delay exceeds the initial set time of the cement paste (Arman and Saifan 1965). In such a case, cementitious bonds begin to form between the loosely configured soil and/or aggregate particles, and a comparatively high compaction effort is needed to overcome the increased resistance to densification during construction (Ferguson 1993, Cowell and Irwin 1979). Although some research indicates that compaction delay does not adversely affect the strength of soil-cement as long as the required density is met, achieving target dry densities may not be possible using reasonable compaction efforts in cases of excessive compaction delay, especially in materials treated with high concentrations of cement (Cowell and Irwin 1979). Although such a practice can make soil-cement more prone to shrinkage cracking, contractors may consider mixing at moisture contents higher than OMC when compaction delay is anticipated; research has shown, though not uniformly, that, if soil-cement is mixed at a moisture content greater than OMC, then the relative strength and dry density will increase, to a certain level, before decreasing, as compaction delay increases (Arman and Saifan 1965).

When elevated compaction efforts are not implemented, both the density and strength of soil-cement have been shown in multiple studies to experience dramatic reductions after 2 hours of compaction delay (Arman 1972, Arman and Saifan 1965, Ferguson 1993, Senol et al. 2002). Indeed, one study reports that after only 1 hour the MDD decreased as much as 10 pcf (Mackiewicz and Ferguson 2005). In another study investigating the possibility of pulverizing poorly compacted cement-treated base material, remixing with additional cement, and recompacting the “sweetened” layer one day after initial mixing to correct strength deficiencies, BYU researchers found that adding 75 percent of the original cement content was required to achieve the target strength (Guthrie and Brown 2005). Thus, special care must be taken during construction of soil-cement layers to ensure high quality and cost effectiveness.

## Summary

Portland cement has been used for several decades for stabilization of soils and aggregates in pavement construction because the addition of small amounts of cement can improve both the strength and durability of the treated materials. Although understanding of cement hydration has been well developed, the effects of certain environmental factors on the quality of soil-cement construction have not been explicitly investigated in previous research. In particular, higher wind speed and air temperature and lower relative humidity are theoretically associated with higher rates of water evaporation, thus leading to potential compaction problems, but the effects of these climatic variables on the relative compaction and strength of soil-cement have not been previously quantified. Furthermore, while soil-cement construction guidelines have been established, they do not facilitate direct consideration of these effects nor provide contractors a means of determining the maximum allowable compaction delay time for a given project under a given set of environmental conditions. Instead, a generic specification requiring compaction within 2 hours after mixing is commonly employed.

# EXPERIMENTAL METHODOLOGY

## Overview

This section includes explanations of the experimental design, materials characterization, specimen preparation and testing, and statistical analyses performed in this research.

## Experimental Design

As stated in the background section, several factors affect the quality of soil-cement construction. Specific factors selected for investigation in this research include material type, cement content, wind speed, temperature, relative humidity, and compaction delay. The laboratory work involved testing of two different materials, an aggregate base material and a subgrade soil, each treated with two levels of cement. The base was a crushed limestone aggregate obtained from BYU Grounds Services, and the subgrade was a silty soil obtained from Sunroc Corporation gravel pit in Spanish Fork, Utah. Table 5 depicts the testing matrix established for the experimental program conducted in this study. Each of the material types was systematically tested at low, medium, and high values of wind speed, temperature, relative humidity, and compaction delay. In each case, the value of only one variable at a time was altered, and the remaining variables were held constant at the corresponding average values. The three levels of each of these experimental variables were selected for testing based on information previously presented in the background section.

With respect to wind speed, several blow tests were performed in the BYU Highway Materials Laboratory to confirm that 10 mph is a maximum value at which cement might be placed, following the Extended Land Beaufort Scale presented in the background section. An anemometer was utilized to determine the perpendicular distance from the face of a standard box fan at which the desired wind speed occurred. The results of the blow test performed at 10 mph are shown in Figure 2, in which the box fan is shown in use at the right edge of the photograph, and clearly depict the dispersion of cement into the air as cement is poured off a linear edge of one laboratory pan onto a soil-cement slab specimen prepared in another pan.

A wind speed of 10 mph was thus selected as a maximum value for consideration in this research. So that a no-wind condition could also be evaluated, 0 mph was selected as another level, and 5 mph was subsequently selected as a midpoint. In the Extended

**Table 5. Experimental Design**

| Factor | Levels | | | |
|---|---|---|---|---|
| Wind Speed (mph) | 0, 5, 10 | 5 | 5 | 5 |
| Temperature (ºF) | 80 | 60, 80, 100 | 80 | 80 |
| Relative Humidity (%) | 50 | 50 | 25, 50, 75 | 50 |
| Delay Time (hr) | 2 | 2 | 2 | 1, 2, 3 |

**Figure 2. Cement powder dispersion during blow test.**

Land Beaufort Scale, wind speeds of 0, 5, and 10 mph correspond to descriptions of "no wind," "wind felt on face," and "raises dust and loose paper, hair disarranged." Researchers then evaluated the distribution of geographical wind speed averages among the following three categories: 0 to 5 mph, 5 to 10 mph, and greater than 10 mph. These categories include 5, 70, and 25 percent, respectively, of the data on which Table 2 is based.

Concerning air temperature and relative humidity, analysis of the data presented in Table 3 led to the selection of low, medium, and high levels of 60, 80, and 100ºF and 25, 50, and 75 percent, respectively. Fifty-four percent of the air temperature data on which Table 3 is based were below 60ºF, while the temperature data comprising the other 46 percent were between 60 and 80ºF; zero percent of the data were above 80ºF. For relative humidity, 0 percent of the data were less than 25 percent, 8 percent were between 25 and 50 percent, 80 percent were between 50 and 75 percent, and 12 percent were greater than 75 percent relative humidity. Levels beyond the overall averages were included in the testing to account for the realistic low relative humidity and high temperature values that can occur at some locations.

Specifically, the average air temperatures for the North Atlantic, North Central, and Western LTPP Program Regions, which range from 57 to 58ºF as displayed in Table 3, correspond well with the low level, while the medium level is characteristic of average temperatures during warmer months in the Southern LTPP Program Region. The high level of 100ºF is representative of mid-day construction temperatures experienced by many southern states like Texas, where the air temperature at a BYU test site was measured at 101ºF. Likewise, the low level for relative humidity corresponded well with the value of 22 percent measured in Idaho at another BYU test site during the month of July. The average relative humidity values of 55 percent for the state of Utah and 59 percent for the Western LTPP Program Region, as shown in Table 3, correspond to the medium level, while the average relative humidity values for the North Atlantic, North Central, and Southern LTPP Program Regions, which range from 69 to 72 percent, correspond to the high level selected for evaluation in this research.

Finally, regarding compaction delay time, the currently recognized maximum allowable delay of 2 hours was selected as the medium value, and low and high values were selected by subtracting and adding 1 hour, respectively. Although compaction delay less than 1 hour is probably achievable on soil-cement projects, average delays approaching just a few minutes are not expected due to the fact that typical rolling patterns require multiple passes of a compactor.

Control specimens were prepared according to the procedures outlined in the following sections except that they were not subjected to any environmental conditioning. That is, for the control specimens, the wind speed was 0 mph, the specimens were cured at room temperature inside sealed plastic bags, and the samples were compacted immediately after being mixed so that compaction delay was negligible. After compaction, control specimens were cured for 7 days, capped, and tested for UCS following the same protocols used for the rest of the specimens.

## Materials Characterization

Upon being delivered to the BYU Highway Materials Laboratory, both the aggregate base material and the subgrade soil selected for evaluation in this research were first dried at 230ºF and then separated over the 1/2-in., 3/8-in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves. A particle-size distribution was developed for each of the bulk materials as a basis for preparing replicate specimens. A washed sieve analysis was also performed to classify each material according to the Unified Soil Classification System (USCS) and the AASHTO method.

The AASHTO soil classifications were then used in conjunction with information provided by ACI in Table 4 to determine the low value of cement content to be used for evaluation of each material in this research. Specifically, the low value was based on obtaining a typical 7-day UCS as shown in Table 4, and the high value was determined by simply multiplying the lower value by three (ACI 1990). These resulting higher values were consistent with the recommended cement levels appropriate for materials subjected to frost action, as is the case with the native Utah materials used in this research. No cement content less than 1 percent was tested because fractional values below this percentage are not practical in the field. A Type I/II cement blend was provided by a local cement manufacturer for this research because the Utah Department of Transportation specifies the use of Type II or a mixed cement blend of Type II for soil-cement construction (UDOT 2005); this cement simultaneously satisfies the requirements for both Type I and Type II cements.

Initially, based on an estimated dry density and the previously established gradation for a given material, five to seven dry samples were weighed out in calculated quantities to produce specimens of the desired volume. Materials retained on the No. 4 sieve, or coarse fraction, were weighed out separately from those passing the No. 4 sieve, or fine fraction. In accordance with PCA protocol, the coarse fraction of each sample was soaked in de-ionized water for 24 hours prior to compaction (PCA 1992). Directly before compaction, the cement portion of the mixture was uniformly blended with the fine fraction prior to being mixed with the coarse fraction and varying amounts of water for moisture-density testing in accordance with ASTM D558 (Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures) Method B.

The base material was compacted into a 4-in.-diameter steel mold to a target height of 4.6 in. using modified Proctor compaction effort in accordance with ASTM D1557 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft$^3$ (2,700 kN-m/m$^3$))) Method B. The modified Proctor procedure requires compaction of the specimen in five lifts, with each lift consisting of 25 blows of a 10-lb hammer dropped from a height of 18 in. The subgrade was also compacted into a 4-in.-diameter steel mold to a target height of 4.6 in. However, standard Proctor compaction effort was used for the subgrade in accordance with ASTM D698 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft$^3$ (600 kN-m/m$^3$))) Method B. Standard compaction effort requires the use of a 5.5-lb hammer dropped from a height of 12 in. to compact the specimen in three lifts. The height and weight of each specimen were measured after compaction while the specimen remained in the steel mold. After extrusion, each specimen was dried at 230ºF to constant weight to facilitate determination of moisture content. OMC and MDD were determined for each soil-cement combination from the resulting moisture-density plots prepared from the collected data.

## Testing

After completion of moisture-density testing, two replicates of each soil-cement combination were prepared at OMC for UCS testing following the same mixing and compaction procedures outlined in the previous section; these specimens were control specimens. For specimens prepared to investigate the levels of the different factors described in Table 5, a conditioning process was required after the normal mixing procedure, however. After the soil, cement, and water were mixed together, the soil-cement was spooned into a 4-in.-diameter plastic mold in five lifts for the base and three lifts for the subgrade. A target of 80 percent relative compaction was used to simulate the condition of soil-cement in the field just after mixing. Therefore, each lift was consolidated by dropping the mold two to three times from 1 to 2 in. above the laboratory work bench so that, after all the material was loaded, the soil-cement was level with the top of the mold as depicted in Figure 3. The molds for the base and subgrade materials were 5.5 and 7.0 in. in height, respectively. This laboratory approach was designed to simulate field conditions, in which the ambient wind speed, air temperature, and relative humidity interact directly with the surface of the soil-cement.

Immediately after the soil-cement was loaded, the sample was placed in a computer-controlled environmental chamber within the BYU Highway Materials Laboratory, where it was subjected to one of the unique combinations of wind speed, temperature, relative humidity, and compaction delay selected for evaluation in this research. To reduce any fluctuation in air temperature or relative humidity that may have occurred with opening the main door of the environmental chamber to insert or retrieve the samples, an inner room was built of structural timber inside the environmental chamber, as depicted in Figure 4, with a small door that allowed easy sample access. Within the inner room, samples were placed at locations in front of a box fan that experienced wind speeds of 0, 5, and 10 mph, as confirmed using a handheld anemometer, while the environmental chamber maintained the temperature and relative


**Figure 3. Specimen of base material prepared for conditioning**.

**Figure 4. Access to inner room of environmental chamber**.

humidity at specified values. Samples to be conditioned for 1, 2, and 3 hours were tested simultaneously in groups of two or three, when possible, for efficiency.

Once removed from the environmental chamber, the conditioned soil-cement samples were emptied into a bowl and immediately compacted. Care was taken so that the soil was not remixed in the bowl but rather spooned directly into the compaction mold in uniform lifts, as described previously, because in most cases soil-cement would not be remixed prior to compaction at a construction site. As stated earlier, the base and subgrade materials were compacted following modified and standard Proctor procedures, respectively. To minimize changes in moisture content of soil-cement material during compaction, the bowls were placed in plastic bags during the compaction process. After a specimen was compacted following either standard or modified Proctor procedures, it was then extruded from the mold, sealed in a plastic bag, and cured at room temperature for 7 days for consistency with the control specimens.

After the 7-day cure, all specimens were soaked for 4 hours according to PCA guidelines in preparation for UCS testing (PCA 1992). The height and weight of each specimen were measured immediately following the 4-hour soak to facilitate calculation of wet density. Next, the specimens were capped with a high-strength gypsum compound placed on each end of every specimen to create a level testing surface for equal load distribution. The specimens were covered with plastic while the caps were drying in order to minimize moisture loss before UCS testing.

Directly after the capping compound was sufficiently dry, which usually required approximately 45 minutes for both ends, the specimens were then ready for UCS testing according to ASTM D1633 (Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders) Method A. The test was performed on a compression machine at a constant strain rate of 0.05 in./minute using a floating bottom platen, and the compressive strength was calculated by dividing the maximum load sustained by the specimen by the nominal cross-sectional area of the specimen. The capping compound was then quickly removed from both ends of the specimen, which was immediately weighed and placed in an oven at 230ºF for drying to constant weight so that moisture content could be computed. The resulting moisture content and previously calculated wet density were then used to determine the dry density of each specimen. Relative compaction was subsequently calculated by dividing the measured dry density for a test specimen by the MDD for the given soil-cement combination. Similarly, the relative strength of each specimen was calculated by dividing the measured 7-day UCS of a test specimen by the average 7-day UCS of the appropriate control specimens.

Following the laboratory strength testing, moisture profiles were constructed for two replicates of each soil-cement combination conditioned at the mean values of each environmental variable included in the testing: wind speed of 5 mph, temperature of 80ºF, relative humidity of 50 percent, and compaction delay of 2 hours. These samples were prepared in the same manner in which the UCS test specimens were prepared except that the molds in which they were placed were split and taped together prior to being filled. Then, instead of being compacted after conditioning was complete, these samples were divided into five approximately equal lifts. The samples were laid on their sides, the tape was cut, and the top half of each mold was slid down the specimen incrementally as the soil-cement was removed in approximately 1-in. lifts for the base and approximately 1.5-in. lifts for the subgrade. Each lift was weighed after removal, and all five lifts were dried at 230ºF to constant weight to enable calculation of moisture content with depth.

## Statistical Analysis

Upon completion of testing, a fixed effects analysis of variance (ANOVA) was performed on both relative strength and relative compaction, the primary dependent variables in this research and properties often used as measures of soil-cement construction quality. The null hypothesis in each case was that the value of the dependent variable did not depend on the level of the independent variable, while the alternative hypothesis was that the value of the dependent variable did depend on the level of the independent variable. Independent variables evaluated for each material type included cement content, wind speed, temperature, relative humidity, and compaction delay. When the *p*-value was less than or equal to the statistical Type I error rate of 0.05, the null hypothesis was rejected and the alternative hypothesis accepted. However, if the *p*-value was greater than 0.05, the null hypothesis could not be rejected.

The main effects of the independent variables on the dependent variables were determined by computing the average values of the dependent variables for each level of each independent variable. Interactions were not evaluated because the levels of the independent variables were not crossed in the experimental design. As a comparison of the relative strength and relative compaction variables, a correlation chart was also produced.

Then, because relative strength is of primary interest in this research, further analyses were performed on that dependent variable. Specifically, regression analysis was performed to develop a best-fit relationship between the independent variables and relative strength for each of the material types evaluated in this research. Initially, Mallows' Cp statistic was used to select the best-fit model in each case, in which linear and squared terms associated with each independent variable were utilized together with all possible interactions. This approach resulted in selection of the best-fit model characterized as having a minimum Cp statistic as defined in Equation 1 (Ramsey and Schafer 2002):

$$Cp = p + (n - p)\frac{\left(\hat{\sigma}^2 - \hat{\sigma}^2_{full}\right)}{\hat{\sigma}^2_{full}} \qquad (1)$$

where:

$Cp$ = Mallows' Cp Statistic
$p$ = number of regression coefficients
$n$ = number of all observations
$\hat{\sigma}^2$ = estimate of variance for the tentative model
$\hat{\sigma}^2_{full}$ = estimate of variance for model with all possible explanatory variables

In short, this approach assigns a penalty to each variable, and, if the benefits of including the variable are greater than the assigned penalty, as reflected by a lower adjusted $R^2$ value, the variable is included in the model (Ramsey and Schafer 2002). While the standard $R^2$ value, which was also computed, describes the percentage of the variability in the dependent variable that can be described by variability in the independent variable, the adjusted $R^2$ value is a measure of the efficiency of the model (Ramsey and Schafer 2002).

Following standard statistical practice, each of the best-fit models was then modified as needed to ensure inclusion of the linear term of each independent variable that was included as a squared term or as part of an interaction term in the initial model. After these modifications, the coefficients of some squared and interaction terms were not estimable because the experiment was not fully crossed. In effect, these squared and interaction terms were absorbed into the linear terms added into the model and were subsequently deleted.

Once the regression analyses were complete for both the base and subgrade materials, the independent variables were systematically varied as shown in Table 6, and predicted relative strength values in each case were computed for all possible 6,660 combinations using the previously determined best-fit relationships. These artificial data sets were then used to assess relationships among the independent variables at fixed relative strength values for each of the materials. The values of relative strength that were of interest to the researchers were the 5 percent lower bounds for three 90 percent confidence intervals computed for each of the artificial data sets. In particular, the lower bounds of 90-percent confidence intervals associated with predicted relative strengths of 85, 90, and 95 percent were of interest. These values correspond to typical boundaries associated with reductions in pay, with the value of 85 percent sometimes set as a limit below which the contractor may have to remove and replace the soil-cement.

The values of predicted relative strength within the artificial data sets were therefore organized into three non-inclusive ranges of 84 to 86 percent, 89 to 91 percent, and 94 to 96 percent for each material type. Table 7 displays the number of values within the artificial data sets that met the search criteria in each case. Each of the resulting six sets of values was then analyzed, again using Mallows' Cp statistic, for the purpose of quantifying the relationship between compaction delay time and the other independent variables for a given material type and range in relative strength. In these analyses, however, none of the interaction terms were allowed to be included in the best-fit model, as this complexity could not be readily addressed in the nomographs subsequently prepared to solve each of the resulting regression equations. Thus, only linear and squared terms associated with cement content, wind speed, air temperature, and relative humidity were available for consideration as independent variables in developing each

**Table 6. Values of Independent Variables Used to Populate Artificial Data Set**

| Variable | Unit | Values |
|---|---|---|
| Cement | % of dry soil or aggregate weight | 1, 3, 9 |
| Delay | minute | 0 to 180 on intervals of 5 |
| Wind | mph | 0, 5, 10 |
| Temperature | $^oF$ | 60, 70, 80, 90, 100 |
| Humidity | % | 25, 35, 45, 55, 65, 75 |

**Table 7. Number of Data Points Used to Determine Regression Equations**

| Material Type | Lower Bound (%) | Number of Data Points |
|---|---|---|
| Base | 85 | 228 |
| | 90 | 186 |
| | 95 | 143 |
| Subgrade | 85 | 209 |
| | 90 | 167 |
| | 95 | 143 |

model for delay time. As before, both the $R^2$ and adjusted $R^2$ values were computed for each regression.

Once the equations were finalized for each combination of material type and lower bound on relative strength, nomographs were produced as simple tools for engineers and contractors to use in the field for determining the allowable compaction delay time for a given set of environmental conditions. The use of nomographs to represent complex equations is a routine practice in materials engineering (Mindess 2003, Huang 2004) and is a graphical method of displaying the ranges in independent variables for which a given equation is valid. The nomographs are a primary product of this research.

## Summary

Specific factors selected for investigation in this research included material type, cement content, wind speed, temperature, relative humidity, and compaction delay. The laboratory work involved testing of two different materials, an aggregate base material and a subgrade soil, each treated with two levels of cement. Each of the material types was systematically tested at low, medium, and high values of wind speed, air temperature, relative humidity, and compaction delay. Wind speeds of 0, 5, and 10 mph; air temperatures of 60, 80, and 100ºF; relative humidities of 25, 50, and 75 percent; and compaction delay times of 1, 2, and 3 hours were evaluated.

After environmental conditioning, base and subgrade specimens were compacted using modified and standard Proctor methods, respectively, and then sealed in a plastic bag and cured at room temperature for 7 days. Following the curing period, the specimens were subjected to UCS testing. Relative strength and relative compaction were then computed and analyzed as the primary dependent variables in this research. The collected data were analyzed using a fixed-effects ANOVA and regression techniques to quantify the significance of the main effects and to produce regression equations for each material type. Based on the final equations, nomographs were produced relating material and environmental factors to allowable delay time for specified lower bounds in relative strength of 85, 90, and 95 percent.

# RESULTS AND ANALYSIS

## Overview

This section presents the findings from materials characterization, testing, and statistical analyses. All results presented in this section are limited in their application to the material types and ranges of the independent variables used in the experimental design in this research.

## Materials Characterization

The results of the washed sieve analyses are presented in Table 8 and Figure 5. As stated in the experimental methodology section, both the base and the subgrade were classified using both the USCS and AASHTO methods. The base was classified in the USCS as GP-GM, poorly graded gravel with silt and sand, and as A-1-a in the AASHTO method. The subgrade was classified in the USCS as ML, inorganic sandy silt, and as A-4 in the AASHTO method. Based on the AASHTO soil classifications, in particular, cement contents of 1 and 3 percent were chosen for the base material, and cement contents of 3 and 9 percent were chosen for the subgrade material. Cement percentages were based on the dry weight of the base and subgrade materials. The OMC and MDD values determined for each soil-cement combination are presented in Table 9.

**Table 8. Particle-Size Distributions**

| Sieve Size | Percent Passing (%) | |
|---|---|---|
| | Base | Subgrade |
| 3/4 in. | 100.0 | 100.0 |
| 1/2 in. | 82.6 | 100.0 |
| 3/8 in. | 68.4 | 100.0 |
| No. 4 | 46.1 | 95.9 |
| No. 8 | 31.7 | 92.8 |
| No. 16 | 23.2 | 91.1 |
| No. 30 | 18.6 | 90.1 |
| No. 50 | 15.4 | 89.3 |
| No. 100 | 11.2 | 85.1 |
| No. 200 | 6.6 | 72.6 |

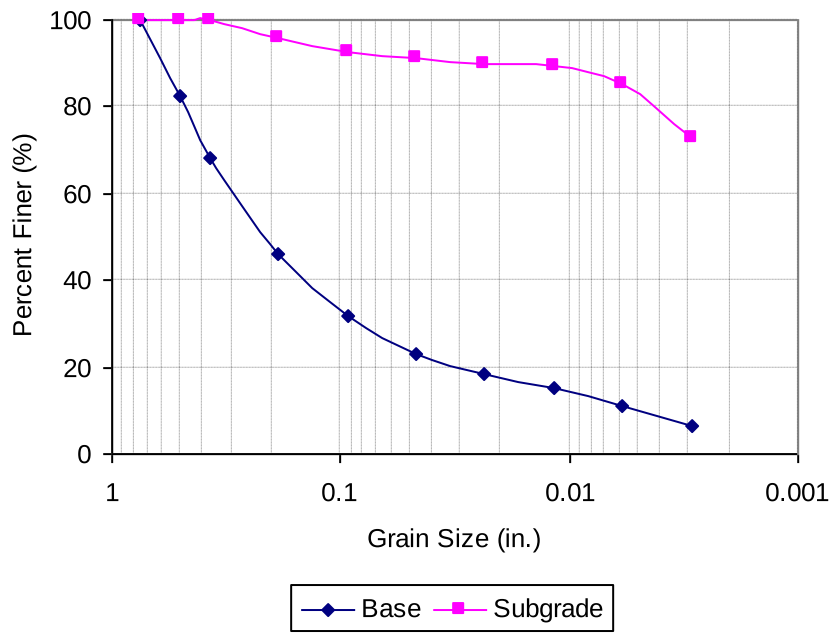


**Figure 5. Particle-size distributions**.

**Table 9. OMC and MDD Values**

| Material Type | Cement Content (%) | Optimum Moisture Content (%) | Maximum Dry Density (pcf) |
|---|---|---|---|
| Base | 1 | 6.2 | 141.1 |
| | 3 | 6.2 | 141.8 |
| Subgrade | 3 | 13.7 | 114.5 |
| | 9 | 14.3 | 115.6 |

## Testing

The UCS test results for all of the soil-cement combinations evaluated in this research for the base and subgrade materials are presented in Tables 10 and 11, respectively. These data are the basis for the statistical analyses given in the next section.

The average moisture profiles computed for base and subgrade samples after environmental conditioning at 5 mph, 80ºF, and 50 percent relative humidity for 2 hours are presented in Figure 6. The variation in moisture content for the base material was negligible with sample height, although both moisture profiles suggest that some water may have drained to the bottom of the mold during the conditioning process. Unlike the base, the subgrade behaved as anticipated by losing a significant amount of water in the upper layer, attributable to evaporation during conditioning, while maintaining a relatively constant moisture content throughout the lower lifts. After conditioning, the average water contents for the bulk specimens were below OMC by 0.9, 0.8, 0.4, and 0.5 percentage points for base with 1 percent cement, base with 3 percent cement, subgrade with 3 percent cement, and subgrade with 9 percent cement, respectively. In both materials, lower overall water contents were associated with lower cement contents.

**Table 10. Test Results for Base Material**

| Cement Content (%) | Delay Time (hr) | Wind Speed (mph) | Temperature (ºF) | Relative Humidity (%) | Specimen | Unconfined Compressive Strength (psi) | Dry Density (pcf) |
|---|---|---|---|---|---|---|---|
| 1 | Control | | | | 1 | 393 | 141.0 |
| 1 | Control | | | | 2 | 492 | 141.2 |
| 1 | 1 | 5 | 80 | 50 | 1 | 427 | 139.7 |
| 1 | 1 | 5 | 80 | 50 | 2 | 396 | 138.7 |
| 1 | 2 | 0 | 80 | 50 | 1 | 404 | 138.2 |
| 1 | 2 | 0 | 80 | 50 | 2 | 262 | 138.2 |
| 1 | 2 | 5 | 60 | 50 | 1 | 333 | 137.4 |
| 1 | 2 | 5 | 60 | 50 | 2 | 405 | 139.0 |
| 1 | 2 | 5 | 80 | 25 | 1 | 271 | 137.5 |
| 1 | 2 | 5 | 80 | 25 | 2 | 318 | 137.6 |
| 1 | 2 | 5 | 80 | 50 | 1 | 315 | 137.5 |
| 1 | 2 | 5 | 80 | 50 | 2 | 215 | 135.9 |
| 1 | 2 | 5 | 80 | 75 | 1 | 323 | 138.6 |
| 1 | 2 | 5 | 80 | 75 | 2 | 338 | 138.5 |
| 1 | 2 | 5 | 100 | 50 | 1 | 214 | 136.4 |
| 1 | 2 | 5 | 100 | 50 | 2 | 179 | 135.8 |
| 1 | 2 | 10 | 80 | 50 | 1 | 335 | 137.3 |
| 1 | 2 | 10 | 80 | 50 | 2 | 256 | 137.3 |
| 1 | 3 | 5 | 80 | 50 | 1 | 255 | 137.4 |
| 1 | 3 | 5 | 80 | 50 | 2 | 234 | 135.2 |
| 3 | Control | | | | 1 | 1206 | 141.3 |
| 3 | Control | | | | 2 | 1022 | 142.3 |
| 3 | 1 | 5 | 80 | 50 | 1 | 981 | 139.7 |
| 3 | 1 | 5 | 80 | 50 | 2 | 1064 | 139.5 |
| 3 | 2 | 0 | 80 | 50 | 1 | 1167 | 138.8 |
| 3 | 2 | 0 | 80 | 50 | 2 | 944 | 138.6 |
| 3 | 2 | 5 | 60 | 50 | 1 | 1029 | 139.4 |
| 3 | 2 | 5 | 60 | 50 | 2 | 992 | 138.4 |
| 3 | 2 | 5 | 80 | 25 | 1 | 980 | 140.0 |
| 3 | 2 | 5 | 80 | 25 | 2 | 707 | 137.8 |
| 3 | 2 | 5 | 80 | 50 | 1 | 933 | 138.8 |
| 3 | 2 | 5 | 80 | 50 | 2 | 935 | 138.3 |
| 3 | 2 | 5 | 80 | 75 | 1 | 1156 | 137.6 |
| 3 | 2 | 5 | 80 | 75 | 2 | 957 | 140.5 |
| 3 | 2 | 5 | 100 | 50 | 1 | 805 | 139.6 |
| 3 | 2 | 5 | 100 | 50 | 2 | 805 | 139.6 |
| 3 | 2 | 10 | 80 | 50 | 1 | 945 | 133.6 |
| 3 | 2 | 10 | 80 | 50 | 2 | 890 | 138.9 |
| 3 | 3 | 5 | 80 | 50 | 1 | 789 | 137.7 |
| 3 | 3 | 5 | 80 | 50 | 2 | 750 | 137.5 |

**Table 11. Test Results for Subgrade Material**

| Cement Content (%) | Delay Time (hr) | Wind Speed (mph) | Temperature (ºF) | Relative Humidity (%) | Specimen | Unconfined Compressive Strength (psi) | Dry Density (pcf) |
|---|---|---|---|---|---|---|---|
| 3 | Control | | | | 1 | 272 | 114.7 |
| | | | | | 2 | 308 | 114.3 |
| | 1 | 5 | 80 | 50 | 1 | 259 | 104.0 |
| | | | | | 2 | 229 | 110.7 |
| | 2 | 0 | 80 | 50 | 1 | 227 | 107.9 |
| | | | | | 2 | 215 | 108.1 |
| | | 5 | 60 | 50 | 1 | 237 | 109.9 |
| | | | | | 2 | 236 | 109.2 |
| | | | 80 | 25 | 1 | 187 | 107.4 |
| | | | | | 2 | 236 | 109.1 |
| | | | | 50 | 1 | 154 | 106.8 |
| | | | | | 2 | 219 | 109.4 |
| | | | | 75 | 1 | 228 | 87.9 |
| | | | | | 2 | 224 | 109.0 |
| | | | 100 | 50 | 1 | 143 | 105.9 |
| | | | | | 2 | 189 | 107.1 |
| | | 10 | 80 | 50 | 1 | 224 | 108.8 |
| | | | | | 2 | 200 | 108.6 |
| | 3 | 5 | 80 | 50 | 1 | 232 | 112.5 |
| | | | | | 2 | 190 | 106.8 |
| 9 | Control | | | | 1 | 631 | 115.1 |
| | | | | | 2 | 693 | 116.1 |
| | 1 | 5 | 80 | 50 | 1 | 610 | 111.1 |
| | | | | | 2 | 563 | 112.0 |
| | 2 | 0 | 80 | 50 | 1 | 443 | 108.6 |
| | | | | | 2 | 472 | 109.0 |
| | | 5 | 60 | 50 | 1 | 517 | 111.0 |
| | | | | | 2 | 441 | 110.1 |
| | | | 80 | 25 | 1 | 454 | 109.3 |
| | | | | | 2 | 439 | 109.3 |
| | | | | 50 | 1 | 424 | 109.0 |
| | | | | | 2 | 345 | 108.6 |
| | | | | 75 | 1 | 515 | 109.4 |
| | | | | | 2 | 509 | 105.1 |
| | | | 100 | 50 | 1 | 428 | 107.2 |
| | | | | | 2 | 302 | 106.9 |
| | | 10 | 80 | 50 | 1 | 451 | 108.4 |
| | | | | | 2 | 419 | 109.3 |
| | 3 | 5 | 80 | 50 | 1 | 366 | 104.6 |
| | | | | | 2 | 432 | 107.7 |

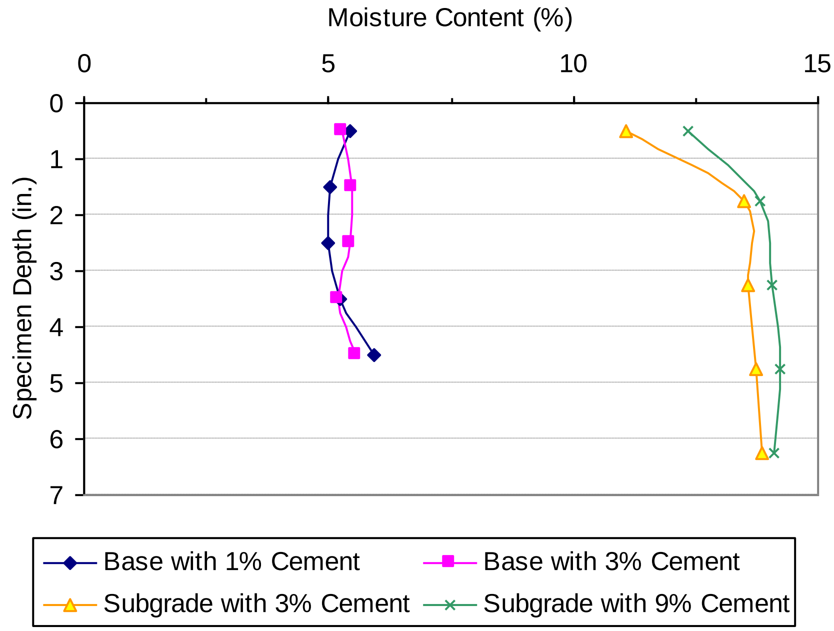


**Figure 6. Moisture profiles after conditioning.**

## Statistical Analysis

The results from each of the fixed-effects ANOVAs utilized to analyze the relative strength and relative compaction data are presented in Table 12. *P*-values less than or equal to 0.05 were computed for every independent variable evaluated with respect to relative strength but only for material type with respect to relative compaction. Thus, relative strength is sensitive to variability among these independent variables within the ranges investigated in this research, while relative compaction is not. Plots of the main effects of material type, cement content, wind speed, air temperature, relative humidity, and delay time on relative strength are given in Figures 7 to 12, respectively, while corresponding plots of the main effects of the same variables on relative compaction are given in Figures 13 to 18.

Consistent with theory, the subgrade material is more sensitive to environmental effects due to its higher cement content, with higher cement content corresponding to lower relative strength values, as shown in Figure 7, at the average values of wind speed, air temperature, relative humidity, and delay time evaluated in this research.

**Table 12. Significance Levels for Main Effects**

| Factor | *p*-Values | |
|---|---|---|
| | Relative Strength | Relative Compaction |
| Material | 0.0004 | <0.0001 |
| Cement Content | <0.0001 | 0.8401 |
| Wind Speed | 0.0197 | 0.9407 |
| Air Temperature | <0.0001 | 0.4009 |
| Relative Humidity | 0.0032 | 0.1248 |
| Delay Time | <0.0001 | 0.4521 |

Interestingly, as depicted in Figure 8, the base material exhibits higher relative strength values with increasing cement contents within the range of cement contents examined in this study; further research is needed to investigate the mechanism associated with this behavior, however. As expected, Figures 9 to 12 show that higher wind speed, higher air temperature, lower relative humidity, and higher compaction delay time generally result in lower relative strength, as increased evaporation of water from the soil-cement leads to inadequate moisture content for compaction and curing. Furthermore, higher air temperatures especially accelerate cement hydration, which resists subsequent densification of the soil-cement.

The only exception to the stated trends is the apparent effect of relative humidity on relative strength for the subgrade material displayed in Figure 11. The collected data suggest that relative strength improves slightly as relative humidity decreases from 50 to 25 percent, which is probably an artifact of the experimental process. If more specimen replicates had been tested, a monotonic trend would likely have resulted. Nonetheless, this result required elimination of the squared term for relative humidity from the best-fit model produced from the artificial data set for the subgrade material.

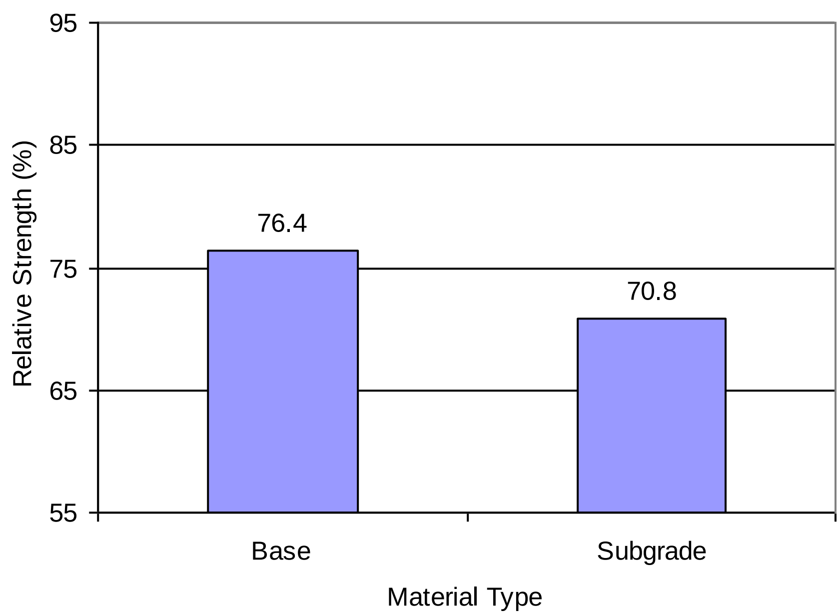


**Figure 7. Main effects of material type on relative strength.**

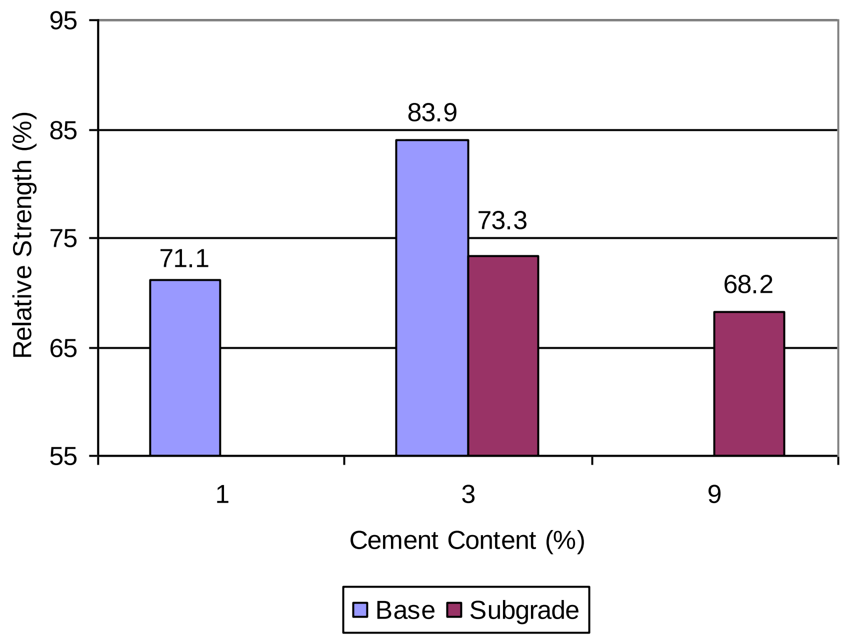


**Figure 8. Main effects of cement content on relative strength.**

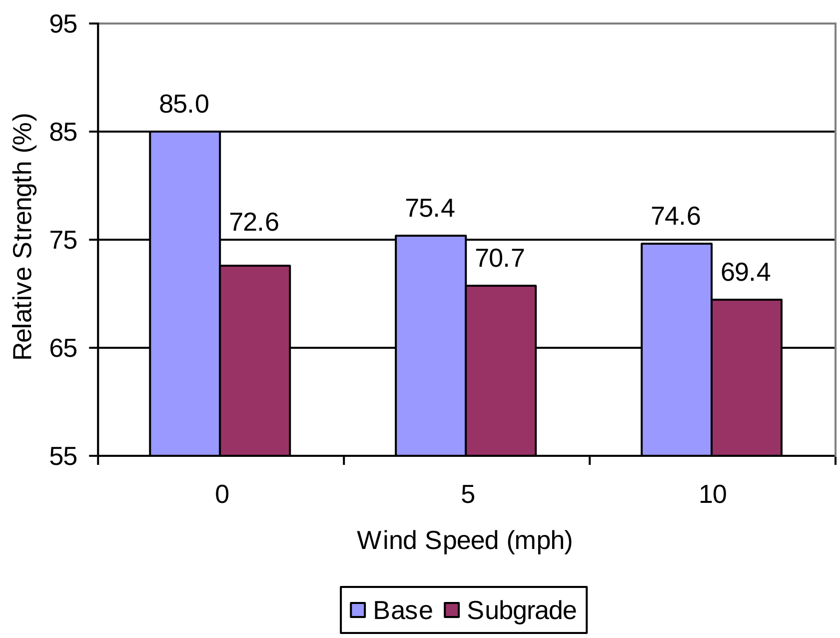


**Figure 9. Main effects of wind speed on relative strength.**

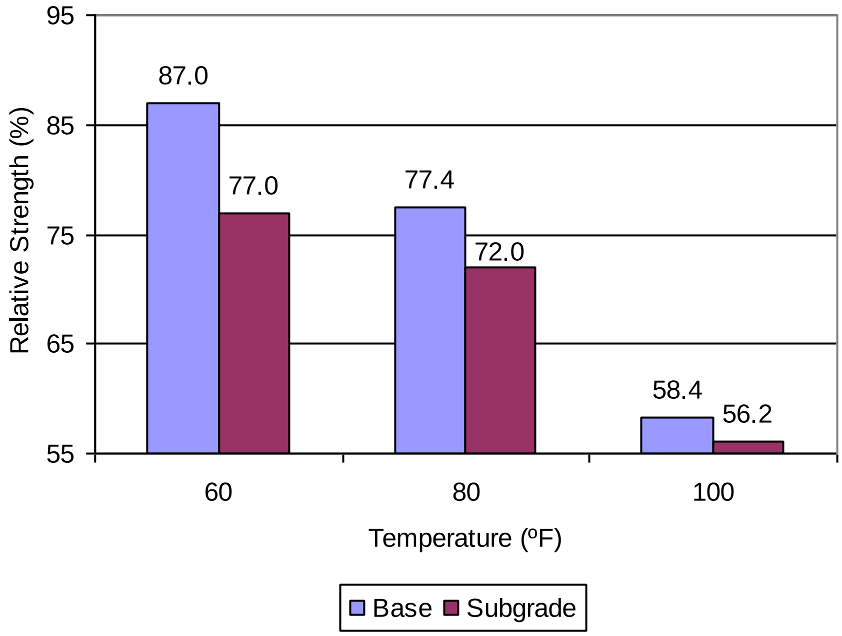


**Figure 10. Main effects of temperature on relative strength.**

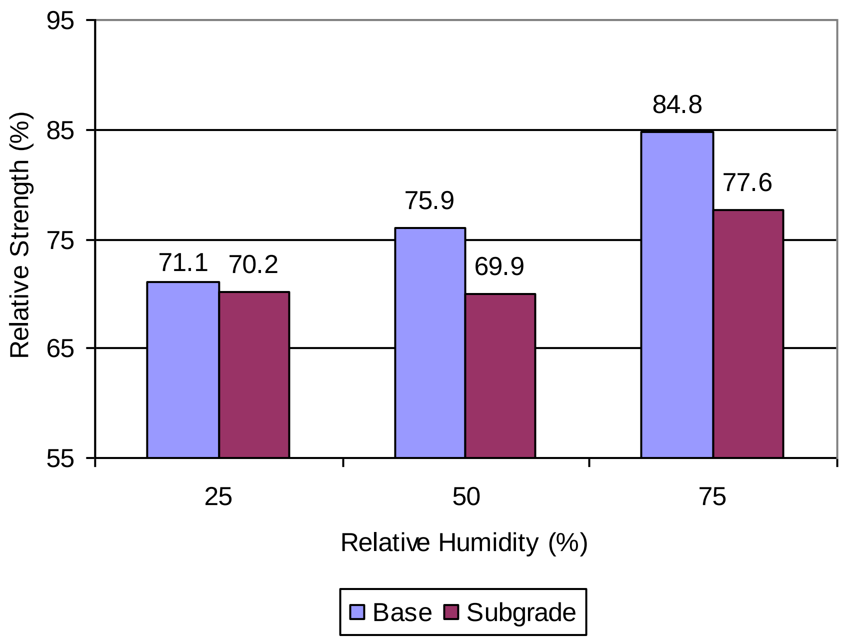


**Figure 11. Main effects of relative humidity on relative strength.**

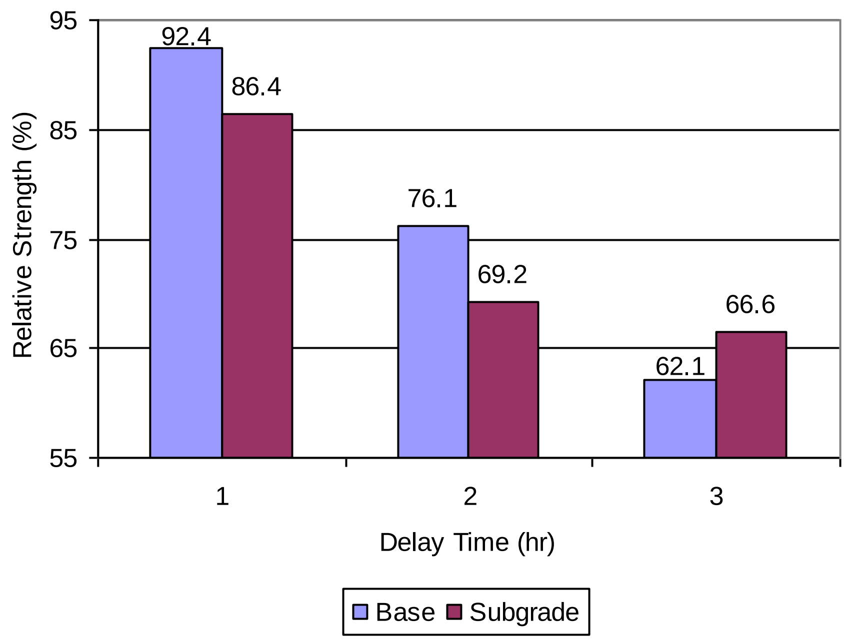


**Figure 12. Main effects of delay time on relative strength.**

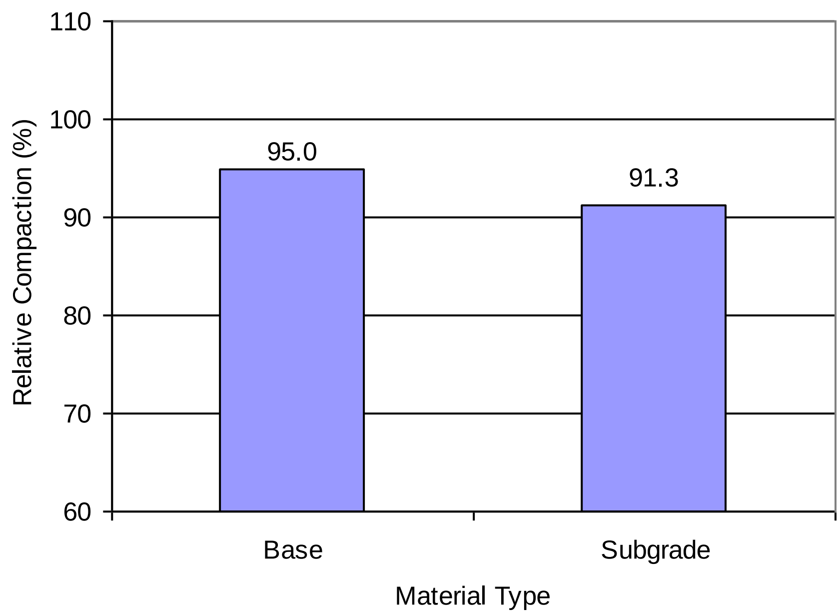


**Figure 13. Main effects of material type on relative compaction.**

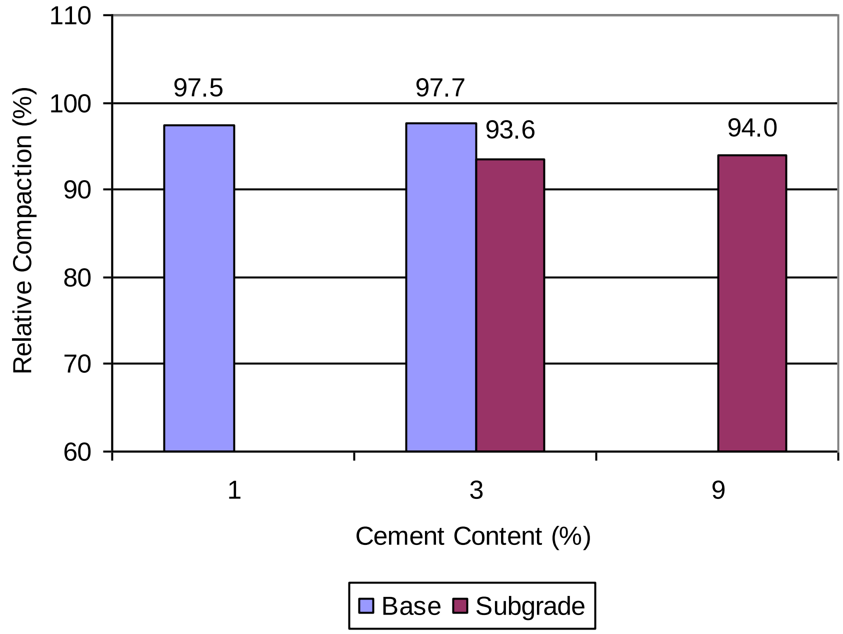


**Figure 14. Main effects of cement content on relative compaction.**

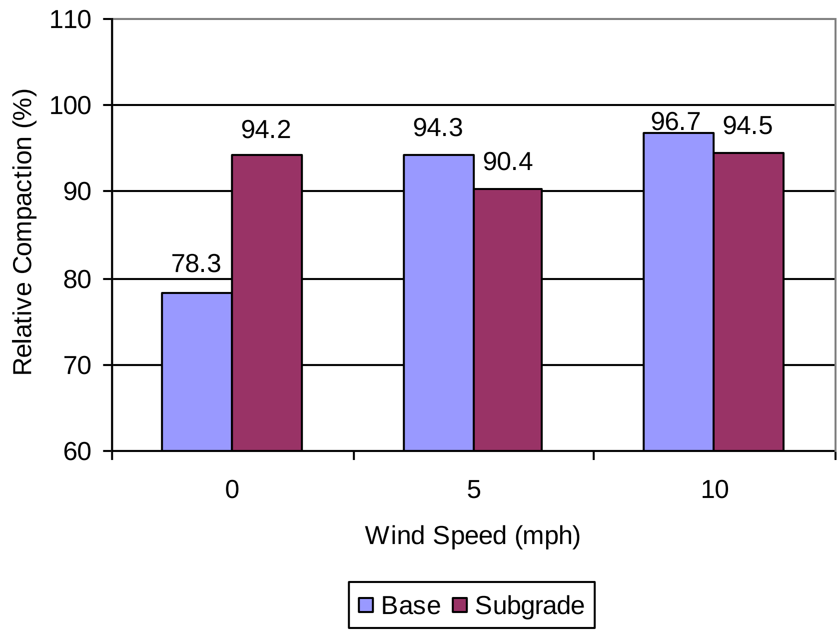


**Figure 15. Main effects of wind speed on relative compaction.**

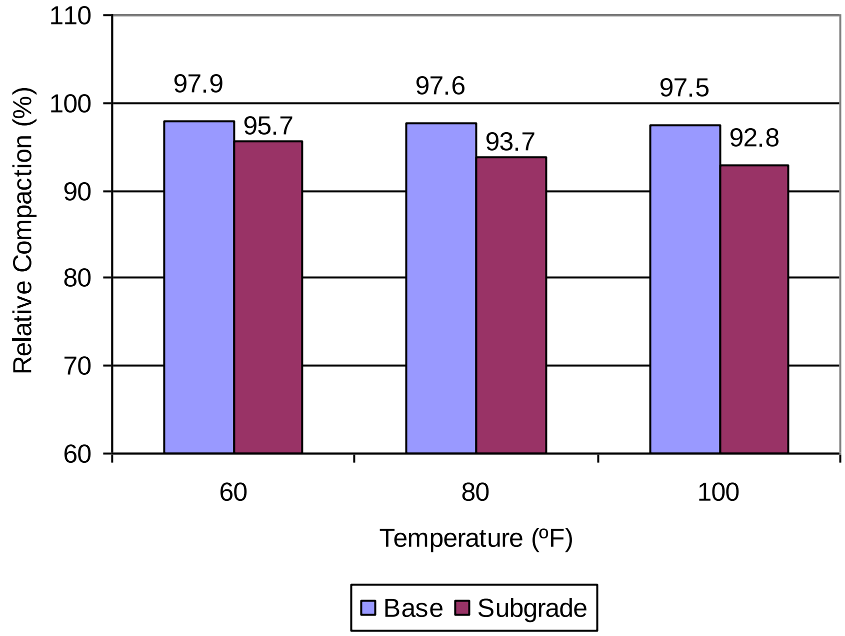


**Figure 16. Main effects of temperature on relative compaction.**

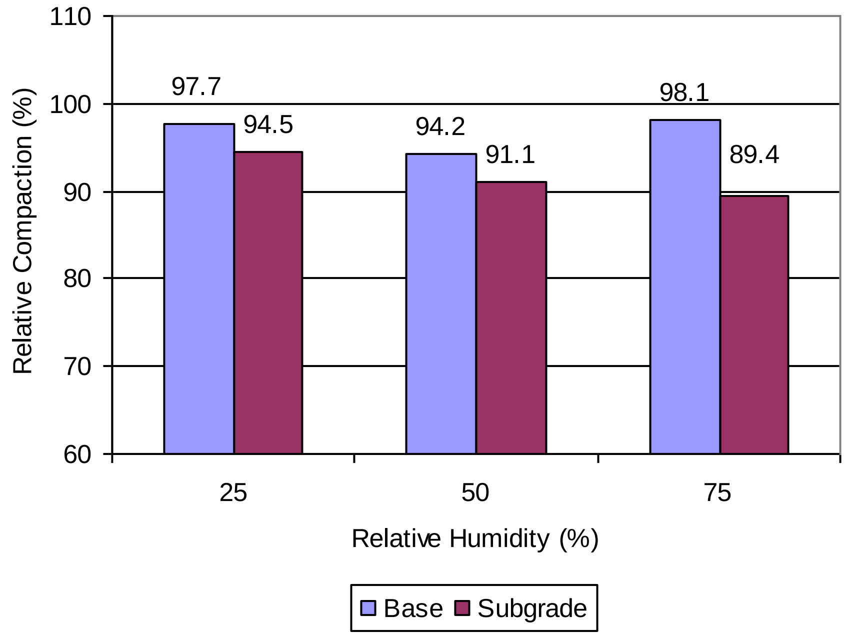


**Figure 17. Main effects of relative humidity on relative compaction.**

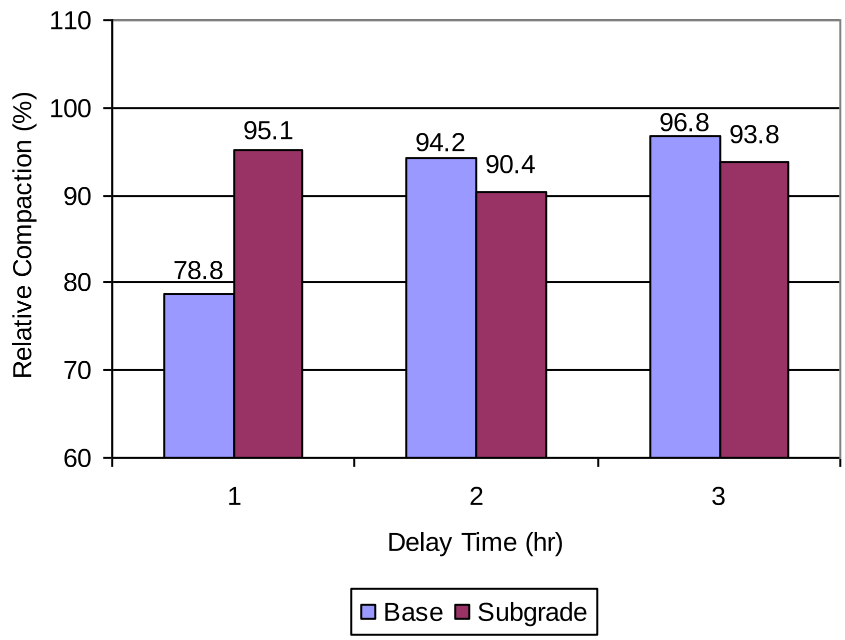


**Figure 18. Main effects of delay time on relative compaction.**

As previously mentioned, relative strength is sensitive to variability among these independent variables within the ranges investigated in this research, while relative compaction is not. The correlation chart given in Figure 19 highlights this observation; given the $R^2$ value of 0.0688, no meaningful relationship exists between relative compaction and relative strength. The severity of the situation is best illustrated by examining the main effects of air temperature for the base material at 100°F. If a state

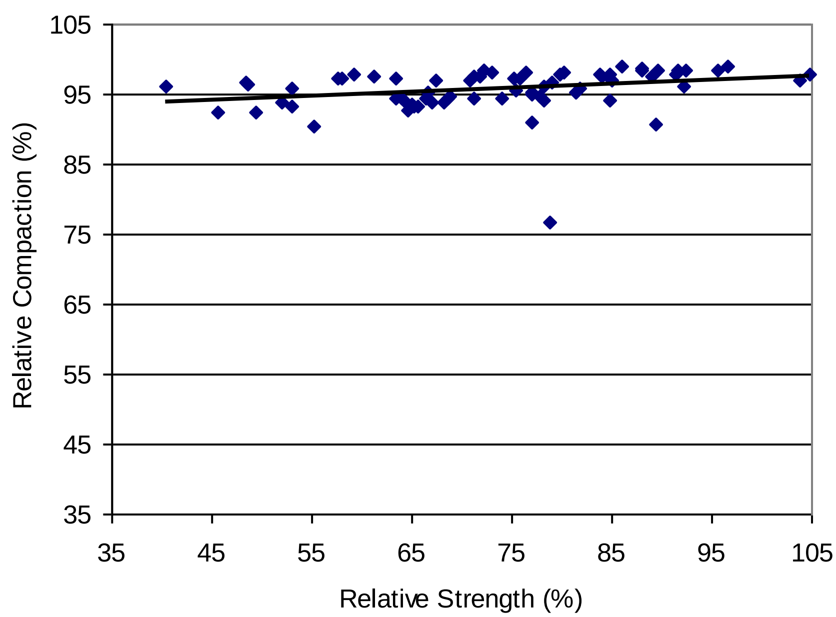


**Figure 19. Correlation between relative strength and relative compaction.**

department of transportation, for example, were to test a soil-cement project constructed at that temperature, a relative compaction of 97.5 percent, which would likely be satisfactory for any compaction standard, would be expected based on the data presented in Figure 16. However, the corresponding relative strength for that material would be expected to be just 58.4 percent as shown in Figure 10, and an inadequate material would therefore have been accepted on the project. Even though soil-cement achieves its highest strength where it is highest compacted, inferring relative strength from relative compaction is therefore not a reliable approach on soil-cement projects.

In this research, additional statistical analyses were therefore performed only on the relative strength data as described previously in the experimental methodology section. The resulting regression equations relating the independent variables and relative strength of the base and subgrade materials are given as Equations 2 and 3, respectively:

$$RSB = 76.67112 - 1.04272W + 1.17284T + 0.05740H + 2.16612C - 0.25238D - 0.01181T^2 + 0.10803C \cdot H \tag{2}$$

$$RSS = 174.73130 - 0.32660W - 0.52001T - 0.92018H + 1.98371C - 0.64031D - 0.02360C \cdot D + 0.00257D^2 + 0.01068H^2 \tag{3}$$

where:

*RSB* = relative strength of base material, %
*RSS* = relative strength of subgrade material, %
*W* = wind speed, mph
*T* = air temperature, ºF
*H* = relative humidity, %
*C* = cement content, % by dry weight of soil or aggregate
*D* = compaction delay time, minutes

The $R^2$ values associated with Equations 2 and 3 were computed to be 0.703 and 0.653, respectively, while the corresponding adjusted $R^2$ values were computed to be 0.629 and 0.550.

As described in the experimental methodology section, additional regression analyses were performed on these artificial data sets for the purpose of quantifying the relationship between compaction delay time and the other independent variables for a given material type and range in relative strength. While the regression equations for the base and subgrade materials included different terms, the terms were the same for regression equations prepared for the same material type as indicated in Equations 4 through 9:

$$DB_{85} = -371.95765 - 1.67886W - 0.32253W^2 + 9.39908T - 0.07897T^2 + 3.72089H - 0.02381H^2 + 36.27276C \tag{4}$$

$$DB_{90} = -429.77596 - 2.25797W - 0.27912W^2 + 9.88185T - 0.08231T^2 + 4.14002H - 0.02661H^2 + 38.30676C \quad (5)$$

$$DB_{95} = -491.67401 - 2.74499W - 0.23480W^2 + 10.21983T - 0.08540T^2 + 4.69278H - 0.02958H^2 + 41.94272C \quad (6)$$

$$DS_{85} = 156.50503 - 0.08657W - 0.09355W^2 - 2.16107T + 0.00416T^2 + 0.48305H + 2.24302C \quad (7)$$

$$DS_{90} = 141.84695 - 0.07148W - 0.08193W^2 - 2.38057T + 0.00672T^2 + 0.42954H + 2.87223C \quad (8)$$

$$DS_{95} = 113.81898 - 0.28141W - 0.04544W^2 - 2.16749T + 0.00634T^2 + 0.41273H + 3.18091C \quad (9)$$

where:

$DB_{85}$ = maximum delay time associated with minimum relative strength of 85 percent for base material, minutes
$DB_{90}$ = maximum delay time associated with minimum relative strength of 90 percent for base material, minutes
$DB_{95}$ = maximum delay time associated with minimum relative strength of 95 percent for base material, minutes
$DS_{85}$ = maximum delay time associated with minimum relative strength of 85 percent for subgrade material, minutes
$DS_{90}$ = maximum delay time associated with minimum relative strength of 90 percent for subgrade material, minutes
$DS_{95}$ = maximum delay time associated with minimum relative strength of 95 percent for subgrade material, minutes
$W$ = wind speed, mph
$T$ = air temperature, °F
$H$ = relative humidity, %
$C$ = cement content, % by dry weight of soil or aggregate

The $R^2$ values and associated adjusted $R^2$ values for these regression equations used to create the six base and subgrade nomographs are presented in Table 13.

**Table 13. $R^2$ Values**

| Material Type | Minimum Relative Strength (%) | $R^2$ Value | Adjusted $R^2$ Value |
|---|---|---|---|
| Base | 85 | 0.956 | 0.955 |
| | 90 | 0.951 | 0.949 |
| | 95 | 0.966 | 0.966 |
| Subgrade | 85 | 0.903 | 0.901 |
| | 90 | 0.910 | 0.907 |
| | 95 | 0.901 | 0.896 |

Figures 20 to 25 display the final products of the regression analyses performed in this research. As stated previously, these nomographs are intended for use by engineers and contractors in the field but are limited in their application to the material types and ranges of the independent variables used in the experimental design. When values for cement content, wind speed, air temperature, and relative humidity are known for a given project, the allowable delay time permitted for compaction of either a base or subgrade material similar to those tested in this research can be determined for target relative strengths of 85, 90, or 95 percent. The results of the nomographs will be most accurate when the soil-cement is properly sealed in the field against water evaporation, when average field temperatures are similar to room temperature, and when trafficking is not permitted for the first 7 days after construction.

To begin, the user must identify the wind speed on the left-most scale of the appropriate chart and then extend a straight line from that point through the cement content scale at the appropriate level to the first turning line; turning lines are marked as "TL." The user should then draw a second line segment from the point of termination of the first segment to the second turning line through the appropriate value on the temperature scale. A third line segment should be drawn from the point of termination of the second segment to the appropriate value on the relative humidity scale at the far right. This line segment will intersect the delay time scale at the maximum value recommended for the given conditions. If the final line segment falls below the delay time scale, the user should realize that the given set of conditions will not be conducive to achieving the specified target relative strength value. If acceptable, a lower relative strength value may be considered, requiring a different chart. However, using a set retarder, mixing at water contents above OMC, or constructing at night are other possible solutions for achieving target relative strength values. Extrapolation beyond the ranges of numerical values given for variables included in the nomographs is not recommended.

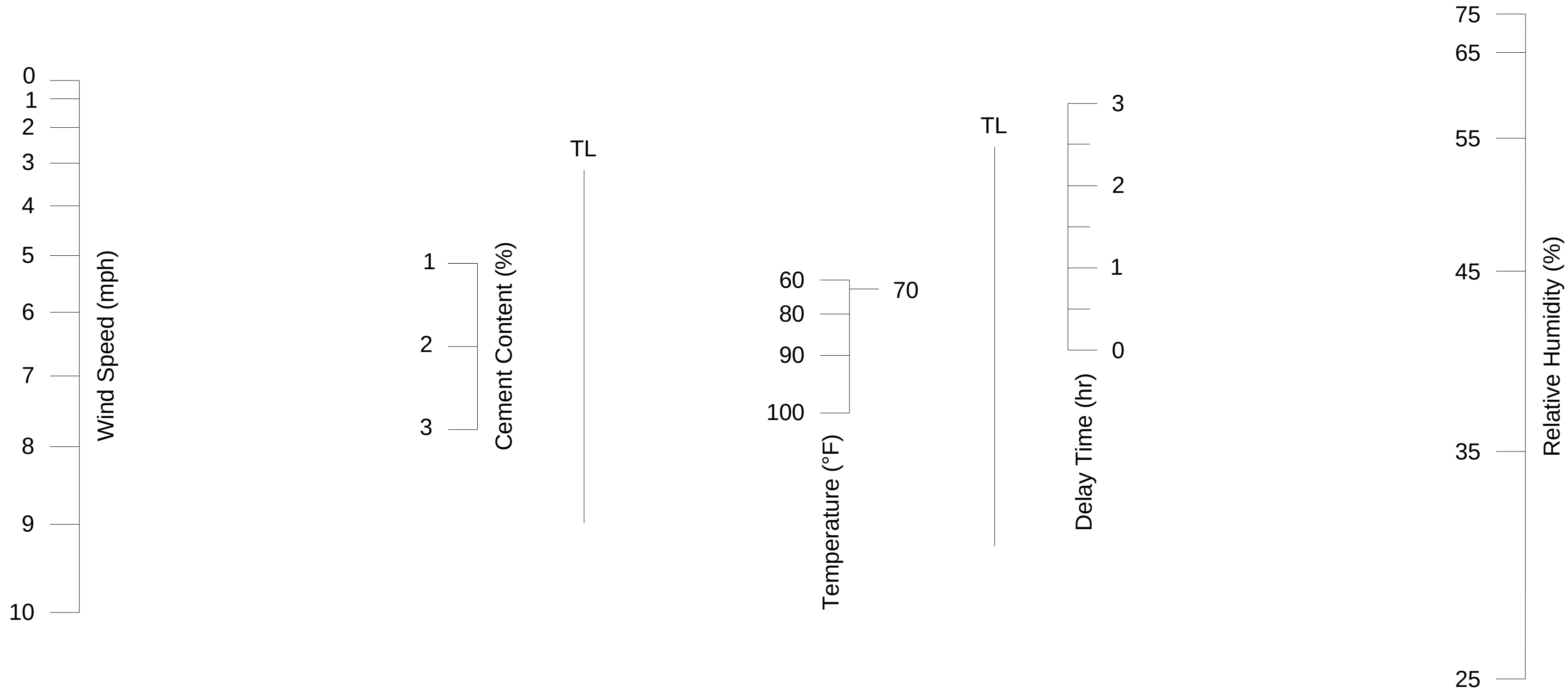


**Figure 20. Base nomograph for minimum of 85 percent relative strength.**

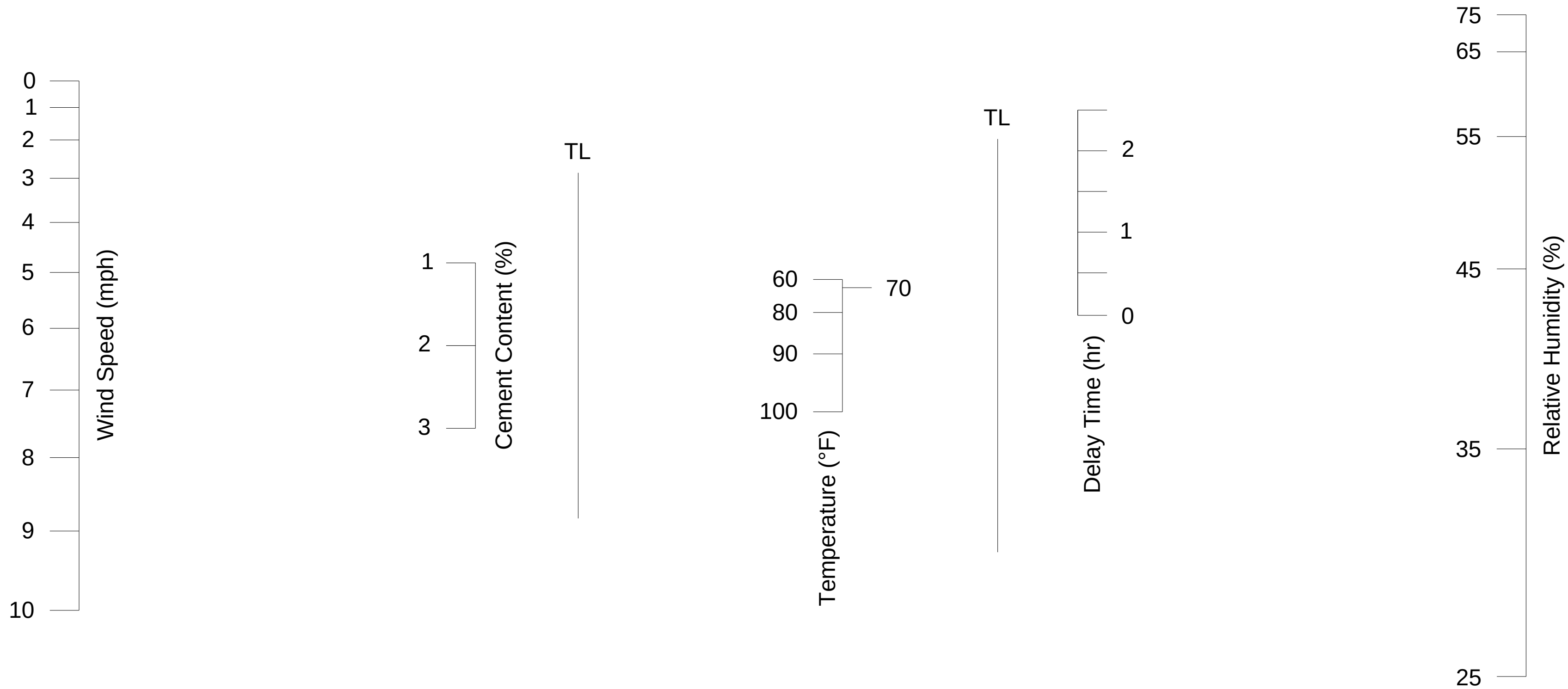


**Figure 21. Base nomograph for minimum of 90 percent relative strength.**

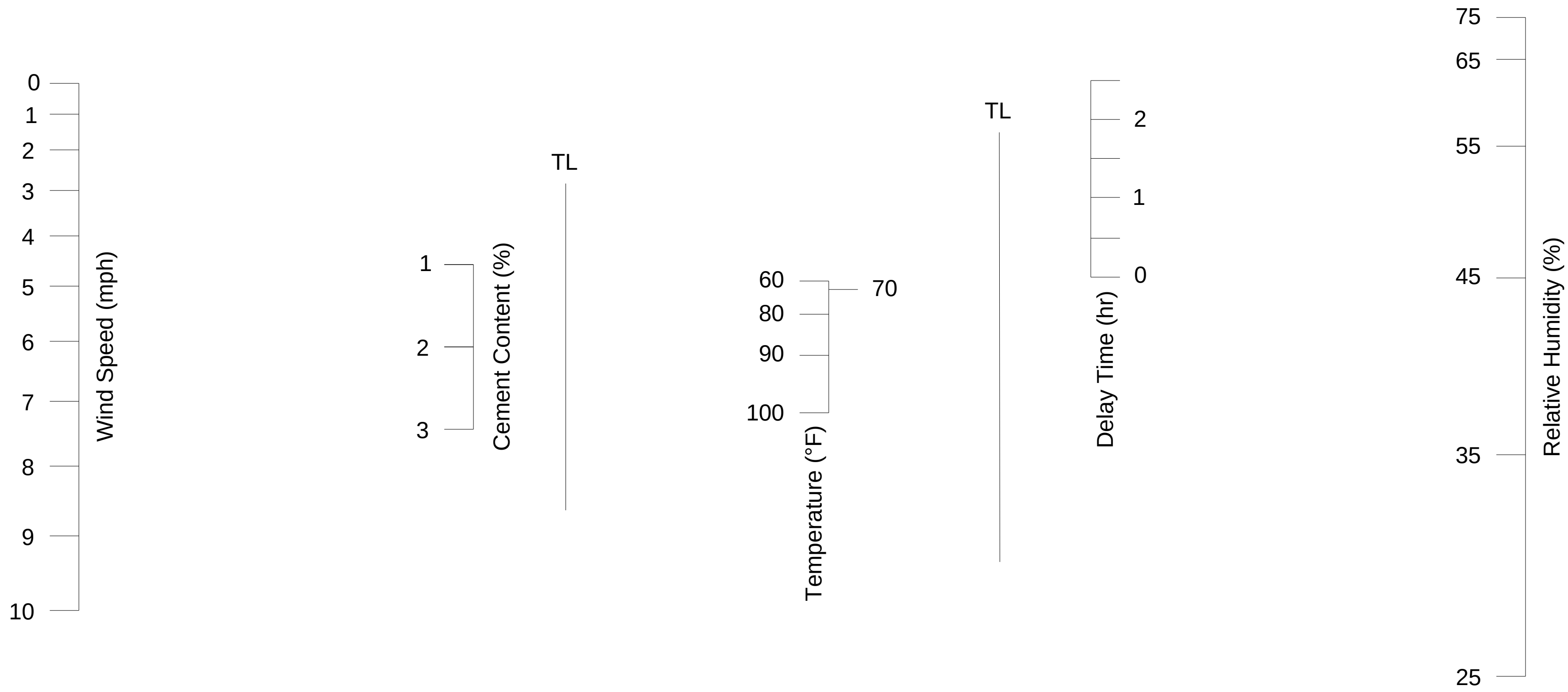


**Figure 22. Base nomograph for minimum of 95 percent relative strength.**

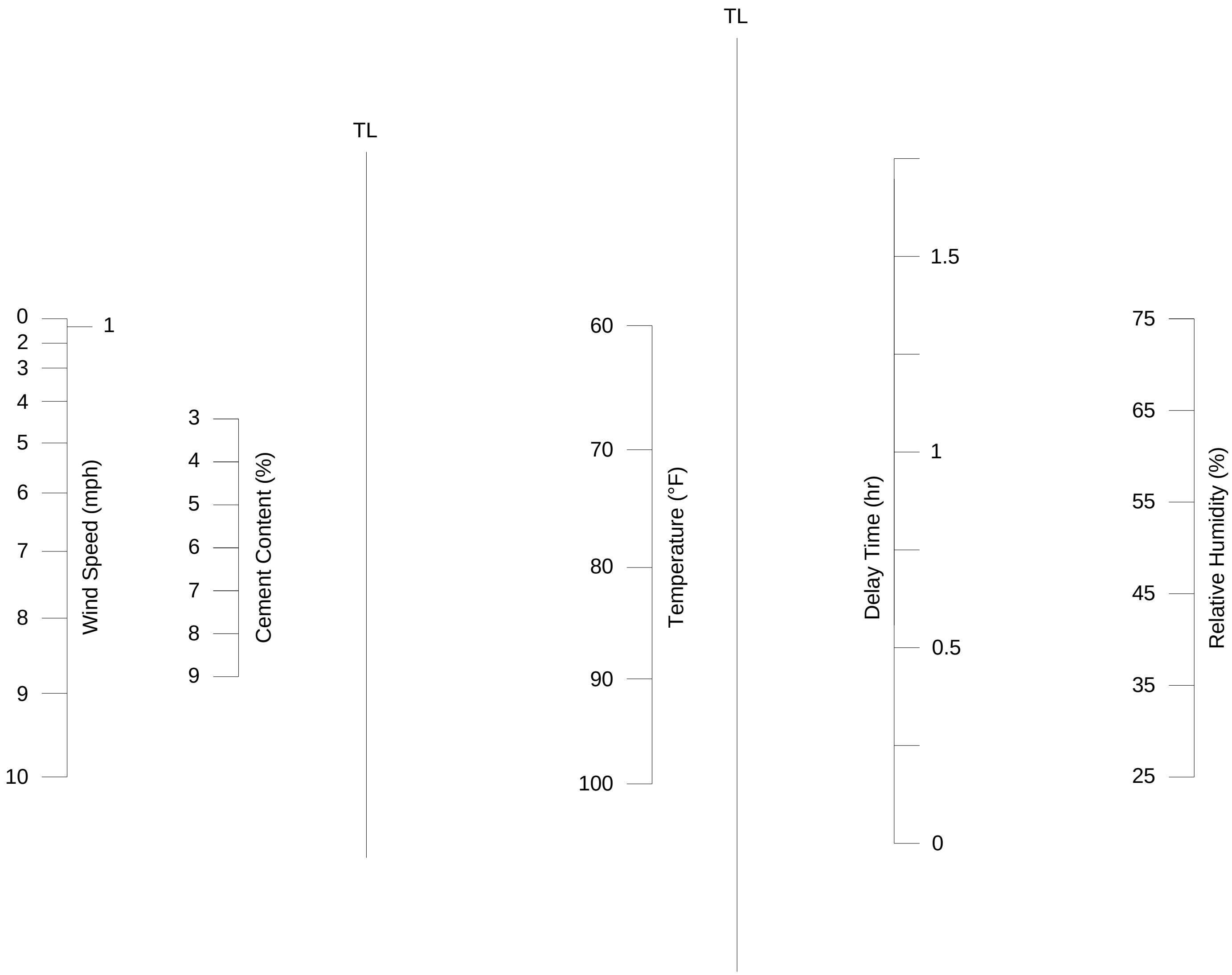


**Figure 23. Subgrade nomograph for minimum of 85 percent relative strength.**

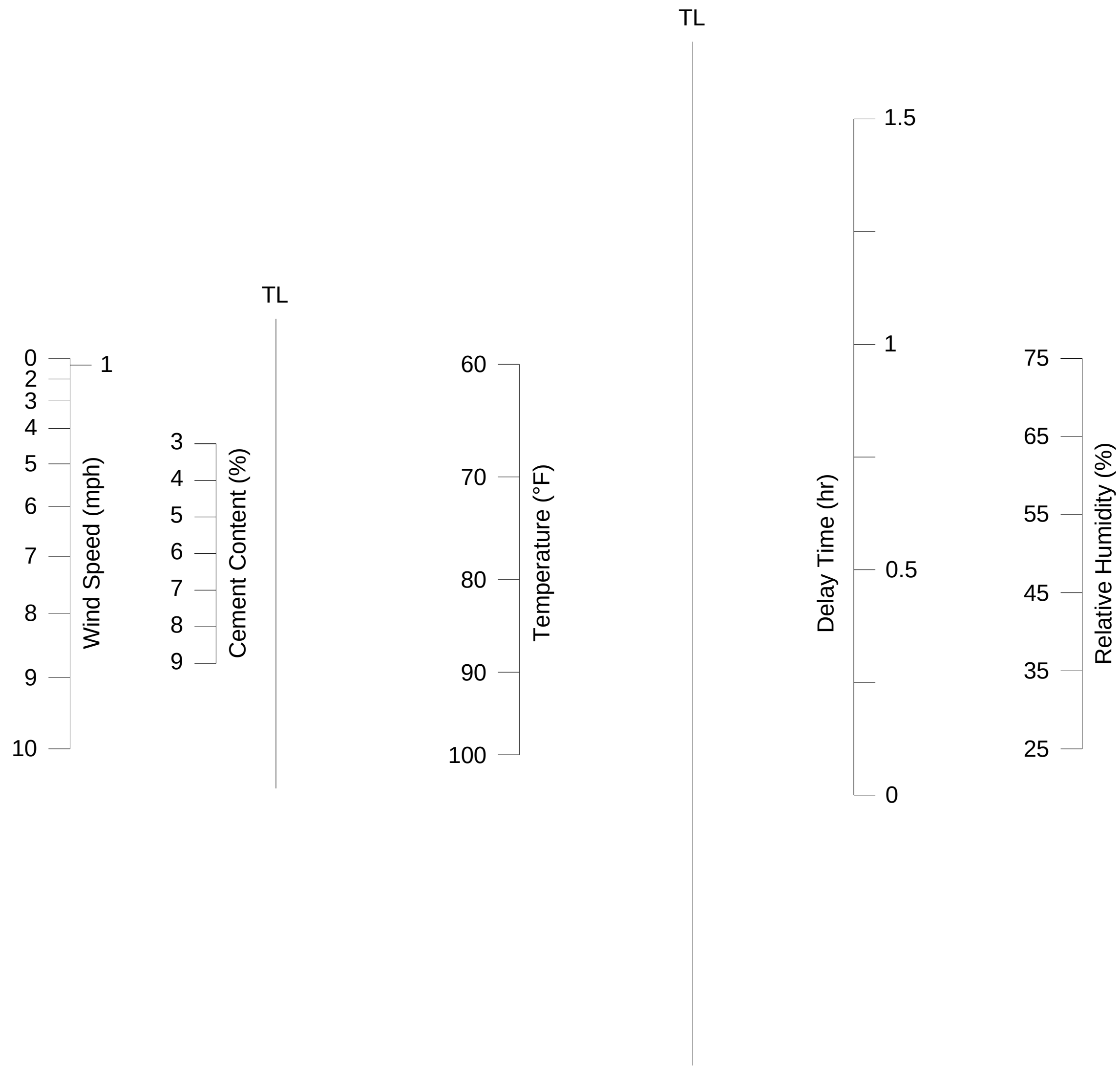


**Figure 24. Subgrade nomograph for minimum of 90 percent relative strength.**

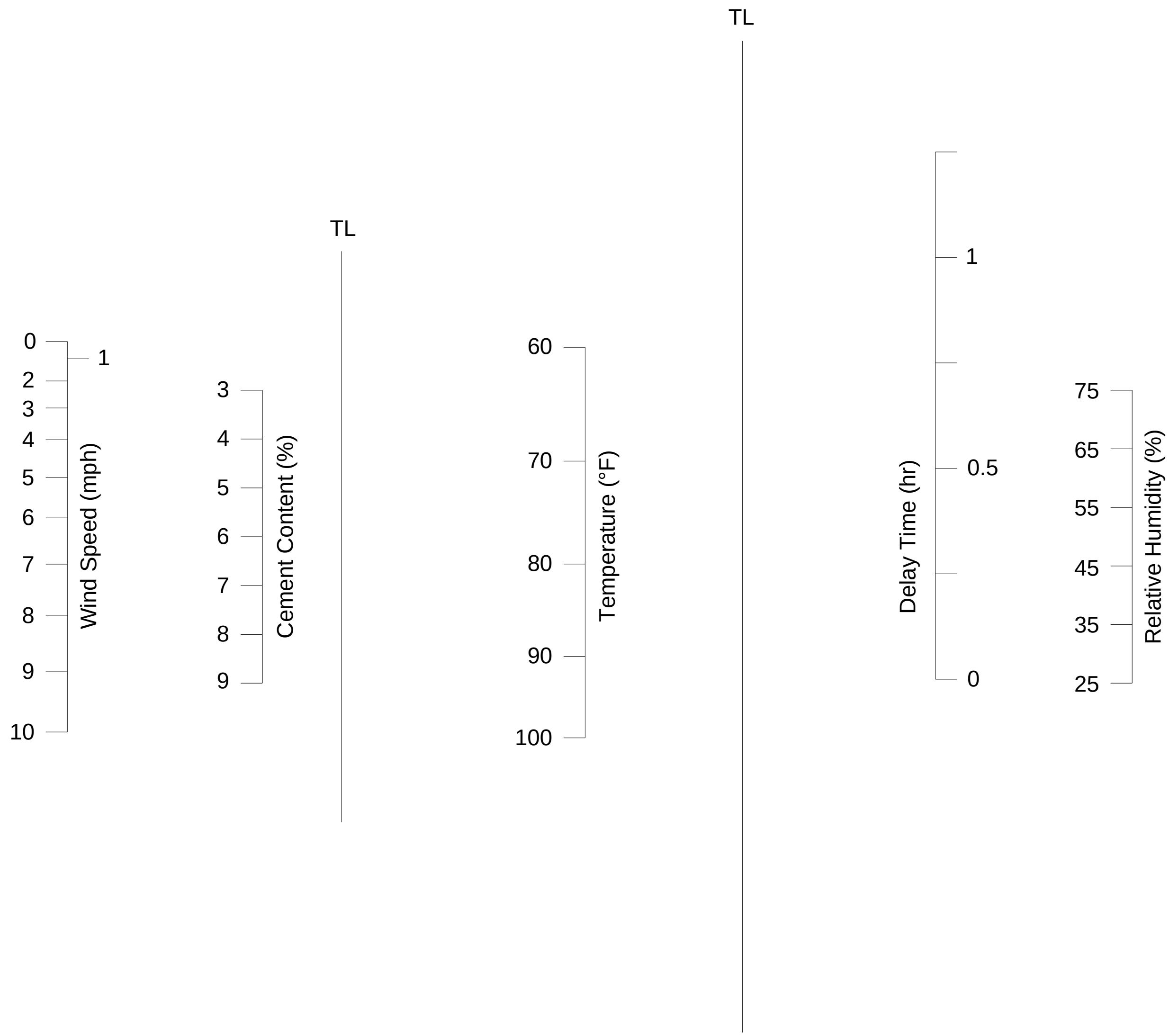


**Figure 25. Subgrade nomograph for minimum of 95 percent relative strength.**

## Summary

The base material utilized in this research was classified in the USCS as GP-GM, poorly graded gravel with silt and sand, and as A-1-a in the AASHTO method. The subgrade material was classified in the USCS as ML, inorganic sandy silt, and as A-4 in the AASHTO method. Based on the AASHTO soil classifications, cement contents of 1 and 3 percent were chosen for the base material, and cement contents of 3 and 9 percent were chosen for the subgrade material.

In the ANOVA utilized to analyze the relative strength and relative compaction data, every independent variable evaluated with respect to relative strength, but only material type evaluated with respect to relative compaction, resulted in *p*-values less than or equal to 0.05. Thus, relative strength is sensitive to variability among the independent variables investigated in this research, while relative compaction is not.

Consistent with theory, the subgrade material is more sensitive to environmental effects due to its higher cement content, with higher cement content corresponding to lower relative strength values at the average values of wind speed, air temperature, relative humidity, and delay time evaluated in this research. Interestingly, the base material exhibits higher relative strength values with increasing cement contents within the range of cement contents examined in this study; further research is needed to investigate the mechanism associated with this behavior, however. As expected, higher wind speed, higher air temperature, lower relative humidity, and higher compaction delay time generally result in lower relative strength, as increased evaporation of water from the soil-cement leads to inadequate moisture content for compaction and curing. Furthermore, higher air temperatures especially accelerate cement hydration, which resists subsequent densification of the soil-cement.

Correlation analysis showed that no meaningful relationship exists between relative compaction and relative strength. Inferring relative strength from relative compaction is therefore not a reliable approach on soil-cement projects.

From the final regression equations, six nomographs were produced for use by engineers and contractors in the field. When values for cement content, wind speed, air temperature, and relative humidity are known for a given project, the allowable delay time permitted for compaction of either a base or subgrade material similar to those tested in this research can be determined for target relative strengths of 85, 90, or 95 percent. The results of the nomographs will be most accurate when the soil-cement is properly sealed in the field against water evaporation, when average field temperatures are similar to room temperature, and when trafficking is not permitted for the first 7 days after construction. Extrapolation beyond the ranges of numerical values given for variables included in the nomographs is not recommended.

# CONCLUSION

## Summary

The premise of this research is that the allowable delay time between mixing of a soil-cement mixture and completion of compaction may be shorter or longer than the widely adopted industry standard of 2 hours, depending upon environmental factors.

Accordingly, the specific objectives of this research were to quantify the effects of certain environmental factors on the relative strength loss of soil-cement subjected to compaction delay and to develop a numerical tool that can be easily used in the field by engineers and contractors for determining an acceptable compaction delay time for individual projects based on environmental conditions at the respective sites. Knowing in advance how much time is available for working the soil-cement will help contractors schedule their activities more appropriately and ultimately produce higher quality roads.

Specific factors selected for investigation in this research included material type, cement content, wind speed, temperature, relative humidity, and compaction delay. The laboratory work involved testing of two different materials, an aggregate base material and a subgrade soil, each treated with two levels of cement. Each of the material types was systematically tested at low, medium, and high values of wind speed, air temperature, relative humidity, and compaction delay. Wind speeds of 0, 5, and 10 mph; air temperatures of 60, 80, and 100ºF; relative humidities of 25, 50, and 75 percent; and compaction delay times of 1, 2, and 3 hours were evaluated.

After environmental conditioning, base and subgrade specimens were compacted using modified and standard Proctor methods, respectively, and then sealed in a plastic bag and cured at room temperature for 7 days. Following the curing period, the specimens were subjected to UCS testing. Relative strength and relative compaction were then computed and analyzed as the primary dependent variables in this research. The collected data were analyzed using a fixed-effects ANOVA and regression techniques to quantify the significance of the main effects and to produce regression equations for each material type. Based on the final equations, nomographs were produced relating material and environmental factors to allowable delay time for specified lower bounds in relative strength of 85, 90, and 95 percent.

## Findings

The base material utilized in this research was classified in the USCS as GP-GM, poorly graded gravel with silt and sand, and as A-1-a in the AASHTO method. The subgrade material was classified in the USCS as ML, inorganic sandy silt, and as A-4 in the AASHTO method. Based on the AASHTO soil classifications, cement contents of 1 and 3 percent were chosen for the base material, and cement contents of 3 and 9 percent were chosen for the subgrade material.

In the ANOVA utilized to analyze the relative strength and relative compaction data, every independent variable evaluated with respect to relative strength, but only material type evaluated with respect to relative compaction, resulted in $p$-values less than or equal to 0.05. Thus, relative strength is sensitive to variability among the independent variables investigated in this research, while relative compaction is not.

Consistent with theory, the subgrade material is more sensitive to environmental effects due to its higher cement content, with higher cement content corresponding to lower relative strength values at the average values of wind speed, air temperature, relative humidity, and delay time evaluated in this research. Interestingly, the base material exhibits higher relative strength values with increasing cement contents within the range of cement contents examined in this study; further research is needed to investigate the mechanism associated with this behavior, however. As expected, higher wind speed, higher air temperature, lower relative humidity, and higher compaction delay time generally result in lower relative strength, as increased evaporation of water from the soil-cement leads to inadequate moisture content for compaction and curing. Furthermore, higher air temperatures especially accelerate cement hydration, which resists subsequent densification of the soil-cement.

Correlation analysis showed that no meaningful relationship exists between relative compaction and relative strength. Inferring relative strength from relative compaction is therefore not a reliable approach on soil-cement projects.

## Recommendations

From the final regression equations, six nomographs were produced for use by engineers and contractors in the field. When values for cement content, wind speed, air temperature, and relative humidity are known for a given project, the allowable delay time permitted for compaction of either a base or subgrade material similar to those tested in this research can be determined for target relative strengths of 85, 90, or 95 percent. The results of the nomographs will be most accurate when the soil-cement is properly sealed in the field against water evaporation, when average field temperatures are similar to room temperature, and when trafficking is not permitted for the first 7 days after construction. Extrapolation beyond the ranges of numerical values given for variables included in the nomographs is not recommended. When acceptable compaction delays are not obtainable due to adverse environmental conditions, a contractor may consider using a set retarder, mixing at water contents above OMC, or constructing at night as possible solutions for achieving target relative strength values.

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