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Optimizing Portland cement concrete mix design to environmental and construction variables with the aid of computer design software

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Optimizing Portland cement concrete mix design to environmental and construction variables with the aid of computer design software

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Chapter 1. Introduction

Over the years, the number of concrete mixing ingredients has changed drastically. It started with the simple mixing of water, cement, and coarse and fine aggregates. Now contractors must choose between multiple admixtures and various cement and aggregate types in order to produce a desired mixture. To create the desired quality and attributes of concrete, a contractor must be well informed of the ever-changing materials market.

Concrete mix designs are not universal anymore. For example, a highway paving project in Florida will not have the same mix design as one in Iowa due to the difference in available construction materials and weather patterns. Florida has virtually no need for the concrete to have freeze-thaw durability, where in Iowa freeze-thaw durability is a crucial characteristic. Even the cement and aggregate types produced in Iowa will vary across the state.

There is a need in the concrete industry to optimize the characteristics of concrete during and after construction. The characteristics of the concrete during placement will greatly affect the performance characteristics after the concrete has hardened. If a concrete mixture is very workable during placement, its water to cementitious materials ratio may be too high to produce the desired strength. If the chemical composition of the aggregates is not known before batching, the aggregates may be susceptible to sulfate attack, causing deterioration in the finished concrete product. There are many characteristics to choose from. It is very difficult to pick and choose which characteristics of concrete are more critical during placement to produce the desired results for long term performance. This is why there is a need for a program with information and recommendations on how to optimize the mix design across a project to yield the desired results.

Concrete Mixture Performance Analysis System (COMPASS) is a computer-based program designed to help contractors and clients evaluate their concrete mix design ingredients. COMPASS can help to optimize the mix design with the given ingredients to produce the desired characteristics of the concrete. Given a certain type of ingredient, COMPASS will provide recommendations for utilizing the properties of that particular ingredient to the fullest potential. COMPASS shows how different ingredients will interact within the mixture and will help to determine what ingredients to manipulate in order to yield the desired characteristics of the concrete.

COMPASS contains a module for assessing local weather patterns. The weather data is linked to the National Oceanic and Atmospheric Administration (NOAA). Users are able to input the local weather patterns and determine when the optimal time period for paving will occur.

There are sixteen different characteristics of concrete that were defined and incorporated into COMPASS. These characteristics range from fresh to hardened concrete traits. The characteristics included in COMPASS are:

- Fresh Characteristics
  - Workability
  - Bleeding
  - Segregation/Uniformity
  - Set
  - Plastic Shrinkage Cracking (PSC)
- Hardened Characteristics
  - Thermal Shock
  - Coefficient of Thermal Expansion (CTE)
  - Strength
  - Stiffness
  - Drying Shrinkage
  - Permeability

- Durable Characteristics
    - Freeze-Thaw/Scaling Resistance
    - Alkali-Silica Reaction (ASR)
    - Sulfate Attack
    - Abrasion Resistance
    - Corrosion

A series of materials was selected to investigate for each concrete characteristic. These materials are categorized into major groups that are used in concrete mixes, such as cement type, aggregate type, and admixtures. Each material was researched to discover how it affects each characteristic individually. For instance, water affects the workability characteristic differently from the way that it affects the freeze-thaw characteristic.

Environmental factors such as hot or cold climates were considered for each characteristic. Weather patterns can affect the placing and curing of the concrete, along with indicating the need for some hardened concrete properties, for instance, freeze-thaw resistance. COMPASS helps make decisions based on when to place concrete according to environmental conditions and weather patterns.

Aggregates in Iowa vary from each corner of the state, giving Iowa at least four different coarse aggregate types throughout the state. There are also two major cement producers utilized across Iowa. COMPASS will be used to evaluate the performance of four Iowa paving mixes. These projects will be field tested and the results will be compared to COMPASS predictions. This will give an indication as to how accurate COMPASS predictions match the actual field results. The following Iowa paving projects were selected to evaluate COMPASS. Cass County (Hwy 71) in southwest Iowa, Sac County (Hwy 175) in central Iowa, Osceola County (Hwy 60) in northwest Iowa, and Wapello County (U.S. 63) in southeast Iowa. These will be evaluated individually based on the varying aggregates and cement producers found across the state.

Paving projects were selected from each side of Iowa to incorporate the different aggregates and cement producers. COMPASS was used to evaluate the following six characteristics of the concrete: workability, bleeding, permeability, segregation, strength, and abrasion. By conducting these evaluations, it showed how accurately COMPASS can predict concrete characteristics, create mix designs and optimize cost for paving projects.

Chapter 2. Concrete Characteristics

The following are the concrete characteristics included in COMPASS. Each characteristic has a general definition and key points that are considered to be the major subject matter for that characteristic.

2.1 Fresh Concrete Characteristics

2.1.1 Workability

Workability can be defined as "the property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished." [19] Consistency is an important part of workability and is defined as "the relative mobility or ability of freshly mixed concrete or mortar to flow." [22] Ample consistency of the concrete mixture is necessary for maintaining homogeneity during handling and placement. Concrete mixtures with high consistency tend to segregate and bleed, making the concrete hard to finish. Concrete mixtures with low consistency could make the concrete more difficult to place and consolidate, which may result in segregation during placement. [1]

Workability is not a primary property of concrete, but is governed by the particular conditions under which concrete is being placed. These conditions include reinforcement configurations and the equipment used to place and consolidate the concrete, among other factors. A concrete mixture considered workable for one application (e.g. fixed-form paving) is therefore unworkable for another application (e.g. slip-form paving). [1]

Key information for workability:

- Water content is the single most important factor affecting workability. Water content should be kept to the minimum amount necessary to provide sufficient workability without compromising other concrete properties. [1]

- Water reducing admixtures are commonly used in fast-track mixes to achieve higher strengths by reducing the water/cement ratio while still maintaining a workable mix. [20]
- As aggregate particles get closer to a spherical shape, workability of the mix will increase. [1]

2.1.2 Bleeding

Bleeding is the development of a layer of water on the surface of freshly placed concrete. It is caused by the simultaneous settlement of solid particles (e.g. cement and aggregate) and the upward movement of water. Bleeding is normal and it is helpful in controlling plastic shrinkage cracking. Bleeding capacity and bleeding rate are affected by the ratio of the surface area of solids to the unit volume of water.

The rate of bleeding depends on the concrete mixture ingredients and proportions, the depth of the member being cast, and on the type of consolidation and finishing. Bleeding of concrete is influenced by mixture proportions and by material characteristics, air content, slump, admixtures, and particularly the angularity and grading of the fine aggregate.

Factors that can reduce bleeding are the increased use of finer fine aggregates, blending sand, improved control/grading of manufactured fine aggregates, increased cement/pozzolan content, and the use of some chemical admixtures and air entrainment. With little or no bleed water available at the concrete surface for evaporation, plastic cracking can readily develop, especially on hot, windy days if special precautions are not taken. [2, 9]

Key information for bleeding:

- Many of the concrete mixture ingredients and proportions that can be altered to change the rate of bleeding are controlled by other characteristics such as strength and durability.
- Individual products that can cause significant bleeding (i.e. retarders) or lack of bleeding (i.e. silica fume) should be identified along with advising the needed precautions and possible curing materials and methods to avoid any damage or problems.

- The use of certain admixtures (i.e.) can cause scaling by blocking bleed water from reaching the surface. Recommendations such as the use of fog sprays, evaporation retardants, and others should be then given to prevent crusting. [2, 9]

2.1.3 Segregation/Uniformity

Segregation in concrete is defined as the separation of mixture components resulting from differences in the particle size or density. Segregation is the tendency of coarse aggregate to separate from the sand-cement mortar, causing part of the mix to have too much coarse aggregate, leaving a shortage in the remainder of the mix. Segregation is mainly dependent upon the density and viscosity of the concrete matrix.

Improper proportioning and insufficient mixing of the concrete batch can result in segregation. Segregation does not normally occur in concrete containing high-range water reducers (HRWR) used as a water reducer. However, when the admixtures are used to create flowing concrete, segregation could occur if precautions are not taken. Improper proportioning and inadequate mixing can both result in localized excess fluidity and segregation. [6]

Segregation may occur in many types of concrete when excessive slump or prolonged vibration occurs. [6] When admixtures are used to create workable concrete, segregation could occur if precautions are not taken. [5]

Key information for segregation/uniformity:

- The amount of segregation that occurs in a mix depends on internal factors such as aggregates and chemical admixtures. External factors that affect the segregation are the mode of transportation, placement/paving method, and the environment (weather conditions).
- Segregation can be controlled by correctly proportioning aggregates and admixtures. If higher amounts of silt-size or clay-sized fines or a supplemental cementitious material (e.g.

fly ash) is added, the mixture will have improved cohesion and workability, therefore decreasing the tendency to segregate.

- Improper handling of the concrete will lead to segregation. The mode of transportation and placement method will influence the amount of segregation that occurs within the mix.
- The addition of fibers as an admixture will affect segregation if not uniformly distributed throughout the mixture. Different types of fibers have different effects on segregation.
- The project environment will determine the need to adjust the water content of the mixture, which will affect the amount of slump. If the slump becomes excessive, the mixture will have a greater risk of experiencing segregation.

2.1.4 Set

Set is defined as “the condition reached by a cement paste, mortar, or concrete when it has lost plasticity to an arbitrary degree, usually measured in terms of resistance to penetration or deformation.” [19] The setting of concrete can be recognized by a loss of workability that usually occurs within a few hours after mixing. It depends on the composition and fineness of cement, admixtures, mixture proportions and temperature conditions. [4] Set is also significantly affected by particle concentration and particle packing within the system.

Set is influenced by ambient and concrete temperatures, cement type, source, fineness and content, water content of the paste, water soluble alkalis, use and dosages of chemical admixtures, amount of pozzolans, and fineness and chemical composition of the pozzolans. When these factors are considered properly during the concrete mixture proportioning, a desired set time window can be achieved. [4, 8, 9]

Key information for set:

- Environmental conditions will determine the time of set. Daily weather patterns need to be considered when choosing an appropriate admixture to control the time of set.

- Set times can often be controlled through the use of chemical admixtures. Tests should be conducted to determine how a specific group of materials interact.
- The chemical composition of different cement types will affect set time. It should be confirmed which type of cement will be used for construction.
- Water reducers should be used with caution. Too much or too little of a water reducer can greatly affect the amount of setting time. [1]

2.1.5 Plastic Shrinkage Cracking (PSC)

Plastic shrinkage cracking (PSC) is an early-age concrete distress that forms before the freshly placed concrete has time to fully set. Plastic shrinkage cracks are short irregular cracks that form on the concrete surface. They can be from a few inches to several feet long. PSC is caused by the rapid loss of water from the surface of the fresh concrete. The cracks form when the rate of evaporation is faster than the rate of bleeding of the concrete.

If climatic conditions result in the rate of evaporation being higher than the rate of bleeding, capillary tension will develop in the concrete pores and result in shrinkage of the concrete. At this time, concrete does not have adequate strength to resist these capillary stresses within the fresh paste and plastic shrinkage cracks form. [1, 3]

Key information for plastic shrinkage cracking:

- Plastic shrinkage cracking is directly related to the rate of bleeding.
- Daily weather patterns should be considered during mixture design and appropriate curing techniques should be utilized to minimize the amount of plastic shrinkage cracking. Weather conditions will dictate the amount of plastic shrinkage cracking experienced by a mix.
- The rate of evaporation depends upon wind velocity, relative humidity, and temperatures of the air and concrete surface. An estimate of the rate of evaporation should be obtained before selecting techniques to control plastic shrinkage cracking.

- Certain admixtures and supplemental cementitious materials will cause alterations in bleeding rates, leading to or solving problems with plastic shrinkage cracks. Appropriate curing techniques should be utilized for the type of admixture used. [1]

2.2 Hardened Concrete Characteristics

2.2.1 Thermal Shock/Cracking

Under hot weather conditions, when ambient air temperatures exceed 32 °C (90^{o} F), concrete temperatures often increase quickly after placement. This causes the concrete to set at a high temperature. Any significant cooling soon after the concrete sets will produce high thermal stresses in the concrete. Cracks will develop from the rapid temperature change and adversely affect the concrete performance. This premature cracking is commonly called thermal shock. [14] Thermal shock typically occurs when there is a large difference in temperature between the relatively warm concrete and the ambient air temperature and/or the subgrade.

Thermal shock/cracking may reduce the service life of the concrete by promoting early deterioration or excessive maintenance. In order to control temperature changes due to exothermic reactions, the mixture may be cooled with ice as part of the mixing water or by placing during cooler temperatures. Aggregate stockpiles can be watered or the amount of Portland cement can be limited by substituting supplemental cementitious materials, such as fly ash or ground granulated blast furnace slag (GGBFS). [17] The choice of proper mixture proportions is only one means of controlling temperature increase. [21]

Key information for thermal shock/cracking:

- The amount of thermal shock/cracking depends on the rate of the heat of hydration of the cement, admixtures, and materials within the concrete mixture.
- The selection of proper mixture proportions is only one means of controlling temperature increases.

- Cool weather conditions are more favorable for concreting. Cool weather keeps concrete temperatures lower and slows the rate of the heat of hydration. Concrete can still be placed in hot weather conditions, but it becomes harder to control the heat of hydration.
- Appropriate curing practices and techniques during all weather conditions will decrease the risk of thermal shock/cracking.
- Incorporating fly ash and GGBFS into the mixture will slow the heat of hydration, thus lowering the peak internal temperature of the concrete.
- Chemical admixtures usually do not affect the heat of hydration or temperature of the mixture which are properties that can cause thermal shock/cracking.

2.2.2 Coefficient of Thermal Expansion (CTE)

The coefficient of thermal expansion (CTE) is defined as a change in linear dimension per unit length, or a change in volume per unit volume, per degree of temperature change. (19)

The CTE for concrete can be computed approximately as the average of the values for the components weighted in proportion to the volumes present. The moisture content of the concrete can influence the coefficient of thermal expansion, as well as the thermal diffusivity. Thermal expansion and contraction of concrete varies with factors such as aggregate type, cement content, water-cement ratio, temperature range, concrete age, and relative humidity. Aggregate type has the greatest influence of all the ingredients. (2, 9) The average CTE of concrete is about 5.5 x 10^{-6} ^{o}F, although values ranging from 3.2 to 7.0 x 10^{-6} ^{o}F have been observed. (9)

Key information for the coefficient of thermal expansion:

- The greatest influence on the concrete's CTE is the CTE of the aggregate and the amount of aggregate within the mixture.
- Mineral composition of the aggregate will have the greatest influence on that particular aggregate's CTE.

- Other components of the concrete mixture will not have enough of a significant effect on the CTE of the concrete and can be neglected.

2.2.3 Strength

Strength development in concrete begins after the concrete has set. Strength develops as a function of the w/cm ratio, cement content, admixtures, and aggregate characteristics and quantities, along with the curing temperature, and moisture state. The strength of the concrete depends on the strength of the aggregates, cement paste, and the bond strength of the cement/aggregate interface.

The rate of strength development is a function of the cement properties such as the cement fineness and cement compounds, along with supplemental cementitious materials and admixtures used. The primary mode of failure during early-age is tensile stress. Economical proportioning of the mixture for increasing the compressive strength includes using a minimum w/cm and proper aggregate size. (22)

The rate of heat of hydration parallels the rate of strength increase. Strength gain of concrete can be increased by:

- Decreasing the w/cm ratio
- Increasing the amount of cementitious materials
- Using high early strength cementitious materials
- Increasing the curing temperature
- Using an accelerating admixture. (4, 23)

With a given concrete mixture, compressive strength at the surface is improved by:

- Avoiding segregation
- Limiting bleeding
- Properly timed finishing
- Minimizing surface water

- Hard toweling of the surface
- Proper curing procedures [22]

Key information for strength:

- Water to cement and water to cementitious material ratios greatly affects the strength of the mixture. Maintaining these ratios at the lowest possible value will yield the highest strength. The addition of water beyond the initial amount will lower the strength development.
- Curing and protecting the concrete properly will determine the rate of early strength gain. If concrete is not protected correctly, it will not develop the desired strength.
- Different admixtures have different effects on concrete strength. Some will aid in early strength gain, while others will slow early strength gain but raise overall final strength.
- Cement composition will affect the strength of the mix. It should be known what type of cement is being used and its chemical composition to correctly estimate overall strength development.

2.2.4 Drying shrinkage

Drying shrinkage can cause is a cause of cracking in concrete. It is defined as the change in volume (shrinkage) resulting from a loss of moisture. [10, 19] Drying shrinkage is a function of the paste volume, water content, cement content and type, aggregate type, presence and type of admixtures, and proportions of the materials used. [7]

The extent of shrinkage depends on many factors including the material properties, temperature and relative humidity of the environment, the age of the concrete when subjected to the drying environment and the size of the concrete mass. The crack widths are a function of the degree of drying, crack spacing and age at which the crack occurs. [7, 9, 13]

The combined effects of unfavorable materials and practices can produce concretes with drying shrinkage cracks possibly seven times larger than those obtained by selection of favorable of materials and practices. [4] Cracks caused by drying shrinkage must be minimized because they allow deicers to more easily penetrate the concrete and cause deterioration. [6]

Key information for drying shrinkage cracking:

- Drying shrinkage is influenced by the size and shape of the concrete element. A larger surface area of concrete structures leads to increased risk drying shrinkage damage.
- Using reinforcement will reduce the amount of drying shrinkage that occurs by giving the concrete a resisting force. However, using too much reinforcement can cause more drying shrinkage cracks to form.
- Reducing the amount of water in the mixture will lower the amount of drying shrinkage that happens. The addition of water at the job site will increase the tendency for drying shrinkage cracks to form.
- The amount of shrinkage concrete undergoes given certain drying conditions is dependent on the shrinkage potential of the paste and the properties and amounts of the aggregates. The absorption properties of the aggregate will determine how much drying shrinkage occurs.
- Some factors that affect plastic shrinkage cracking also affect drying shrinkage cracking.

2.2.5 Permeability

Permeability refers to the rate at which water is transmitted through a saturated specimen of concrete under an externally maintained hydraulic pressure gradient. [9] The permeability of concrete is dependent on the effective placement and consolidation of freshly mixed concrete without undesirable voids and honeycombing. Permeability of concrete is governed by many factors such as amount of cementitious material, water content, aggregate grading, and curing efficiency. It also depends greatly on placing, finishing, and curing procedures, particularly consolidation. Most admixtures that reduce the w/cm ratio will reduce permeability. Permeability will increase with drying. [2, 7, 9, 16]

Decreasing the permeability of the concrete improves its freeze/thaw resistance, re-saturation, sulfate and chloride-ion penetration, and other chemical attack resistance. The permeability of concrete also depends on the permeability of the paste and aggregate and the relative proportions of each. The permeability of the paste is particularly important because the paste surrounds all the components in the concrete. Paste permeability is related to the w/cm ratio, degree of cement hydration, and length of moist curing. The permeability of concrete to liquid water or water vapor is not a simple function of its porosity, but depends on the size, distribution, and continuity of the pores in both the cement paste and the aggregates. [4, 9]

Concrete with a low permeability will reduce ion mobility and delay the chemical reaction. The formation of calcium silicate hydrates in pore spaces, normally occupied by alkalis and calcium hydroxide, reduces the permeability of the paste and prevents the invasion of the aggressive sulfates. However, there are negative effects of low permeability. The lower water content will result in a higher alkali concentration of the concrete pore solution. [12, 24]

The permeability of mature hardened cement paste kept continuously moist ranges from 0.1×10^{-12} to 120×10^{-12} cm/sec. for w/cm ratios ranging from 0.3 to 0.7. The permeability of rock commonly used as concrete aggregate varies from approximately 1.7×10^{-9} to 3.5×10^{-13} cm/sec. The permeability of mature, good-quality concrete is approximately 1×10^{-10} cm/sec. [9]

Key information for permeability:

- The most significant effect on permeability is the amount of water (w/cm ratio) contained within the concrete mixture. The lower the w/cm ratio, the lower the permeability.
- Aggregate porosity will have an effect on the amount of permeability of the hardened mixture, as water will settle into the pores of the coarse aggregates. The fine aggregate has little effect on permeability.

- Permeability is reduced by utilizing good curing techniques because of the increased hydration of the cement. The longer the moisture is retained within the concrete, the longer the cement can be hydrated. This causes a greater the degree of hydration to occur.
- Most natural pozzolans will reduce the permeability of the mixture by helping to hydrate the concrete through pozzolanic reactions.
- Admixtures such as soap and butyl stearate can be used to lower permeability. These are newer admixtures and should be tested before use.

2.3 Durable Concrete Characteristics

2.3.1 Freeze-thaw/Scaling resistance

Freeze-thaw resistance is the most potentially destructive weathering factor. Freeze-thaw resistance is defined as the ability of concrete to withstand cycles of freezing and thawing. (9) Freeze-thaw deterioration can occur when water freezes and expands within a concrete binder containing a poor air-void distribution or if the concrete contains poor-quality aggregates. (20, 25) The vulnerability of the concrete to freeze-thaw deterioration is a function of whether it becomes critically saturated with water, if the aggregates are frost resistant (causing D-cracking), if sufficient strength has developed prior to the first freeze cycle (500 psi), if sufficient strength prior to cyclic freeze-thaw cycles can develop (3000 psi for moderate exposure and 4000 psi for extended freezing), and if adequate air voids are present. Scaling of the concrete surface can also occur from poor freeze-thaw resistance. Scaling is defined as when the concrete surface, exposed to cyclic freeze-thaw cycles, loses the mortar fraction and exposes coarse aggregate particles. (4, 9, 11)

Freeze-thaw resistance is significantly increased with the use of the following:

- a good quality aggregate
- a low water to cementitious materials ratio (maximum 0.45) to obtain higher strengths
- a minimum cementitious materials content of 335 kg/m^3 (564 lb/yd^3)

- proper finishing and curing techniques
- a compressive strength of 28 MPa (4,000 psi) when exposed to repeated freeze-thaw cycles.[9]

Key information for freeze-thaw resistance:

- Air entrainment is the most beneficial factor in protecting the concrete from freeze-thaw and deicer chemicals.
- Aggregate properties such as absorption and porosity will affect the amount of water contained in the mixture, therefore causing the concrete to be more susceptible to freeze-thaw.
- Placement of concrete should be done in the spring months to allow a sufficient drying time for the concrete before the concrete experiences the first freeze/thaw cycle. If late season concreting is unavoidable, then proper curing methods should be practiced to allow proper strength to develop before exposure.
- During construction, it is important to maintain the air content of the mixture. Proper curing and consolidation should be completed to ensure that air content loss is minimized.

2.3.2 Alkali-silica reaction (ASR)

"Alkali-silica reaction is the reaction between the alkalis (sodium and potassium) in portland cement and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates; the products of the reaction may cause abnormal expansion and cracking of concrete in service". [19] Typical results of ASR are expansion, dislocation of structural elements and machinery, closing of joints, and cracking (usually map or pattern cracking). Other effects of ASR are expulsion of alkali-silicate gel through pores or cracks which then form jellylike or hard beads on surfaces, reaction rims on affected aggregate particles within the concrete, and popouts. [2]

Key information for alkali-silica reaction:

- The absorption of water that contains ions or alkalis will contribute to ASR. These are mainly seawater and marine environments.
- Aggregate composition is the main contributing factor to ASR. The chemical composition of the aggregates in the mixture needs to be determined and tested before use.
- Most pozzolans and supplemental cementitious materials will reduce the amount of ASR that occurs, when used in the optimum dosage.
- An additional factor that affects ASR is permeability, since this will determine how fast and the amount of water and ions that move within the paste.

2.3.3 Sulfate Attack

Sulfate attack is defined as "either a chemical reaction, physical reaction, or both between sulfates usually present in soil or ground water and concrete or mortar; the chemical reaction is primarily when calcium aluminate hydrates in the cement paste matrix, often causing deterioration." (19) Sulfate attack is a common form of chemical attack on concrete. It is caused by naturally occurring sulfates (sodium, potassium, calcium or magnesium) in the groundwater or soil. It is noticeable by expansion and disintegration of the concrete. The attack is greater in concrete that is exposed to cycles of wetting and drying, such as foundation walls and posts. Sulfate attack usually results in an expansion of the concrete because of the formation of solids from the chemical action or salt crystallization. (9)

Two theories exist to explain why sulfates cause deterioration in concrete; chemical and physical. The chemical theory is that sulfates (SO_4) in the soil or ground water can cause the volumetric expansion of concrete because of the formation of ettringite. They react chemically with the cement paste constituents. To increase resistance to sulfate attack, use cement with a low C_3A content, low w/cm, or use supplemental cementitious materials. The formation of ettringite can lead to expansion and cracking in the concrete. The formation of gypsum can lead to softening and loss of concrete strength.

The physical theory states that when sulfate salts form and crystallize, they expand by repeated wetting and drying cycles. This is the predominant mechanism that causes the deterioration. Concrete should have low permeability to resist the effects of a sulfate attack. [7, 11, 26]

The two best recognized chemical consequences of sulfate attack on concrete components are the formation of ettringite and gypsum. The presence of ettringite or gypsum in concrete by itself is not an adequate indication of sulfate attack. Evidence of sulfate attack should be verified by petrographic and chemical analyses. [12]

Resistance to sulfate attack is greatly dependent on the permeability of the concrete or cement paste. The formation of calcium silicate hydrates in pore spaces reduces the permeability of the paste and prevents the intrusion of the aggressive sulfates. [12] Protection against sulfate attack is obtained by using concrete that retards the access and movement of water and concrete-making ingredients appropriate for producing concrete having the needed sulfate resistance. [9, 14]

For the best defense against external sulfate attack:

- Design concrete with a low water to cementitious materials ratio (around 0.4).
- Use cements specially formulated for sulfate environments. [9]

Key information for sulfate attack:

- Sulfate attack occurs from mainly outside sources of water that are absorbed into and migrate through the structure. Sulfate attack is worse in environments that experience periods of cyclic wetting and drying.
- The type of cement can increase resistance to sulfate attack. In order to identify cements that will resist sulfate attack, tests are needed according to ASTM C 1012 or ASTM C 452.
- Reducing the water to cement ratio to reduce the permeability will increase the concrete's ability to resist sulfate attack.

- Any supplemental cementitious materials that help to reduce permeability are beneficial in guarding against sulfate attack.

2.3.4 Corrosion

Corrosion is one cause of premature deterioration in concrete. In concrete there is initially a passive/protective layer that forms over the steel, which is destroyed by the presence of chlorides. Corrosion of steel leads to cracking, spalling and delamination of the concrete. [(15)] For corrosion to happen water and oxygen must be present at the surface of the embedded steel and the normal alkalinity of the concrete must be lowered below a pH of 9. [(4)] Steel in concrete is typically protected against corrosion by the high pH of the surrounding cement paste. [(11)]

Mixture proportions of the concrete, depth of concrete covering the reinforcing steel, crack-controlling measures, and the use of procedures designed especially for corrosion protection are some of the factors that help control the onset and rate of corrosion. Exposure of reinforced concrete to chloride ions is the major cause of premature corrosion of steel reinforcement. [(16)] A low permeability, low water-cement ratio, and low to moderate cement content can increase the resistance of concrete to acids or corrosion. The use of silica fume or other pozzolans helps keep the corrosive agent from penetrating into the concrete. [(9)]

Once it begins, the rate of steel corrosion is affected by the concrete's moisture content, electrical resistance, and the rate at which oxygen passes through the concrete to the steel. High alkalinity is required to protect embedded steel from corrosion. [(9)] Corrosion of the reinforcement can be decreased through the use of corrosion inhibitors or the application of cathodic protection. [(16)]

In some circumstances, corrosion can occur in the absence of chloride ions. Carbonation of concrete will reduce concrete's alkalinity, therefore allowing corrosion of embedded steel. Carbonation-induced corrosion is not as common as chloride-induced corrosion.

Three major factors that influence the onset of carbonation-induced corrosion are

- thin concrete cover
- the presence of cracks
- high permeability associated with a low cement factor and high w/cm. [16]

A significant reduction in the rate of either cathodic or anodic reactions will result in a considerable reduction in the rate of corrosion. [16] Cathodic protection methods will reverse the corrosion current flow through the concrete and reinforcing steel. [9]

Key information for corrosion:

- Corrosion is related to permeability in terms of chloride penetration. Lowering the permeability of the concrete will lower the risk of corrosion. The intrusion of sulfates will corrode steel reinforcement. Topics that relate to corrosion are sulfate attack, alkali-silica resistance, and permeability.
- Exposure of concrete to marine environments will increase the risk of corrosion. Epoxy coated reinforcement and adequate cover depth will aid in fighting corrosion.
- The use of supplemental cementitious materials will lower the microscopic permeability of the concrete, therefore reducing the macroscopic permeability of the concrete.
- Certain admixtures (i.e. chloride-containing accelerators) will enhance the rate of corrosion. Admixtures should be tested before use. Mineral admixtures such as fly ash, slag, and silica fume will reduce the risk of corrosion by reducing the permeability of the concrete.
- Refer to ACI 222 for the latest techniques on identifying and testing for corrosion.

2.4 Aggregates

Concrete mixtures produced with a well-graded aggregate combination tend to decrease the need for water, provide and maintain sufficient workability, require minimal finishing, and consolidate the mixture without segregation. These properties tend to improve fresh concrete characteristics, like workability and segregation, as well as hard concrete characteristics, such as strength and durability. Concrete mixtures produced with gap-graded aggregates tend to segregate easily, contain higher amounts of fines, require more water, and increase vulnerability to shrinkage. [18]

Achieving a uniform gradation may require the use of three or more different aggregate sizes. For Iowa paving projects, Iowa Department of Transportation (IDOT) specifies a three aggregate gradation for PCC pavement mix designs. It is the responsibility of the mix designer to consider particle shape when creating a mix. When using the coarseness/workability chart it is assumed that particles are rounded or cubical shaped. Rounded or cubical shaped aggregates typically enhance workability and fresh concrete characteristics. Flat and elongated aggregates typically limit the fresh concrete characteristics. [18]

2.5 COMPASS Program

The information for each characteristic was entered into COMPASS to create modules (Figure 2.1). These modules help the user to define what characteristics of the mix they wish to optimize and how to create that desired mixture by using the ingredients they have available. COMPASS considers the properties of the ingredients and the environment in which they will be used when making recommendations. COMPASS also considers the construction techniques and contractor practices when making recommendations.

The program begins by offering the user a random concrete fact that changes each time the program is opened (Figure 2.1). Upon starting the program, the user can then choose which module of COMPASS to begin their analysis. It is recommended that the user begin with the mix expert module. This module provides the user with a list of concrete characteristics, shown across the top bar in Figure 2.2. The user can select which characteristics are the most beneficial for their particular paving project. COMPASS considers these selections and gives recommendations for the mix proportions. The user can then elect to accept or decline the information provided (Figure 2.3).

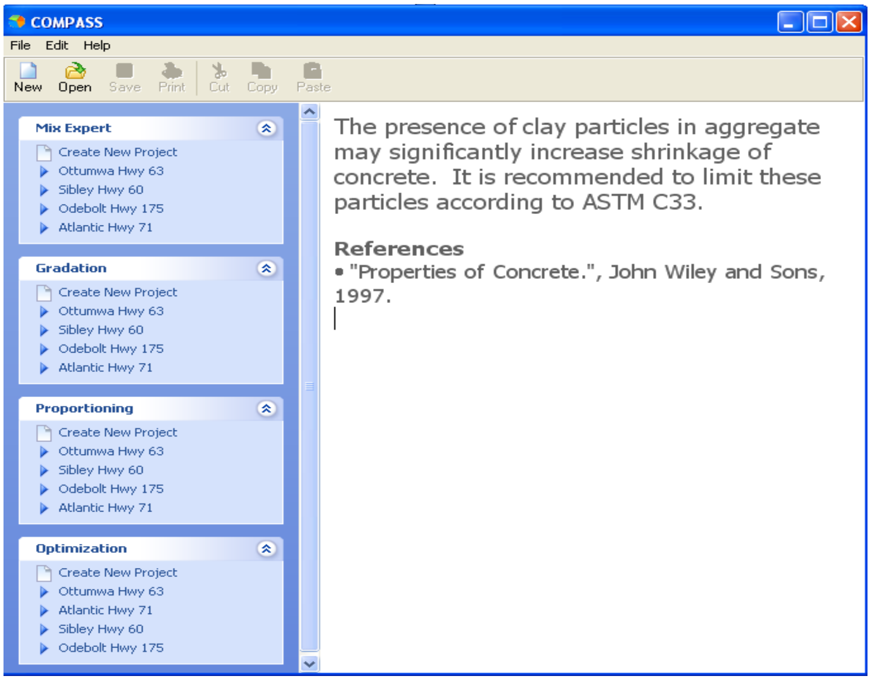

Figure 2.1 COMPASS Modules

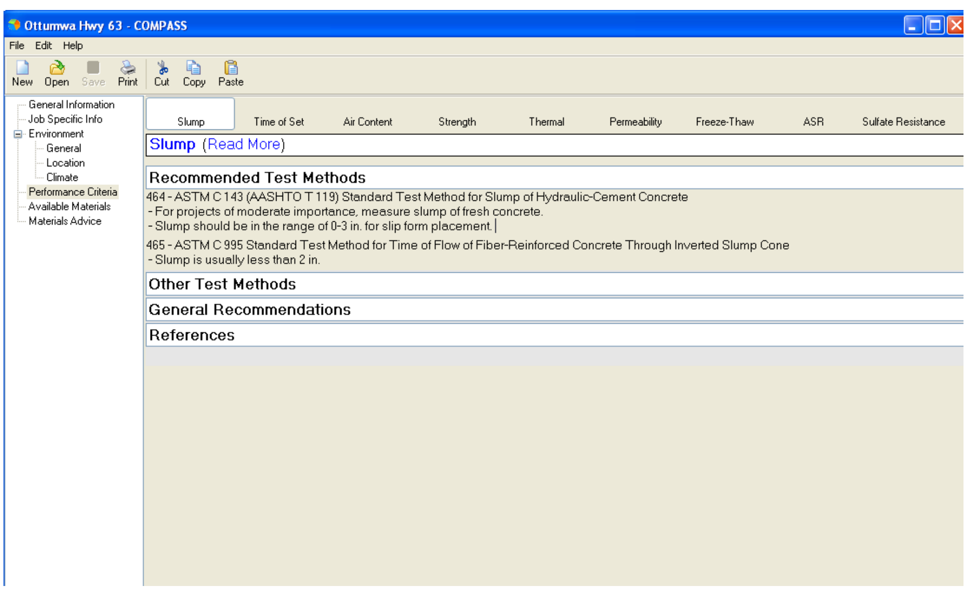

Figure 2.2 Mix Expert Module

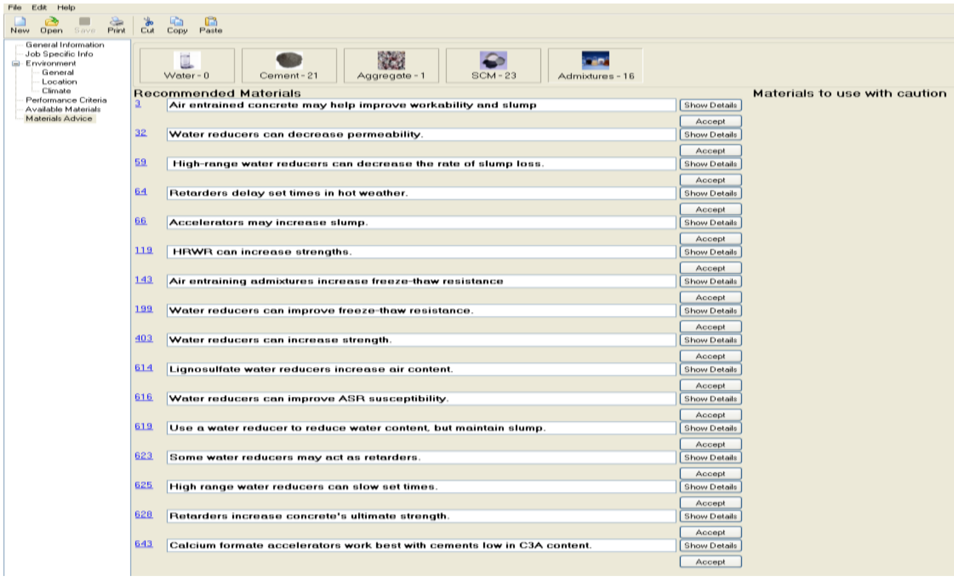

Figure 2.3 Material Information and Recommendations

COMPASS also creates virtual batches of concrete, which the user can utilize to develop mix proportions. The user can accept these initial mix proportions or refine them by using the commands shown on the right of Figure 2.4. When the mix proportions are adjusted, COMPASS creates multiple concrete batches that appear in a randomly ordered list (Figure 2.5). The adjusted batches meet the criteria set forth by the initial mix proportions. However, they vary slightly in the quantity of individual ingredients in order to optimize the mix proportions. These virtual batches can be created and tested in the laboratory or the user can simply choose a mix from the list.

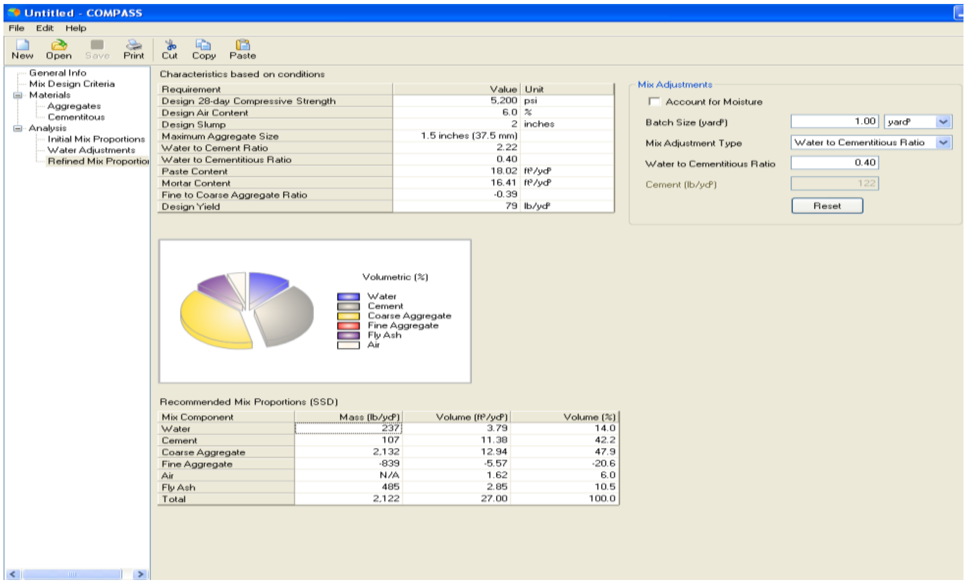

Figure 2.4 Initial Mix Proportioning

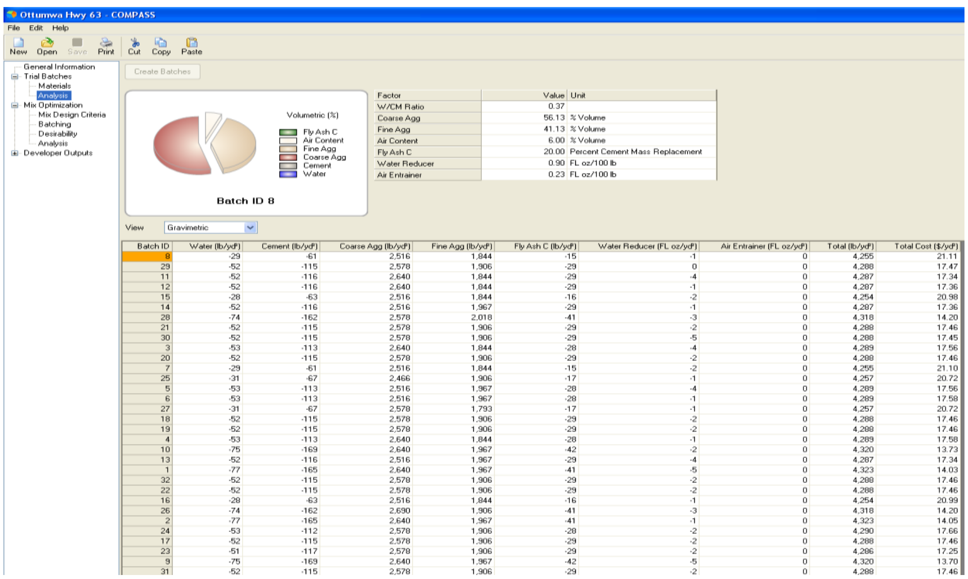

Figure 2.5 Trial Batches

COMPASS verifies the aggregates and their gradations. It utilizes the unit weights of the aggregates and the sieve analysis to create a gradation chart and optimum amounts of each aggregate (Figure 2.6). Along with typical gradation charts, COMPASS produces a 0.45 power chart (Figure 2.7). Traditionally, the 0.45 power curve has been used to create uniform gradations for asphalt mix designs. It is increasingly being used to develop uniform gradations for PCC mix designs. The 0.45 power curve is based on the mathematically combined percent passing gradation determined in accordance with IM 531. [18]

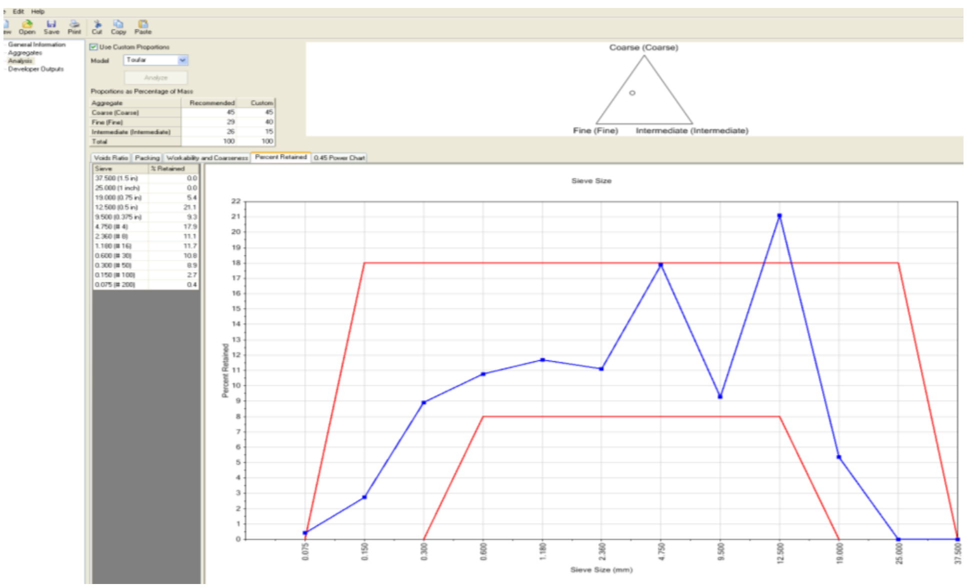

Figure 2.6 COMPASS Aggregate Gradation Chart

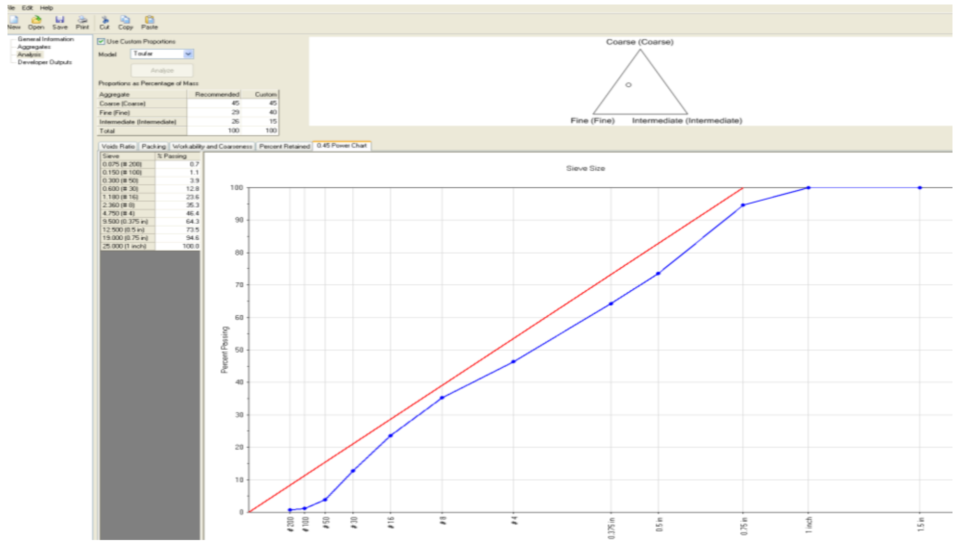

Figure 2.7 COMPASS 0.45 Power Chart

There is also a module of COMPASS that allows the user to assess the weather patterns in the region of paving (Figure 2.8). The weather module is linked to the National Oceanic and Atmospheric Administration (NOAA) weather database around the country. When a project location is selected in COMPASS, the weather database is activated for weather stations near that region. Using an algorithm, the most applicable weather stations are selected and the weather information is obtained from those weather stations. The weather information for the specified location is calculated from a weighted average that is interpolated from the selected weather stations. The weather database contains average hourly readings for the entire year, based on 30 years of historical data. The user can select the dates of paving in COMPASS and be given averages of the weather patterns a region will experience during the particular time of paving. This information is beneficial in determining when the optimal time to place concrete will occur. [1]

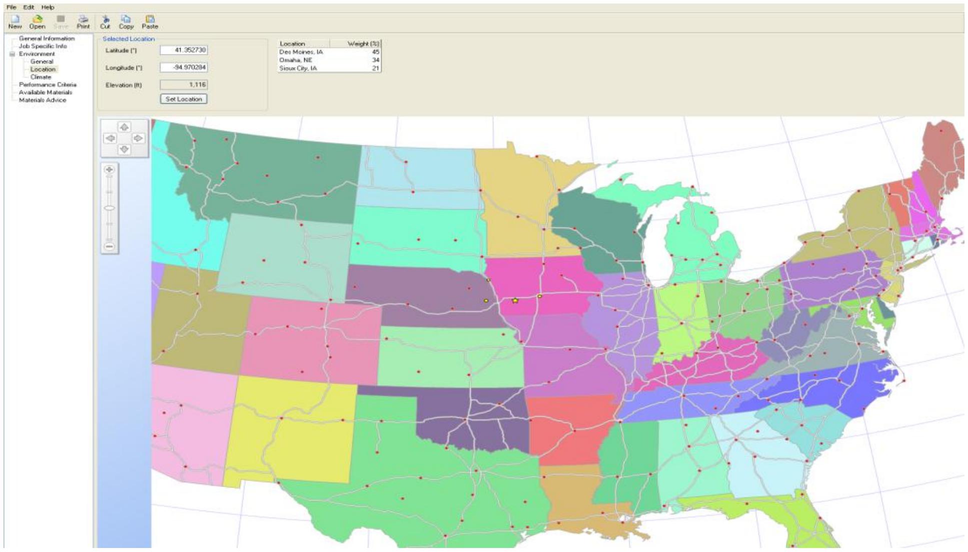

Figure 2.8 COMPASS Weather Module

The techniques used during construction are taken into consideration by COMPASS. Some construction practices are incompatible with certain types of aggregates or materials. COMPASS will recognize these incompatibilities and alert the user. It is then up to the user to either change the mix ingredients or construction techniques so that paving operations can run efficiently.

Chapter 3. Experimental Field Evaluation

COMPASS was used to evaluate the performance of four Iowa paving mixes. Each project was evaluated individually to analyze the varying aggregates and cement types found across the state. Aggregates in Iowa are different from each corner of the state, yielding four different types of coarse aggregate throughout the state. There are also two different cement types produced in Iowa. Paving projects were selected from different areas of Iowa to incorporate the different aggregates and cement types.

The following Iowa paving projects were selected to evaluate COMPASS: Cass County (Hwy 71) in southwest Iowa, Sac County (Hwy 175) in central Iowa, Osceola County (Hwy 60) in northwest Iowa, and Wapello County (U.S. 63) in southeast Iowa. Refer to Fig 3.1 for Iowa Map. Refer to Appendix A for a site map of each project.

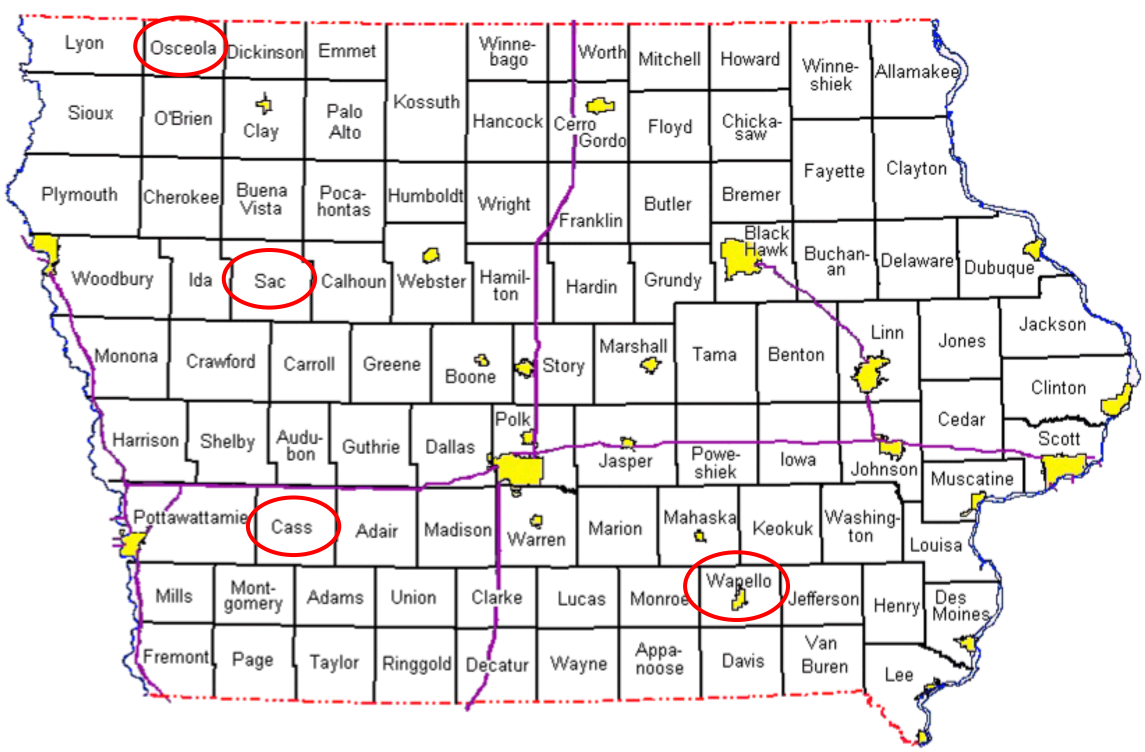

Figure 3.1 Iowa County Map

3.1 Cass County

This paving project was U.S. Highway 71 from the Montgomery County Line north to County Road G-43 near the city of Atlantic. This project was a PCC overlay, 8 inches thick, covering approximately ten miles. The existing pavement width is 24 feet. Flynn Company, Inc. was the contractor for the project. They used a slip-form paver to create the slab. The cement was Type IP (F) blended cement. The cement was supplied from Ash Grove Cement in Louisville, NE. This type of cement is a portland cement blended, or inter-ground, with up to 15% pozzolan content. Class C fly ash was supplied from Council Bluffs Unit #3, in Council Bluffs, Iowa. The mix design for this project is shown in Table 3.1. A water reducer was added to the mix at a dosage rate of 652.5 mL/yd^3.

Table 3.1 Cass County Mix Design Ingredients

Materials	**Absolute Volume**	**Weight, lbs/yd^3**
Cement Type IP(F)	0.089	442
Fly Ash Class C	0.025	110
Water	0.131	221
Air	0.060	-
Fine Aggregate	0.299	1340
Intermediate Aggregate	0.119	545
Coarse Aggregate	0.277	1269

The three aggregates used on this project include a 1 ½ "road stone (coarse), ¼ "stone chips (intermediate) and concrete sand (fine). The aggregates used for this project were supplied from Hallet Lakeview Materials. Table 3.2 shows the aggregate gradation for Cass County.

Table 3.2 Aggregate Gradation for Cass County

Sieve Size	% Passing		
	1 ½" Stone	*¼ " Chips*	*Conc. Sand*
1 ½ "	100	100	100
1 "	75.4	100	100
¾ "	55.9	100	100
½ "	30.3	100	100
3/8 "	12.8	100	100
#4	0.3	35.9	94.3
#8	0.1	3.2	83.7
#16	0.1	2.6	69.3
#30	0.1	2.0	47.8
#50	0.1	1.4	15.7
#100	0.1	0.8	1.8
#200	0.1	0.2	0.7

3.2 Sac County

This project was a PCC overlay on Hwy 175 through the town of Odebolt. It was 4 ½ inches deep and approximately ten miles long. The contractor for this paving project was Cedar Valley Corporation. Cedar Valley Corporation utilized a slip-form paver for construction of the slab. The mix design for this project is stated in Table 3.3. The cement was Duracem Type IP (F) and was supplied by Ash Grove Cement in Louisville, NE. This type of cement is a portland cement blended, or inter-ground, with 15-40% pozzolan content. It was used with a Class C fly ash supplied from Council Bluffs Unit #3, in Council Bluffs, IA. Along with the ingredients in Table 3.3, a water reducer (GRACE WRDA 82) and air entraining agent (GRACE DARA 1400) were added to the mixture. The dosage rates were 652.5 mL/yd^3 and 1141.9 mL/yd^3, respectively.

Table 3.3 Sac County Mix Design Ingredients

Materials	**Absolute Volume**	**Weight, lbs/yd^3**
Cement Type IP (F)	0.089	442
Fly Ash Class C	0.036	110
Water	0	0
Air	0.060	-
Fine Aggregate	0.347	1590
Intermediate Aggregate	0.088	432
Coarse Aggregate	0.383	1755

The aggregates used for this project were supplied from Hallet Materials Co., in Audubon and Sac Counties. The three aggregates include a 1 ½ “road stone, ¼ “stone chips and concrete sand. Table 3.4 shows the aggregate gradation for Sac County.

Table 3.4 Aggregate Gradation for Sac County

Sieve Size	**% Passing**		
	1 ½” Stone	*¼ “ Chips*	*Conc. Sand*
1 ½ “	100.0	100.0	100.0
1 ”	97.0	100.0	100.0
¾ ”	79.0	100.0	100.0
½ “	41.0	100.0	100.0
3/8 ”	15.0	99.6	100.0
#4	0.3	33.4	99.8
#8	0.1	1.5	85.4
#16	0.1	1.2	61.3
#30	0.1	0.9	32.8
#50	0.1	0.7	6.6
#100	0.1	0.4	0.8
#200	0.1	0.1	0.4

3.3 Osceola County

Hwy 60 in Sibley is a four lane roadway consisting of ten inches (260 mm) of PCC concrete. This was a two-stage paving project. The first stage of the project was paving Hwy 60 from 0.6 km S. of 190th St. to 0.5 km S. of County Road A-22 (170th St.). This part of this project was approximately six miles long. The second stage of the paving was from N. of Co. Road A-30 (180th St.) N. to 0.5 km N. of 120th Street. This portion of the project was approximately three and one-half miles long. Cedar Valley, Corporation was the paving contractor for this project and they used the same model of a slip-form paver as the Sac County project.

Table 3.5 shows the mix design used for this project. Duracem Type IP (F) cement was supplied from Ash Grove Cement in Louisville, NE. This type of cement is a portland cement blended, or inter-ground, with 15-40% pozzolan content. The fly ash was supplied from Port Neal IV in Sioux City, Ia. A water reducer (WRDA-82) and air entraining agent (W.R. Grace) were also added to the mix. The water reducer was added at a rate of 652.5 ml/yd^3 and the air entraining agent was added at a rate of 978.8 ml/yd^3.

Table 3.5 Osceola County Mix Design Ingredients

Materials	Absolute Volume	Weight, lbs/yd^3
Cement-Type IP (F)	0.089	442
Fly Ash Class C	0.025	110
Water	0.141	238
Air	0.060	-
Fine Aggregate	0.274	1219
Intermediate Aggregate	0.103	469
Coarse Aggregate	0.308	1370

The coarse aggregate was supplied from Concrete Sand and Materials in Dickinson County and the intermediate and fine aggregates were supplied from Higman Sand and Gravel. The three aggregates include a 1 ½ "road stone (coarse), ¼ "stone chips (intermediate) and concrete sand (fine). The aggregate gradation for Osceola County is shown in Table 3.6.

Table 3.6 Aggregate Gradation for Osceola County

Sieve Size	% Passing		
	1 ½" Stone	*¼ " Chips*	*Conc. Sand*
1 ½ "	100.0	100.0	100.0
1 "	100.0	100.0	100.0
¾ "	88.1	100.0	100.0
½ "	41.2	100.0	100.0
3/8 "	20.6	100.0	100.0
#4	2.9	33.9	100.0
#8	1.6	2.4	85.5
#16	1.4	2.1	56.6
#30	1.2	1.8	30.0
#50	0.9	1.6	8.1
#100	0.7	1.3	1.6
#200	0.5	1.0	0.9

3.4 Wapello County

This project was the city of Ottumwa bypass from U.S. 63/ IA 149 South to Steller Avenue. This bypass consists of 10 inches (260 mm) of PCC concrete and is approximately seven miles long. Manatt's Corporation was the paving contractor for this project. The mix design for this project can be seen in Table 3.7. The cement used for this project was Type ISM and was supplied by Lafarge North America in Buffalo, Iowa. Type I(SM) cement is a portland cement blended, or inter-ground, with up to 25% ground granulated blast furnace slag (GGBFS). Fly ash Class C was added to the cement and was produced at Ottumwa Generating Station in Chillicothe, IA. Along with these ingredients, a water reducer (WR) and air entraining agent (AEA 92) were added. The dosage rates were 654.8 mL/yd^3 and 49.1 mL/yd^3, respectively.

Table 3.7 Wapello County Mix Design Ingredients

Materials	**Absolute Volume**	**Weight, lbs/yd^3**
Cement Type ISM	0.085	443
Fly Ash Class C	0.024	111
Water	0.132	222
Air	0.060	-
Fine Aggregate	0.287	1291
Intermediate Aggregate	0	-
Coarse Aggregate	0.412	1846

The coarse and fine aggregates used for this project were supplied from Douds Stone, Inc. in Keokuk and Davis counties. There is no intermediate aggregate for this project. The two aggregates include a 1 ½ “road stone and concrete sand. The following table (Table 3.8) shows the aggregate gradation for Wapello County.

Table 3.8 Aggregate Gradation for Wapello County

Sieve Size	**% Passing**	
	1 ½” Stone	*Conc. Sand*
1 ½ “	100.0	100.0
1 ”	97.0	100.0
¾ ”	77.0	100.0
½ “	42.0	100.0
3/8 ”	28.0	100.0
#4	6.5	97.0
#8	1.5	86.0
#16	1.4	69.0
#30	1.2	44.0
#50	1.1	10.0
#100	0.9	1.0
#200	0.8	0.5

Chapter 4. Data Collection Process

4.1 Field Testing

Field tests were conducted to assess workability, bleeding and permeability characteristics. The workability and bleeding characteristics were tested at the time of paving. The permeability was tested after the slab had hardened and cured, typically seven days after paving. The workability was assessed by slump cone (Figure 4.1) and air pot (Figure 4.2) tests. These tests were done according to ASTM C 143 and ASTM C 231, respectively.

Figure 4.1 Slump Cone

The air tests were used to determine the target air content in front of the paver in the fresh concrete. Most concrete samples were taken before the concrete passed under the placer. Typically, these air contents were around eight percent. Iowa DOT specifications state that six percent air content is needed in the hardened concrete. The fresh concrete air content was higher than IDOT specifications because a loss of air occurs as the concrete passes under the paver and through the vibrators.

Figure 4.2 Air Pot

Cylinder samples were cast according to ASTM C 31 for use in strength testing in the laboratory. The samples were cast at the time of paving to assure the same batch of concrete being tested for workability and permeability was also tested for strength. These samples were cast using 4 x 8 inch cylinder molds. Cylinders were cast in sets of three (Figure 4.3) and there were three sets made for each project, yielding a total of nine cylinders for each project.

Bleeding rates were evaluation by visual inspection of the concrete slab. The amount of moisture the slab gave off, along with a professional's opinion on the slab's performance, was used to give the bleeding characteristic a ranking. This ranking was on a scale of one to five, one being very dry and five being very moist. In order to maintain consistency during the evaluation, the same professional conducted each inspection.

The surface moisture of the slab was tested at three different locations on the slab; at the paver, before, and after the texture machine using a James Instrument, Inc. M-60 Aquameter (Figure 4.4). This information was used to aid in determining a ranking for the amount of bleeding the slab experienced.

Figure 4.3 Cylinder Molds

Figure 4.4 James Instrument, Inc. M-60 Aquameter

Bleeding rates were also affected by daily weather. Nova Lynx 110-WS-18A Portable Weather Stations were set up at the beginning of paving each day to more accurately measure and record weather data. This data was compared to climate data in COMPASS. Along with these portable weather stations, handheld weather devices for measuring air temperature, relative humidity, wind speed and direction, and slab moisture were used to gather data alongside the paver (Figure 4.5 and Figure 4.6).

Figure 4.5 Davis Instruments Turbometer

Figure 4.6 Handheld Weather Device

Permeability tests were conducted with a Poroscope Plus permeability meter manufactured by James Instruments, Inc. (Figure 4.7). This machine required that a series of four holes, two inches deep, be drilled into the concrete (Figure 4.8). A rubber plug was inserted into the holes and the permeability machine was attached to the plugs (Figure 4.8). The test hole was pressurized with air to a pre-determined pressure. The machine measured the time it took for a pressure change of five pounds per square inch to occur. This amount of time was then compared to a chart of time ranges to determine if the permeability was in an acceptable range. The machine can also test for water permeability, however only air permeability tests were conducted. This was done at approximately the same locations where the cylinder samples were cast. This was to ensure that the same concrete batch was being tested throughout the process.

Figure 4.7 James Instrument Permeability Meter

Figure 4.8 Permeability Meter Plug Configuration

4.2 Laboratory Testing

Along with these field tests, laboratory tests for abrasion, strength, and segregation characteristics were done. Abrasion tests were conducted according to ASTM C 944. To run this test, cylinders were mounted in a wooden jig on the drill press (Figure 4.9). The test was done on one end of the cylinder, then the cylinder was weighed to record the total mass lost (Figure 4.10). The cylinder was flipped over and the test was conducted on the remaining end of the cylinder, and then weighed again to record total mass lost.

If the cylinders were initially cured on an uneven surface, they were trimmed prior to testing to create a flush surface. Trimming the cylinders will cause more aggregate surface to become exposed, causing less abrasion to occur.

Figure 4.9 Abrasion Testing Apparatus

Figure 4.10 Abrasion Test

The strength tests were conducted according to ASTM C 39. For each project, three sets of samples were cast during paving, creating nine cylinders for each project. Cylinders were wet cured for 7, 14, and 28 days. One cylinder from each of the three sets was selected randomly and tested for strength on the respective dates (Figure 4.11). This gave three different strength values for each date of testing. These values were then averaged to show the strength gain occurring over time for the project.

Figure 4.11 Strength Testing

The evaluation of the segregation characteristic was another visual inspection of the concrete. The amount of segregation was ranked on a scale of one to five, one being very segregated and five being very uniform. Segregation inspections were done on the cylinder samples after the strength tests had been conducted (Figure 4.12).

Figure 4.12 Visual Segregation Inspection

In addition to evaluating these six characteristics, contractor techniques were also observed. Some of the projects observed were new constructions and some were overlays (Figures 4.13 and 4.14). There were also various pavement depths and widths that occurred throughout the projects.

Figure 4.13 New Pavement Construction

Figure 4.14 Overlay Pavement Construction

There was also a difference in finishing techniques used on the slab. Most projects were finished with standard magnesium hand floats. One contractor utilizes a V-float to finish the slab (Figure 4.15). It is a float designed by the contractor to help them achieve a smooth pavement surface. This enables them to use less man-power and they believe it produces a better finish on the slab.

Figure 4.15 V-Float

Chapter 5. Data Analysis

The slump and air test concrete samples were taken before the concrete passed under the placer. In some cases, the Department of Transportation (DOT) air content was also recorded. Throughout the entire research project, it was found that the student air tests were consistently lower than the DOT air tests. This can be attributed to the difference in calibrations of the air pots. For a tabular form of the data from each project, refer to Appendix C.

5.1. Cass County

The following figures show the workability test results for Cass County. The DOT specification for slump on this project was one and one half inches and specification for air content in hardened concrete is six percent. Contractors have found that by batching the concrete with an air content around ten percent will allow them to achieve the specification at six percent in the hardened concrete. The concrete will lose roughly four percent of the air content as it passes through the paver. Figure 5.1 and Figure 5.2 show a graphical representation of the data. The highest slump value recorded for the project was five inches. The highest value of air content recorded was 7.5 %.

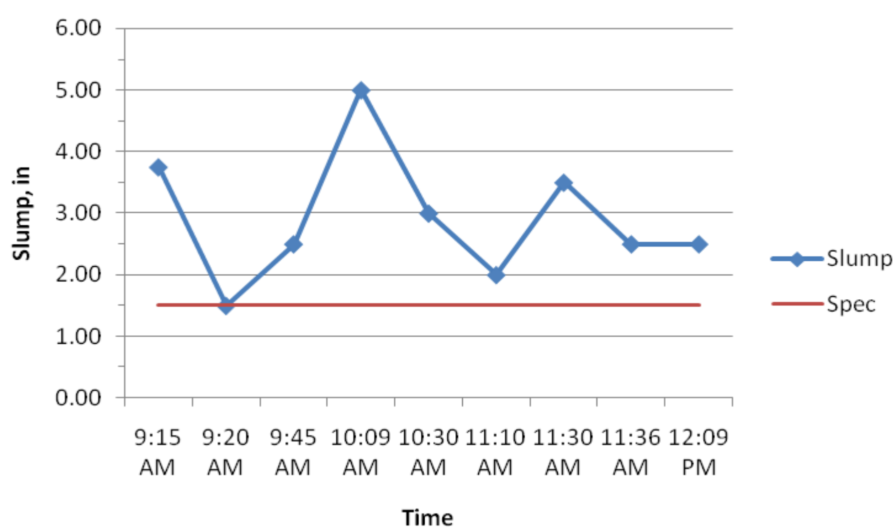

Figure 5.1 Cass County Slump Test Results

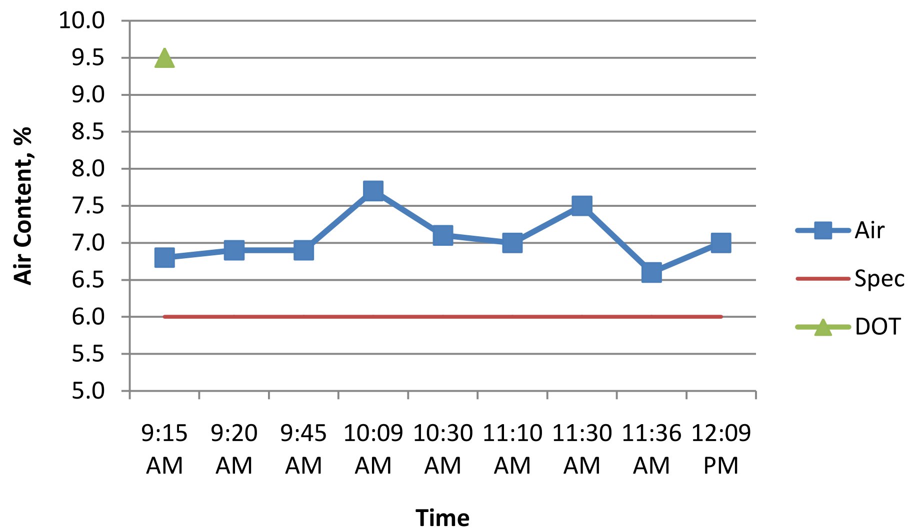

Figure 5.2 Cass County Air Test Results

The bleeding rate evaluation was a visual inspection of the slab. Slab surface moisture was assessed along with slab performance to assign a ranking to the slab. The ranking was on a scale of one to five, with one being very dry to five being very moist. For Cass County, the slab received an average ranking of 3.0. This ranking corresponds to a damp condition. At the beginning of paving the slab was scoring a ranking of a 3.0. As the day progressed, this ranking was lowered to a 2.0. A two ranking is said to be slightly dry. The slab was showing very good closing characteristics and the finishers were putting in little effort to achieve the desired finish on the slab. This is indicative of the performance of the slab.

The permeability tests results are shown in Figure 5.3. The dashed line on the graph represents the range where the 'fair' permeability range begins. There is a lot of scatter in the data, not only within each test site, but throughout the entire project. The permeability times were averaged over the project to produce an overall permeability time of 320 seconds.

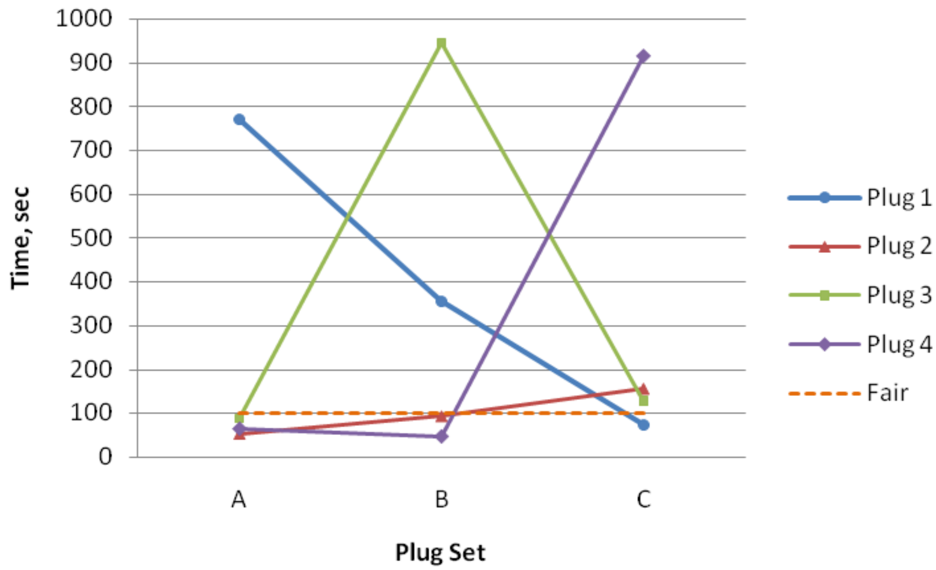

Figure 5.3 Cass County Permeability Test Results

Figure 5.4 shows the strength test results for Cass County. There was a 12.8% strength increase between 7 and 14 day breaks and a 30.7% strength increase between 7 and 28 days. The final 28 day strength was 3760 psi.

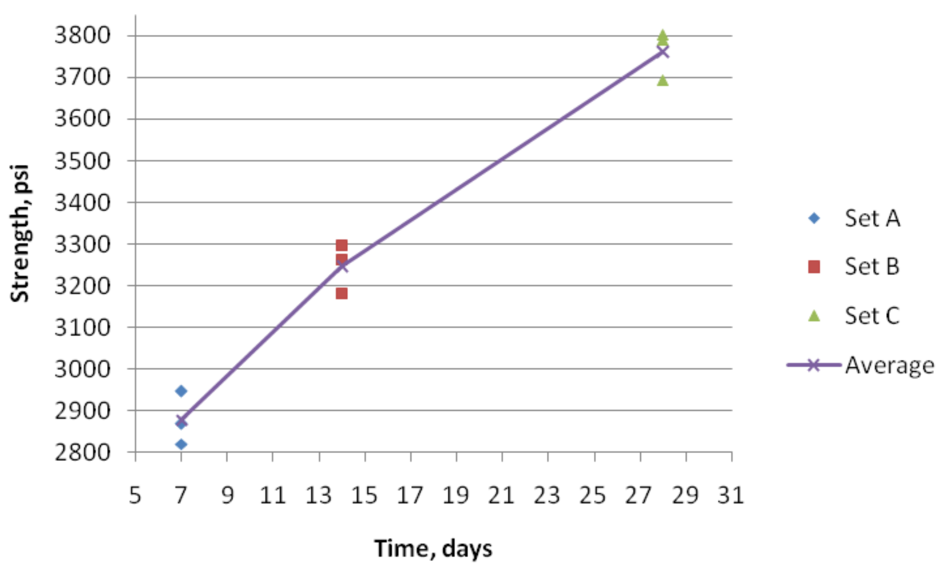

Figure 5.4 Cass County Strength Test Results

The abrasion tests were conducted at the time of the strength tests, 7, 14, and 28 days. Figure 5.5 shows the mass loss during the abrasion testing for Cass County. It can be seen that the longer the concrete cured, the less mass it lost. The amount of mass lost is reflective of the strength gain in the concrete. The total mass lost from the 7 to 28 day tests was 0.0031 lbs.

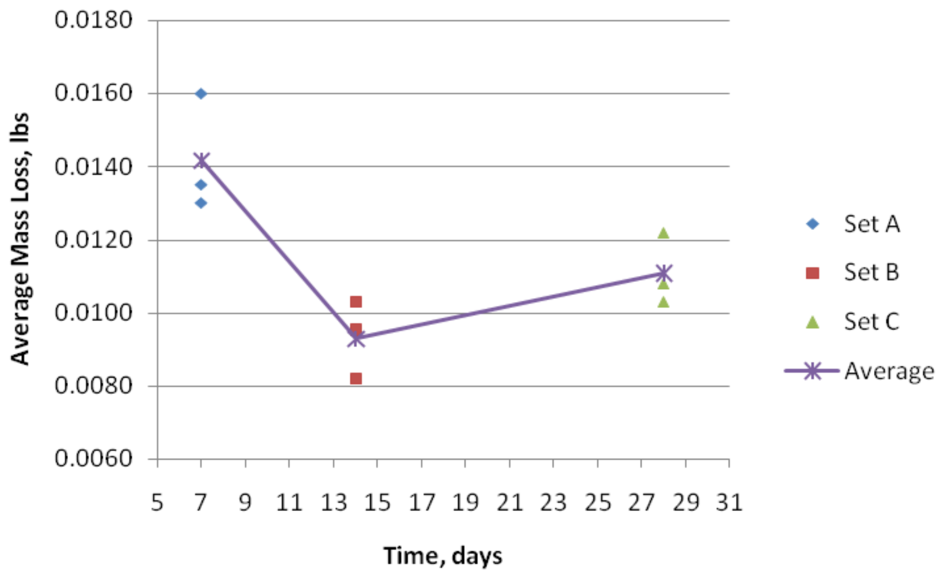

Figure 5.5 Cass County Abrasion Test Results

The segregation ranking was assessed in the same manner as the bleeding ranking. The ranking was on a scale of one to five, with one being very segregated and five being very uniform. Cass County showed an average segregation value of 5.0. This value corresponds to a very uniform distribution of the paste and aggregates.

5.2. Sac County

The test results for Sac County can be seen in the following figures. The slump and air test samples were taken ahead of the concrete placer. The DOT specification for slump on this project was two inches and specification for air content in hardened concrete is six percent. Figure 5.6 and

Figure 5.7 show a graphical representation of the data. The highest value of slump recorded for this project was 5.5 inches. The highest value of air content recorded was 9.8 %.

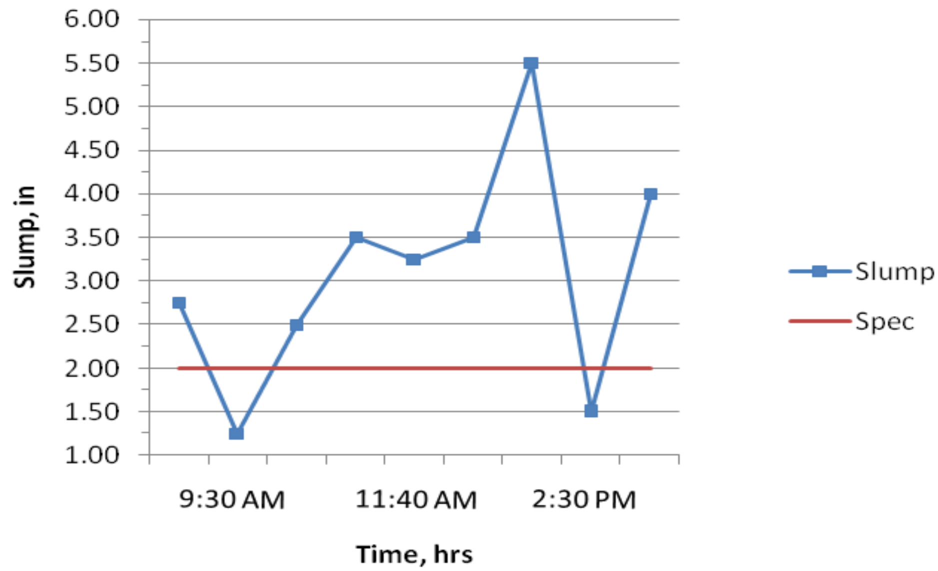

Figure 5.6 Sac County Slump Test Results

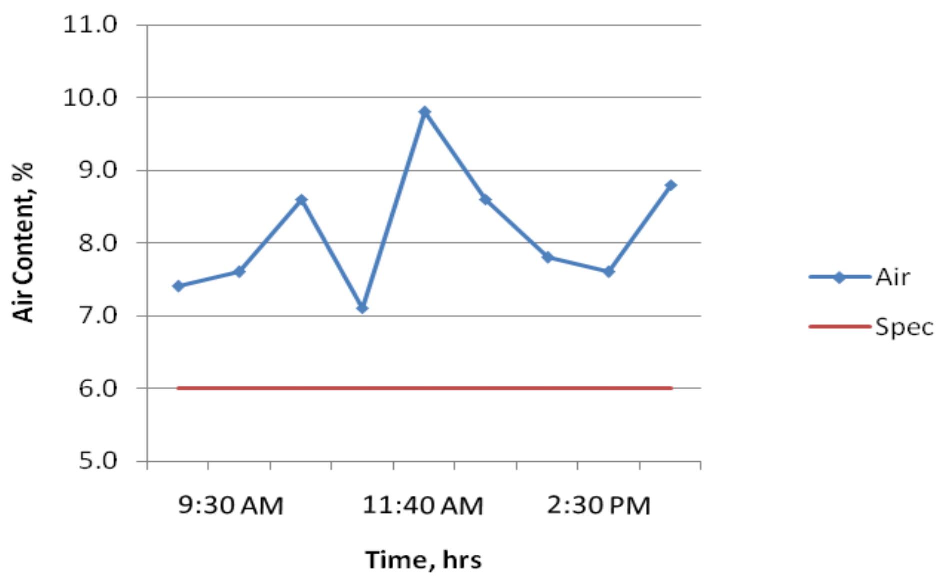

Figure 5.7 Sac County Air Test Results

For Sac County, the slab received an average ranking of 2.0. This ranking corresponds to a slightly drier than damp condition. The surface of the slab was initially hard to close, but got better as the day progressed.

Figure 5.8 shows the permeability results for Sac County. Most of the plugs had a permeability time lower than the fair category (dashed line on graph). This can be related to the installation of the plugs. If the plugs were not sealed correctly, the data will not be accurate. The data was very scatted throughout this project. The permeability times were averaged over this project to yield an overall permeability time of 70 seconds. This is below the fair range.

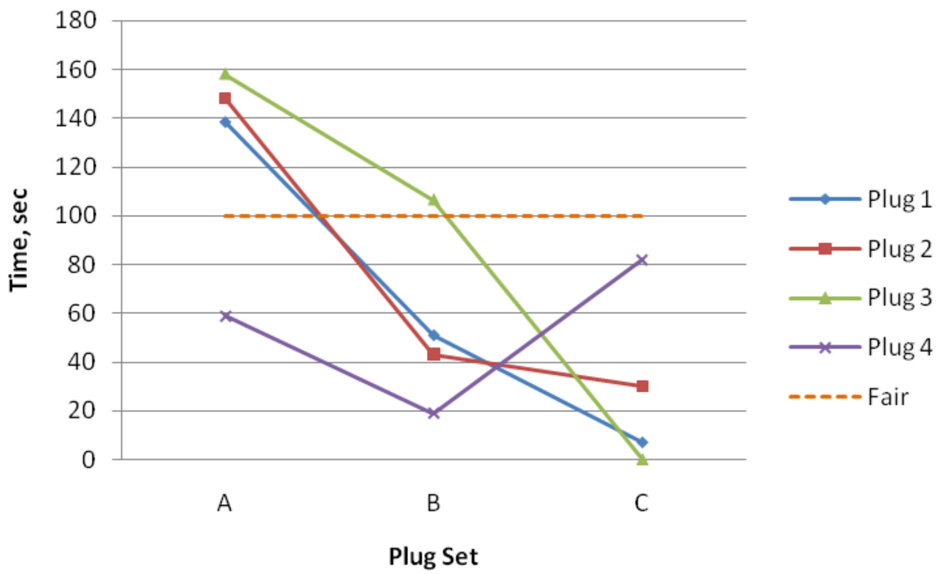

Figure 5.8 Sac County Permeability Test Results

The strength test results for Sac County can be seen in Figure 5.9. There was a 21.5% strength increase between 7 and 14 day breaks and a 28.6% strength increase between 7 and 28 days. The maximum average strength reached at 28 days for this project was 3760 psi.

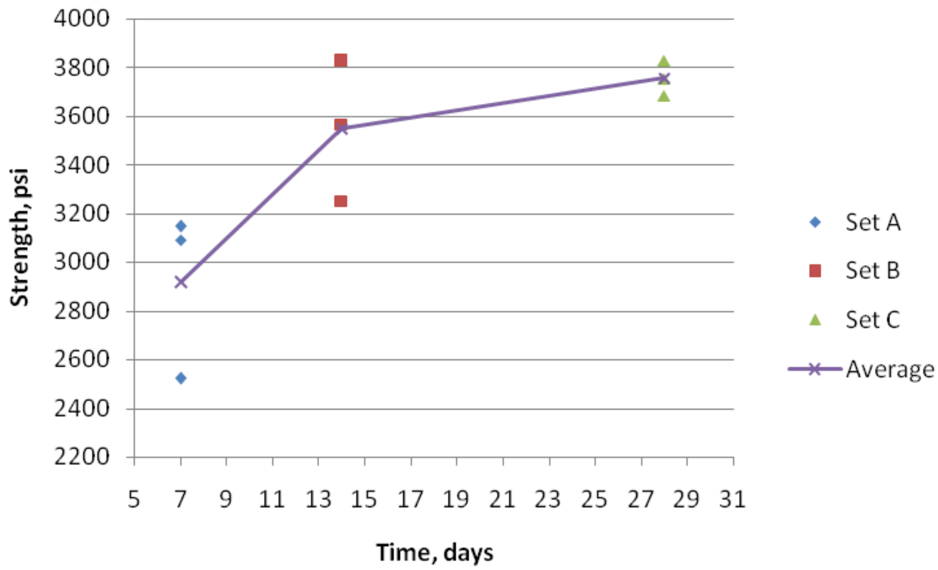

Figure 5.9 Sac County Strength Test Results

Figure 5.10 shows the results of the abrasion testing for Sac County. The abrasion tests were conducted at the time of the strength tests, 7, 14, and 28 days. It can be seen that the longer the concrete cured, the less mass it lost. The amount of mass lost is reflective of the strength gain in the concrete. The total mass lost from the 7 to 28 day tests was 0.0068 lbs.

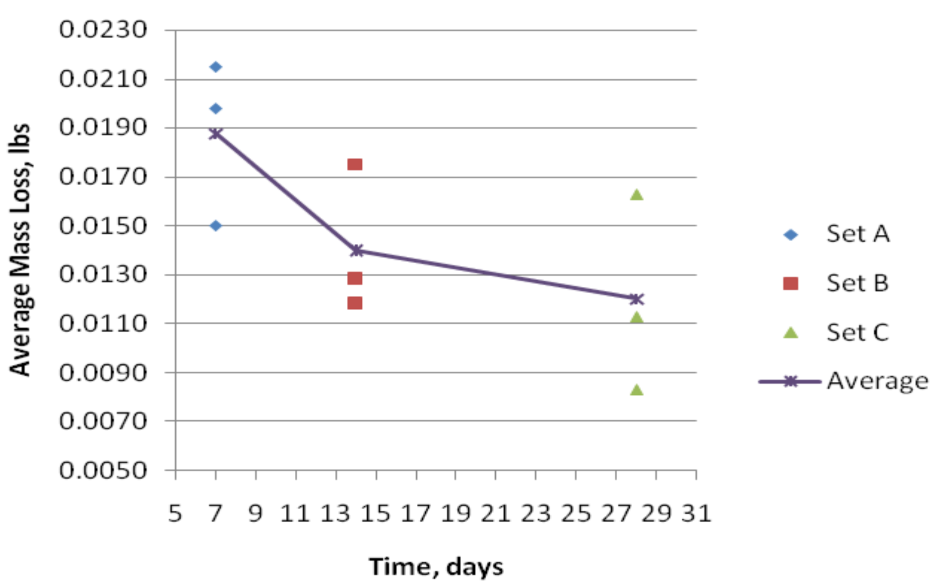

Figure 5.10 Sac County Abrasion Test Results

The amount of segregation was visually inspected after the samples had been tested for strength. The average segregation ranking for Sac County was a 5.0. This value corresponds to a very uniform distribution of the paste and aggregates. The coarse and fine aggregates were well distributed within the paste.

5.3 Osceola County

Figures 5.11 and 5.12 are the workability test results for Osceola County. The DOT specification for slump on this project was one and one half inches and specification for air content in hardened concrete was six percent. The concrete was batched ten percent air to account for air loss that happens as the concrete passes through the paver. The highest value of slump recorded for Osceola County was 2.4 in. The highest value of air content was 9.0%.

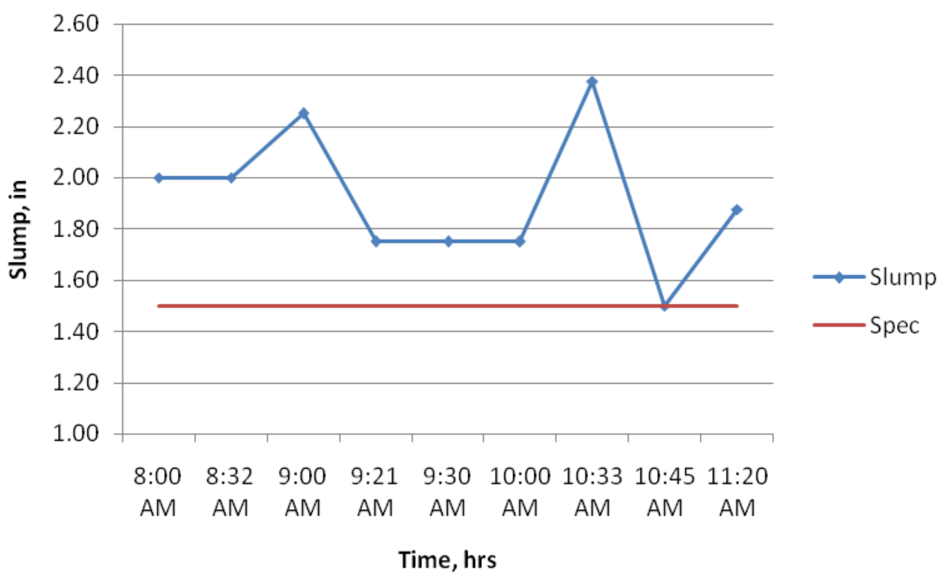

Figure 5.11 Osceola County Slump Test Results

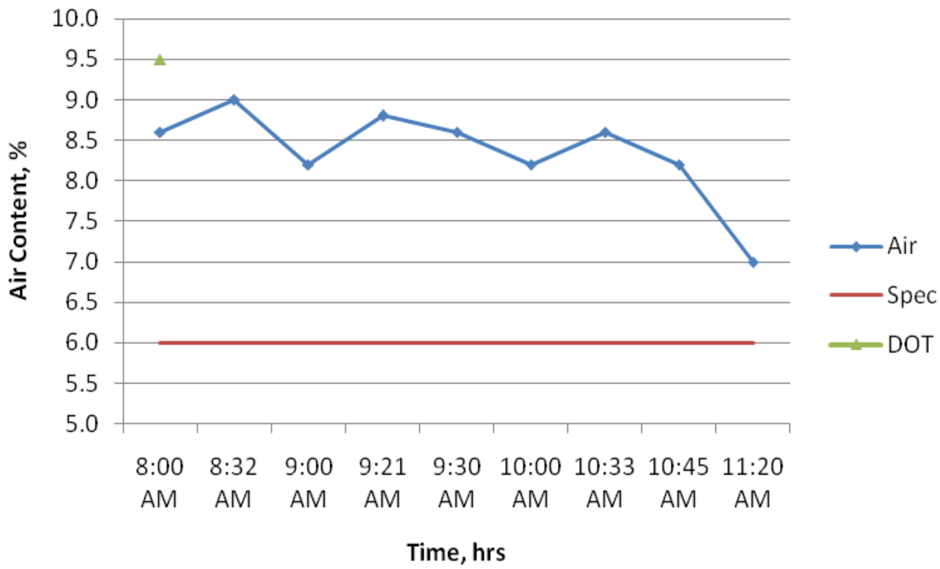

Figure 5.12 Osceola County Air Test Results

For Osceola County, the bleeding ranking was determined to be an average of 2.0. This ranking corresponds to a slightly drier than damp condition. The slab was showing very good closing characteristics and the burlap drag was staying very moist for the finishers. The finishers were putting forth little effort to achieve the desired finish on the slab.

The results of the permeability testing can be seen in Figure 5.13. Roughly half of the test plugs recorded times that were below the fair mark. Again, this could be related to the installation of the plugs. The average value of permeability time for the entire project was found to be 120 seconds. This is just above the fair range.

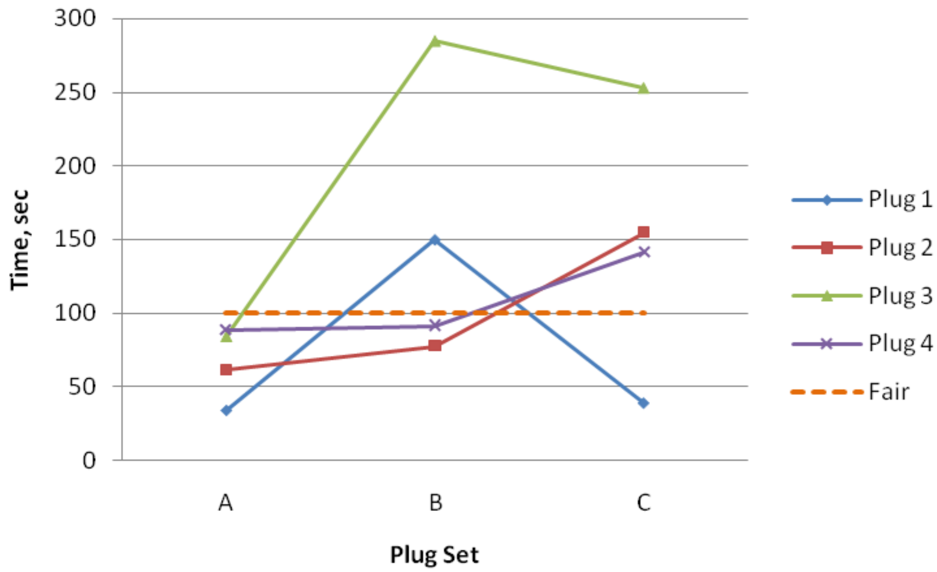

Figure 5.13 Osceola County Permeability Test Results

The following graph (Figure 5.14) shows the strength test results for Osceola County. There was a 20.9% strength increase between 7 and 14 day breaks and a 39.5% strength increase between 7 and 28 days. The highest strength value 3090 psi.

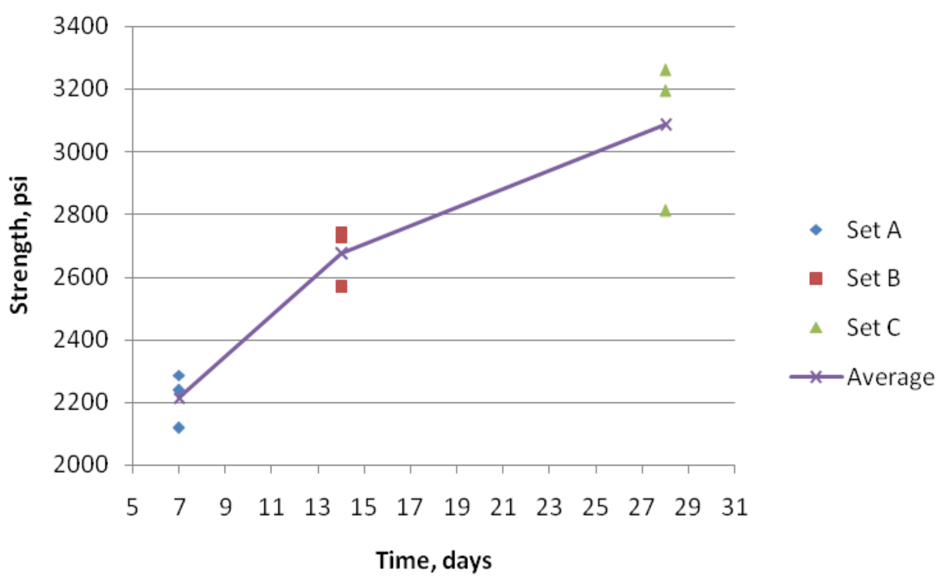

Figure 5.14 Osceola County Strength Test Results

The abrasion test results can be seen in Figure 5.15. The abrasion tests were conducted at the time of the strength tests, 7, 14, and 28 days. The samples appeared to lose more mass at 28 days than at 14. This could be attributed to the trimming of the samples. If the samples were trimmed prior to testing, this would expose more aggregate faces and cause less abrasion to occur. The total mass lost from the 7 to 28 day tests was 0.004 lbs.

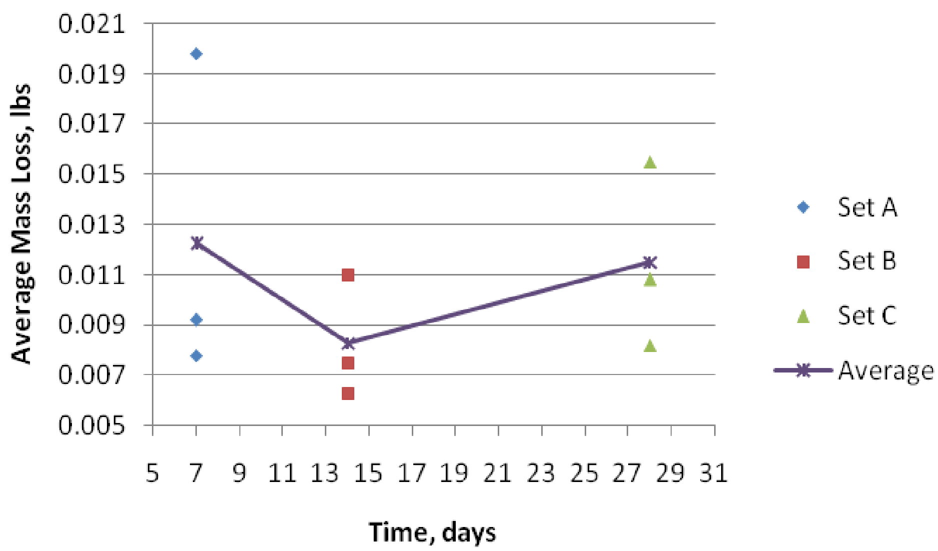

Figure 5.15 Osceola County Abrasion Tests Results

The average segregation ranking for Osceola County was a 5.0. This value corresponds to a very uniform distribution of the paste and aggregates. The coarse and fine aggregates were well distributed in the paste.

5.4. Wapello County

Wapello County was the last of the projects tested. The DOT specification for slump on this project was two inches and specification for air content in hardened concrete is 6 %. The concrete was batched at 10 % air to accommodate air loss that occurs through the paver. Figure 5.16 and

Figure 5.17 show a summary of the workability data. The highest value of slump recorded was 1.375 inches. The highest value of air content recorded was 10.2%.

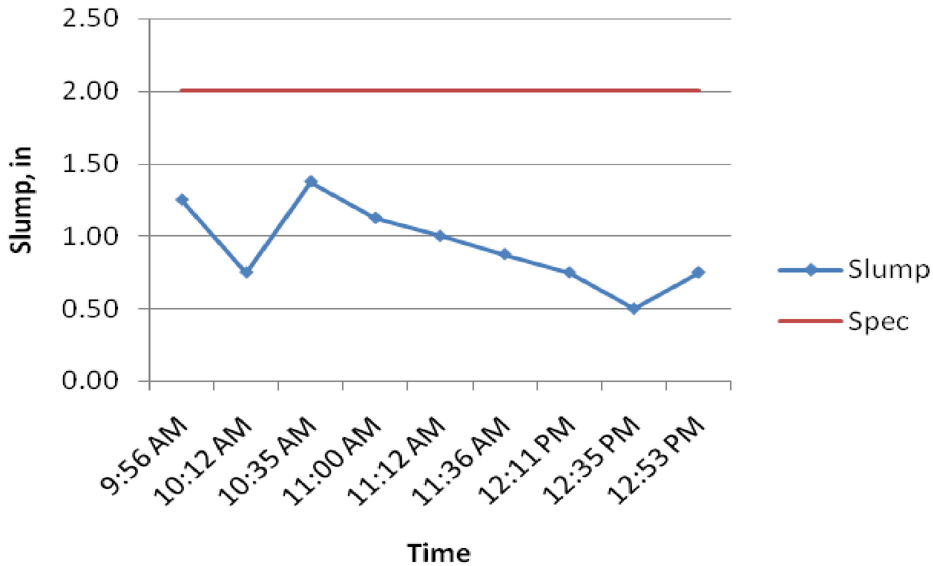

Figure 5.16 Wapello County Slump Results

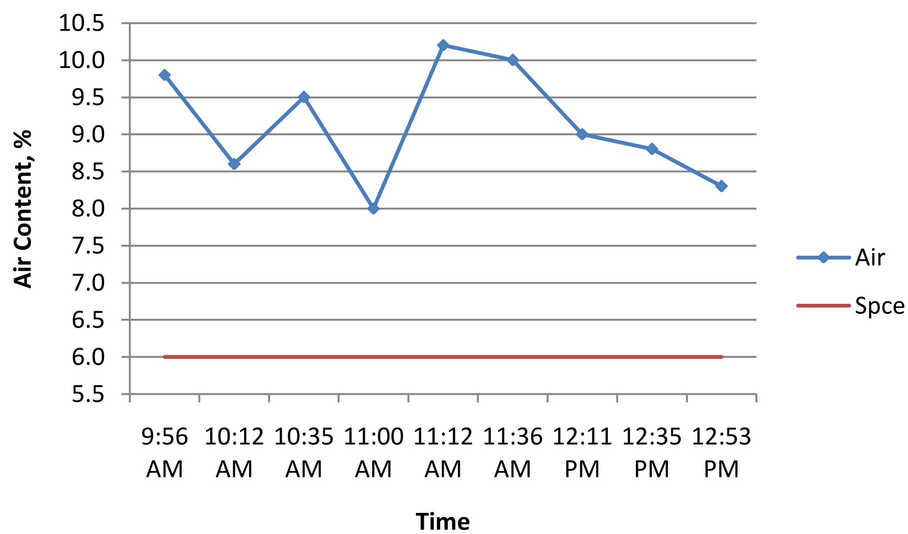

Figure 5.17 Wapello County Air Test Results

The bleeding rate evaluation for Wapello County showed the slab to have an average ranking of 2.0. This ranking corresponds to a slightly drier than damp condition. The slab was showing a lot of paste at the surface, but was still closing well.

The permeability results for Wapello County can be seen in Figure 5.18. The permeability test results were the best for this project. The slab performed as expected and produced very good permeability results. The average value of permeability time recorded for this project was 16 minutes.

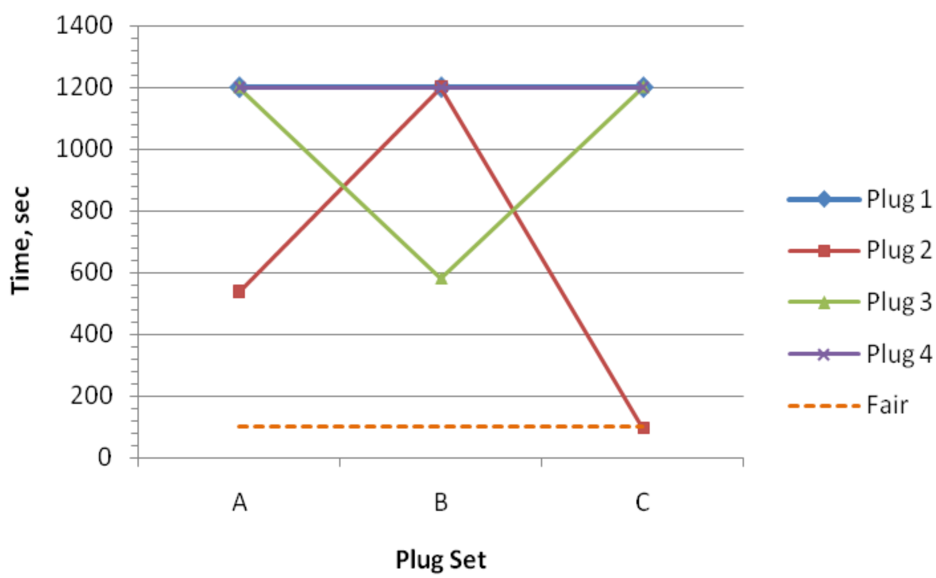

Figure 5.18 Wapello County Permeability Test Results

Figure 5.19 shows the strength results for Wapello County. There was a 27.8% strength increase between 7 and 14 day breaks and a 34.5% strength increase between 7 and 28 day breaks. The final strength value achieved for Wapello County was 5450 psi.

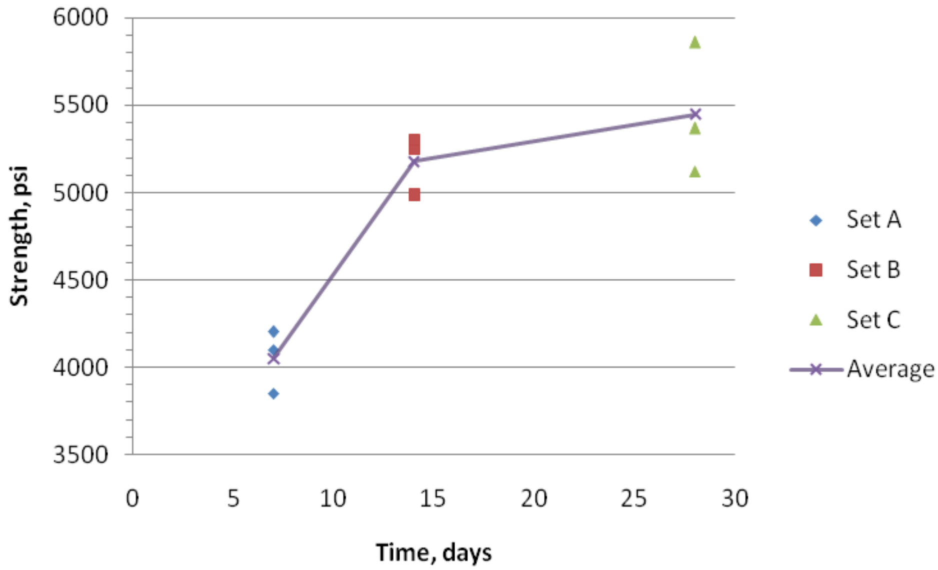

Figure 5.18 Wapello County Strength Results

The abrasion results can be seen in Figure 5.19. There was more mass lost at the 28 day strength than at the 14 day strength. This could be a result of trimming the samples prior to testing. By trimming the samples, the aggregate faces become more exposed and yield a harder surface to resist abrasion. The total mass lost from 7 to 28 days was 0.0066 lbs.

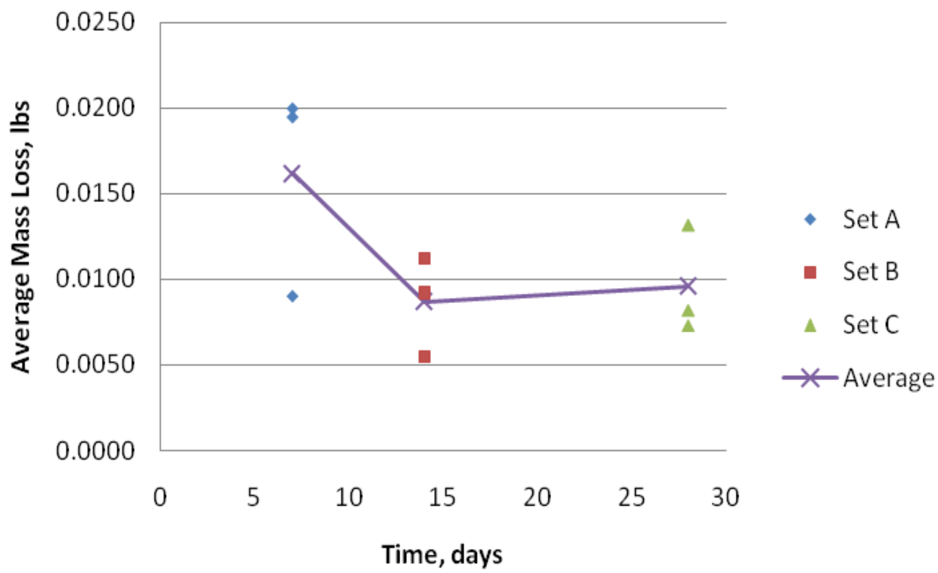

Figure 5.19 Wapello County Abrasion Results

The average segregation ranking for Wapello County was a 5.0. This value is associated with a very uniform distribution. The coarse and fine aggregates were well distributed in the paste. The rock and paste were very uniform throughout the samples.

5.5. Evaluation of Field/Lab Testing

The workability tests were chosen because the slump and air tests are quick tests that produce rapid results. If something went wrong, the test could be repeated immediately. The slump test gives a good indication of the need to adjust the water content of the mix and how drastic those adjustments should be. Air pot tests are somewhat subjective in the sense that each air pot can give different results. It depends on the equipment and operator as to how accurate the test results are. The main difference between the student air pot values and the DOT values was the manner in which the air pots were calibrated. The student pot was calibrated at 5% air content and the DOT air pot was calibrated at 10% air content.

Bleeding rates were visually inspected by a professional that has experience with concrete paving mixes. It was a hard characteristic to judge, but to a trained eye, it was easy to recognize the characteristic. The moisture contents and weather data helped to assign a bleeding ranking to each project, but the values were mainly based on a professional opinion. It was important to use the same person to evaluate the bleeding rates. This ensured consistency throughout the research project.

The permeability tests were very subjective. The test was easy to induce a large amount of error, if not done correctly each time. It was difficult to ensure the plug was air-tight and secure in the test holes. If the plugs were not installed correctly into the test hole, inaccurate data was obtained. These false data points are still shown in the graphical analysis. By showing these points, it shows how precise the permeability test needed to be administered in order to produce accurate data.

The abrasion test is an ASTM standard that shows evidence of the amount of relative wear resistance of mortar and concrete based on testing core samples or lab-created cylinder samples

(ASTM C944). This test method has been used successfully in quality assurance and control of highway and bridge concrete surfaces.[41] There is no reference database for the abrasion test to quantify the test results. Only the mass lost can be reported, there are no comparison values to correlate the mass lost to abrasion resistance.

Strength testing was done on 4 x 8 inch cylinder samples because the samples were easy to handle. They are smaller than the beam molds typically used by IDOT inspectors. They were easier to transport and the testing equipment was already set up for testing cylinder samples of various sizes.

The segregation tests were another visual test. This visual inspection was easier to recognize than the bleeding rates. This visual inspection was performed by the student. It was easier to inspect the samples after they had been tested for strength. All of the samples exhibited excellent uniformity throughout the project. This was an expected result because segregation typically happens as a result of material incompatibility or incorrect placement methods.

5.6 Comparison of COMPASS Predictions

The following figures show the aggregate gradations, 0.45 power charts and workability charts created from the DOT mix designs. The gradations, 0.45 power charts and workability charts developed by COMPASS are also shown. The two sets of graphs match very closely to one another. This shows how well COMPASS was able to predict the mix design and gradations for each project.

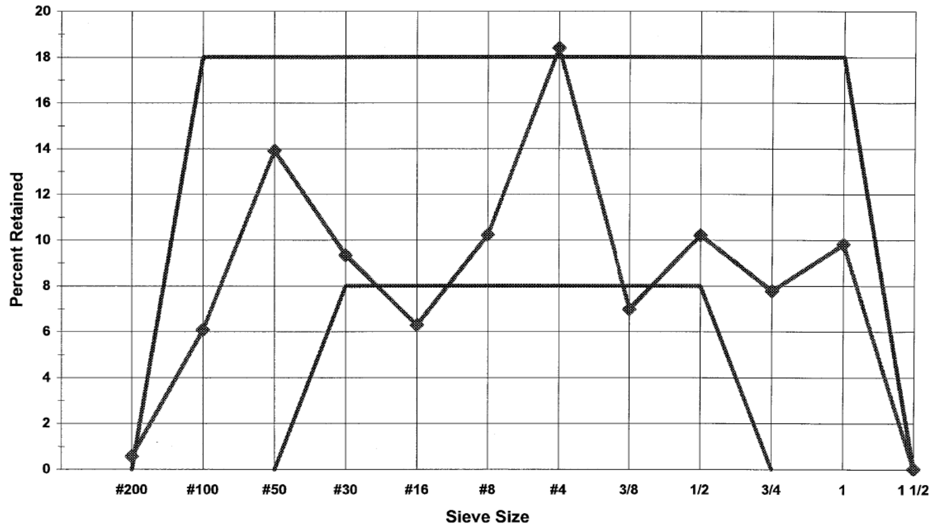

Figure 5.20 Cass County DOT Gradation

Figures 5.20 and 5.21 show the DOT and COMPASS aggregate gradations for Cass County. These graphs are based on the percent retained on the sieves. It can be seen that both graphs are very similar.

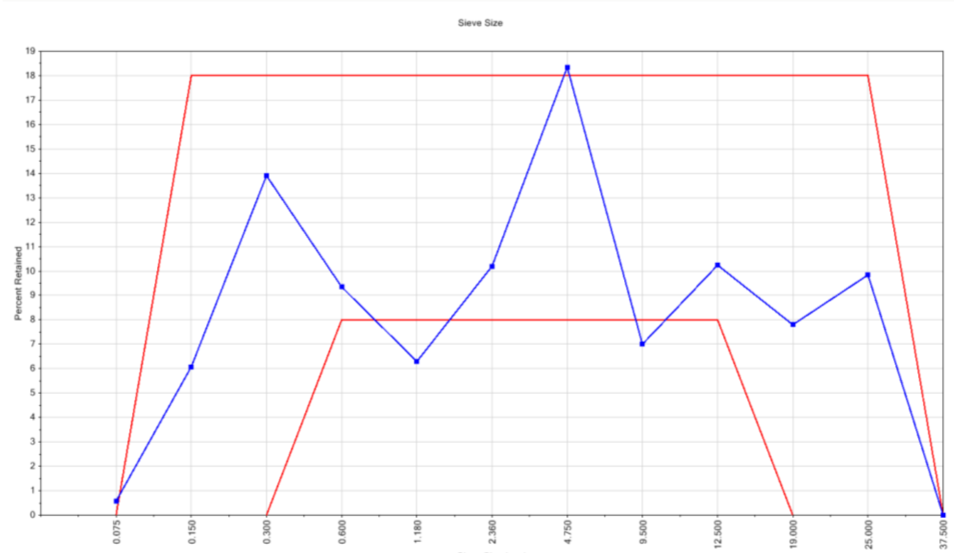

Figure 5.21 Cass County COMPASS Gradation Prediction

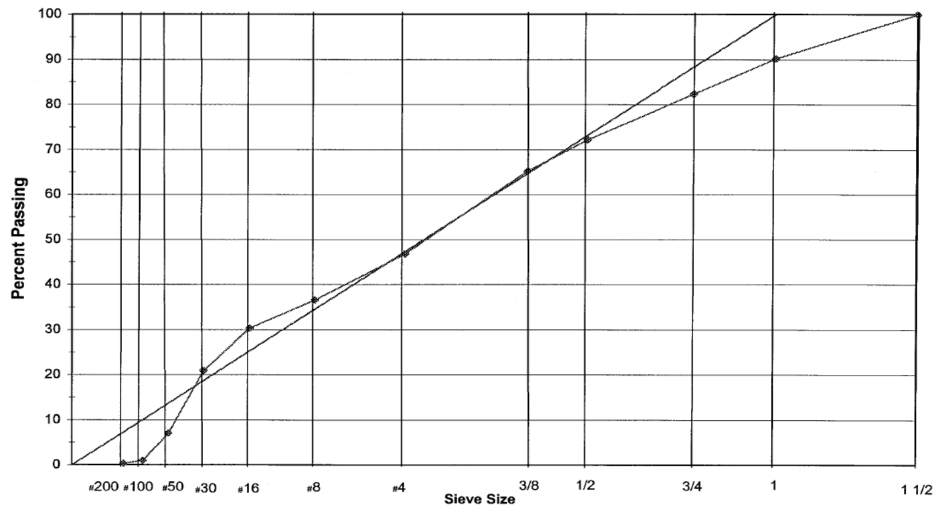

Figure 5.22 Cass County DOT 0.45 Power Chart

The 0.45 power charts for Cass County can be seen in Figures 5.22 and 5.23. Like the aggregate gradation charts, these charts are very similar in shape. Both graphs come very close to the 0.45 line in the middle of the sieve series.

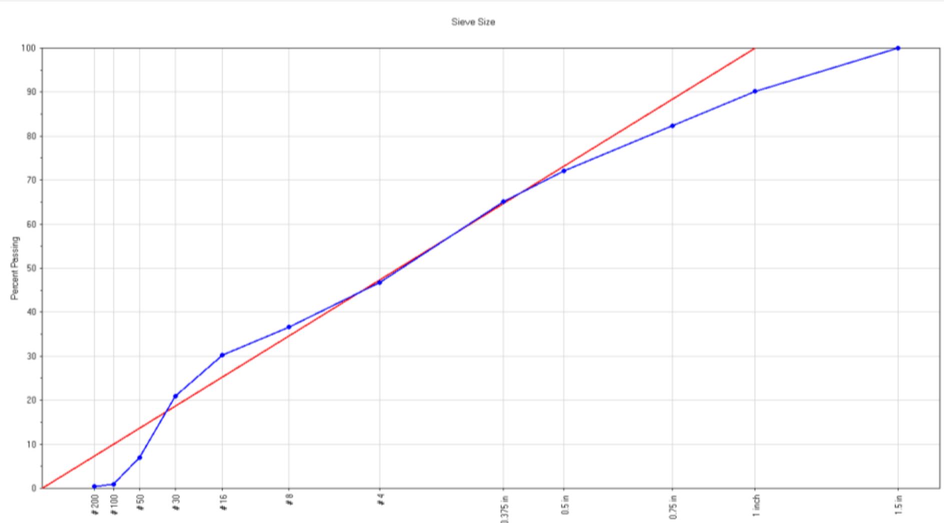

Figure 5.23 Cass County COMPASS 0.45 Power Chart

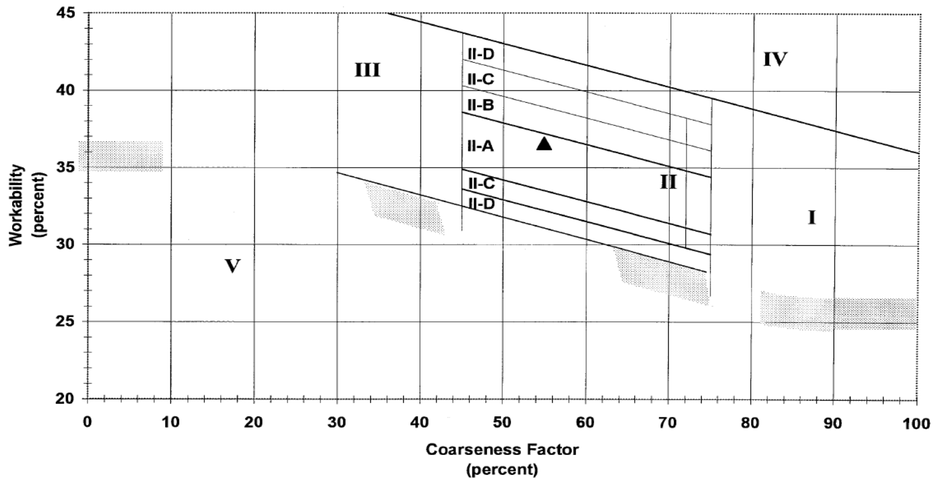

Figure 5.24 Cass County DOT Workability Chart

It can be seen from the DOT workability chart that Cass County has a workability ranking of 36% (Figure 5.24). COMPASS predicted that Cass County would have a workability ranking of 36% (Figure 5.25). The DOT coarseness factor was 55% which matches the coarseness factor of 55% from COMPASS.

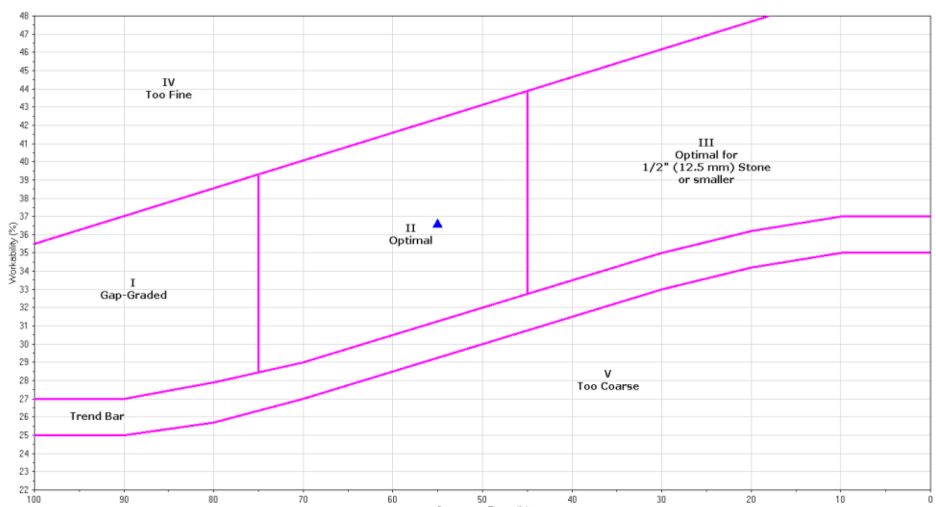

Figure 5.25 Cass County COMPASS Workability Chart

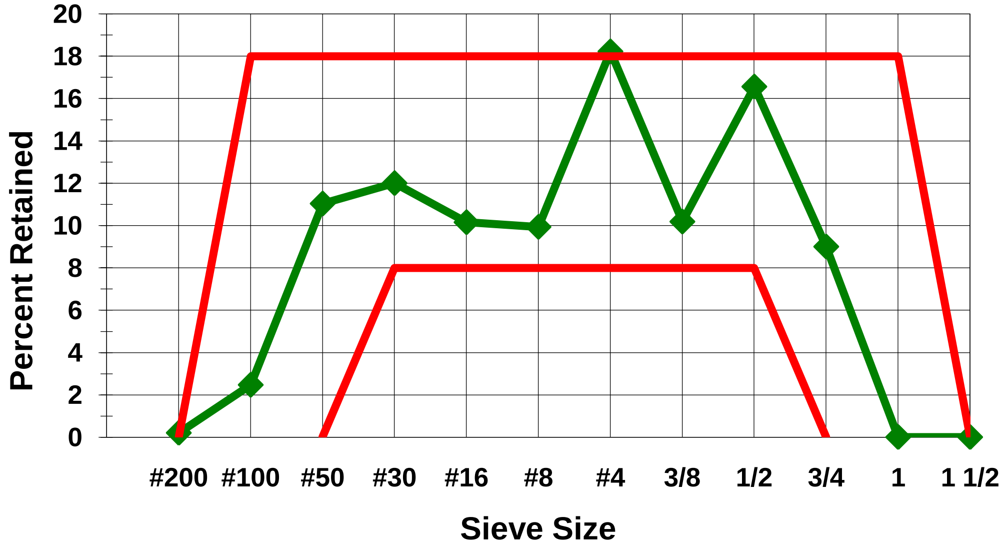

Figure 5.26 Sac County Gradation Chart

Figures 5.26 and 5.27 show the DOT and COMPASS aggregate gradations for Sac County. These graphs are based on the percent retained on the sieves. It can be seen that both graphs are very similar in shape, having peaks in the gradation on the larger sieves.

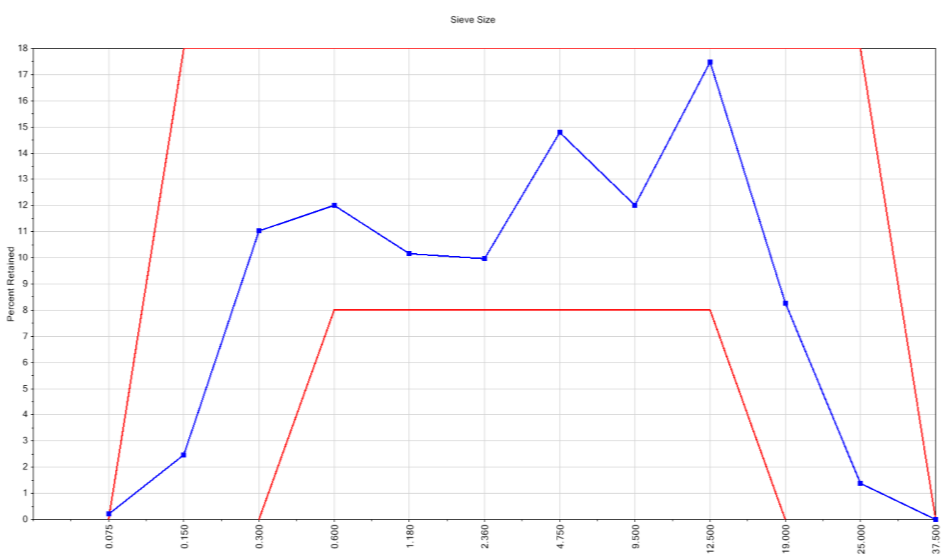

Figure 5.27 Sac County COMPASS Gradation Chart

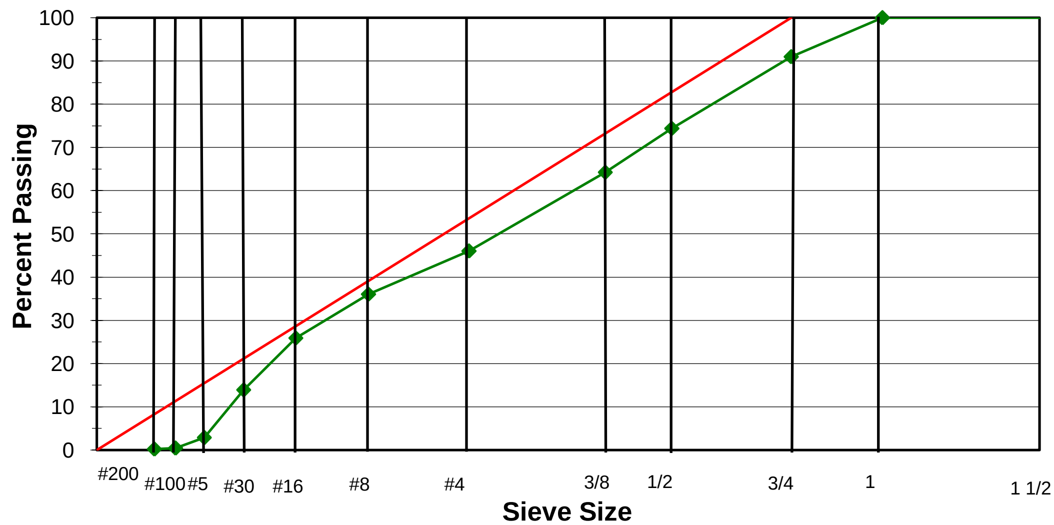

Figure 5.28 Sac County 0.45 Power Chart

The Sac County 0.45 power chart from the DOT and COMPASS are shown here (Figures 5.28 and 5.29). These graphs have the same curvature, coming close to the 0.45 line at the lower end of the graph.

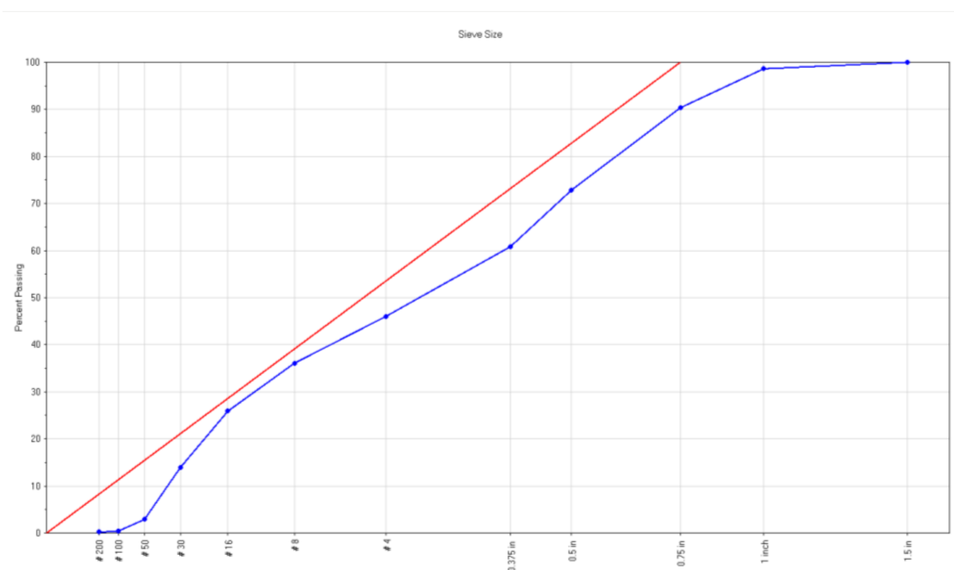

Figure 5.29 Sac County COMPASS 0.45 Power Chart

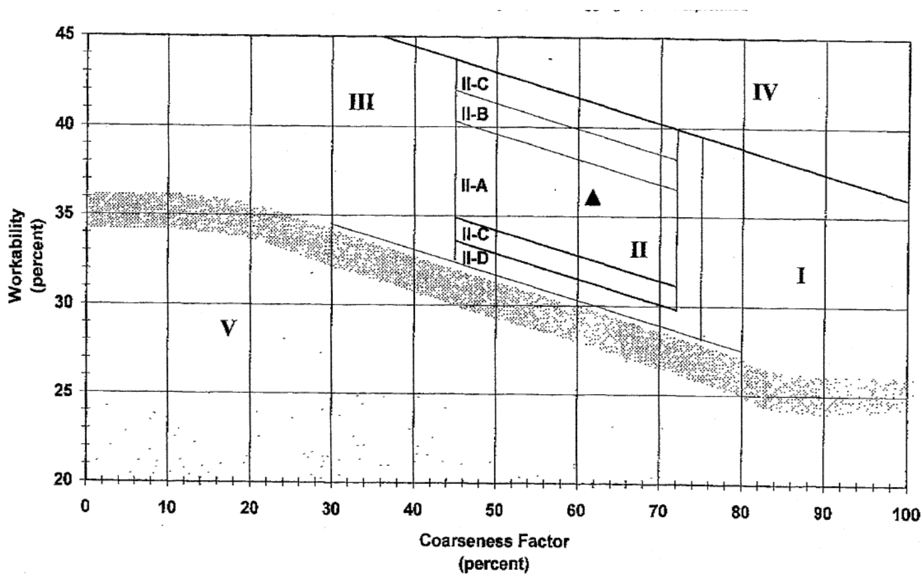

Figure 5.30 Sac County DOT Workability Chart

For Sac County, the DOT workability ranking was 36%, with a coarseness factor of 61% (Figure 5.30). COMPASS predicted that Sac County would have a workability ranking of 36% with a coarseness factor of 61% (Figure 5.31).

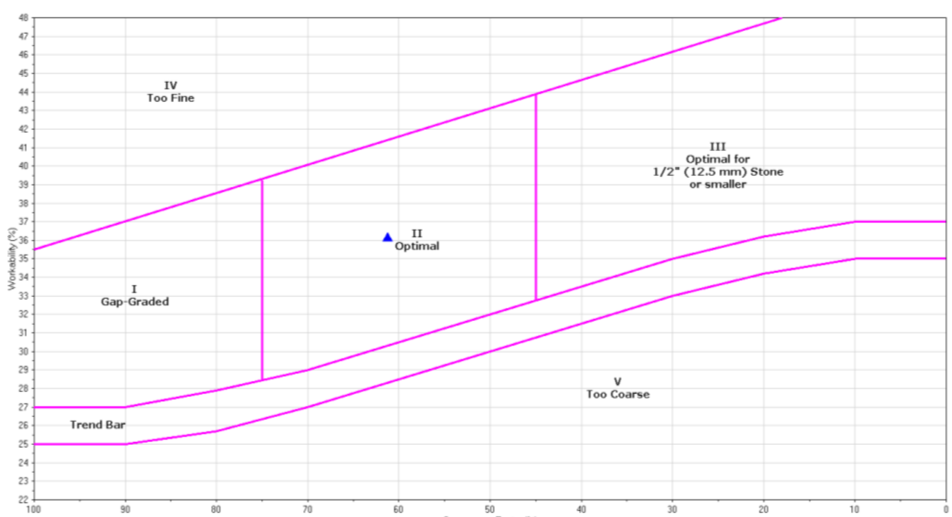

Figure 5.31 Sac County COMPASS Workability Chart

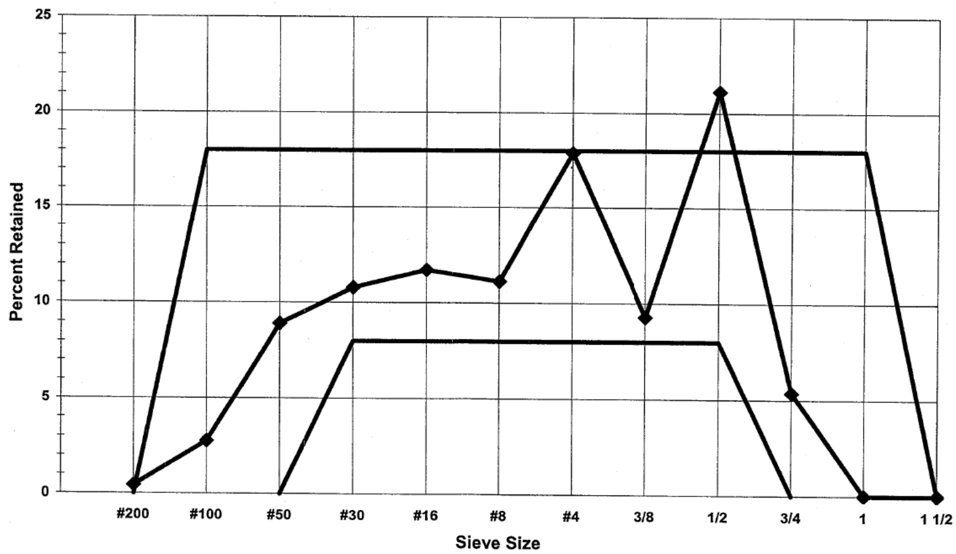

Figure 5.32 Osceola County DOT Gradation Chart

The aggregate gradation charts produced by the DOT and COMPASS for Osceola County are shown in Figures 5.32 and 5.33. These graphs are very similar to each other.

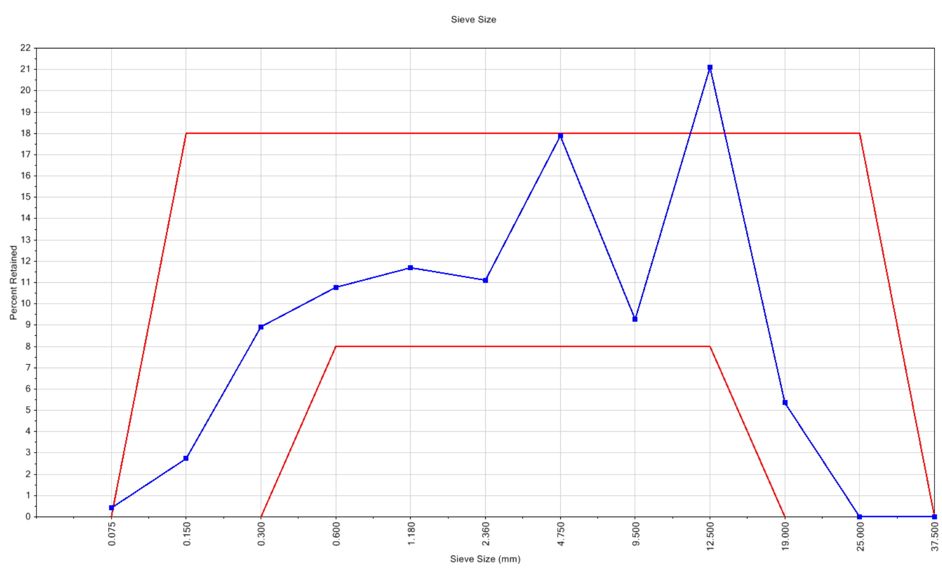

Figure 5.33 Osceola County COMPASS Gradation Chart

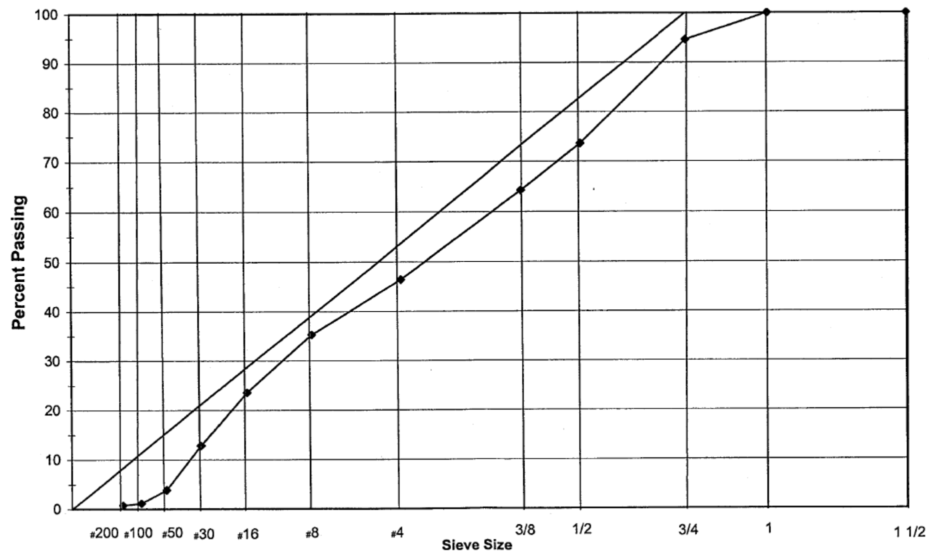

Figure 5.34 Osceola County 0.45 Power Chart

Figures 5.34 and 5.35 show the 0.45 power charts for Osceola County. These charts are very similar in shape, just like the aggregate gradation charts shown previously.

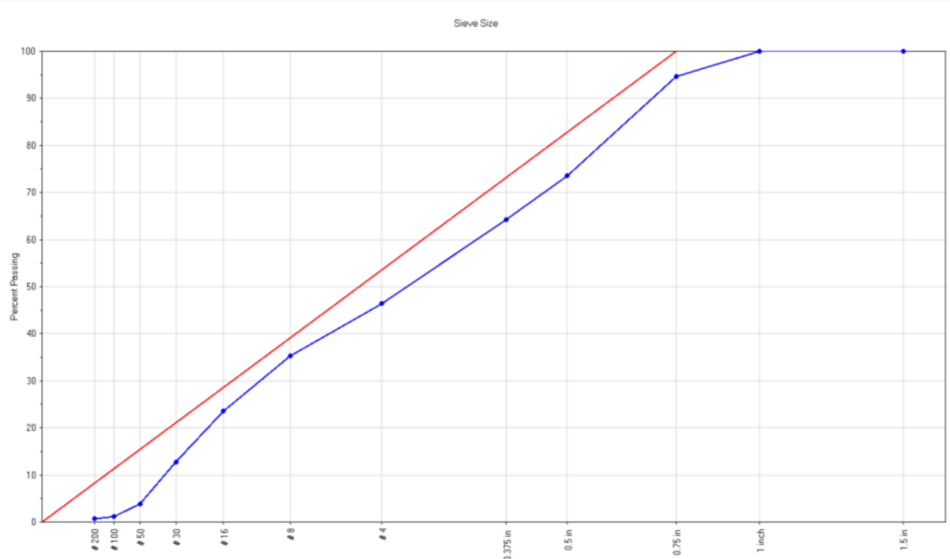

Figure 5.35 Osceola County COMPASS 0.45 Power Chart

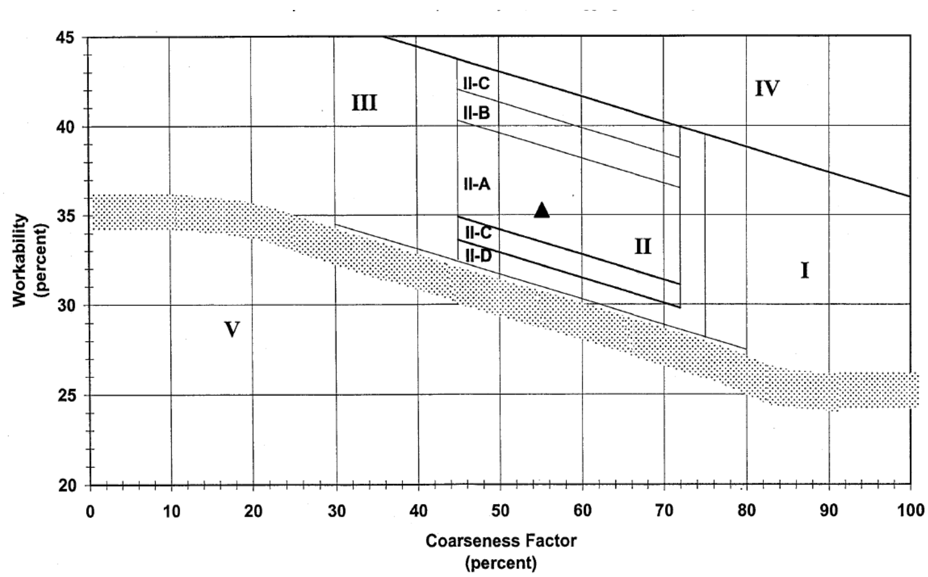

Figure 5.36 Osceola County Workability Chart

For Osceola County, the DOT workability factor was 35% at a coarseness of 55% (Figure 5.36). COMPASS found the workability to be 35% with a coarseness of 56% (Figure 5.37). These values are very similar.

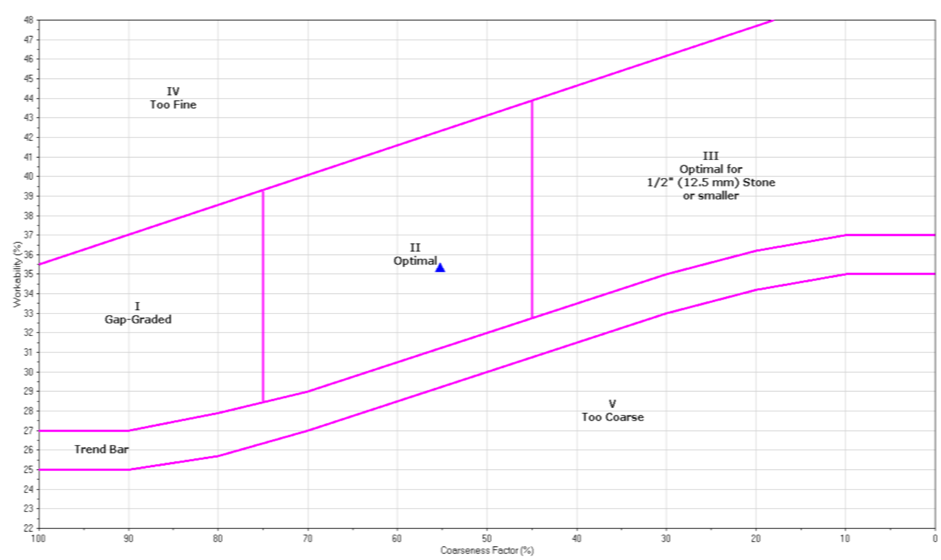

Figure 5.37 Osceola County COMPASS Workability Chart

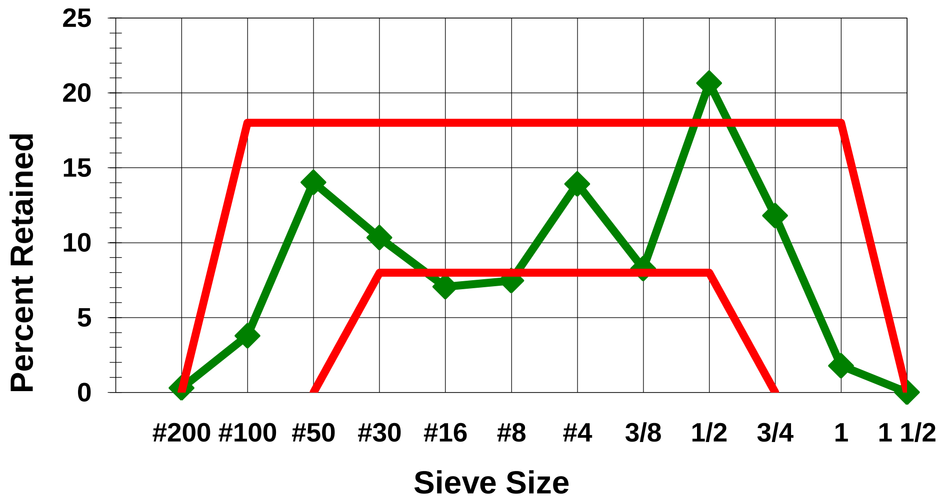

Figure 5.38 Wapello County DOT Gradation

For Wapello County, the aggregate gradation charts are shown in Figures 5.38 and 5.39. These graphs were produced by the DOT and COMPASS are very similar in shape to one another.

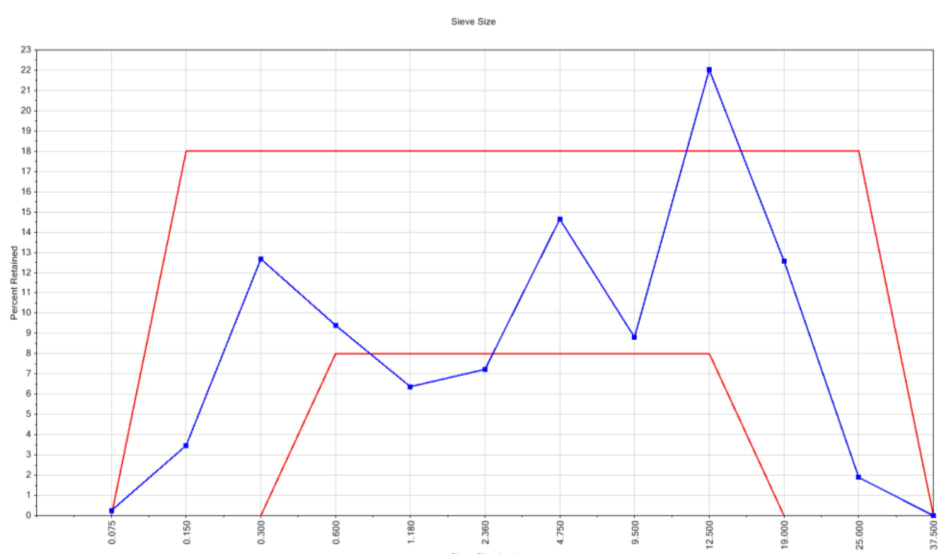

Figure 5.39 Wapello County COMPASS Gradation

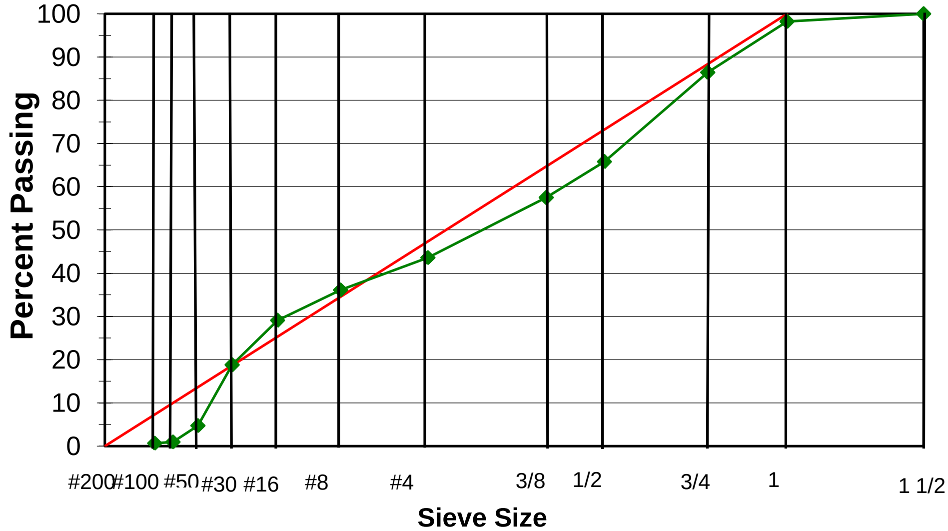

Figure 5.40 Wapello County 0.45 Power Chart

The 0.45 power charts for Wapello County can be seen in Figures 5.40 and 5.41. These charts are similar in shape, with the COMPASS chart having a gradation closer to the 0.45 line on the smaller sieve sizes.

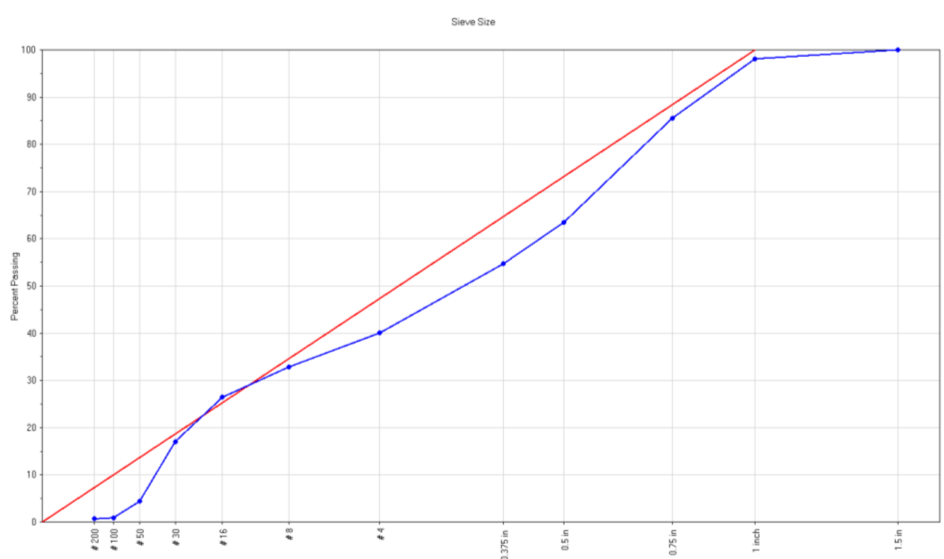

Figure 5.41 Wapello County COMPASS 0.45 Power Chart

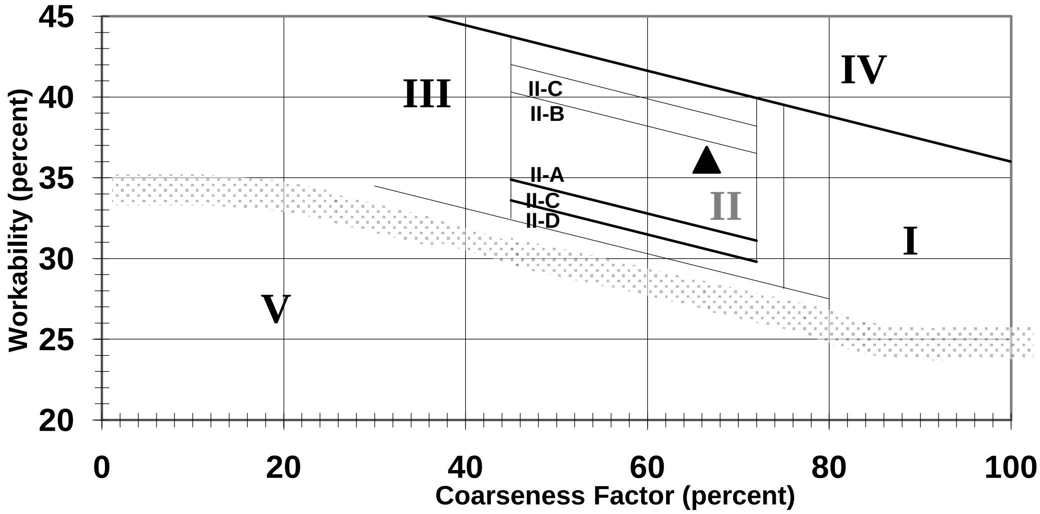

Figure 5.42 Wapello County Workability Chart

The DOT workability factor for Wapello County was 36% (Figure 5.42). The coarseness factor was 67%. From COMPASS, the workability factor was found to be slightly lower, at 33%, with a coarseness factor of 67% (Figure 5.43).

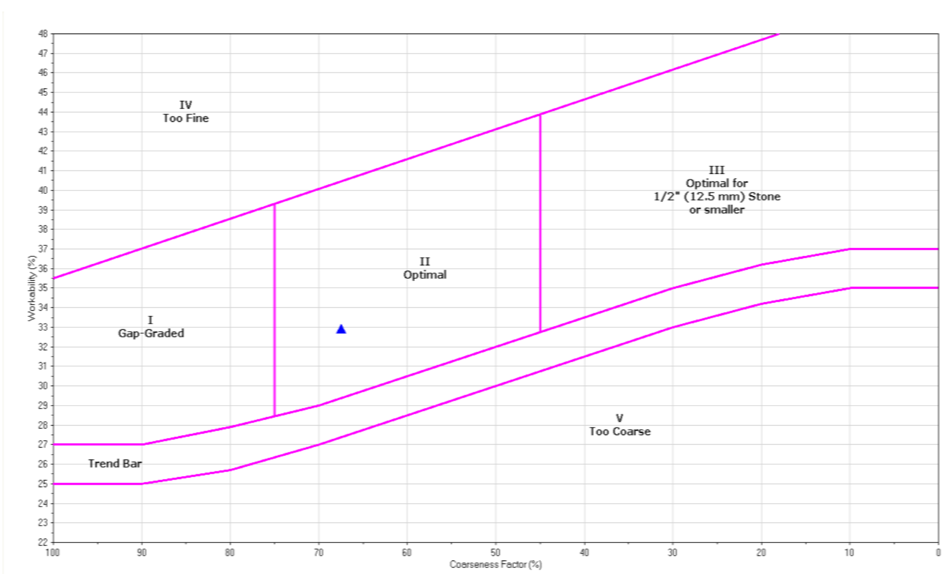

Figure 5.43 Wapello County COMPASS Workability Chart

Chapter 6. Summary and Conclusions

6.1 Summary

There is a need in the concrete industry to optimize the characteristics of concrete during and after construction. By optimizing the ingredients of the mix, the industry saves time and money. The characteristics shown by the concrete during placement will significantly affect the performance characteristics after the concrete has hardened. It is very difficult to pick which characteristics of concrete are more significant during placement to produce the preferred results for long term pavement performance.

COMPASS is a computer software program designed to help the industry evaluate concrete characteristics and mix design ingredients. It helps to optimize the mix design with the given ingredients to produce the desired characteristics of the concrete. It can also predict material incompatibility within the mixture. COMPASS contains an environmental module that is linked to NOAA to help determine when the optimal time for paving will occur.

In order to evaluate COMPASS, the field data had to be gathered before COMPASS programming was completed. Instead of using COMPASS to make recommendations for the projects, the mix designs, specifications, mix ingredients and other useful information were gathered at the time of paving. The information that resulted from these tests was then used to assess how COMPASS created mix designs. The results and recommendations from COMPASS were compared to the field mix designs and project information to see how accurately COMPASS could make predictions.

6.2 Discussions

It was found that for each project, COMPASS yielded mix proportions similar to the actual project mix designs. COMPASS found only minor material incompatibilities for any of the projects. The program provided multiple warnings for each project about characteristics such as flash set and loss of workability that are caused by certain materials within the mixes. However, most of the contractors observed in this project have worked enough with the given materials that these warnings were not a major concern. The contractors were able to anticipate problems and resolve them before they became an issue.

The batch ingredient amounts found in COMPASS exhibited minor differences from the DOT amounts. There are also some minor programming errors that occurred in COMPASS that may have resulted in these slight deviations in material amounts. It could also be due to rounding errors within the software programming.

The aggregate gradations that COMPASS predicted matched well with the DOT gradations. The charts produced were similar to the DOT gradation charts. The gradation charts that COMPASS creates are the 0.45 power chart, workability and coarseness, and percent retained charts. It also creates a void ratio and packing ability chart. These extra charts allow the user to identify at what gradation the aggregates will obtain the lowest void ratio and highest packing density.

What makes COMPASS unique is that it is able to take the basic material properties, such as the material specific gravity or aggregate gradation, and create a mix design. It takes less time to create the batches in COMPASS and it produces multiple batches at one time. The user can take the trial batches to the laboratory for testing quicker than if they had to produce the batch quantities one at a time, which is how some spreadsheet mix design programs operate.

COMPASS gives the user a lot of information on each of the mix ingredients. It aids in the mix design process by giving the user information on material properties and compatibility. The information obtained from COMPASS is at the user's discretion. As with any design tool, the user must decide to apply this information or to disregard it.

6.3 Recommendations

COMPASS will be a powerful tool for creating mix designs in the field. It takes into account the material availability and compatibility. For instance, if a contractor runs low on a material and must switch manufacturers to purchase more of the material, the material properties could change. This could have a major effect on the project. Before purchasing the material, the contractor could use COMPASS to see if the material will likely perform to their specifications.

Another field application of COMPASS is the ability to set criteria for the mix design, such as cost, and design around those criteria. COMPASS can incorporate the cost per unit of each ingredient and create a total cost per unit for the entire mix. This helps the user to design on a budget. It also helps if the mix must be changed in the field. COMPASS can incorporate the change in material cost and give instant feedback.

The software should be used prior to paving, instead of after construction, like this research project. It would have been ideal to have a full version of COMPASS prior to conducting field tests. This way the COMPASS predictions would have been available in the field. The trial batches that COMPASS creates could have been tested in the laboratory along with field tests for verification.

The weather module in COMPASS is linked to the NOAA database. The environmental data given is an average weather pattern, for more long term paving projects. It gives the user an idea of typical weather patterns for the area. This is useful for someone who is new to the area and unfamiliar with the environment. It would be easier for the user to understand the weather data if they could pin-point the paving location better. As of now, there is some uncertainty as to where exactly the location is unless the user knows the latitude and longitude of the paving project. It would create more accurate weather data if the location was easier to pin-point.

With the up and coming generation of engineers being more technology orientated, COMPASS will be one link between past and future generations. For the younger generation, they want information presented in an efficient way and accessible at the touch of a button. This will allow engineers to stay abreast of changing technology. COMPASS contains the knowledge and presents it in a manner that is easy to understand and access. The program is able to keep up with the ever-changing materials market and the world of changing technology.

There are still some programming glitches in the software. Some of the major ones that need to be addressed are the lack of headings on certain pages and the batching calculations. The headings would be helpful so the user can identify which module of the program they are currently working with. It is a bit difficult to recognize certain screens. The batching calculations are a major error. Currently, when the user selects a batch size greater than one cubic yard, the aggregate masses produced are given as a negative number. This error needs to be corrected prior to releasing COMPASS to the industry.

It would be helpful for COMPASS to have some color coding in the mix expert module. This is the module where all of the material information is presented to the user. The user can then accept or decline this information. It is difficult for visual learners to see and recognize which material they have accepted or declined. The overall appearance of the program is user-friendly, but some of the fonts are small. It is difficult to read certain screens. A larger font would be more helpful to view the information.

Throughout the course of the research project, I learned a lot about modern construction techniques. I learned how to adapt to the paving environment and how to handle unforeseen situations. Paving contractors need to be able to think on their feet in order to have a successful project outcome. After conducting the literature review for use as the knowledge base of the program, I feel that I have learned more about concreting materials and the how fast the market can change. This information will be useful to me when working with both DOTs and contractors. It will enable me to communicate on multiple levels of the profession.

In my opinion, COMPASS is a very valuable program. It takes a lot of information into account and displays it in an understandable manner. The program produces accurate results that are easy to interpret. I feel that COMPASS will aid in creating mix designs by being able to keep up with the ever-changing materials market. With my generation of engineering being very computer orientated, this program meets their need for using computers and design software.

I feel there are still areas of COMPASS to be improved. The materials module will need to be updated frequently to keep up with fast changing materials market. For instance, new types of blended cements are always being created and will need to be incorporated into the software. There is not much information in COMPASS on fiber reinforced concrete. This may be an area that needs to be further developed within the program.

I recommend that COMPASS be introduced to the industry by means of a stepped or phased process. The Iowa DOT typically introduces new design tools by starting with one project a year and adding additional projects in following years. They recommend using one project the first year, three projects in the second year and ten projects in the third year. People will need some instruction on how to operate the software. They will need to be instructed on how to interpret the results and information given by COMPASS. If COMPASS was introduced at a workshop seminar where the industry could be given hand-on learning for the first trial, it would be accepted more readily.

I recommend that DOTs be given the first version of COMPASS. If the DOTs are willing to use the software and create paving design standards from it, the industry might be more receptive to the program. It would be valuable to have large scale paving contractors use the software. Certain contractors may construct a large amount of DOT projects and giving them access to the software may make communications between the DOT and the contractor easier.

6.4 Future Research Recommendations

It is recommended that additional research be done with COMPASS outside of Iowa. While Iowa was able to produce different materials for concreting, there are still materials this research project did not cover. For instance, none of the mix designs called for ground-granulated blast furnace slag (GGBFS). Also, Iowa experiences freeze-thaw cycles that other geographic locations will not. Environmental factors as well as individual material chemical properties need to be analyzed further.

There could be more research done with evaluating the optimization module. The optimization module produces trial batches for use in laboratory testing. It will also allow the user to see the cost associated with each mix ingredient. For this project, there were no laboratory batches created or cost per unit of ingredient examined. The trial batches created by COMPASS could be created and tested in the laboratory and the results could be compared to COMPASS predictions.

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Appendix A. Site Maps

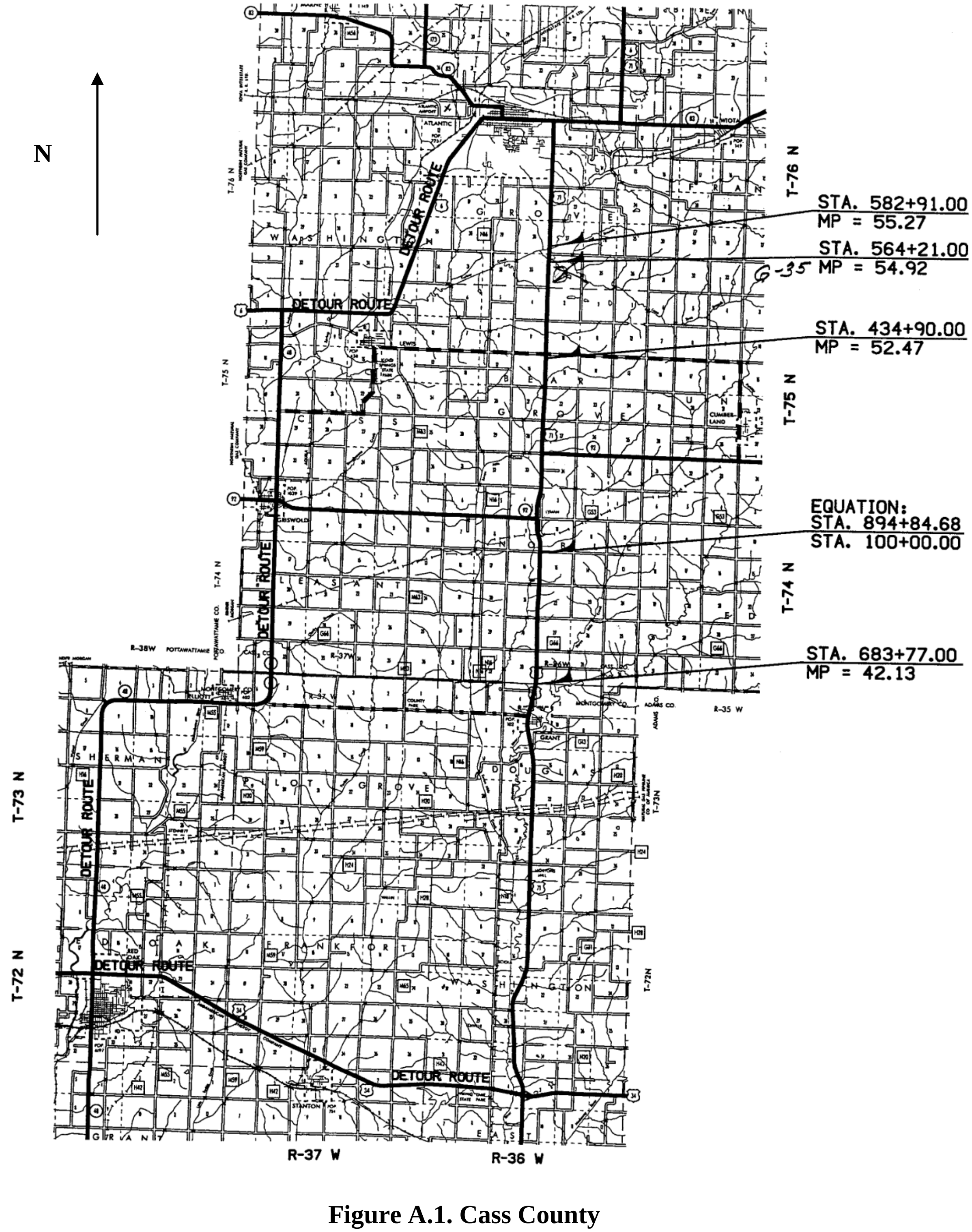

Figure A.1. Cass County

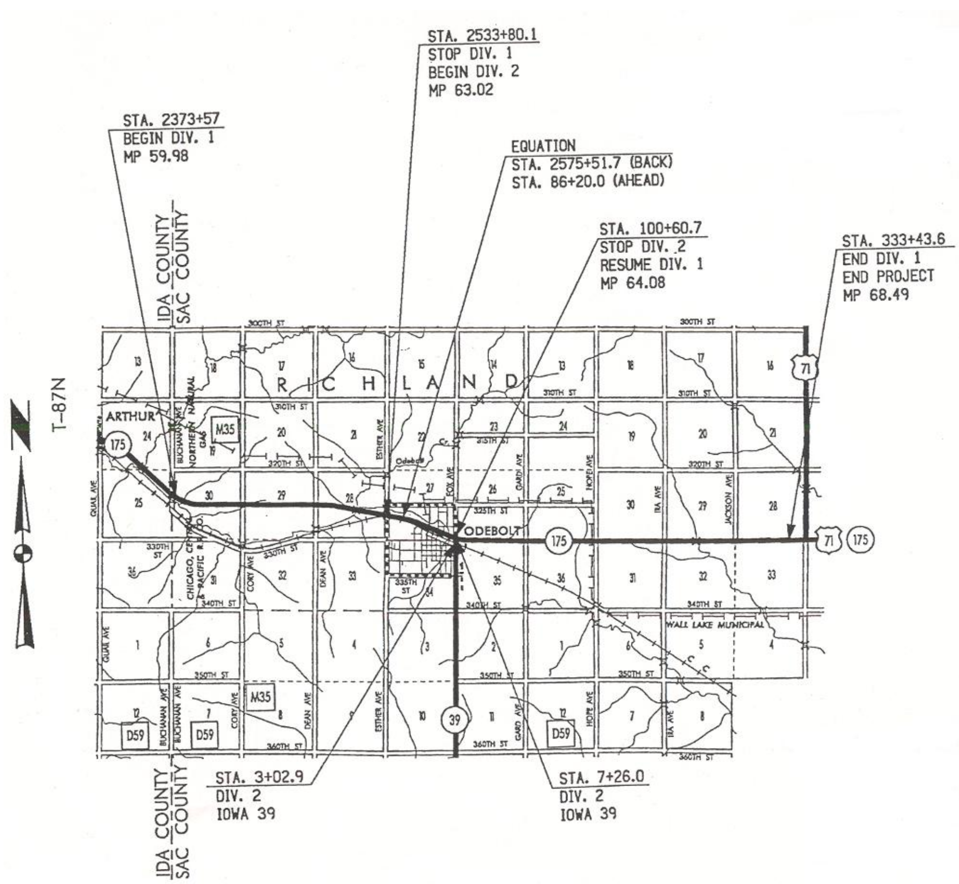

Figure A.2. Sac County

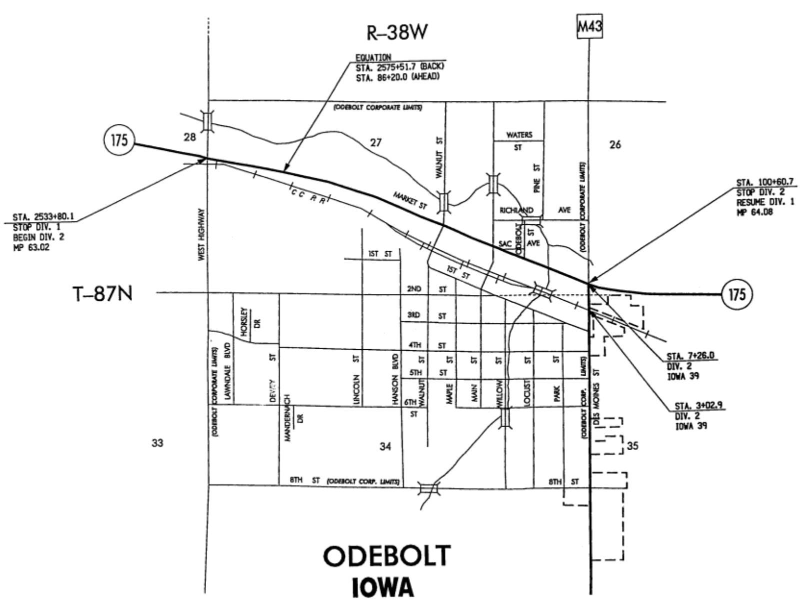

Figure A.3. Sac County-Town of Odebolt

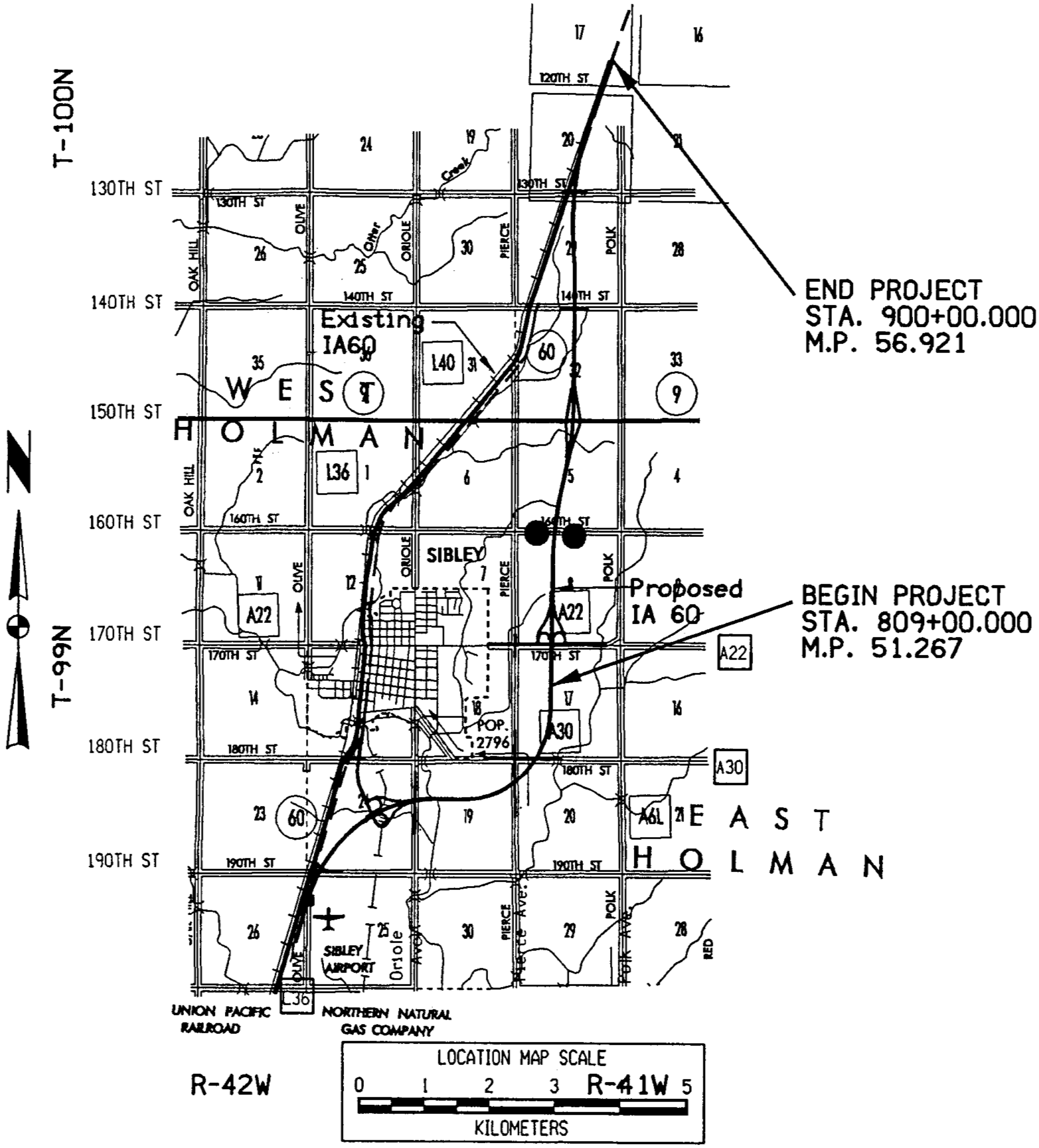

Figure A.4. Osceola County

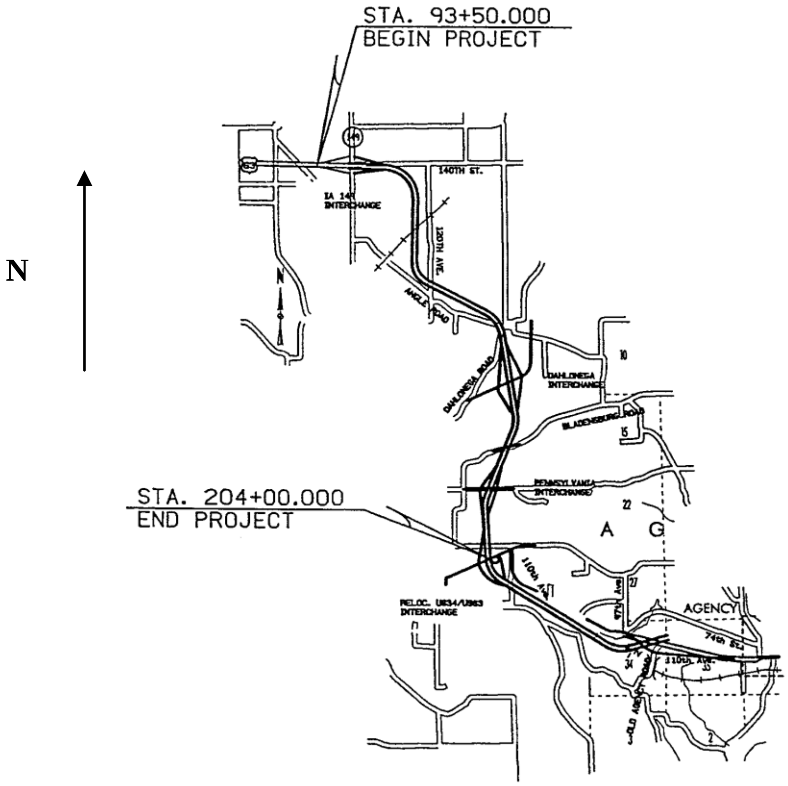

Figure A.5. Wapello County

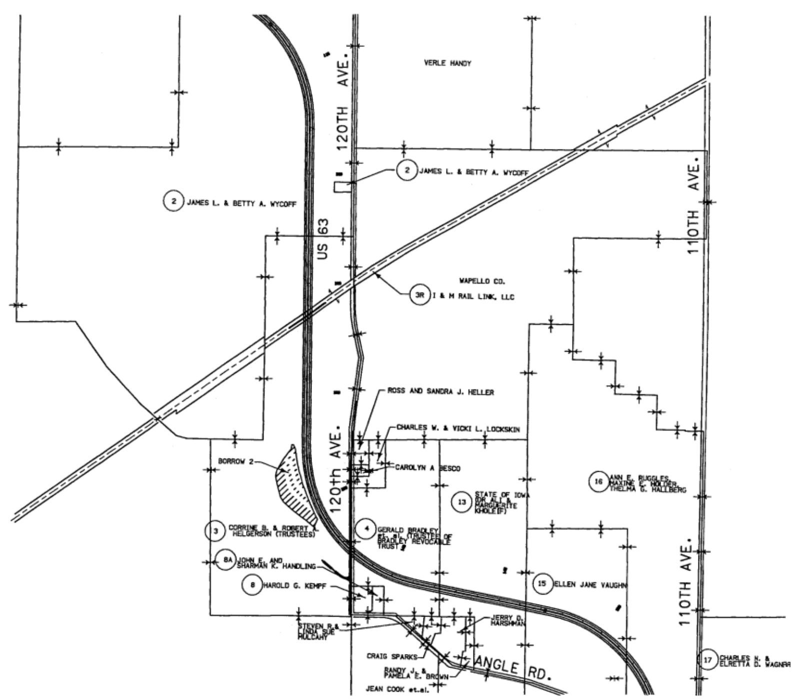

Figure A.6. Wapello County- City of Ottumwa

Appendix B. Sample Data Sheets

Field Data Sheet

Project: Date:

Weather: Tested By:

Property: **WORKABILITY**

Target Values: Slump (in): Air %:

Truck/Ticket # Time:		Location/Station:
Slump (in)		Cylinder Set
Concrete Temperature (^oF)		
Air Content (%)		

Truck/Ticket # Time:		Location/Station:
Slump (in)		Cylinder Set
Concrete Temperature (^oF)		
Air Content (%)		

Truck/Ticket # Time:		Location/Station:
Slump (in)		Cylinder Set
Concrete Temperature (^oF)		
Air Content (%)		

Property: **BLEEDING Tested By:** **Date:**
Location/Station:

Time of Day	Air Temperature, F	Relative Humidity	Wind Speed, mph	Wind Direction	Cylinders
Moisture, %	At Paver	At Texture	Behind Texture		

Rank Amount of Bleeding: 1 Very Dry – 5 Very Moist

1 2 3 4 5

Comments:

Location/Station:

Time of Day	Air Temperature, F	Relative Humidity	Wind Speed, mph	Wind Direction	Cylinders
Moisture, %	At Paver	At Texture	Behind Texture		

Rank Amount of Bleeding: 1 Very Dry – 5 Very Moist

1 2 3 4 5

Comments:

Location/Station:

Time of Day	Air Temperature, F	Relative Humidity	Wind Speed, mph	Wind Direction	Cylinders
Moisture, %	At Paver	At Texture	Behind Texture		

Rank Amount of Bleeding: 1 Very Dry – 5 Very Moist

1 2 3 4 5

Comments:

Property: **PERMEABILITY** **Date:**

Location/Station: **Plug Configuration**

Air Temperature (^oF)

Air (Min, Sec)		

Comments:

Location/Station: **Plug Configuration**

Air Temperature (^oF)

Air (Min, Sec)		

Comments:

Location/Station: **Plug Configuration**

Air Temperature (^oF)

Air (Min, Sec)		

Comments:

Lab Data Sheet
Project:

Date:
Tested By:

Property: **STRENGTH**

Target Values:

Specimen # Dimensions: Height (in)	
Cylinder Weight, lbs	
4 x 8 cylinders Strength, psi	
Break Pattern	

Specimen # Dimensions: Height (in)	
Cylinder Weight, lbs	
4 x 8 cylinders Strength, psi	
Break Pattern	

Specimen # Dimensions: Height (in)	
Cylinder Weight, lbs	
4 x 8 cylinders Strength, psi	
Break Pattern	

Comments:
Property: **ABRASION** Date Tested:
Tested by:

Specimen #

Mass Before Test, lbs	Mass After Test, lbs

Specimen #

Mass Before Test, lbs	Mass After Test, lbs

Specimen #

Mass Before Test, lbs	Mass After Test, lbs

Comments:

Property: **SEGREGATION** Date Tested:
Tested By:

Specimen #

Rank Amount of Segregation: 1 Very Segregated – 5 Very Uniform

1 2 3 4 5

Comments:

Specimen #

Rank Amount of Segregation: 1 Very Segregated – 5 Very Uniform

1 2 3 4 5

Comments:

Specimen #

Rank Amount of Segregation: 1 Very Segregated – 5 Very Uniform

1 2 3 4 5

Comments:

Appendix C. Tabular Field and Lab Data

Table C.1 Cass County Workability Results

Time	Station	Concrete Temperature ^oF	Slump, in	Air Content, %	DOT Air Content, %	Cylinder Set
9:15 AM	726+00	82	3.75	6.8		
9:20 AM	726+50	80	1.50	6.9	9.5	
9:45 AM	727+00	80	2.50	6.9		1
10:09 AM	727+50	84	5.00	7.7		
10:30 AM	728+50	83	3.00	7.1		
11:10 AM	729+00	88	2.00	7.0		2
11:30 AM	729+50	83	3.50	7.5		
11:36 AM	730+00	86	2.50	6.6		3
12:09 PM	731+00	86	2.50	7.0		

Table C.2 Cass County Permeability Test Results

Station	Air Temperature ^oF	Plug Number	Air		Total Seconds	Average Time
			min	sec		
728+00	85	1	12	51	771	771
		2	0	52	52	51.5
		2	0	51	51	
		3	1	26	86	88
		3	1	30	90	
		4	1	4	64	64.5
		4	1	5	65	
730+00	85	1	5	47	347	356
		1	6	5	365	
		2	1	35	95	92
		2	1	29	89	
		3	15	45	945	945
		4	0	46	46	47
		4	0	48	48	
726+00	85	1	1	13	73	73
		1	1	13	73	
		2	2	30	150	155.5
		2	2	41	161	
		3	2	5	125	127.5
		3	2	10	130	
		4	15	15	915	915

Table C.3 Cass County Strength Test Results

Day Break	Cylinder	Height, in	Weight, lbs	Area, in^2	Load, lbs	Strength, psi	Average Strength, psi
7	1A	7.96	8.38	12.57	35450	2821	
7	2A	7.94	8.32	12.57	37030	2947	2879
7	3A	7.94	8.36	12.57	36050	2869	
14	1B	7.87	8.30	12.57	41444	3298	
14	2B	7.67	8.09	12.57	39990	3182	3248
14	3B	7.81	8.25	12.57	41010	3263	
28	1C	7.83	8.28	12.57	46420	3694	
28	2C	7.88	8.26	12.57	47780	3802	3762
28	3C	7.90	8.35	12.57	47620	3789	

Table C.4 Cass County Abrasion Test Results

Day Break	Cylinder	Mass Before, lbs	Mass After, lbs	Total Mass Loss, lbs	Average Mass Loss, lbs	Percent Total Mass Loss
7	1A	8.3830	8.3600	0.0230	0.0160	0.2744
7	1A	8.3600	8.3510	0.0090		0.1077
7	2A	8.3205	8.3040	0.0165	0.0130	0.1983
7	2A	8.3040	8.2945	0.0095		0.1144
7	3A	8.3640	8.3450	0.0190	0.0135	0.2272
7	3A	8.3450	8.3370	0.0080		0.0959
14	1B	8.2970	8.2820	0.0150	0.0103	0.1808
14	1B	8.2820	8.2765	0.0055		0.0664
14	2B	8.0900	8.0770	0.0130	0.0095	0.1607
14	2B	8.0770	8.0710	0.0060		0.0743
14	3B	8.2480	8.2365	0.0115	0.0082	0.1394
14	3B	8.2365	8.2315	0.0050		0.0607
28	1C	8.2790	8.2585	0.0205	0.0122	0.2476
28	1C	8.2585	8.2545	0.0040		0.0484
28	2C	8.2585	8.2420	0.0165	0.0103	0.1998
28	2C	8.2420	8.2380	0.0040		0.0485
28	3C	8.3480	8.3315	0.0165	0.0108	0.1977
28	3C	8.3315	8.3265	0.0050		0.0600

Table C.5 Sac County Workability Results

Time	Station	Concrete Temperature ^oF	Slump, in	Air Content, %	Cylinder Set
9:30 AM	2530+50	85	2.75	7.4	
9:40 AM	2531+50	80	1.25	7.6	1
10:00 AM	2534+00	89	2.50	8.6	
11:40 AM	2535+00	84	3.50	7.1	
12:00 PM	2537+50	85	3.25	9.8	2
12:30 PM	2540+00	86	3.50	8.6	
2:30 PM	2549+00	88	5.50	7.8	
2:45 PM	2551+00	85	1.50	7.6	3
3:20 PM	2553+00	88	4.00	8.8	

Table C.6 Sac County Permeability Test Results

Station	Air Temperature °F	Plug Number	Air		Total Seconds	Average Time
			min	sec		
2531+50	75	1	2	17	137	138.5
		1	2	20	140	
		2	2	27	147	148
		2	2	29	149	
		3	2	37	157	158
		3	2	39	159	
		4	0	58	58	59
		4	1	0	60	
2538+50	75	1	0	52	52	51
		1	0	50	50	
		2	0	43	43	43
		2	0	43	43	
		3	1	47	107	106.5
		3	1	46	106	
		4	0	19	19	19
		4	0	19	19	
2551+00	75	1	0	7	7	7
		1	0	7	7	
		2	0	30	30	30
		2	0	30	30	
		3	0	0	0	0
		4	1	21	81	82
		4	1	23	83	

Table C.7 Sac County Strenght Test Results

Day Break	Cylinder	Height, in	Weight, lbs	Area, in^2	Load, lbs	Strength, psi	Average Strength, psi
7	1A	8.06	8.43	12.57	31690	2522	
7	2A	8.06	8.50	12.57	38840	3091	2920
7	3A	8.02	8.42	12.57	39540	3146	
14	1B	7.92	8.36	12.57	40840	3250	
14	2B	8.07	8.53	12.57	44820	3567	3547
14	3B	7.95	8.48	12.57	48060	3824	
28	1C	7.78	8.17	12.57	46310	3685	
28	2C	8.07	8.43	12.57	48100	3828	3756
28	3C	8.05	8.51	12.57	47170	3754	

Table C.8 Sac County Abrasion Test Results

Day Break	Cylinder	Mass Before, lbs	Mass After, lbs	Total Mass Loss, lbs	Average Mass Loss	Percent Total Mass Loss
7	1A	8.4320	8.4175	0.0145	0.0198	0.1720
7	1A	8.4175	8.3925	0.0250		0.2970
7	2A	8.5010	8.4895	0.0115	0.0150	0.1353
7	2A	8.4895	8.4710	0.0185		0.2179
7	3A	8.4185	8.3950	0.0235	0.0215	0.2791
7	3A	8.3950	8.3755	0.0195		0.2323
14	1B	8.3565	8.3405	0.0160	0.0128	0.1915
14	1B	8.3405	8.3310	0.0095		0.1139
14	2B	8.5325	8.5110	0.0215	0.0175	0.2520
14	2B	8.5110	8.4975	0.0135		0.1586
14	3B	8.4760	8.4615	0.0145	0.0118	0.1711
14	3B	8.4615	8.4525	0.0090		0.1064
28	1C	8.1670	8.1545	0.0125	0.0083	0.1531
28	1C	8.1545	8.1505	0.0040		0.0491
28	2C	8.4320	8.4180	0.0140	0.0113	0.1660
28	2C	8.4180	8.4095	0.0085		0.1010
28	3C	8.5135	8.4950	0.0185	0.0163	0.2173
28	3C	8.4950	8.4810	0.0140		0.1648

Table C.9 Osceola County Workability Results

Time	Station	Concrete Temperature °F	Slump, in	Air Content, %	DOT Air Content, %	Cylinder Set
8:00 AM	834+70	77	2.00	8.6		1
8:32 AM	834+20	77	2.00	9.0		
9:00 AM	834+00	81	2.25	8.2		
9:21 AM	833+60	76	1.75	8.8	9.5	
9:30 AM	833+30	79	1.75	8.6		2
10:00 AM	832+00	81	1.75	8.2		
10:33 AM	832+40	77	2.38	8.6		
10:45 AM	831+90	79	1.50	8.2		3
11:20 AM	831+60	81	1.88	7.0		

Table C.10 Osceola County Permeability Results

Station	Air Temperature °F	Plug Number	Air		Time, sec	Average Time, sec
			min	sec		
834 + 70	95	1	0	34	34	33.5
		1	0	33	33	
		2	1	0	60	61.5
		2	1	3	63	
		3	1	25	85	84
		3	1	23	83	
		4	1	29	89	88.5
		4	1	28	88	
833 + 30	95	1	2	25	145	150
		1	2	35	155	
		2	1	17	77	77.5
		2	1	18	78	
		3	4	35	275	285
		3	4	55	295	
		4	1	29	89	91.5
		4	1	34	94	
831 + 90	95	1	0	36	36	38.5
		1	0	41	41	
		2	2	31	151	154.5
		2	2	38	158	
		3	4	4	244	253
		3	4	22	262	
		4	2	20	140	141.5
		4	2	23	143	

Table C.11 Osceola County Strength Test Results

Day Break	Cylinder	Height, in	Weight, lbs	Area, in^2	Load, lbs	Strength, psi	Average Strength, psi
7	1A	7.98	8.07	12.57	28730	2286	
7	2A	7.84	7.92	12.57	26600	2117	2214
7	3A	7.80	7.89	12.57	28120	2238	
14	1B	7.91	8.00	12.57	32250	2566	
14	2B	7.90	8.03	12.57	34260	2726	2676
14	3B	7.87	7.97	12.57	34380	2736	
28	1C	8.03	8.15	12.57	35330	2811	
28	2C	7.74	7.92	12.57	40960	3259	3088
28	3C	7.82	7.97	12.57	40131	3194	

Table C.12 Osceola County Abrasion Test Results

Day Break	Cylinder	Mass Before, lbs	Mass After, lbs	Total Mass Loss, lbs	Average Mass Loss, lbs	Percent Total Mass Loss
7	1A	8.0740	8.0550	0.0190	0.0198	0.2353
	1A	8.0550	8.0345	0.0205		0.2545
	2A	7.9150	7.9045	0.0105	0.0078	0.1327
	2A	7.9045	7.8995	0.0050		0.0633
	3A	7.8945	7.8810	0.0135	0.0092	0.1710
	3A	7.8810	7.8760	0.0050		0.0634
14	1B	8.0050	7.9940	0.0110	0.0110	0.1374
	1B	7.9940	7.9830	0.0110		0.1376
	2B	8.0280	8.0230	0.0050	0.0075	0.0623
	2B	8.0230	8.0130	0.0100		0.1246
	3B	7.9665	7.9615	0.0050	0.0063	0.0628
	3B	7.9615	7.9540	0.0075		0.0942
28	1C	8.1490	8.1280	0.0210	0.0155	0.2577
	1C	8.1280	8.1180	0.0100		0.1230
	2C	7.9190	7.9125	0.0065	0.0082	0.0821
	2C	7.9125	7.9025	0.0100		0.1264
	3C	7.9690	7.9605	0.0085	0.0108	0.1067
	3C	7.9605	7.9475	0.0130		0.1633

Table C.13 Wapello County Workability Results

Time	Station	Concrete Temperature ^oF	Slump, in	Air Content, %	Cylinder Set
9:56 AM	150+50	88	1.25	9.8	
10:12 AM	150+20	92	0.75	8.6	1
10:35 AM	149+70	91	1.38	9.5	
11:00 AM	149+30	90	1.13	8.0	
11:12 AM	149+00	92	1.00	10.2	2
11:36 AM	148+60	90	0.88	10.0	
12:11 PM	148+00	90	0.75	9.0	
12:35 PM	147+50	80	0.50	8.8	3
12:53 PM	147+10	85	0.75	8.3	

Table C.14 Wapello County Permeability Results

Station	Air Temperature ^oF	Plug Number	Air		Total Seconds	Average Time
			min	sec		
149+90	90	1	20		1200	1200
		2	8	51	531	536
		2	9	1	541	
		3	20		1200	1200
		4	20		1200	1200
148+80	90	1	20		1200	1200
		2	20		1200	1200
		3	9	41	581	581
		4	20		1200	1200
147+30	90	1	20		1200	1200
		2	1	35	95	95.5
		2	1	36	96	
		3	20		1200	1200
		4	20		1200	1200

Table C.15 Wapello County Strength Results

Day Break	Cylinder	Height, in	Weight, lbs	Area, in^2	Load, lbs	Strength, psi	Average Strength, psi
7	1A	8.00	8.35	12.57	52800	4202	
7	2A	8.00	8.40	12.57	51540	4101	4052
7	3A	7.83	8.25	12.57	48420	3853	
14	1B	7.81	8.11	12.57	65940	5247	
14	2B	8.00	8.37	12.57	66660	5305	5178
14	3B	7.76	8.20	12.57	62600	4982	
28	1C	8.00	8.38	12.57	73620	5858	
28	2C	7.80	8.16	12.57	67440	5367	5449
28	3C	7.79	8.21	12.57	64350	5121	

Table C.16 Wapello County Abrasion Results

Day Break	Cylinder	Mass Before, lbs	Mass After, lbs	Total Mass Loss, lbs	Average Mass Loss, lbs	Percent Total Mass Loss
7	1A	8.3545	8.3305	0.0240	0.0195	0.2873
7	1A	8.3305	8.3155	0.0150		0.1801
7	2A	8.4015	8.3740	0.0275	0.0200	0.3273
7	2A	8.3740	8.3615	0.0125		0.1493
7	3A	8.2500	8.2400	0.0100	0.0090	0.1212
7	3A	8.2400	8.2320	0.0080		0.0971
14	1B	8.1065	8.1000	0.0065	0.0055	0.0802
14	1B	8.1000	8.0955	0.0045		0.0556
14	2B	8.3730	8.3565	0.0165	0.0112	0.1971
14	2B	8.3565	8.3505	0.0060		0.0718
14	3B	8.1990	8.1905	0.0085	0.0092	0.1037
14	3B	8.1905	8.1805	0.0100		0.1221
28	1C	8.3760	8.3670	0.0090	0.0132	0.1074
28	1C	8.3670	8.3495	0.0175		0.2092
28	2C	8.1635	8.1555	0.0080	0.0073	0.0980
28	2C	8.1555	8.1490	0.0065		0.0797
28	3C	8.2060	8.1985	0.0075	0.0082	0.0914
28	3C	8.1985	8.1895	0.0090		0.1098