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INFLUENCE OF PARTICLE SIZE AND SPECIMEN PREPARATION ON THE IOWA PORE INDEX

by

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ABSTRACT

This study was performed in order to identify a size correction that would allow aggregate of different sizes, other than the standard ½-¾-inch fraction, to be used in the Iowa Pore Index (IPI) test. This size correction would allow for the IPI to be determined for aggregate gradations of material that have a nominal maximum size (NMS) smaller than ¾-inch. The interest in a size correction for the IPI developed from its use in a Durability Factor (DF) estimation equation. The estimation equation was developed with the use of 19 different DF from Missouri aggregate sources, where eight aggregates had a NMS smaller than ¾-inch. By using the same sized particles in the IPI test that was used to achieve the DF, a better relationship is thought to be attainable. In addition to the size correction, procedures and variables that influence the data acquired by the IPI test were observed and refined in order to standardize the IPI test procedure.

A size correction was developed so that #4 sieve-⅜-inch and ⅜-½-inch aggregate fraction sizes can be corrected to the industry standard ½-¾-inch. Also researched is the effect of drying on the IPI, effect of re-pressurization on the IPI, and material re-testability in the IPI test. In researching the IPI test procedure and variables, a new method of data collection from the IPI test was developed. This method allows for the measurement of water that is expelled from the aggregate after depressurization. This data has shown to have a better correlation with the DF than the IPI. The effect of oven drying the aggregate on the IPI and the effect of different operators was found to be negligible. It was found that a material can be re-tested and produce a similar IPI, and that the material re-testing is more favorable than re-pressurizing the aggregate.

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1. INTRODUCTION

1.1. STATEMENT OF PROBLEM

D-cracking is a coarse aggregate durability problem that results in portland cement concrete pavements (PCCP) failing prior to their designed life. The Iowa Pore Index (IPI) is currently used as a test procedure for determining the durability and susceptibility of an aggregate to D-cracking in PCCP. An IPI of 27 (produced by ½-¾-inch size particles) is used as the threshold for predicting D-cracking in PCCP (Dubberke and Myers, 1980).There are several state departments of transportation (DOT) that use this index in their materials acceptance criteria for PCC pavements (Iowa DOT, 2000; Michigan DOT, 2001; Kentucky Transportation Cabinet, 2008), with at least one other state DOT evaluating its potential (Missouri DOT). It has been found that the IPI is an important variable to a Durability Factor (DF) estimation that uses several simple durability tests. For certain types of evaluation, the DF estimation would replace the time intensive ASTM C 666 Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing (or AASHTO T161) test that is currently used to determine the DF (Richardson, 2009). Because there are multiple tests used to derive the DF, it is important that each test has as little subjectivity as possible. The current standard for the IPI test is limited to only one aggregate size fraction (½-inch to ¾-inch). No one has developed an aggregate specific or universal correction that would be applicable for particles of smaller fractions to include ⅜-inch to ½-inch and the #4 sieve to ⅜-inch. This limits the IPI test capabilities of predicting D-cracking potential to an aggregate gradation with a nominal maximum size (NMS) of ¾-inch. Without knowing the effects of the test on smaller size aggregate, one cannot accurately predict the D-crackability of aggregate of a smaller NMS with the IPI test.

In order for an aggregate to be resistant to D-cracking, the length of the aggregate pores must be less than the critical length (the length that allows for water to escape without damage to the aggregate when freezing) and not critically saturated. Currently, the ASTM C 666 test method is performed using the NMS of the selected aggregate gradation. If a NMS produces a DF too low to be accepted, then a smaller NMS is used until a DF is produced that will be accepted. The aggregate is then assumed to have pores shorter than the critical length and should perform favorably in field conditions. Currently an IPI from aggregate of ½ to ¾-inch is used even though a passing Durability Factor from the ASTM C 666 test may have been found using an aggregate gradation of a smaller nominal max size than ¾-inch. In order to correlate the two tests, it would be more appropriate to use the same size aggregate in each of the tests. As quality aggregate sources with a good service record are depleted throughout the world, marginal aggregate sources are being introduced into PCC resulting in premature failures (Korhonen and Charest, 1995). Using a size correction factor or new IPI standard for aggregate of smaller NMS will allow for the determination of these aggregates potential for failure before they are widely used.

There are times when delays in testing occur and a specimen prepared for the IPI test would need to be set aside. This presents a problem since the aggregate for an IPI test must be in an oven dried state. Therefore, if equipment failure occurs, the material must be re-dried prior to testing. The effects on the aggregate’s pore structure from drying and re-drying in an oven at 110°C (230°F) on the IPI is unknown at this time. The

IPI tests the pore structure of the aggregate by measuring the amount of water that can be forced into the aggregate slowly over a given time known as the Secondary pore index. If the pore structure is damaged due to repeated oven drying, the Secondary pore index may be changed and it is possible the results could be misleading. The effect of repeatedly oven drying an aggregate specimen needs to be investigated in order to determine how it impacts the IPI.

Variables within the IPI test procedure can provide inaccurate results. Therefore, an observation and refinement of the IPI testing procedure needs to take place. This refinement will help to minimize testing errors with in the IPI test. The IPI of the aggregate is sensitive to the aggregate's absorption rate, the condition of the water used for testing, and the equipment dilation, known as pot expansion. The errors associated with the test are random and can change daily or with different aggregates. In an attempt to standardize the test procedure, a step by step procedure evaluation should be performed. An attempt to alleviate errors in the IPI test has been performed by (Olsen, et al., 1983), but due to the advancement of the IPI testing apparatus since their study, the recommendations made cannot be performed as stated in their report.

To further explore the potential of the IPI as a variable in DF estimation, more data specific to the freeze/thaw mechanism needs to be collected from the IPI test. Further testing measures that can be performed with the IPI apparatus should be researched to maximize the amount of useable data that can be collected during the test duration.

Many testing standards that are adopted by transportation departments have a standard on how to settle a dispute between conflicting results from quality control and quality assurance. The IPI test is thought to be a nondestructive test procedure which would indicate that the test could be performed repeatedly without significant variation in results (Olsen, et al., 1983). The material re-testability in an IPI test, with the current apparatus and standard, should be known so that an appropriate standard for disputes can be adopted.

1.2. OBJECTIVES

The main objectives of this research are to develop a size correction of the IPI that will allow for different aggregate particle sizes to be tested, and to answer questions about material re-testability, repeated oven drying, re-pressurization, and certain test procedure variables. Upon completion of these objectives, the IPI test and apparatus will be explored for the possibility of additional data that can be acquired.

The size correction will continue in the investigation of the IPI’s use as a test for durability that can be applied to a regression equation developed by (Richardson, 2009) in order to predict a Durability Factor without performing the ASTM C 666 test. Data collected during the course of research for a Durability Factor regression equation will be used in collaboration with IPI data collected from tests performed during this study.

It is to be determined if the IPI Secondary load index for aggregates of smaller fractions than that caught between the ½-inch and ¾-inch sieve correlate with the IPI Secondary load index of the ½-inch size and the ⅜-inch size. Upon testing the smaller sized aggregate, the data will be used to determine if an aggregate size correction factor or regression equation can be developed or if a new IPI test procedure for smaller aggregate should be developed.

The research will also include a study on the effects of repeated oven drying on the aggregate. This is to simulate aggregate that may be prepared for testing and then set aside until a later date so it would have to be oven dried again. Upon collection of data, a determination is to be made about the effect of oven drying on the aggregates. The effect of a repeated test cycle will be determined that to allow for the materials re-testability to be known. The material re-testability will be used to determine if a specimen can be re-tested in the event of a disagreement between two different parties, such as quality control and quality assurance. In addition, the effect of a re-pressurization procedure on the aggregate will be determined. The re-pressurization would take place in the event data collection during an IPI test is interrupted so that a new test would be necessary.

Variables in the IPI testing procedure and apparatus can skew the results of a test. In order to reduce testing deviations, these variables will be explored so that a standard method of testing can be developed and applied. Along with standardizing a testing procedure, any additional data that can be collected from the test in order to help understand the mechanics of the aggregate's pore network when under pressure is to be taken and analyzed. This is to include data gathered from the standard IPI procedure as well as data from alternative methods utilizing the IPI testing apparatus.

1.3. SCOPE OF THE INVESTIGATION

1.3.1. Aggregate Size. The aggregate caught between the ⅜-inch and #4 sieves is tested in the Missouri S&T's IPI testing apparatus. The aggregate tested is material supplied from the Missouri Department of Transportation from various quarries and ledges across Missouri. The material collected from the same ledge has had prior durability testing at Missouri S&T, so a correlation with the IPI can be made without completing other durability tests. Data gathered by Missouri S&T on the IPI of the aggregate from the ⅜-½-inch and ½-¾-inch sizes will be used in a regression analysis to determine a possible size correction factor. Any new aggregate samples (labeled 2011) will have the IPI test performed on all three fraction sizes to determine any difference in the aggregate source from 2008 to 2011 (year samples were collected).

1.3.2. Repeated Oven Drying. The testing will be performed on specimens from aggregate samples with known IPI values. These indices were gathered using only one wash/dry procedure. The difference in the present study is that the specimens will undergo a second washing and oven drying procedure prior to the IPI test. The results of the IPI will then be compared to the IPI of the material from the standard procedure (only one washing and oven drying cycle).

1.3.3. Iowa Pore Index Testing Procedure. IPI variables need to be explored in order to determine a standard procedure, so that the testing results can be reproduced. The testing procedures and variables to be explored are: apparatus filling time, de-airing, re-pressurization method, recovery of water data collection, and effect of temperature on the system compliance (pot expansion).

1.3.3.1. Apparatus filling time. The aggregate is tested at an oven dried moisture condition. When the aggregate comes in contact with water, absorption begins. The time that is taken to fill the apparatus to the starting condition is time where the aggregate is in contact with water but no data is being recorded. It is not until the system is pressurized that the actual test begins. During this time, water is being absorbed into the aggregate and can skew the results of the Primary and Secondary index if filling time varies. The Primary and Secondary index both rely on a timed measure of water that is forced in the aggregate, and any water absorbed prior to the start of the test is not included in the indices. A standard time to fill the pot and cylinders will be determined, so that the filling is performed in an expedient manner, yet does not cause excess turbulence that will put compressible air bubbles into suspension within the water.

1.3.3.2. Re-Pressurization method. A method is to be determined for re-pressurizing the aggregate once an IPI test has been performed while the specimen is still in the test vessel. This method allows the IPI test to be performed immediately after the completion of a test. In the event a reading is not taken at the specified time due to an equipment failure or technician error, the specimen being tested will not be wasted if a correlation between the data from a re-pressurized test and a initial IPI test exists. The method to be determined should follow the same procedure for the IPI with alterations as to how the sample is handled after the initial test is performed.

The re-pressurized IPI could also act as an index performed on aggregate that is at a degree of saturation greater than the oven dried state.

1.3.3.3. Recovery of water-data collection. Upon completion of an IPI or a re-pressurized IPI test, after the pressure is released the water flows out of the aggregate's pore system. A procedure for collecting this data should be developed so that it does not interfere with the standard testing procedure but allows for data to be collect.

1.3.3.4. Temperature. The temperature of the water and aggregate, after the IPI test has been performed, is to be measured. The data will be used to determine if varying temperatures will affect the pot expansion and any other data collected during the study.

1.3.4. Material Re-Testability. The IPI test is performed on an aggregate that has been washed and oven dried. To evaluate the effect of re-testing, following the initial IPI test the material will be washed and oven dried again for a second time. After the material cools from the oven drying process, the IPI test will be performed a second time.

2. REVIEW OF LITERATURE

2.1. FREEZE/THAW MECHANISM

When the temperature drops to the point that water starts to freeze, the expansion of the water forces movement through the pores. When water is prevented from flowing by already frozen sections, or because the pores are smaller than 4-μm, the tensile forces within the aggregate increase above the strength of the aggregate and causes failure. The rate of freezing and the permeability are two key variables in the water's ability to flow out of or through the aggregate's pore system. High internal stresses are associated high freezing rates because the outer pores to freeze first, blocking the escape path. When freezing occurs, a low permeability may not allow the water to flow fast enough to escape the pores before a detrimental pressure is reached (Lewis, et al., 1953).

Powers states that the objective of a freeze/thaw test is to simulate field deterioration in a laboratory setting so that the rate or quality can be measured. Although cement paste and aggregates differ in makeup, it was freeze/thaw tests for cement paste and building materials that was first applied to aggregates. He believes that freeze/thaw damage occurs during the initial freezing of the aggregate and water due to hydraulic forces (Powers, 1955).

Freezing water within an aggregate will cause it to dilate. This dilation can cause a permanent expansion of the aggregate that can disrupt the paste, or cause the aggregate to break upon dilation. Freezing of water in aggregate differs from water freezing in cement paste. Due to the macro sized pores in aggregates, the water will freeze close to the natural melting point. Powers states that the destructive force of the water must be hydraulic since there is not enough water in an aggregate's pore system to allow for ice crystals to grow, causing destructive tensile forces. The crystalline ice that may cause an aggregate to dilate would most likely be outside of the aggregate: this ice would draw water out of the aggregate creating a hydraulic gradient that would force water through the pores. When the water accumulates in the outer pores, crystalline ice forms and dilation occurs. It is also possible that over long periods of freezing temperatures, the aggregate can draw water from the surrounding cement paste, therefore allowing dilation to occur. The faster freezing rate will also increase the dilation of the aggregate which increases the stress that is felt (Powers, 1955).

Hudec found that the durability of an aggregate is dependent upon the aggregates' expansion and contraction characteristics. He presents this in a model that shows that the isothermal expansion of an aggregate is greater at low temperatures than at high temperatures. He also shows that a durable aggregate has a smaller amount of isothermal expansion than one that has durability issues. He states that an aggregate's inter-crystalline bonds may break down upon repeated wetting and drying. This breakdown can form small cracks within the aggregate that in turn can hold water. With this he concludes that the durability of the aggregate is a function of its thermal properties as opposed to expansion due to an increased volume change of freezing water. The breakdown of the aggregate due to the expansion of water is just a secondary effect of the inter-crystalline breakdown from wetting and drying (Hudec, 1980).

The freezing and thawing of aggregate in general will not affect its durability unless the aggregate is saturated with water at or above the critical saturation level. This is around 90% saturated for most aggregates. At this level of saturation, the freezing and thawing of the water within the aggregate causes a tensile stress on the aggregate from either the expansion of the water as it freezes, or the hydraulic pressure from the ice pushing on the encapsulated liquid water. Since the water will not freeze instantaneously, frozen water in the outer intra pores (within the aggregate particle) of the aggregate or cement paste can block water from escaping the pores as pressure builds due to the freezing process (Winslow, 1994). A pressure release is needed within the aggregate or cement paste in order to allow for water to flow when freezing occurs. In concrete, air voids within the paste provide this pressure release area, but in aggregates the pressure must be relieved by the water escaping into the aggregate pores to avoid an increase in pressure. Since the water in aggregates must flow in the pore system, aggregates that are critically saturated prevent that flow and tensile stresses increase with the pressure from the expanding water as it freezes (Detwiler, et al., 1989).

Testing with concrete has shown that water absorption during a freezing and thawing cycle was the primary cause of degradation. Samples that were not saturated and had no external water source to draw from during the cycle showed internal signs of degradation from the first freeze/thaw, but no signs of further propagation of cracks during repeated freeze/thaw. Specimens that were considered 100% saturated had freeze/thaw degradation during the testing. It is believed that water was being drawn into the pores during the freezing phase of the cycle due to the differences in thermal properties of the water, paste, and aggregate. Since the water contracts at a faster rate than the solids, it will draw more water into the pores by decreasing the internal pressure resulting in a pumping action. With the added water, the solid is super saturated and now will have very poor freeze/thaw durability due to the increased internal stresses from the expansion of the freezing water (Gagné, et al., 2003).

Another cause of freezing problems is that the pores have a variety of shapes and sizes within the aggregate. This can leave larger pores that are closed off by smaller pores filled with frozen water. If deicing salts are used, they can infiltrate into the aggregates pore system and affect the freezing rate of the water. This again has the potential to produce a situation where fluid water is trapped by frozen water. Any of these mechanisms or a combination of them can cause degradation of aggregates (Winslow, 1994).

It has been found that when water in cement pores was cooled below its equilibrium freezing temperature, there was a greater formation of ice crystals upon heating up to its equilibrium freezing temperature than when cooling. It was noted that the lack of water expulsion during heating was due to the formation of ice within the pore voids and not on the surface. It was concluded that the ice structure was dependent upon the structure of the pore it formed in (Schulson, et al., 2000).

2.2. D-CRACKING

Deterioration cracking and durability cracking, commonly called D-cracking,is an aggregate durability issue. It is characterized by fine cracks in concrete pavement that are near and parallel to joints. The surface cracking is actually a result of aggregate degradation at the bottom of the concrete slab, where moisture conditions can cause the aggregate to be in a critically saturated state (Sawan, 1987). The cracking occurs when there is repeated freeze/thaw cycles of the coarse aggregate in a critically saturated state.

The condition occurs moistly at joints in concrete pavements with the worst degradation at the joint. The condition can be limited to an area 12-inches (300mm) on either side of the joint, but can occur farther out into the slab. By decreasing the maximum aggregate size, a reduction of D-cracking has been seen. This decrease in size reduces the length of the escape path that water must travel to exit the pores. Once the escape path is less than the critical length for D-cracking to exist, the aggregate will not exhibit deterioration resulting in D-cracking (Koubaa and Snyder, 1996).

D-cracking is associated with the coarse aggregate in portland cement concrete. The aggregates that have deteriorated and result in D-cracking are sedimentary in nature. Sedimentary aggregates that have undergone metamorphism have not shown a history of D-cracking problems. Sorption and pore properties have shown to be contributing factors in aggregates with D-cracking problems. Finding a correlation between individual aggregate’s physical properties and D-cracking that is consistent between different aggregates has not been achieved (Stark, 1976).

D-Cracking can be prevented by controlling or removing one of the variables (environment, moisture condition, or aggregate durability) required for D-cracking to occur. Stark states that D-cracking has been observed in portland cement concrete pavement that is placed on various bases with and without drainage. It may not be feasible to change the environment that the pavement will be exposed to, so in order to prevent D-cracking, the coarse aggregate must be durable in terms of freeze/thaw mechanisms. Stark’s contributor elimination theory is seen in bridge decks; this is the only system of a pavement where D-cracking has not been found. On the bridge deck the concrete and aggregate are not in contact with a material that may retain moisture or a high humidity level, as with other pavements. Therefore, the aggregate never reaches its critical saturation point (Stark, 1976).

The Kansas Department of Transportation found that of all the aggregates used in their concrete pavements, D-cracking was associated with limestone coarse aggregates, especially if the coarse aggregate made up more than 35% of the mix. They also found that in some cases the D-cracking did not start at the bottom of the pavement as previously thought (Clowers, 1999).

D-cracking is a concrete durability problem associated with coarse aggregate. Surface cracks in the pavement allow water to flow down into the base of the pavement. If the water is not drained away the aggregate's degree of saturation will increase. Upon repeated freeze/thaw cycles of a critically saturated aggregate, internal tensile forces cause failure that leads to degradation of the concrete. This degradation then allows for more water to be become available to the aggregate, further saturating the material. The deterioration usually starts at the bottom of a concrete slab and moves towards the surface, although the D-cracking can start at the top or middle of the slab. To prevent D-cracking, sound aggregate must be used, the aggregate must not be allowed to become critically saturated, or the number of freeze/thaw cycles needs to be reduced. As of 2001, eliminating the critical saturation of the aggregate was the most effective way of D-crack prevention, but not as feasible as reducing the Nominal Maximum Size. At this time there was still not a single test that accurately measured an aggregate's D-cracking susceptibility. The tests performed would only identify susceptibility for certain types of aggregate, not all aggregate types used in PCCP. The lack of a reliable test has pushed states like Minnesota to adopt strict aggregate acceptance guidelines to combat D-cracking (Koubaa and Snyder, 2001).

2.3. CRITICAL LEVELS

2.3.1. Saturation. A 91% degree of saturation is the critical saturation level for aggregates. Freeze/thaw damage will occur in aggregate when this critical saturation is reached if the aggregate is exposed to repeated freeze thaw cycles (Lewis, 1953; Powers, 1955; Fagerlund, 1975).

Unsaturated aggregates should not exhibit freeze/thaw damage. The aggregate must be at some critical saturation or have no drainage for the damage to occur. The aggregate will not become saturated through capillary action alone, even with very small pores connecting to the surface. When an aggregate is at or above its critical saturation, there is no room for water to flow when freezing occurs. Although saturation of 91% is said to be the maximum an aggregate can have before freeze/thaw durability is a problem, a saturation of 85% is given as the maximum to account for a non-uniform distribution of water throughout the aggregate (Lewis, et al., 1953).

Powers states that if an aggregate is critically saturated, dilation of the aggregate will occur upon freezing. If saturation is above this level the aggregate must accommodate the increased volume due to the freezing water or failure will occur. The critical saturation coefficient can be different for each type of aggregate and 91% is just a theoretical value. Depending upon the mineral homogeneity and saturation continuity, the critical saturation level may be lower than 91%. Another reason for a lowered critical saturation coefficient is the pore structure. If macro-sized pores are connected by pores connected by capillary sized pores, the capillary pore system may be under the critical diameter and can cause dilation failure at a much lower saturation coefficient (Powers, 1955).

An aggregate's freeze/thaw resistance is highly dependent upon its degree of saturation. Above this level, water within the aggregate does not have enough room to accommodate the increased hydraulic pressure as it freezes. The increased pressure then causes the aggregate to fail in a tensile manner since water cannot be expelled into open pores or out of the aggregate into the cement paste (Verbeck and Landgren, 1960). Below the critical degree of saturation, the number of freeze/thaw cycles an aggregate undergoes does not influence the amount of damage since the hydraulic pressure does not reach a point greater than the tensile strength of the aggregate (Fagerlund, 1975)

The degree of saturation is controlled mainly by the cement paste surrounding the aggregate and the quantity of available water. Cement paste that has a high permeability allows water to flow either through capillary action or from water percolating down from the surface. Both of these variables affect the time to saturate the aggregate and may be an indirect cause to the aggregate's failure. A slow rate of saturation to the critical level will allow the aggregate to not resist freeze/thaw damage, but prevent it from occurring since it may never reach a critically saturated level during the colder seasons (Verbeck and Landgren, 1960).

It is possible that an aggregate may have freeze/thaw damage and not be at the critical saturation level. The degree of saturation that an aggregate particle is in is relative to the particle as a whole. However, it may be under the critical degree of saturation, but a portion of the particle could be critically saturated and therefore damage could occur (Fagerlund, 1975).

2.3.2. Size. The length of the pore that water must travel in to be expelled into the cement paste or a large pore depends upon the size of the aggregate. The critical size is one that allows the flow of water without building a hydraulic pressure high enough so damage from freezing will not occur. A pore length less than 0.01-in should be adequate to allow for an aggregate to be resistant to freeze/thaw damage (Arni, 1966).

D-cracking can be avoided by decreasing the maximum aggregate size of the coarse aggregate. Of the ways to prevent D-cracking or prolong pavements that might fail due to D-cracking, this technique is the most used and the easiest accomplished. Field performance records and laboratory testing have indicated that reduction in the coarse aggregate size increases the freeze/thaw durability (Stark, 1976).

The critical saturation theory is a somewhat limited explanation as to why aggregate has freeze/thaw durability problems. The theory assumes that all the water that is freezing within the aggregate has no place to go, therefore there is a build up internal stresses. Dolch believes that in concrete this is rarely the case, even at saturation levels above 0.9 since the water should be able to move into the cement paste if not the unfilled pores of the aggregate. Instead he prefers the hydraulic pressure theory that proposes that the failure is caused by hydraulic pressure of water moving from a critically saturated area when it freezes. Although both theories rely on the idea that there is a critical saturation level, the hydraulic pressure theory has a critical escape path of 0.01-inch that the water moving must not exceed to prevent failure. His preference in “critical” theories is brought on by the field performance of aggregate’s smaller in size. When a smaller aggregate is used in concrete pavement, it has proven to be more durable in terms of freeze/thaw. It is thought that the decreased size of the aggregate brings the escape path below the critical length, therefore increases its durability (Dolch, 1966).

2.4. AGGREGATE PROPERTIES

The Iowa Pore Index was developed as a means of predicting an aggregate's proneness to D-cracking. The freeze-thaw susceptibility of an aggregate is predicted by the Secondary index from the test. The Secondary load is the volume (ml) of water that is pushed into aggregate from the second minute to the fifteenth minute of the test. The Secondary load is then converted into a Secondary index based on the mass of aggregate tested. It is believed that the amount of water taken into the pores slowly over time relates to the pore structure of the aggregate. When aggregate is exposed to temperatures below 0°C (32° F), and the pore's shape resembles that of an "ink-bottle," the fluid is unable to escape and therefore creates an internal pressure that results in tensile stresses and hydraulic flow that act against the aggregate. The restricted flow of fluid is caused by a small pore opening and when frozen, ice in that small neck of the pore will prevent flow. When the larger pore space behind the neck starts to freeze the water is trapped and can not escape when expansion occurs. These forces can rupture or degrade the aggregate and cause what is known as D-cracking (Dubberke, et al., 1980; Dubberke, 1983).

2.4.1. Aggregate Size. Aggregate particle size was compared to the critical escape path length of cement paste because both aggregate and cement paste can be susceptible to freeze/thaw damage. The critical size of an aggregate is larger than the cement paste escape path length because of the size of the material's pores. The majority of pores in cement paste are much smaller than the pores in aggregate which leads to increased capillary action which decreases the critical size. Anything over this critical size is likely to have freeze/thaw durability problems. However, there are aggregates that do not have a critical size and show no resistance to freezing, even when un-saturated. The critical size of an aggregate depends on its physical properties such as porosity and permeability. The strength and degree of saturation plays a role in the critical size as well. Another factor that affects the critical size is the freezing rate because the freezing rate can dictate the stress induced on an aggregate. Smaller sized aggregates can accommodate a faster freezing rate/higher stress resulting in a more durable aggregate. Aggregates that have a large amount of macroscopic voids seem to have a larger critical size, which makes sense because the macroscopic voids have a higher permeability to allow fluid flow (Powers, 1955).

The size of the aggregate is one of the main conditions that relate to the durability in terms of freeze/thaw damage. The size affects the amount of time it takes before the aggregate reaches its critical saturation point and the time it takes for water to exit the aggregate, lowering degree of saturation. A study to determine the effect of aggregate size on freeze/thaw resistance has shown that concrete with ¾-inch sized aggregate expanded more while undergoing a single freeze/thaw test than the concrete with ⅜- inch or ¼-inch aggregate (Macinnis and Lau, 1971). Verbeck and Landgren also have researched aggregate size and the data concurs: smaller particles are more resistant to freeze/thaw problems even in repeated freeze/thaw cycles (Verbeck and Landgren, 1960).

2.4.2. Pore Structure. The aggregate's pore size is determined by the size of the crystalline grains that form the aggregate matrix. Depending upon the arrangement of the grains, the structure of the pores may not be consistent in size. This leads to variability in the hydraulic behavior of water entering and exiting the pores. When water travels in a porous medium, such as aggregate, LaPlace's capillarity equation shows that the capillary pressure is inversely related to the pore radius and directly related to the surface tension of the fluid. Fluids with the same surface tension will have higher capillary pressure as the radius of the pore space decreases, therefore if the pressure is known, one can determine the size of the pores the fluid is flowing through (Corey, 1977).

Lewis, Dolch, and Woods state that an aggregate's pore characteristics influence the physical properties such that it may be the most important property to the aggregate's physical performance, especially freeze/thaw durability. The pore characteristics critical to the physical properties include pore size, shape, and distribution. All three play a role in the aggregates absorption, absorption rate, and the ability of the aggregate to pass and retain fluids. The sizes of continuous pores control the rate of absorption and the rate at which water leaves the aggregate. A critical diameter for freeze/thaw durability that correlates to porosity is 4 to 5-μm. Aggregates with a large distribution of pores smaller than this critical size have shown poor durability to freeze/thaw (Lewis, et al., 1953).

Aggregates pores are larger than cement paste pores and there are fewer of them due to the formation of the crystals that make up the aggregate. It is this difference that causes aggregates to behave differently than cement paste upon freezing. Porosity should not alone be used to estimate to frost resistance, because good frost resistance does not rely on the total volume of pores, but on the amount of macro pores. It is assumed that an aggregate’s pore structure is interconnected by capillary pores. This assumption is based on the fact that aggregates can absorb water and therefore must have an interconnection to internal voids (Powers, 1955). This is discussed by Powers again in 1978, when he states that aggregates with a fine texture like argillaceous limestone are unsuitable for concrete due to the amount of fine interconnected voids (Powers, 1978).

Dolch states that the pore system of the coarse aggregate is responsible for much of its physical performance in concrete. It is the pore system that affects the absorption and rate at which water can be expelled. The size of the pore plays an important role in how much drag is inflicted on the flowing water. An increased drag due to small pores will increase the stress that is placed on the pore of the aggregate. In his experimental work, Dolch used aggregates that have 4-µm size pores and a large porosity. These aggregates are known to be poor performers in freeze/thaw conditions. Dolch made assumptions that the shape of a pore is circular and that the contact angle of water and the aggregate is zero. These assumptions were made so that some mathematical understanding of the pore system could be made. Although there are variances in his findings due to the assumptions, trends show that the absorptivity of an aggregate is a better way to relate the aggregate to frost resistance than permeability. The increased absorptivity, which relates to a larger surface area (indicating smaller sized pores) proved to correlate to freeze/thaw durability better than the measure of permeability (Dolch, 1959).

Along with the absorptivity of the aggregate, Dolch also states that the pores also can affect mechanical properties such as modulus of elasticity and Poisson’s ratio. Both the absorption and mechanical properties can effect the durability of the aggregate, but the influence on the aggregate's moisture condition is of greater importance to the freeze/thaw durability of the aggregate. Studies have shown that the difference between water and aggregate's thermal properties can affect the aggregate's properties. However Dolch believes that the effect is only minor compared to the moisture conditions (Dolch, 1966).

Kaneuji also agrees that the structure of the pores controls how the aggregate retains water and its ease of flow in and out of the aggregate. When an Expected Durability Factor equation was developed using the pore size distribution found with mercury intrusion porosimetry, it was found that pores 4.5-nm in diameter and smaller did not correlate with the Durability Factor from the ASTM C 666 test. This research also found that aggregate durability is not dependent on the size of the pore, but the volume of pores of the same size. Aggregates that had a greater volume of 0.1 to 0.01-µm sized pores proved to be less durable than aggregate with a smaller volume of similar sized pores. When the volume of median pores is correlated to durability, durable aggregates with a median pore size less than 1-µm the volume is limited to 0.02-cm^3/g. However, when the median pore size was greater than 3-µm, the allowable volume of pores in durable aggregate increased exponentially (Kaneuji, et al.,1980).

The pores within the aggregate are not of the same size, but rather are made up of a distribution of different sizes. The variety in size allows for different freezing and melting temperatures of water. The water may be adsorbed so that it is "un-freezable" or the range of pore sizes will allow water to flow though the pores to be expelled from the aggregate at temperatures below the melting point. The flow of water could also be detrimental to the aggregate if it is drawn towards newly formed ice from capillary action (Powers, 1974).

The aggregate’s pore structure is what determines if it can become critically saturated under drained and un-drained conditions. This in turn will be a factor that determines if the aggregate is susceptible to D-cracking. The pore structure of the aggregate is what determines its ability to become saturated to a point that is at equilibrium with its surroundings. When in cement paste, the aggregate will draw water from the paste to become saturated. It has been shown that the aggregate’s initial pre-mixed moisture state has little effect on its performance in freeze/thaw tests. Oven dried aggregates proved to have very similar expansion during the testing, due to the aggregate’s pore structure determining the saturation level the aggregate ultimately reaches and not the initial moisture state (Stark, 1976).

Korhonen and Charest conducted a study on aggregates based on a cryogenic test method. They believed that aggregate’s freeze/thaw durability was based on two properties: pore structure and mechanical strength. They shifted their focus from developing a single cryogenic test to one that includes pore size distribution. They concluded that aggregates that exhibited poor freeze/thaw durability had pore sizes from 0.01 to 5-µm making up more than ¾ of the pore volume. Since an aggregate’s durability relies on the pore structure, they proposed that more research be invested in pore volume measurement (Korhonen and Charest, 1995).

2.4.3. Absorption. The specific gravity of an aggregate is a property that is related to the mineralogy, grain size, and pore size. With similar mineralogical aggregates, a smaller specific gravity suggests that the aggregate has a higher pore volume compared to an aggregate of higher specific gravity. Aggregates with a low specific gravity trend to have higher absorptions than aggregates with high specific gravity (Hudec, 1989).

Korhonen and Charest state that an absorptive behavior is due to the pore's structure. Fine pores can draw water in through capillary action quicker than larger pores. The capillary action also retains the water in the fine pores, resulting in a higher moisture condition sustained over time. With the aggregate unable to "dry out", a critically saturated state is easily achieved. The degree of saturation caused by the pore's ability to retain water has shown to result in aggregate that is susceptible to freeze/thaw damage (Korhonen and Charest, 1995).

2.4.4. Rate of Absorption. The rate of absorption has been shown to be related to the aggregate's grain size and therefore the pore size. Very fine grain aggregates have the ability to absorb about 35 percent of the aggregate's total absorption in just nine minutes. A medium grained aggregate can only absorb a little over 25 percent of its absorption potential in nine minutes (Hudec, 1989).

Every aggregate absorption rate is different and varies with the aggregate's pore volume and pore size. Both size and volume have such an impact that one of the aggregates could absorb 75% of its potential in just 18 seconds, while another aggregate will took 200 minutes to absorb the same percentage of its potential. This is a critical problem when using the IPI to classify aggregate as D-crackable. Depending on the time that elapses prior to pressurizing and taking measurements, the absorption rate variance between aggregates can lead to false classification. With this finding, it is evident that the initial absorption rate cannot be used to classify aggregate's D-crackability. This study also found that larger aggregate absorbs water slower than finer aggregate, but a size factor could be used to normalize the data to one standard size (Winslow, 1987).

2.4.5. Adsorption. Water molecules that are close to the surface of the aggregate behave differently than “free” water that is absorbed by the aggregate. The adsorbed water is attracted to the surface of the aggregate on a molecular level through Van der Waals forces. The forces of attraction prevent the water molecules from forming the hydrogen bonds allowing an ice structure. Although adsorbed water is thought to be non-freezable, the water still contributes to the degree of saturation.

Stark states that aggregate with low absorption (below 0.3%) can have a high adsorption and still be durable. Adsorbed water bonds to the aggregate on a molecular level and will not form ice therefore would not contribute to an increase in stress even at high saturation. On the contrary, if the aggregate has an adsorption greater than 1.0 and an absorption greater than 0.7 the aggregate will be prone to D-cracking. The high absorption and adsorption indicate a large amount of fine pores that can contain enough water to cause high stress build up when frozen (Stark, 1976).

2.4.6. Aggregate Volume Change

2.4.6.1. Expansion. The elastic expansion of an aggregate is an important variable to freeze/thaw durability. The aggregate’s ability to elastically accommodate the tensile strain to a point greater than that induced by the volume change due to freezing would result in an aggregate that does not breakdown when critically saturated and exposed to freezing temperatures. If the modulus of elasticity is so low that the expanding water will cause an expansion of the aggregate that is beyond the elastic region, it will crack resulting in durability issues. Verbeck and Landgren compared three different limestones with varying elastic moduli to make this point. The limestone with the higher modulus showed no distress upon rapid freezing while the two limestones with a lower modulus cracked. The cracked limestone also had a higher absorption capacity that would indicate more pores for water to fill. This resulted in a higher calculated tensile stress when the water froze putting the strain beyond the elastic capability of the aggregate (Verbeck and Landgren, 1960).

The thermal expansion of the aggregate can affect its durability as a composite material when in a cement paste matrix. When an aggregate is considered to be fine, its thermal properties have little effect on the durability, unless a silica based fine aggregate is used in conjunction with a limestone coarse aggregate. The aggregate and mortar can have thermal coefficients that differ up to 2 times in magnitude. This difference causes maximum stress at the aggregate/mortar interface. The stress can lead to cracking, which will allow water access to the aggregate and cause further durability problems upon repeated freezing and thawing. Callan's research has shown a strong relationship between the thermal expansion properties of aggregate and its ability to resist freeze/thaw damage (Callan, 1952).

Hudec also said that an aggregate's thermal properties can greatly affect its performance in different weather conditions. He found that when heating and then cooling aggregate cores, no hysteresis was found in the expansion and contraction when in a dry state. He also found that the coefficient of thermal expansion for the same aggregate is different when wet, compared to being dry (Hudec, 1980).

The expansion of the aggregate due to an increased internal stress may only be able to accommodate the volume change of water if the aggregate has a very low porosity (Dolch, 1966).

Aggregate expansion occurs due to the formation of silica gel when certain forms of silica are in the presence of high alkali cement. Silica gel expansion was studied and a non-alkali treated limestone was used as a control. When Kingston limestone (the control) samples taken from depths of 10.5 to 12 feet and 24 to 30 feet were exposed to high humidity at an increasing pressure, the limestone's natural stress state is achieved and the expansion is under 0.04%. There is a slight hysteresis in the return to a depressurized state, which might be due to water penetrating into the intercrystals of the aggregate. This intercrystal water is water that can now only be removed with the use of heat, similar to that of expansive soils (Feldmand and Sereda, 1961).

2.4.6.2. Reduction. A material that has an increased external pressure applied will reduce in volume. During the IPI test an external pressure of 35 psi is applied to the aggregate. The reduction follows the physical phenomenon of a change in volume due to a change in pressure and is governed by the bulk modulus of the material. The bulk modulus is related to the elastic modulus through Poisson's ratio and it measures the incompressibility of the material. The difference between the two is that the bulk modulus is the pressure change divided by the volumetric strain instead of a stress over tensile strain for the elastic modulus (Gasiorowicz, et al., 1996). By knowing the change in pressure of 35 psi for an IPI test and the bulk modulus of the aggregate being tested the volume change for a 4500-g sample is less than 0.01-ml. For the IPI test, this change in volume is negligible.

2.4.7. Summary. The IPI test is a measure of (pressurized) absorption and pore size. Both properties relate to D-cracking, while other properties influence the outcome of the test results. The absorption rate of the aggregate will play a role in the Primary and Secondary indices. Any volume change that is measureable with the IPI testing apparatus may alter the indices such that inaccurate results would be produced. The aggregate size is a major contributor to D-cracking. Using a test method that can take the size of the aggregate into account may prove to be beneficial in predicting D-cracking.

2.5. WATER EXPULSION

Water expulsion in coarse and fine grained soil has been explained (McRoberts and Morgenstern, 1975) and is used to understand the expulsion and attraction of water due to freezing. Freezing water can occur in either a closed or open system. Both systems can have positive pore pressure development when there is a progressive freeze such that there is an advancing freezing front. A closed system is one that will not allow water to flow out when a positive pore pressure exists. In an open system, water can flow freely in and out of the system. It is in a closed system that pore pressures can build up to a point that will cause heave in soils. This heave is a change in volume due to the freezing water. The open system will not result in volume change because it will allow the flow of the water away from the freezing front. Even in a coarse gained open system, pore pressures can increase from a blocked drainage path. Water is attracted to the freezing front through capillary action in fine grained soils. A surcharge can be initiated to prevent the attraction of the water and prevent an increase in volume change. The capillarity model described suggests that the pore radius and surface tension of the ice-water interface are inversely related and used to form a material constant. If this constant is larger than the confining pressure minus the pore water pressure, then the freezing front will move through the pores and expel water.

A method of using water expulsion to determine the maximum pore diameter of ceramic filters is ASTM E 128-99, Standard Test Method for Maximum Pore Diameter and Permeability of Rigid Porous Filters for Laboratory Use. In this method, pressurized air is used to expel water from the pores of the rigid filter. The pressure of air that allows for the first air bubble to pass through the filter is related to the maximum pore diameter through the surface tension of the liquid and the filter media (ASTM, E 128-99).

When water starts to freeze within an aggregate’s pore structure, the formation of ice crystals causes an increased volume within the pore. This increased volume then induces hydraulic pressure and water is expelled. If water cannot be expelled from the pore, the pressure will build until the aggregate fails (Pigeon, et al., 2003).

Water expulsion is important to freeze /thaw durability and is partially controlled by the permeability of the aggregate. The aggregates ability to expel water to a point below the critical saturation level influences the performance under freeze /thaw conditions. An inability to expel the water in an expedient time frame would maintain a degree of saturation such that degradation could take place during freeze/thaw cycles. Water expulsion can also be damaging to the concrete if the expelled water is forced into the surrounding cement paste. The damage to the cement paste can be avoided if the expulsion distance to an open void is short and paste permeability is high (Verbeck and Landgren, 1960).

The pore structure determines the aggregate’s ability to retain and expel water. This ability to expel water is crucial to freeze/ thaw durability (Kaneuji, et al., 1980).

2.6. TESTING METHODS

2.6.1. Iowa Pore Index. Dubberke found that aggregates with a poor service record also had a large quantity of small pores. This finding led him to work on the development of the Iowa Pore Index test (Hanson, 2009). The IPI test was first used on aggregate with a service record in 1978. At this time Iowa’s transportation department only tested a ½ to ¾ inch size aggregate, since they had previously set a limit of ¾ inch for a maximum size on D-cracking prone aggregate. They found that the Primary load was not an indicator of aggregate with D-cracking problems. However they did find that the Secondary load showed a correlation to aggregates that had been used in concrete where D-cracking occurred (Dubberke and Myers, 1980).

The Secondary load number is used to determine the ability of the pore structure to allow water flow. The aggregate’s larger pore structure is represented by the Primary load number and these pores are thought to aid in freeze/thaw durability like air-entrainment within the concrete’s paste matrix. Koubaa and Snyder found that the durability of carbonate aggregates had a good correlation with the IPI Secondary load (Koubaa and Snyder, 2001). This finding concurs with the Iowa Department of Transportation’s (DOT) correlation between the IPI and the service record of tested aggregates (Dubberke, 1983). This correlation is important for calcareous aggregates in that their pores tend to be smaller than igneous aggregates. An example of this correlation is granite, which was tested and had no freeze/thaw loss and a zero IPI Secondary index (Grahm, et al., 2007).

Scholer and Shakoor performed a study in 1985 to compare the Iowa Pore Index against the Mercury Intrusion Porosimeter. They found that the IPI test is a more reliable test and with added benefits of reduced cost and testing time than the Mercury Intrusion Porosimeter. However, the IPI does not give a pore size distribution from the results. Shakoor and Scholer also investigated the reproducibility of the IPI test. They stated that the IPI test is reproducible on the same aggregate from the results of running the IPI test four times on the same aggregate. The data that the reproducibility produced has what they call “consistent results,” but in two of the three samples tested, the Secondary load decreased. One of which went from a 29 to a 25 for the Secondary load index. This allows the conclusion to be drawn that this aggregate does not show D-cracking potential if the fourth test is reported. Another sample that was retested started with a Secondary load of 24 and went to a Secondary load of 31 and then back down to 27, thus making an acceptable aggregate show poor results. Although Shakoor and Scholer state that their results are consistent, a definitive trend is not shown by their test results. Their procedure for reproducing the IPI test was not outlined nor was it further investigated (Scholer and Shakoor, 1985).

The Iowa Pore Index test is time-critical because measurements are taken at specific time intervals during the testing process. With all other variables constant, the aggregate’s unique absorption rate can influence the outcome of the test. Some aggregates can absorb about 90% of their potential in the first 18 seconds of becoming wet. With varying absorption rates, some aggregate can be falsely identified as a D-crackable material by the IPI (Winslow, 1987). The IPI has shown to have a fair correlation with both absorption and a vacuum saturated absorption (Richardson, 2009). This test method has been shown to have a good correlation with the ASTM C 666 test (Dubberke, 1983). However, one study was not able to produce as good of a correlation as stated in past studies and suggests that the IPI test alone cannot be used as a means to evaluate aggregate durability like the Durability Factor that comes from the ASTM C 666 test (Carr, 2008; Richardson, 2009).

Koubaa and Snyder recommended that the IPI test be used in a testing program to attempt to identify the durability of aggregates. Also suggested is a further exploration of the different mechanisms associated with freeze/thaw durability (Koubaa and Snyder, 2001).

A report produced by the University of Illinois (U of I) for the State of Illinois Department of Transportation states that the IPI test has the most desirable aspects of a durability index test. Although desirable, the researchers at U of I had trouble getting a relationship between the service history of aggregates and their index from the IPI. A decision was made to explore the mechanisms of the IPI test and modify procedures in order to produce a better correlation between the IPI and freeze thaw durability. One noted weakness of the IPI tests is that a high quality aggregate with a few highly absorptive particles can produce a similar index as a specimen of poor aggregate. Because of this they suggest that the pore distribution be measured with the Mercury Intrusion Porosimetry test in order to help correlate results. During the testing, air trapped within the testing system was troublesome. They recommended using a domed pot lid and possibly using a valve to allow for air to flow out of the system while filling, and utilized a procedure of rocking the sample while filling in order to eliminate air bubbles. The same material has been tested two times in the past with reliable results at 35 psi. The IPI test was performed at four different pressures: 35 psi, 50 psi, 100 psi, and 200 psi. The higher pressure used during the test resulted in a higher degree of saturation and is thought to be a better representation of a property related to durability than the Secondary index from the IPI test. Along with the index gathered from the test, they looked at the degree of saturation that was achieved during the testing and felt that this was a better way of relating to durability. Although their findings did not produce a more conclusive means of identifying aggregate with poor durability, it was felt the test would be best used as a method of comparing the pore characteristics of aggregate that is taken from the same quarry but at different times (Olsen, et al., 1983).

Kansas Department of Transportation (KDOT) studied the Iowa Pore Index test in 1980 as a way to determine the D-crackability of limestone aggregate in a timely manner. The Secondary index proved to have a poor correlation with field performance. It was also noted that the IPI did not have a good correlation with the ASTM C 666 test. In their literature review, the ASTM C 666 test was ultimately chosen as the basis for approving coarse aggregate to be used (Clowers, 1999).

2.6.2. States with Iowa Pore Index Specifications

2.6.2.1. Iowa. The Iowa test method 219-D titled “Method of Test for Determining the Pore Index of Aggregates” utilizes a newer IPI testing apparatus that includes a control board, cylinder/valve board, and a chamber pot. The Primary load, Secondary load, and System Check times are automatically controlled, reducing operator error. The method uses 4500-grams of oven dried aggregate in the standard ½-inch to ¾-

inch size. The stated filling procedure is to use the valve to control the flow of water into the system by feathering it until the water level is at the zero mark. After the system has run through the cycles and data has been recorded, the system is drained and calculations are performed (Iowa Department of Transportation, 2000).

2.6.2.2. Kentucky. Kentucky Transportation Cabinet's KM-64-623-08 is its "Pore Index Value of Aggregate" test method that follows the method developed by the Iowa Department of Transportation (IDOT). Kentucky specifies the apparatus as the IDOT original which is a modified ASTM C 231 type A concrete air meter. A specified 9000 grams of aggregate passing the 1-inch sieve and retained on the ½-sieve is used but an allowed 4500 grams may be used if the test is not going to be used for settling disputes between two varying results. If the test results vary by more than 0.11 percent from the historical data, further investigation of the testing apparatus, field sample, and calculations should be done (Kentucky Transportation Cabinet, 2008).

2.6.2.3. Michigan. The Michigan Test Method 128 is the "Determination of Iowa Pore Index of Coarse Aggregates." A specified 0.8 liter pot is used for determining the IPI after the aggregate is separated into absorptive and not absorptive fractions. The pot is agitated while filling and intermediate reading times of 15, 30, 45, and 60 seconds are recommended to be recorded if an absorption curve is to be constructed. A Calibration factor to account for the actual amount of volume in the system's cylinder versus the indicated amount by the system's graded marks is used along with a Pot Expansion factor in the final calculation of the IPI (Michigan Department of Transportation, 2001).

2.6.3. Un-drained Triaxial Test. ASTM D 4767 Standard Test Method for Consolidated Un-drained Triaxial Compression Test for Cohesive Soils (ASTM, 2004) is for soils, but the section of interest is for the consolidation of the soil. During consolidation the cell of the triaxial apparatus is pressurized at a higher pressure than the soil sample. As water flows from the burette into the cell, readings are taken at 0.1, 0.2, 0.5, 1, 2, 4, 8, and 15 minutes and continue until primary consolidation is complete by doubling the previous time. By taking the burette readings, a volume change in the soil specimen can be calculated. By venting the pressure, the rebound of the soil can be measured by the backflow of the water into the burette.

The IPI testing apparatus is similar to a triaxial compression test apparatus. Both tests use pressurized water to measure a materials property through a volume. The difference between the two is that a venting procedure on the IPI has not been researched. Using a venting procedure on the IPI test similar to the un-drained triaxial test will allow for the backflow of water to be measured as it is expelled out of the aggregate.

2.7. COARSE AGGREGATE PROPERIES

2.7.1. Specific Gravity and Absorption. Specific gravity and absorption contribute to aggregate freeze/thaw durability. It is also important to know the absorption of an aggregate specimen because the degree of saturation can be calculated if the absorption is known. The AASHTIO T 85 (AASHTO, 2010) and ASTM C 127 (ASTM, 2004) test uses material retained on the #4 sieve for the determination of the specific gravity and absorption of the aggregate. The material is dried at 110˚C until reaching a constant mass, and once cooled, soaked in water for 15 to 19 hours. The mass of the saturated surface dry aggregate is taken and then weighed while suspended in water to determine the specific gravity. The material is then oven dried until constant mass so that the absorption value can be calculated. The test method notes that there will be a difference in specific gravities if the material is not oven dried as stated. This is due to water not being able to reach the center of the aggregate particle during the soaking stage. Also noted is the use of different soaking methods. This absorption from this test method would differ from absorption of a boiled soak or a vacuum saturated soak. The boiling of water decreases the contact angle allowing it to “wet” smaller pores, increasing the amount of water absorbed. The vacuum saturated method of soak would also increase the amount of water absorbed because the applied vacuum pulls air out so more water can get into the pores. Any aggregate breakdown or degradation during the soaking stage of the test is an indication that the pore structure of the aggregate has been affected. This breakdown can lead to inaccurate results.

There is a correlation between the absorption of an aggregate and the total load from the IPI test where a higher total load correlates with a high absorption. Although a correlation exists, the IPI test utilizes pressure and the T 85 test does not. This difference does not allow for an accurate comparison between the two values to be made (Grahm, et al., 2007).

Aggregates with high absorption have proved to be non-durable in freeze/thaw conditions. However, durability relies on pore structure which absorption does not measure. Therefore absorption is not a measure of freeze/thaw durability, but can be used in acceptance criteria as a durability indicator (Koubaa and Snyder, 1996).

2.7.2. Vacuum Saturated Absorption. The Vacuum Saturated Absorption (VSA) is a modified AASHTO T85-10 method that uses a pycnometer and vacuum pump to further saturate the aggregate. There are numerous versions of this test method. The method developed by Richardson involves material larger than the #4 sieve in an oven dry state. The aggregate undergoes a vacuum of 27.5±2.5 mm of mercury while underwater for 30 minutes prior to the 24 hour soak time.

There is a fair correlation of the VSA to the IPI, as well as, a good correlation to the T 85 absorption. When comparing the two different types of absorption, the VSA has a stronger correlation to the IPI than the T85 (Richardson, 2009).

2.7.3. Resistance of Concrete to Rapid Freezing and Thawing. AASHTO T161 (AASHTO, 2008) and ASTM C 666 (ASTM, 2008) are test specifications for determining the Relative Dynamic Modulus of Elasticity, Durability Factor and Length Change in Percent. These parameters are found with calculations from data that is attained by a repeated cyclic freezing and thawing of a concrete prism in the presence of water. The prism undergoes 300 cycles of freeze/thaw that takes between 25 to 62.5 days, depending upon the length of the cycle. The freeze/thaw cycles start after a specified amount of time of moist curing. Depending upon the specified curing time, the total duration of the test can take up to 6 months (Dubberke and Myers, 1980). It is assumed that if a prism that is not significantly damaged from the cyclic freeze/thaw, then the aggregate used in the concrete mix is “sound”. Therefore after the 300 cycles, an aggregate’s durability in relation to freeze/thaw can be ranked for approval or rejection in the use of portland cement concrete.

Although this test does not allow one to directly predict the service life of the concrete, it does allow different concrete mix designs to be compared to each other in a standard way. By using the results of the freeze/thaw test, it can be assumed that an aggregate or mix that performs well in the test will have a better performance in the field than an aggregate or mix that performs poorly in the test (Detwiler, et al., 1989). The AASHTO T161/ASTM C666 test results are used for acceptance of aggregates by many state departments of transportation. The Durability Factor calculated from the test is also correlated with the results of the IPI test for an increased accuracy of frost susceptibility prediction.

2.8. CORRELATIONS WITH FREEZE/THAW DURABILITY

According to (Lewis, et al., 1953), there was not enough data at the time of their study on aggregate porosity to make a correlation with the durability of aggregates. Correlations have instead been made with characteristics from other physical properties dependent on the aggregates porosity. This includes absorption, volume of voids with a diameter less than 4-5μm, specific gravity, and the degree of saturation. Of the physical properties, absorption is used by many state departments of transportation as an acceptance test in an attempt to limit durability issues.

In 1996 Koubaa and Snyder found that the IPI test had a correlation with field performance. However, it was not as strong of a correlation as ASTM C 666 and a single cycle slow freeze test. Koubaa and Snyder used results from their 1996 study and a statistical analysis approach to find a better correlation between durability test and field performance. Their regression analysis found the quality number, derived from the IPI test, to fit within their prediction model and the Secondary IPI in their final model. Upon finishing their testing, they found that the ASTM C 666 correlated well with field performance, and that the there was a good correlation with durability of carbonate rocks and the IPI Secondary load (Koubaa and Snyder, 2001).

Aggregates with over three fourths of its pore volume sized between 0.01 and 5µm show poor freeze/thaw durability.   A system of measuring the pore volume of an aggregate is recommended by Korhonen and Charest to aid in singling out aggregates that may have poor freeze/thaw durability. This would allow for the T161 test to be performed if time allows or if an aggregate is flagged due to the pore volume test (Korhonen and Charest, 1995).

The Missouri Department of Transportation (MoDOT) uses the T161 test for aggregate acceptance. This test has been used because of its good correlation with freeze/thaw durability. Richardson’s work on a regression model to estimate a DF from several aggregate index tests shows that bulk specific gravity and absorption have a good correlation to the DF. The IPI has a poor correlation to the DF, but was chosen as a test to be explored so that a better correlation could be found (Richardson, 2009).

3. LABORATORY INVESTIGATION

3.1. EXPERIMENTAL DESIGN

This study used some data from 2008 previously published in “Quick Tests for Durability Factor Estimation,” (Richardson, 2009) and new data that was collected subsequent to 2008. In 2008 the data was collected from AASHTO T161, AASHTO T85, Vacuum Saturated Absorption, and Iowa Pore Index tests performed on 19 different aggregates from quarries throughout the state of Missouri. In addition to this, the IPI test was performed on five aggregates that were collected in 2011 from five of the same quarries and ledges as the 2008 aggregates. The IPI test was also performed on aggregate that was collected in 2008 but was stored in a climate controlled environment at Missouri S&T. The tests in the present study on the 2008 aggregate were performed in order to fill in gaps within the previously collected data.

In the IPI testing, replicate specimens were tested in order to use a “t-critical” outlier analysis, ASTM E 178, Standard Practice for Dealing with Outlier Observations (ASTM, 2008). The number of replicated specimens was usually three, although the number varied with the aggregate sample, particle size and procedure. The average of the non-outlier replicate specimen tests was reported as the IPI for the aggregate. Three specimens were not available for all aggregate samples tested, because of a lack of material. In this event the reported IPI is the average of the two replicate specimens. If the aggregate sample yielded one specimen, then the reported IPI is from just one specimen.

3.2. EQUIPMENT

3.2.1. Iowa Pore Index Apparatus. The Iowa Pore Index test was performed using an apparatus built by Missouri S&T in 2008 and was designed to be a near replicate to the Iowa Department of Transportation's IPI testing apparatus. The apparatus consists of three main parts: a control board, chamber pot, and a valve/cylinder board. The control board consists of timers for the Primary and Secondary loading, as well as a System Check (SC) cycle. The chamber pot is a modified pycnometer that had been designed for determining the maximum specific gravity of asphalt mix under AASHTO T 209-05. This pot holds the aggregate sample, as well as the pressurized water during the test. The valve/cylinder board is made up of three graduated cylinders that represent the Primary load, Secondary load, and the System Check placed left to right on the board. The valve/cylinder board also has numerous valves that regulate the air pressure and switch the air pressure to the appropriate cylinder at the correct time, as displayed on the control board. The apparatus is shown in Figure 3.1.

The Primary, Secondary, and SC cylinders are located from left to right on the cylinder board. The pneumatically controlled valves for each stage of the test are located directly below the cylinders. Once the apparatus has aggregate in the chamber pot and the water is at the desired starting level for the test, the "Start" button is pressed. This initiates a one minute timer, pressurizes the three cylinders, but only opens the Primary load valve. With the Primary valve open, water flows from the Primary cylinder and into the chamber pot where the water is pushed into the aggregate. After the first minute a second timer is started, the Primary valve closes and the Secondary valve opens. This valve remains open to the chamber pot for 14 minutes. After the fourteenth minute of the

Secondary load stage, the Secondary valve closes, a timer for 15 minutes is initiated and the SC valve opens. When the 15 minutes is complete, the SC valve closes and all valves remain closed (system is still pressurized) until the “Stop” button is pressed. The “Stop” button opens all three valves and opens the system up to the atmosphere.

Figure 3.1. Missouri S&T IPI apparatus

3.2.2. Washing of the Aggregate. To wash the aggregate, all specimens were washed in a six inch deep stainless steel pan. The washing step took place on a table outfitted with six spray handles similar to those on a kitchen sink. Cold tap water was used for the washing process. The table allowed the water to drain into the floor drains without impeding flow from the pan used in the washing process.

3.2.3. Drying Oven. The aggregate was dried in an oven capable of maintaining temperatures of 110 ± 5 °C (230 ± 9 °F). For this testing, a Grieve model #333 oven was used to oven dry the aggregate for 24 hours. The aggregate remained in the same pan that it was washed in.

3.2.4. Temperature. The temperature of the water was taken during testing using a digital probe thermometer. After an IPI test the water was drained until the water level was slightly over the aggregate in the chamber pot. With the chamber pot lid removed the probe was inserted into the pot of water and aggregate and temperature was recorded when it stabilized. This act of measuring the temperature took on average 3 to 5 seconds after the IPI test was completed.

3.3. MATERIALS

3.3.1. 2008 Aggregate. Some of the aggregate used in the IPI testing was collected for a study in 2008. The material had 13 different durability related tests performed on it at that time. For the present study the aggregate was labeled as “2008” aggregate. Table 3.1 is a list of the aggregate with the data from four of the test methods that was collected during the 2008 study. In the table the T161 Durability Factor (DF), Vacuum Saturated Absorption (Vac Abs) and the AASHTO T 85 Absorption (T85) are listed along with the IPI. All aggregates are limestone with the exception of two Jefferson City Dolomites, Gable Stone and Muenks Brothers.

Table 3.1. 2008 Aggregate

							Secondary IPI			
Quarry	**Formation**	**Ledge**	**MoDOT ID**	T161 DF	Vac Abs	T85	**½-¾**	**⅜-½**	**#4-⅜**	Name
Bluff City Minerals@Alton	St. Louis	(1-7)	86R3M025	95	1.19	0.8	21.3	15.0	--	Bluff City
Weber New Melle	Plattin	(2-4)	86L2R034	95	1.40	1.2	24.0	18.0	13.0	WNM
NAP Savannah West	Amazonia	(8AZ)	81MA0292	94	2.16	1.9	36.0	31.0	22.7	Amazonia
Weber at Festus	Plattin	(P1-P8)	86R3M031	94	1.41	1.0	--	--	8.7	Weber
Weber New Melle	Plattin	(4-7)	86R3M029	89	1.69	1.9	20.3	14.7	--	WNM 029
Central Stone@Florissant	St. Louis	(12-14)	86L2R021	89	2.12	2.0	--	39.7	28.7	Central
Gable Stone@Willow Sp	JC Dolomite	(1-6)	89TCR067	87	2.33	1.7	13.7	12.0	--	Gable
Joplin Stone- Joplin	Warsaw	(1-3)	87ASM006	81	1.40	0.8	24.0	19.7	--	Joplin
SEMO at Cape Girardeau	Plattin	(15-15A)	80MA0051	78	0.92	1.1	14.0	13.3	--	SEMO
Hunt Martin-Greenwood	Bethany Falls	(1-4)	84SRE039	76	1.89	1.5	46.0	33.7	--	HM
Capital Quarries#5@Calif.	Burlington/Chouteau	(3-7)	85DLR012	75	2.49	1.7	44.0	34.0	--	Capital
Springfield Underground	Burlington	(1-2)	88MA0024	73	0.85	0.8	12.0	6.0	--	SU
Knox Co. Stone	Chouteau	(18-22)	83MA0234	72	2.97	2.6	33.3	25.7	--	Knox
NAP Savannah West	Kereford	(1K)	81MA0379	72	2.09	2.0	43.3	39.0	27.0	NAP
Bussen @St. Louis	St. Louis/Salem	(16-21)	86R3M028	69	3.08	2.2	55.3	51.3	--	Bussen
Fischer-Hughesville@Sedalia	Burlington	1	85DGG007	66	1.75	1.2	11.3	5.5	--	FH
Weber New Melle	Plattin	(4-7)	86L2R020	64	1.79	1.7	22.0	14.0	--	WNM 020
Muenks Bros at Loose Cr	JC Dolomite	(1A-C,2)	85RDP040	54	3.43	3.0	49.0	37.3	--	Muenks
APAC-KS@Harrisonville	Bethany Falls	(1-3)	84SRE203	28	2.90	2.7	--	24.3	15.0	APAC

3.3.2. 2011 Aggregate. Aggregate was collected in 2011 for this IPI study so that sufficient data could be collected on all three particle sizes. In order to achieve similar results to the 2008 study, material was requested from the same quarries, formations, and ledges as the 2008 material. Due to changes in production, only five materials were available at the time of this study. Table 3.2 lists the material used that was collected in 2011 for this IPI study.

Table 3.2. 2011 Aggregate

Quarry	Formation	Ledges	ID	Name
Bluff City Minerals@Alton	St. Louis	1-7	106L2R005/ 86R3M025	Bluff City (11)
Weber New Melle	Plattin	4-7	86R3M029	WNM (11)
Hunt Martin-Greenwood	Bethany Falls	1-4	84SRE039	HM (11)
Capitol Quarries #5 @ California	Burlington/Chouteau	3-7	85DLR012	Capital (11)
Knox Co. Stone	Chouteau	18-22	83MA0234	Knox (11)
Bussen @ St. Louis	St. Louis/Salem	16-21	86R3M028	Bussen (11)

3.4. TEST PROCEDURES

3.4.1. Test Procedure Exploration. In order to provide a more standard IPI procedure, different testing variables were explored to determine their effect on the results prior to the testing of aggregate for the DF and particle size correlation analysis. The types of variables were chosen based on questions that arose from an evaluation of the IPI procedures of Iowa DOT, Michigan DOT, Kentucky Transportation Cabinet, the Missouri S&T method used in the 2008 study, and University of Illinois study.

3.4.2. Filling the Apparatus. The aggregate specimen being tested starts to absorb water as soon as the filling process begins. The water absorbed prior to the start of the test is not measured and any variation of the filling time with each specimen will result in decreased precision (and perhaps accuracy) of the test. The amount of exposure time the aggregate has to the water prior to pressurization has is a basis for criticism of the IPI. The standardized filling time will not alleviate the exposure time prior to pressurization, but will prevent the exposure time from being a random error that could affect the data.

In order to increase the precision (and perhaps accuracy) of the test, the IPI apparatus was filled with water as if an actual IPI test was going to take place with acute observation of the water in the cylinders. First the apparatus, with an aggregate specimen in the pot, was filled multiple times with filling times ranging from sixty to ninety seconds by using a feathering procedure on the inlet/outlet valve to control the water flow. For a 60 second filling time, the valve was opened all the way which allowed the water level to reach the beginning levels quickly and then was feathered until the appropriate water level was reached. For a 75 second filling time, the valve was opened one third of the way until the water entered the cylinders and then was feathered quickly until the appropriate level. For a 90 second filling time, the valve was opened about one third of the way with feathering occurring slowly until the water reached the appropriate level.

3.4.3. De-Airing. The IPI relies on a measurement of volume for the results of the test. The air would compress when the system is pressurized and would be indicated as a decrease in the water's volume. Using de-aired water for the test would solve some of the problem, but turbulence during the filling procedure allows air bubbles to be trapped under aggregate particles. Researchers at the University of Illinois rocked the apparatus from side to side to allow trapped air bubbles to escape while the system was filling with water. The rocking procedure was continued while excess water flowed out the top of the system until no air bubbles were visible (Olsen, et al., 1983). Michigan's Test Method 128 requires the technician to agitate the apparatus while fillings to expel trapped air, while not defining how the agitation is performed.

In the present study, the option of adding agitation of the chamber pot that would allow large air bubbles trapped in voids to be released was found to be beneficial. Most methods of de-airing the water evaluated were performed on the early IPI apparatus (a modified Type A concrete air meter). The Missouri S&T's IPI chamber pot is mounted to a base plate the does not allow rocking. To avoid alterations to the apparatus, a rubber mallet was used to tap the chamber pot 10 times during the filling procedure. The tapping method was adopted from various concrete tests where the container holding the fresh concrete is tapped 10 to 15 times to consolidate the concrete. Due to the instability of the table the apparatus was on, the tapping only took place during the filling of the chamber pot and not during the filling of the graduated cylinders. By restricting the tapping to the chamber pot fill only, the benefit of agitation was achieved while maintaining a 90 second fill time.

3.4.4. Recovery Data Observation. The recovery data is a measure of water that flows back into the cylinder once the pressure is released from the system. It was observed that when a vent lever is opened during the test, water started to flow back into the cylinder. A portion of the water that is recovered from the chamber pot is the pot expansion load. This is the volume of expansion the system increases by when pressurized to 35 psi. The remaining water recovered is water that is expelled from the aggregate specimen. Both actions are believed to be due to elastic recovery upon removal of load and by trapped air volume expansion upon reduction in pressure. Upon opening the vent, the water moves back into the cylinder quickly and then slows to a steady flow until it ceases.

When the system is pressurized, air is trapped in the aggregate. The trapped air in the micro pores equalizes at 35 psi as the water moves into the pores. Once the pressure is removed from the water in the cylinders, the air in the aggregate is now at a higher pressure and pushes the water out until pressure equilibrium is reached. Not all of the water is expelled due to the capillary action of the micro sized pores in the aggregate.

Water recovery data was collected during the SC stage of the IPI test. The SC cylinder was added to the IPI testing apparatus to check for leaks in the system that would indicate an error in the Primary and Secondary loads. The data from the SC stage is for system compliance and not in the calculation of the Primary or Secondary IPI. The SC cylinder can now be used to collect data that can be used with the Primary and Secondary loads or by itself as measurement of a aggregate property.

The water level of the SC cylinder was recorded at the beginning of the SC, and then every minute thereafter until the 15 minute stage was complete. The rate that water moves into the aggregate after the Primary and Secondary loads are complete is negligible. If a leak exists in the IPI apparatus it would be noticeable fairly quickly into the start of the SC stage. At the 2 minute mark of the SC stage (sufficient time to indicate a leak), the IPI system was vented using the ventilation valve so that the system was open to the atmosphere. At this time the pressure gauge read zero, indicating that zero gauge pressure was being applied to the system. The 13 remaining minutes of the SC stage allowed for a maximum recovery period while maintaining the system compliance. At the end of the IPI test cycle the "Stop" button was pressed which opens all the control valves and allows the water to level out evenly across the three cylinders.

3.4.5. Re-pressurization. The re-pressurization is an alternative method to re-testing a specimen if the test is interrupted due to an equipment failure or some unforeseen circumstance. The specimen is to be left in the chamber pot covered with water and then re-pressurized after stopping the initial IPI test. The re-pressurization is started three minutes after the stopping of the IPI test when the Recovery procedure is performed. After fifteen minutes (13 minutes of venting during the SC and 2 minutes in between the stop and start of the re-pressurized IPI) of the aggregate being exposed to only atmospheric pressure, an additional minute is used to refill the apparatus to the starting levels.

3.4.6. Iowa Pore Index. The IPI test was performed using a modified Iowa 219-D test method. The modifications were made to control several troublesome variables in the IDOT procedure: fill time, de-airing, system compliance. System compliance includes the pot expansion (amount of expansion the system undergoes when pressurized) and maintaining a consistent volume in the chamber pot by tightening down the retaining bolts to a specified torque. A new water expulsion step was added. Tests were performed separately on three different fraction sizes (#4 to ⅜-in, ⅜ to ½-in, and ½ to ¾-in) of washed and oven dried aggregate. After washing and a 24 hour oven drying, approximately 4500-g of material was weighed and placed in the chamber pot. The chamber pot lid was bolted in place and torqued to 35 inch-lbs to standardize the chamber pot volume. The system was filled with water up to the midway point in the graduated cylinders (Primary-150ml, Secondary and SC at 50ml), the standard procedure is to fill the graduated cylinders up to the “zero” mark. This alteration was made to allow for water to flow back into the SC cylinder without an overflow. The chamber pot was tapped with a rubber mallet 10 times to remove air bubbles from between the aggregate particles and the pot interior. After the cylinders are filled and the beginning water levels recorded, the test was started. The start time of the test was 90±5 seconds after the filling started. The cylinders were pressurized to 35 psi and the Primary and Secondary loads were recorded at the 1 minute and 15 minute intervals. When the System Check cycle was finished, the water was drained from the cylinders but not from the chamber pot. The water level remained above the aggregate so that the temperature could be taken and not expose the aggregate to air so that a re-pressurization procedure could be performed. The temperature of the water was taken at this time using a digital probe thermometer. The full procedure is located in Appendix A (Iowa Pore Index Test Procedure).

4. RESULTS

4.1. TEST PROCEDURE EXPLORATION AND OBSERVATION

4.1.1. Filling the Apparatus. Air bubbles suspended in the water that is pressurized occurred in the initial observation of the testing procedure. This led to the determination that the filling time and procedure should be evaluated. It was observed that the amount of air bubbles in the water was increased with a faster fill time. Appendix B has a detailed observation of air bubbles visible within the graduated cylinders. A fill time of 90 ±5 seconds was determined to be the standard fill time to minimize the amount of air bubbles from being in the water, while also minimizing time that the aggregate was exposed to water prior to the beginning of the test.

This standard fill time was performed to increase the precision of the IPI test. The increased precision results from the decreased amount of compressible air in the water. Large amounts of air in the water would result in a false high reading. Another degree of precision is attained with the starting degree of saturation. Once the water touches the aggregate, absorption occurs. By standardizing the time, each specimen tested from the same sample of aggregate will have a similar degree of saturation.

4.1.2. De-Airing. After a standard time to fill the apparatus was determined, a method of agitation to the system was evaluated. Vibration has been used to agitate the aggregate in order for any trapped air bubble to escape while filling the apparatus. Other users of the IPI test have agitated the pressure pot or rocked the pressure pot back and forth while water was flowing through the system. In the present study, it was found that once the water was in the graduated cylinders, the tapping was not as beneficial as when the water was filling the pot. The tapping causes motion in the water. This motion does not allow for the water level to be read, thus preventing a repeatable fill time of 90 seconds from being achieved. Having longer tubing connecting the chamber pot to the cylinders so that they could be placed on different tables, or having a more stable table might prevent the movement of water while tapping. This could allow for more taps with a mallet to further the benefit of the tapping procedure. However, these possibilities were not explored. The tapping procedure was then reduced to only tapping the pot prior to the cylinders being filled and was set at 10 taps with a rubber mallet.

4.1.3. System Compliance. To maintain consistency in each IPI test, a torque procedure was adopted. The chamber pot lid is secured to the chamber pot with four threaded rods that pass through the lid and are fastened to the base. Once the lid is in place, four nuts are tightened to a snug position using a cross pattern to tightening evenly. A torque wrench was used to torque the nuts down to 35 inch-lbs, also performed in a cross pattern. After the IPI test is performed the torque of the nuts are checked again. Any loosening of the nut is an indicator that a problem existed during the test and the accuracy of the data may be decreased.

4.1.4. Recovery Observation. Experimentation with the venting valve on the IPI testing apparatus during the Pot Expansion (PE), Primary load, Secondary load and System Check cycles led to the observation that a measurement of water could be taken at intermediate times during the preset cycles. This was discovery was found in between the second and fifteenth minute (Secondary load stage) of an IPI test. The vent was opened and the water level in the cylinder began to quickly rise. The water flowing back into the graduated cylinder once the pressure was removed was a combination of the PE (system compliance) water and water being expelled from the aggregate. To maintain the initial intent of the IPI test, the Recovery would be performed during the SC stage allowing for the Primary and Secondary loads to be collected. This led to the assumption that recovered water from the elastic recovery of the aggregate could be measured when the pressure was vented to the atmosphere.

The IPI test was performed on a Jefferson City Dolomite from a local quarry in Rolla, Missouri. After two minutes of the System Check cycle, the vent valve was opened and the water level in the SC cylinder was observed to be rising. Because the amount of water pushed into the aggregate was greater than the cylinders capacity when initially filled to the “zero” mark, the IPI test was performed again with the initial water level half way up the graduated cylinders. Next the system was vented during the SC cycle. The water level began to rise in the area of gradations so its flow could be measured. This proved that the amount of water that flowed out from the aggregate could be measured.

The triaxial shear strength test (used primarily for soils) was reviewed to develop time intervals for recording data. The triaxial test requires measurements of volume during the first minute of pressure application. The data collected during the first minute is used to calculate the primary consolidation time. There is nothing being consolidated during the backflow of water out after an IPI test, so the time interval of one minute was used to collect data.

During the initial procedure determination, aggregate was subjected to an IPI test cycle with an addition made during the SC stage of the test. After two minutes of the SC cylinder being pressurized, the vent valve was opened on the apparatus. This vented the pressurized system to the atmosphere and allowed the water that was pushed into the aggregate to start flowing into the SC graduated cylinder.

The IPI testing apparatus is preprogrammed to pneumatically open and close valves. To prevent interference with the Primary load and Secondary load readings the Recovery procedure needed to take place during the SC stage of testing. The recovery procedure started after two minutes of the SC stage and continued until the end of the SC stage. This placement in the test duration still allows for the Primary load to be taken at the first minute, the Secondary load to be taken at the fifteenth minute, the SC reading to be taken two minutes after the Secondary load, and recovery data collected from the SC reading until the fifteen minute of the SC stage (13 total minutes of recovery data). This is illustrated by the timeline in Figure 4.1.

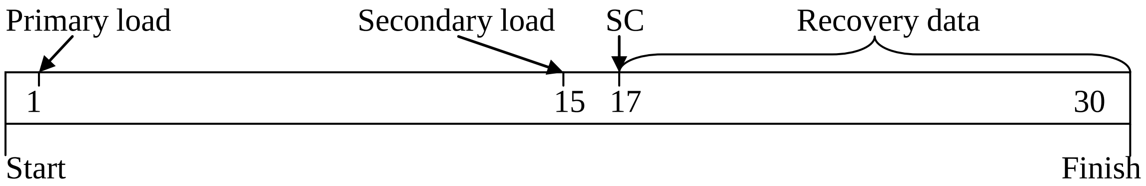

Figure 4.1. Time line of IPI test with the water Recovery

The amount of water recovered from the aggregate during the thirteen minutes of data collection did not equal the total amount of water pushed into the aggregate (Primary load plus Secondary load). When the IPI test is stopped by the control timer, the valves are all in the closed position. Once the “Stop” button is pressed the valves open and the system is vented to the atmosphere. By observing the water levels beyond the duration of the test and 13 minutes of recovery data, it was noted that water flow out of the aggregate was negligible after 15 minutes of being depressurized. Since it is a closed system, the remaining water is assumed to have stayed within the aggregate as “absorbed” water.

4.1.5. Re-pressurization. Since the observation was made that the water flowing out of the aggregate after being pressurized during the IPI test and a Recovery interval during the SC stage was negligible, it was determined that the re-pressurization of the aggregate could take place 2 minutes after the completion of the initial IPI test if the Recovery procedure was used (ie, Primary, Secondary, SC with Recovery equals 30 minutes). As a standard time to start the 2nd (re-pressurization) IPI an additional minute was used to fill the apparatus back to the starting levels. This was found to be sufficient time to drain the water to a point that the aggregate was still covered, take the temperature, and then refill the apparatus.

4.1.6. Temperature. The IPI test methods reviewed use cold tap water as the source to fill the chamber pot for the test. After a PE of 10 was found to be consistent in 2011, the question was raised as to why the PE in 2008 was around 15. One difference between the two tests times is the condition of the water. In order to determine if the temperature of the water could affect the PE to this degree, the temperature of the water was taken during the PE determination and during testing. During the present (2011) study the temperature of the water ranged from 12.8°C (55°F) to 23.4°C (74°F). The PE remained to be 10 for the duration of the testing. It should be noted that the PE and temperatures were recorded after the time to fill procedure was developed (ie.-not recorded in the 2008 study).

The components of the IPI apparatus with the largest volume are the chamber pot, and the three graduated cylinders. Neglecting the volume of water in the tubing, there is about 3100-ml of water in the IPI apparatus when a 4500-gram aggregate sample is in the chamber pot. The variation in the recorded temperatures is about 10°C. This change in temperature will change the volume of water by 6-ml.

The change in volume due to a 10° C change in temperature may be significant when a durable aggregate's Secondary load is under13-ml, but the temperature change was over the course of two months. The only time a 10°C decrease in temperature occurred in one day, was in February when four consecutive PE system compliance procedures was performed. The decrease in water temperature was due to the room temperature water that was initially in the pipes was replaced with cooler water from pipes that are under ground.

The temperature of the water was only recorded once for each specimen tested. This one recorded temperature per specimen does not allow for a water volumetric change, during the course of the IPI test, to be calculated. The highest degree of precision that can be read from the graduated cylinders is on the Secondary and SC cylinders. There are gradations for every one ml. With this precision of measurement, a one degree change in temperature could be detected. This one degree change in temperature would result in a change in volume around 0.5 ml, and for the data to be affected by the change in volume, the temperature would have to significantly change during the test duration.

4.1.7. Preliminary Testing. Prior to testing the 2011 and 2008 material, Jefferson City Dolomite from a local quarry was used in the procedure exploration /observation and in the preliminary testing. All the testing was performed with aggregate of the #4-⅜-inch size. This testing allowed for the standardized test procedure to be performed on material that was readily available without exhausting aggregate that had prior durability testing data. The seven replicate specimens of Jefferson City Dolomite were labeled numerically with a second number and a letter to indicate additional procedures performed on the same specimen. The first number is the specimen identification number and was assigned to the aggregate in the order of testing. The second number indicates the number of washed/oven dried and IPI tests that were performed on that specimen. An “r” was added to the second number to indicate data that was taken during a re-pressurization procedure. Below is an example of the labeling and procedures for the first specimen:

1-1	Specimen has been washed, oven dried, and an IPI test performed
1-2	After the specimen’s first IPI test, the specimen was washed, oven dried, and had a IPI test performed
1-2r	Immediately after the second IPI test was performed a re-pressurization procedure was performed on the specimen.

The results from the preliminary testing are shown in Table 4.1. Two specimens that should be noted are 2-1 and 3-1. The Secondary index of 2-1(28.0) is almost double what the other Secondary indices are for the other IPI tests. While 2-1 was in the Primary index stage it was noticed that the pressure was 25 psi, but the pressure was increased to 35-psi around the 30-sec mark into the test. It is unknown why there is such a profound difference even with the known difference in applied pressure. The specimen 3-1 has a lower Secondary index (11.7) than any of the other specimens (4-1, 5-1, 6-1and 7-1) of the same aggregate sample (11.7-17.0). This is thought to be due to a measuring error in the weight of the aggregate. After an IPI was performed on 3-1, the aggregate was washed, oven dried, and cooled. However, it weighed 1200-g higher than the specified amount. The aggregate sample was then split down to the specified 4500-g prior to performing 3-2 and 3-2r. Both specimens 1 and 2 did not have recovery data recorded and the re-pressurization procedure started immediately after the second IPI test was performed. Samples 3 through 7 had recovery data collected while only 3, 4, and 5 had a re-pressurization procedure performed 15 minutes after the second IPI test. Samples 6 and 7 did not have second IPI and re-pressurization procedures performed since there was a trend in the data from the previous five samples.

Table 4.1. Preliminary Test Data- Jefferson City Dolomite

	Primary	Secondary
1-1	56.0	14.0
1-2	54.0	15.0
1-2r	32.0	7.0
2-1	58.0	28.0*
2-2	68.0	15.0
2-2r	32.0	6.0
3-1	74.7	11.7*
3-2	72.0	15.0
3-2r	48.0	6.0
4-1	78.0	15.0
4-2	74.0	16.0
4-2r	48.0	6.0
5-1	74.0	14.0
5-2	74.0	18.0
5-2r	44.0	5.0
6-1	58.0	13.0
7-1	74.0	17.0

* Possible errors in testing

It should be noted that an outlier analysis for the preliminary testing data was not performed, since the purpose of the data was not for correlation to other tests or aggregate size, but for observation of the test procedure and for determination of further testing. Excluding specimen 2, it can be seen that when the IPI test was performed on the same specimen two times (eg. 3-1 to 3-2), the Secondary index increased from the first IPI test. Also seen is a decrease in the Primary index as the number of IPI tests increased. Although there is not a significant change in the IPI of the first test on a specimen to the second test on the same specimen, the overall trend suggests that performing the IPI test on an aggregate more than once can change the pore structure so that the same material may not be re-testable.

Samples 3 through 7 had recovery data collected during the SC stage of the IPI test. Figure 4.2 shows the relationship between the Primary index and the amount of water that was recovered from the aggregate. The data points represent specimens 3 through 7 and include the first IPI, second IPI, and the re-pressurized IPI. A good correlation coefficient R of 0.9645 is seen with the preliminary data.

Figure 4.3 shows the relationship between the Secondary index and the recovered water from the aggregate. The correlation coefficient R is good (0.9482), but not quite as high as the Primary index relationship with the Recovered. It was expected that the Secondary index would correlate better with the Recovered because the Secondary index is used to predict D-cracking and the Recovered was thought to be an indicator of an aggregates ability to expel water from within its pores (important to freeze/thaw durability). The water that remained in the aggregate would be in the micro pores (indicated by the Secondary index) due to the capillary forces action on the water.

Therefore, the Secondary index should correlate better with the amount of water retained by the aggregate and not the amount expelled.

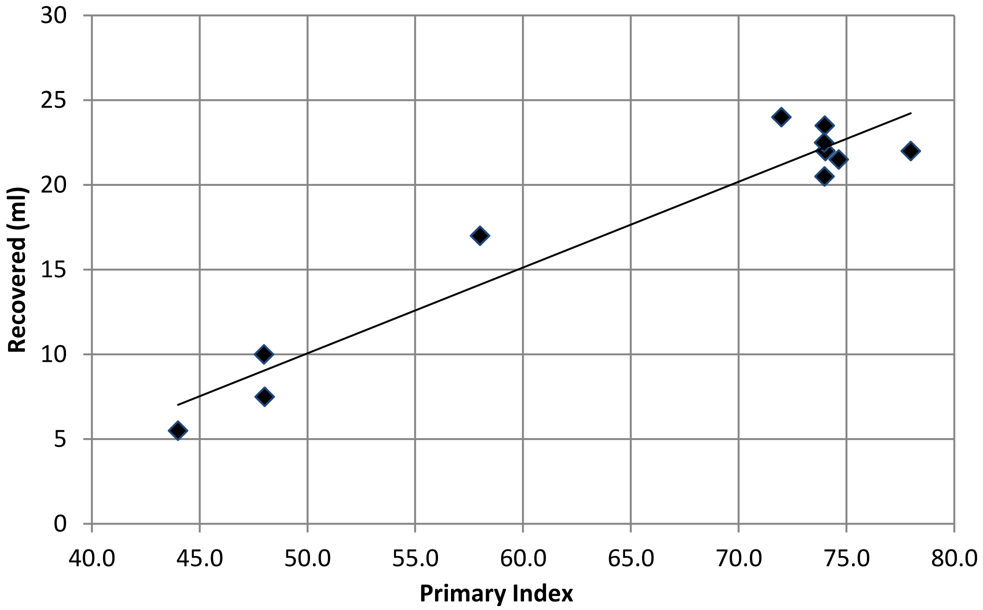

Figure 4.2. Pre Test: Correlation of Primary Index and Recovered Water

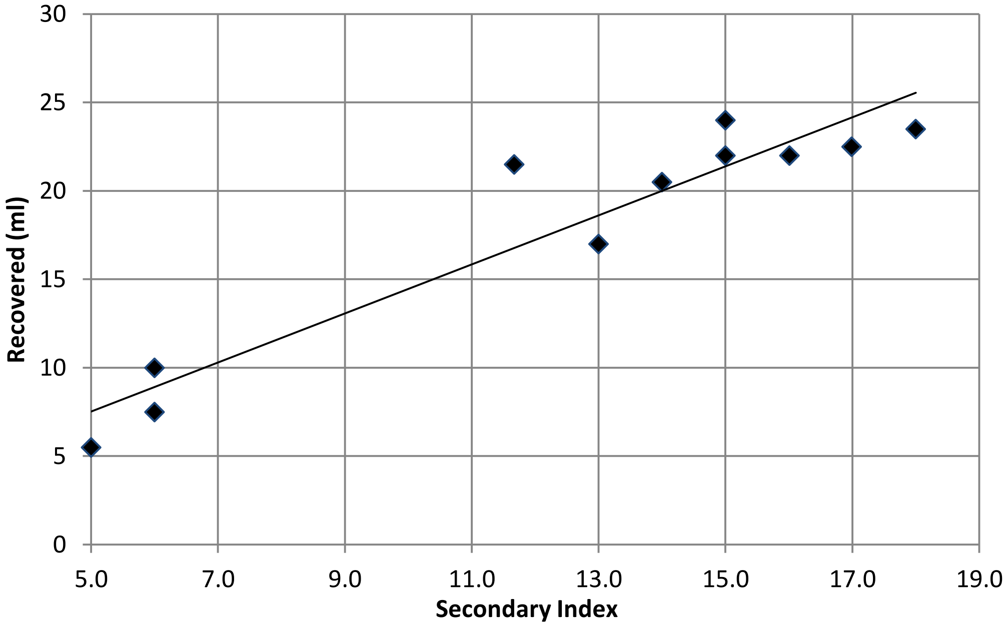

Figure 4.3. Pre Test: Correlation of Secondary Index and Recovered Water

Figure 4.4 shows the relationship between the total load and the recovered water from the aggregate. There is a good correlation coefficient R (0.8979); as expected the positive slope follows the Primary and Secondary index relationship to the recovered.

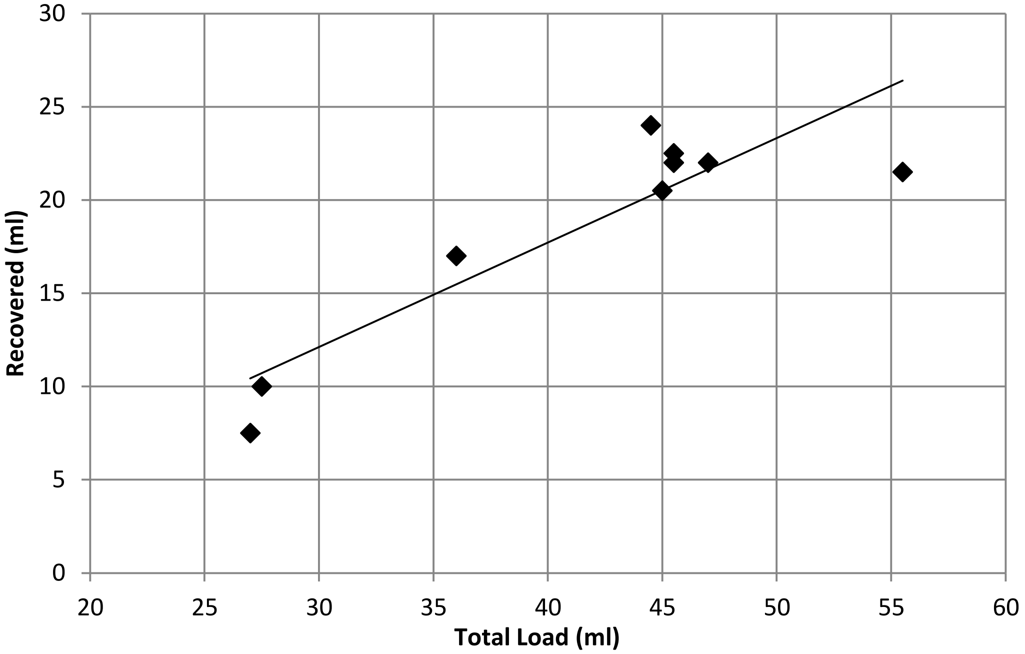

Figure 4.4. Pre Test: Correlation of Total Load and Recovered Water

Along with recovery, a re-pressurization procedure was performed during the preliminary testing. In order to determine the extent at which the re-pressurization affected the aggregates pore system, specimen number 5 had five re-pressurization procedures after the second IPI test.

Table 4.2 shows the data that was collected from specimen 5. Here it can be seen that the Primary load continued to decrease while the Secondary IPI stayed relatively the same after the first re-pressurization procedure. Although the amount of water that was pushed into the aggregate (Primary load) decreased overall each time the re-pressurization was performed, the aggregate only expelled around 5-ml of that water. Since prior preliminary testing showed that after 15 minutes of not being pressurized the amount of water expelled from the aggregate is negligible, it can be assumed that other than the recovered water, the rest stayed in the aggregate. At the end of the fifth re-pressurization a total of 152-ml of water was pushed into the aggregate and only 47.5-ml recovered. That means there was 104.5-ml of water left in the 4500.8-g sample of aggregate. This amount of water in the aggregate puts it at 76%; degree of saturation, even after 5 re-pressurizing procedures the aggregate is still not at a critical saturation level (91%) for freeze/thaw damage to occur. The continuation of the aggregate to accept water during the three hours of pressurization was not expected, but the aggregate has not fulfilled its absorption potential so the results are reasonable.

Table 4.2. Preliminary Re-pressurization of Sample

	Prim. load	Sec. load	Recovered
5-1	37	7	20.5
5-2	37	9	23.5
5-2r	22	2.5	5.5
5-2r2	20	2	5
5-2r3	19	1.5	4
5-2r4	18	2	4.5
5-2r5	17	2	5

An interesting observation is that the Primary load continued to be larger than the Secondary load throughout the five re-pressurization procedures. The Primary load is thought to be a measurement of the macro sized pores in the aggregate, ones that are beneficial to freeze/thaw durability. Even if all the recovered water from this specimen's series of re-pressurizations came from the macro sized pores, the Primary load indicates that more macro sized pores are being created due to pore structure damage: another 17-20 ml are pushed in, but only 4-5 come out each time. If this is the situation, the first two Primary loads (5-1 and 5-2) indicate that damage might not occurred until 5-2r (the third time the aggregate is pressurized).

In the literature, the Secondary IPI is what has been shown to relate better to durability and D-cracking from the IPI test. The recovered water data poses a possible new way to test the aggregate and provide data that can be related to the DF. The Secondary index and the recovered water seem to be of primary interest. There was not a significant change in the IPI or recovered water after the first re-pressurization.

4.2. MAIN STUDY TESTING RESULTS

The data for this study is evaluated using both a graphical analysis from a computer program generated correlation coefficient, and t-tests assuming equal and unequal variances. For the graphical analysis, data is plotted in an x-y format and a trend line is generated. The R correlation coefficient of the trend line is then used to determine how well the trend fits the data. The t-test is performed using Microsoft Excel with an alpha equal to 0.05 in order to produce a 95% probability that the two sets of numbers are different. Two t-tests were performed on the data: one assuming equal variances and one assuming unequal variances. The reported two tail “P” value should be less than the desired alpha in order for a significant difference in data to exist. In the event that P is greater than alpha, the assumption is made that the variable being tested did have an effect on the data with a 95% or greater probability.

4.2.1. Aggregate Size. Eighty-three IPI tests were performed in order to complete the data needed to analyze the influence of aggregate particle size on the IPI. In addition to the data from 2008, the remaining 2008 aggregate with sizes #4-⅜-inch were tested in this study. All of the data for the different sizes of the 2011 material were tested in 2011. The results are tabulated in Table 4.3.

After performing the t-test on the IPI size data, the #4-⅜-inch size particles produce a significantly different IPI than the ½-¾-inch sized particle. The results of the t-test are in Appendix C, and show that there is only an 85% probability of the ⅜-½-inch sized particles producing a different IPI than the ½-¾-inch. There is a 99.9% probability that #4-⅜-inch sized aggregate will produce a different IPI than ½-¾-inch particles and a 95.4% probability that it will be different than the ⅜-½-inch particles.

Figure 4.5 shows the size in inches versus the IPI of the aggregates. The decreasing IPI with decreased particle size was expected. This trend is due to the smaller aggregate particles having a smaller network of capillary sized pores. The smaller network of pores allows for a smaller volume of water to fill the pore spaces. This smaller volume is represented in the Secondary index. Although the general decreasing trend is visible, it is evident that the different aggregates have varying slopes

Table 4.3. IPI of Aggregates for Different Sizes

	Iowa Pore Index		
	#4-3/8	3/8-1/2	1/2-3/4
Bluff City	13.3	15.0	21.3
WNM	13.0	18.0	24.0
Amazonia	22.7	31.0	36.0
Weber	8.7	--	--
WNM 029	9.5	14.7	20.3
Central	28.7	39.7	--
Gable	--	12.0	13.7
Joplin	15.7	19.7	24.0
SEMO	12.0	13.3	14.0
HM	--	33.7	46.0
Capital	28.0	34.0	44.0
SU	4.0	6.0	12.0
Knox	16.0	25.7	33.3
NAP	27.0	39.0	43.3
Bussen	--	51.3	55.3
FH	5.7	5.5	11.3
WNM 020	8.3	14.0	22.0
Muenks	26.2	37.3	49.0
APAC	15.0	24.3	--
HM (11)	16.7	28.0	34.5
Capital (11)	9.3	12.7	18.2
Knox (11)	11.3	17.3	27.2
Bussen (11)	27.2	37.3	42.0
Bluff City (11)	8.3	12.2	11.4

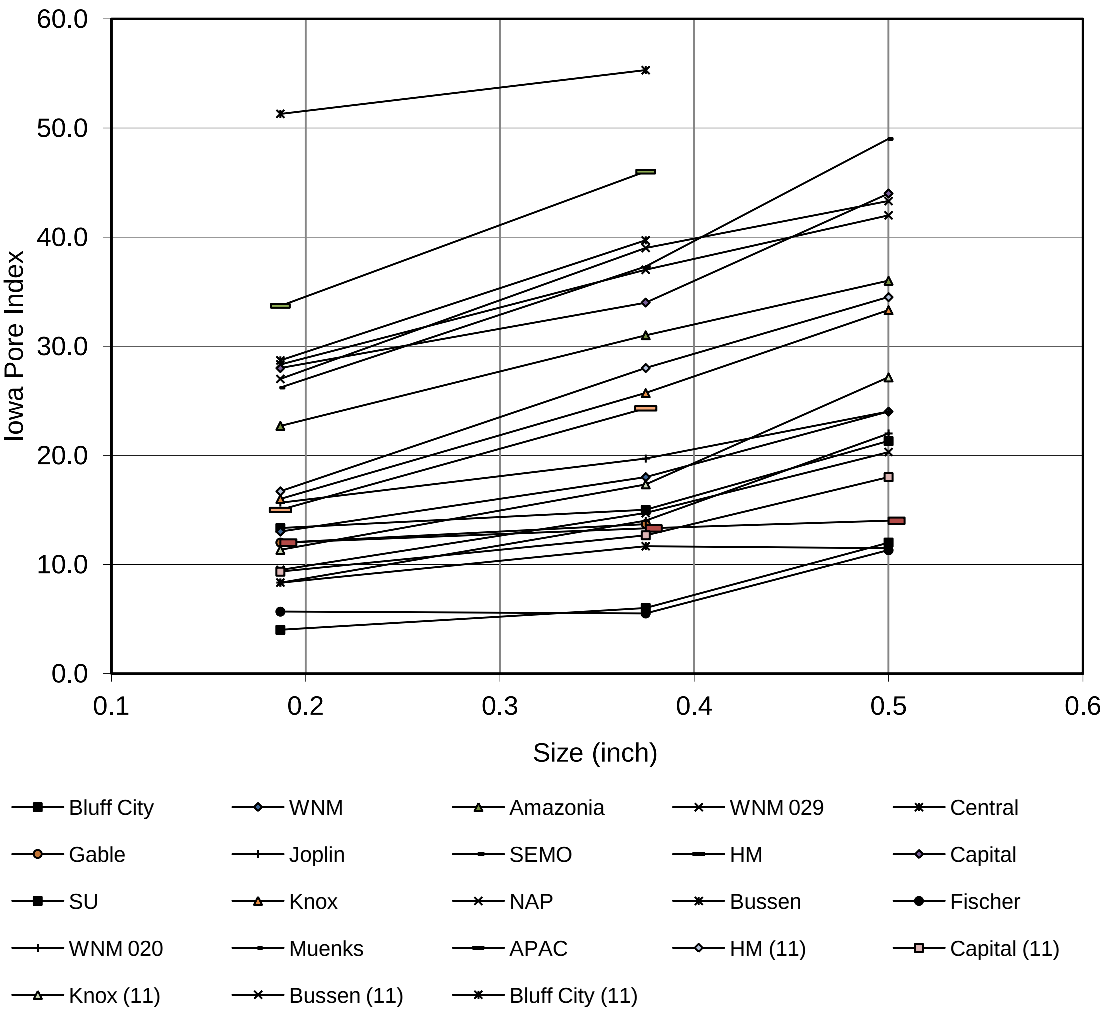

Figure 4.5. Particle Size vs. IPI

In order to determine the correlation between the IPI from the different sizes, the smaller two fractions were plotted against the standard ½-¾-inch fraction. The middle sized fraction is plotted against the standard in Figure 4.6 and has a good R correlation coefficient of 0.9737. Knowing that the IPI decreases with decreasing size, it was expected to see that the majority of the data points fall above the line of equality in this figure. A divergence of the trend line away from the line of equality is seen as the IPI gets larger.

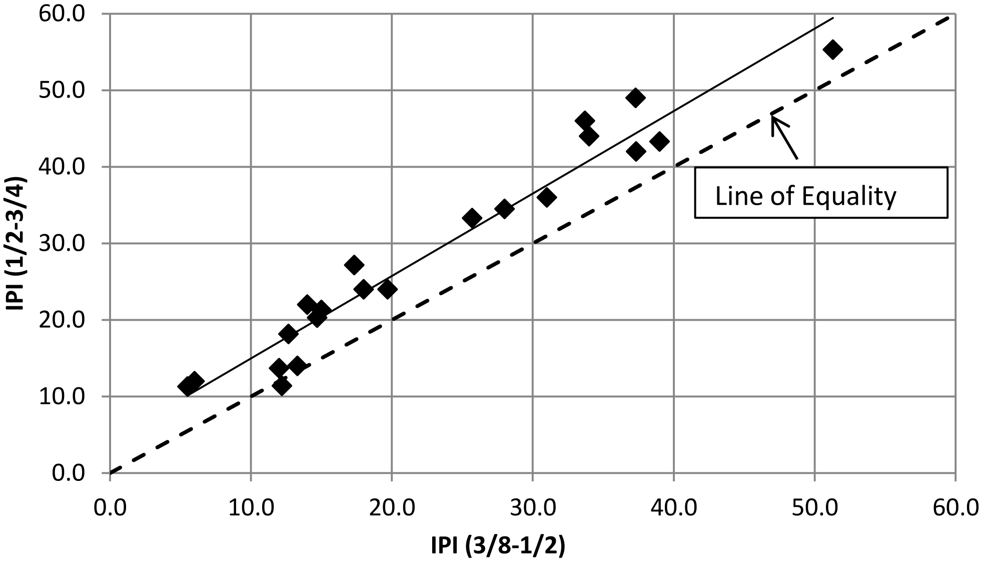

Figure 4.6. Correlation of IPI (⅜-½) and IPI (½-¾)

When the smallest size fraction is plotted against the ⅜-½-inch fraction in Figure 4.7, a good R correlation coefficient (0.9745) is achieved. Again the trend diverges away from the line of equality.

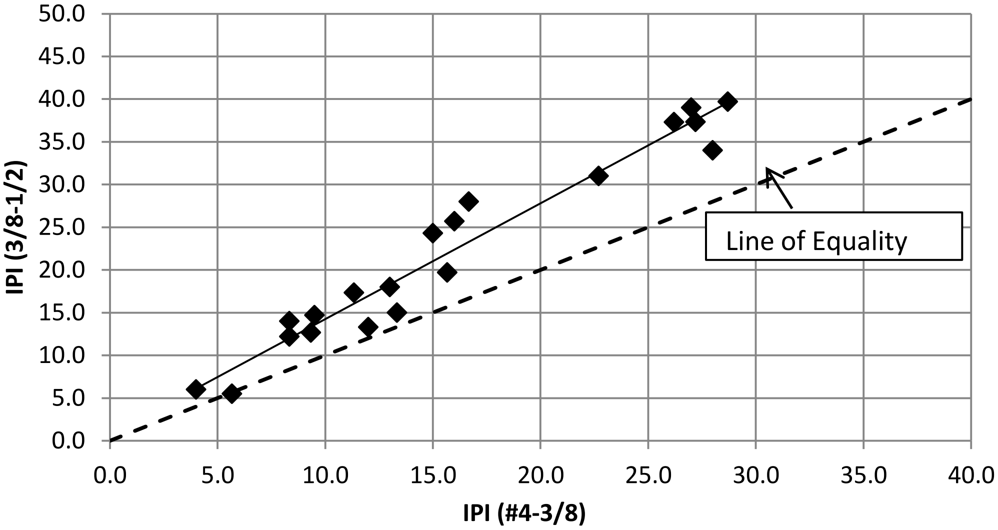

Figure 4.7. Correlation of IPI (#4-⅜) and IPI (⅜-½)

Figure 4.8 shows the relationship between the #4-⅜-inch and ½-¾-inch size fractions. A good correlation coefficient R (0.9400) is produced with this data. The trend of the data diverges away from the line of equality as the IPI increases. This divergence has increased in magnitude from Figures 4.6 and 4.7.

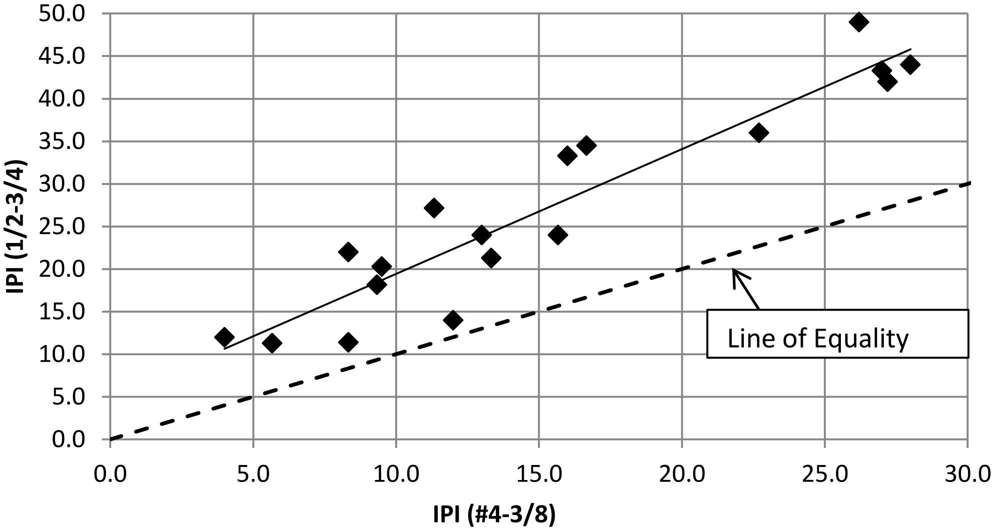

Figure 4.8. Correlation of IPI (#4-⅜) and IPI (½-¾)

In determining a size correction for the smaller two fractions of aggregate the equation of the software generated trend lines were used. Equation 1 is generated from the trend line in Figure 4. 8 and is to be used for correcting the #4-⅜-inch fraction to a ½-¾-inch IPI. Equation 2 is generated from Figure 4. 6 and is to be used for the correction of the ⅜-½-inch fraction. In order to evaluate the certainty of the trend lines generated by the software, the results of the t-test and the slopes of the lines were used to make sense of them. The probability that the #4-⅜-inch IPI is different than the ½-¾-inch IPI is 99.8%. This is higher than the probability of the ⅜-½-inch IPI differing from the ½-¾-

inch IPI of 85.0%. An increased probable difference in IPI would be indicated by the trend being farther away from the line of equality. This is evident in Figures 4.6 and 4.8, and can be seen in the equations. Equation 1 has a larger y-intercept and slope than Equation 2. This puts the generated line farther away from the line of equality and shows that there is a larger difference in indices for the #4-⅜-inch aggregate.

(1)

(2)

Using Equation 1 to calculate the estimated IPI, Figure 4.9 shows that the trend falls nearly on the line of equality. Although the equations provide a method to estimate the IPI at the ½-¾-inch size, the term “correction” will be used. Since the derived equation from the trend in Figure 4.8 was used, the overall R coefficient of correlation is the same as in Figure 8, 0.9400. A t-test analysis was performed to compare the corrected and actual IPI. Using Equation 1, the corrected IPI has a 99.9% probability that it will be the same as the actual IPI which is also indicated by the proximity of the trend line to the line of equality.

Figure 4.10 shows similar results as Figure 4.9. The trend of the corrected vs. the actual IPI also falls on the line of equality. A correlation coefficient R (0.9737) shows that there is a good relationship between the corrected and actual IPI. Using a t-test analysis, the corrected IPI has a 99.9% probability of being the same as the actual IPI using Equation 2.

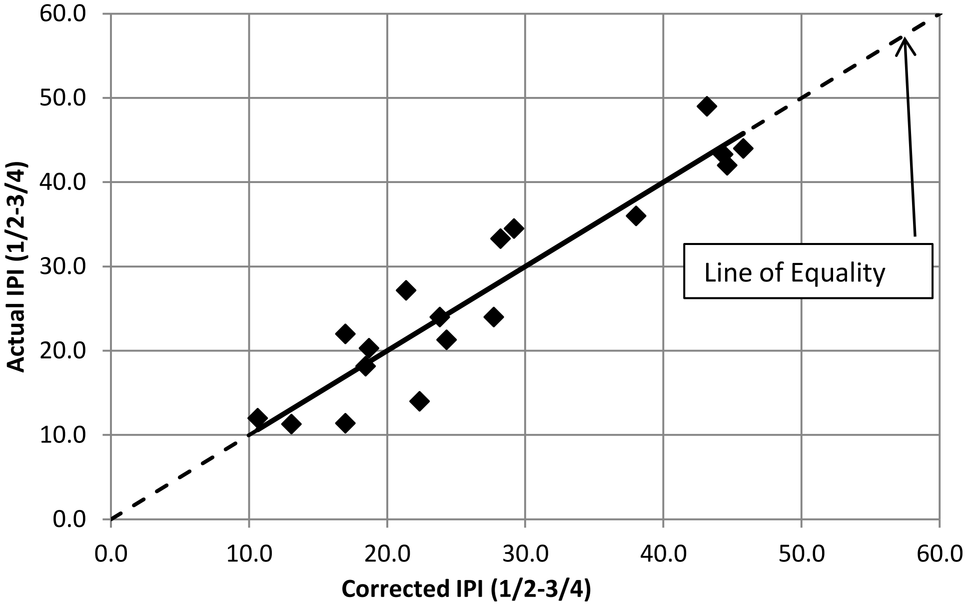

Figure 4.9. Correlation of Corrected IPI from #4-⅜ and Actual IPI

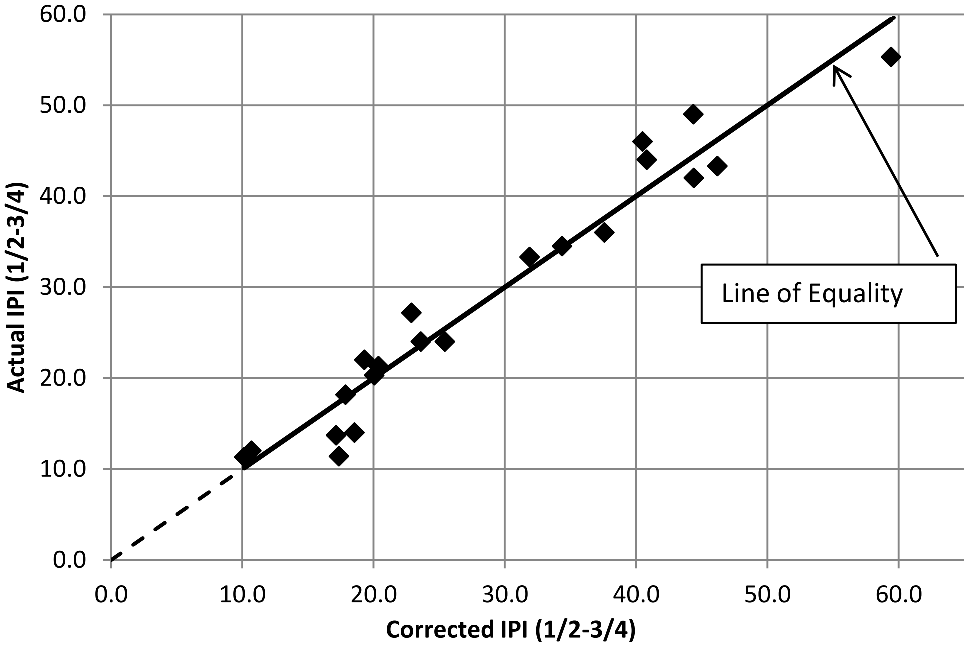

Figure 4.10. Correlation of Corrected IPI from ⅜-½ and Actual IPI

By using the equations presented above, one can correct an IPI that relates to an aggregate particle size different than the standard ½-¾-inch size. The data in this study suggests that an IPI correction from either the #4-⅜-inch size or the ⅜-½-inch particles size can be used with a high degree of confidence that it will represent that IPI of the standard particle size. By using the IPI of 27 as a limit to screen for D-cracking prone aggregate, only two of the 38 corrected IPI produced would have passed an aggregate with the actual IPI over 27. Both of the corrected IPIs from the Knox (11) aggregate were under 27, but the actual IPI as tested was 27.2.

The IPI is being looked at as a quick test for durability a even though there has been mixed results as to the relationship between the IPI and durability. The IPI has a poor correlation with the DF from ASTM C 666 (Richardson, 2009). Figure 4.11 shows the relationship between the IPI and the DF of 19 aggregate samples from 2008. The data includes two IPIs from specimens of the ⅜-½-inch size and one specimen of the #4-⅜-inch particle size. The smaller sized IPI was used because there was not enough material to test the ½-¾-inch size aggregate. Also included is the WNM 020 (NMS= 1.0-inch) aggregate IPI recorded from ½-¾-inch material. The trend in the data shows a poor correlation coefficient R (0.198). A vertical line has been inserted in the figure that represents the IPI threshold of 27 that is used as in aggregate acceptance.

Figure 4.12 shows the relationship between the IPI and DF with data points corrected for size. The three data points in Figure 4.12 that represent an IPI from aggregate of a smaller particle size than ½-¾- inch have been corrected using the appropriate correction equation. An R correlation coefficient of 0.211 is poor, but as a comparison against the non –corrected data in Figure 12 it is an improvement.

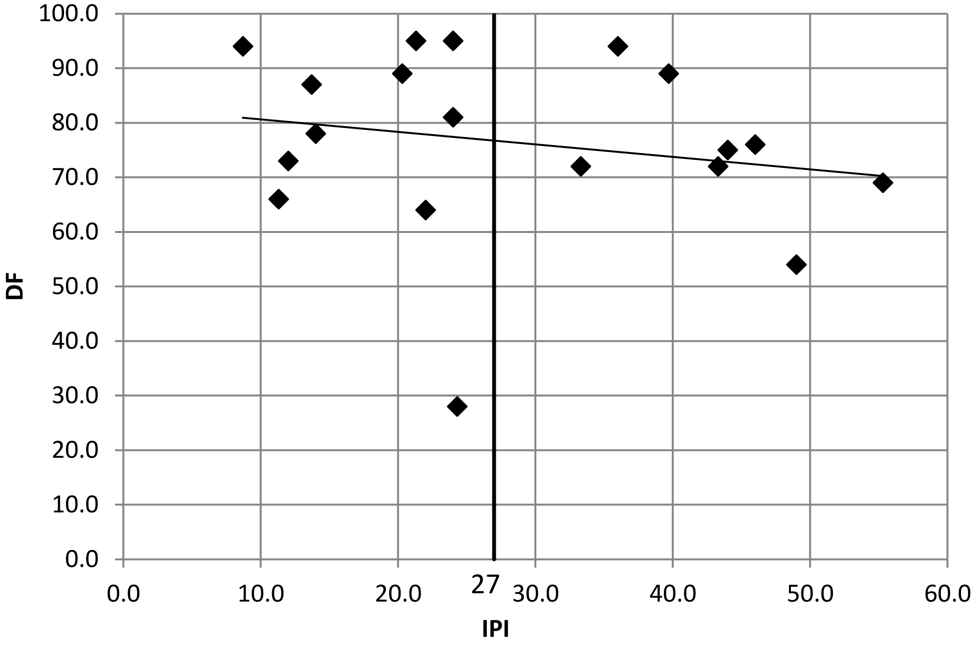

Figure 4.11. Non-Corrected 2008 IPI vs DF (mixed NMS)

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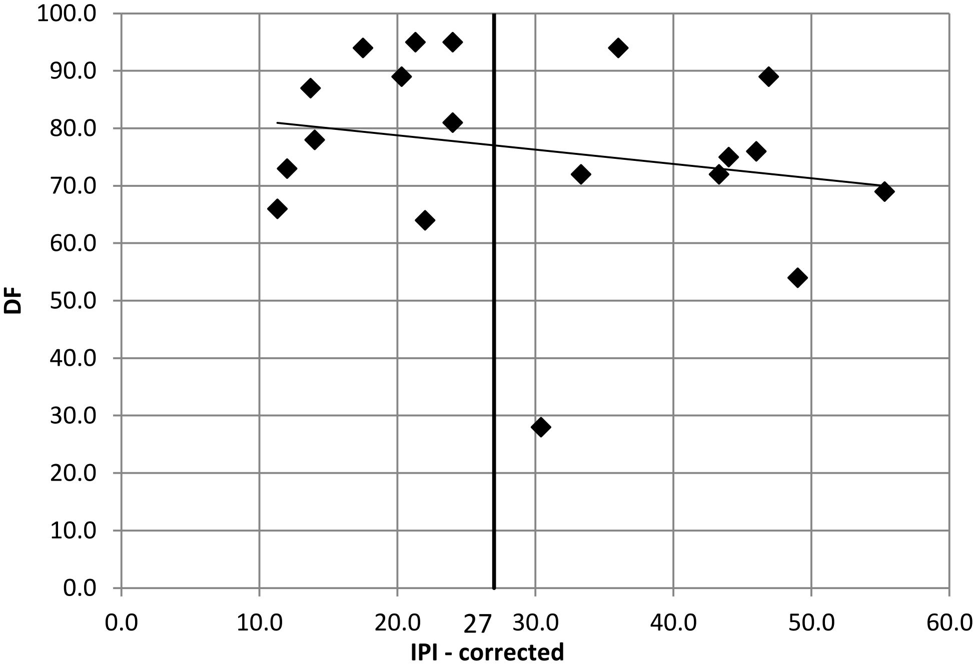

Figure 4.12. Corrected 2008 IPI vs DF (mixed NMS)

One important observation in Figures 4.11 and 4.12 is that the IPI of the APAC aggregate (DF=28) moved from a “passing” index of 24.3 to a “failing” index of 30.4 when corrected to the ½-¾-inch size. The APAC aggregate’s low DF may have contributed to the shift across the IPI threshold, but the IPI proximity to the threshold seems to be the primary reason for the cross over. As expected from the equations used in the correction, the corrected IPI increased in all three data points. Knowing that the correction of an IPI could change the aggregates acceptance rating is beneficial

The IPI from the particle size that matches the aggregate size used in the T161 DF is shown in Figure 4.13 against the DF. There are only 17 aggregates used in this relationship. One of the 19 aggregate samples had a NMS larger than ¾-inch and the other did not have enough material to test an IPI that matched the T161, and therefore was omitted from this comparison. The correlation coefficient R (0.252) is poor. This relationship was performed to determine if the matching size IPI produced a better correlation with the DF than the ½-¾-size IPI shown in Figure 4.11. With the samples tested, there was a slight improvement in the correlation coefficient of the matched size relationship.

The IPI data used in Figure 4.14 was corrected to the ½-¾-inch size and plotted against the DF. The Festus aggregate (omitted from Figure 4.13) was added because an IPI could be corrected to the ½-¾-inch IPI, allowing 18 data points to be plotted. Figure 4.14 shows this relationship to have a poor correlation coefficient R (0.302), an improvement over the non-corrected data. This is the best correlation coefficient obtained by the size correction analysis.

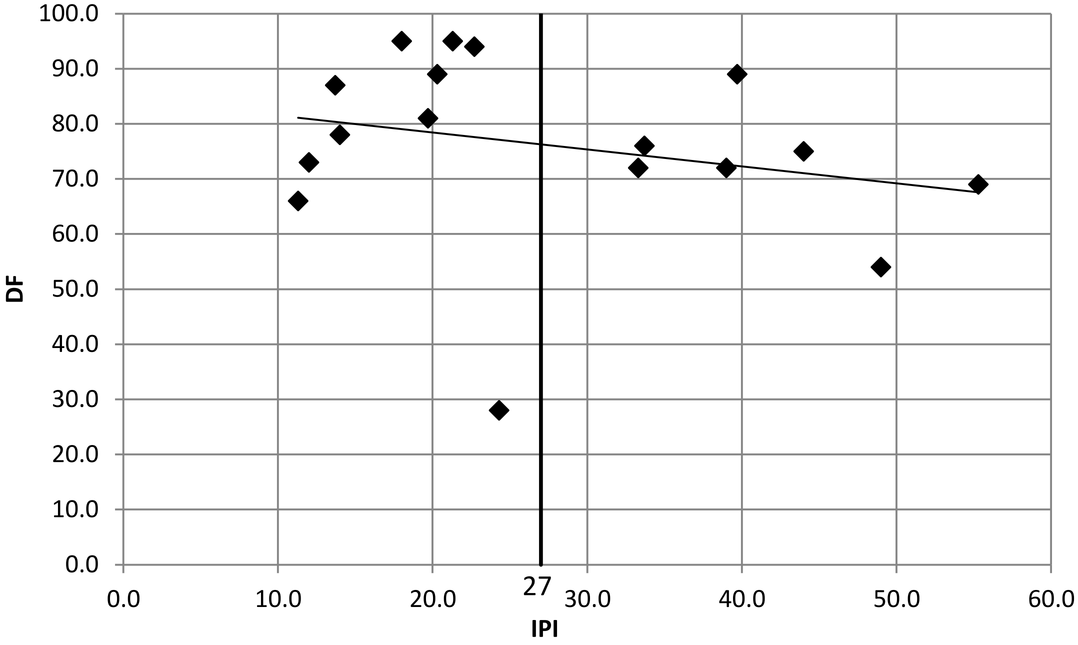

Figure 4.13. Non-Corrected T161 size IPI vs DF (Matched size)

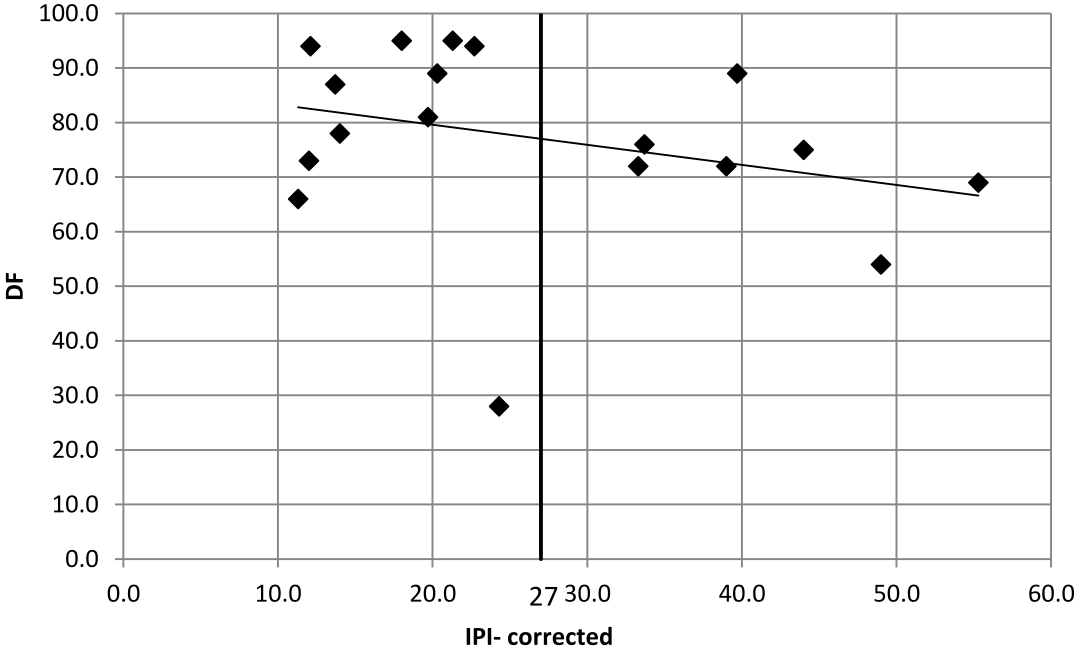

Figure 4.14. Corrected T161 size IPI vs DF (Matched size)

The WMN 020 IPI and DF were left out of the following relationships in order to compare non-corrected and corrected with only data from aggregate samples with a NMS less than ¾-inch. Only using data from aggregates that are under ¾-inch NMS should give a truer size correction comparison. Figure 4.15 shows the relationship between the non-corrected IPI of the 2008 material. The data plotted is the same as in Figure 4.11 but without the WNM 020. A poor correlation coefficient R (0.222) was produced by the relationship. This correlation coefficient is an improvement over the coefficient from Figure 4.11, when the WNM 020 was included.

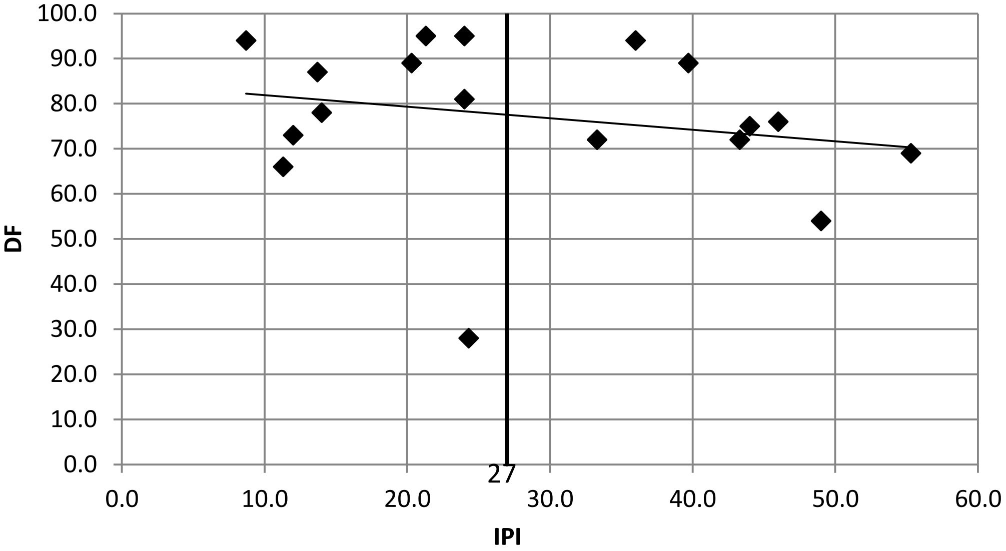

Figure 4.15. Non-Corrected IPI vs DF (NMS less than ¾-inch)

Figure 4.16 shows the corrected IPI and DF relationship without the WNM 020. A poor correlation coefficient R (0.242) is produced by this data trend. The increase in correlation coefficients, from 0.222 to 0.242, shows that the correction of an IPI to the ½-¾-inch size improves the IPI and DF correlation.

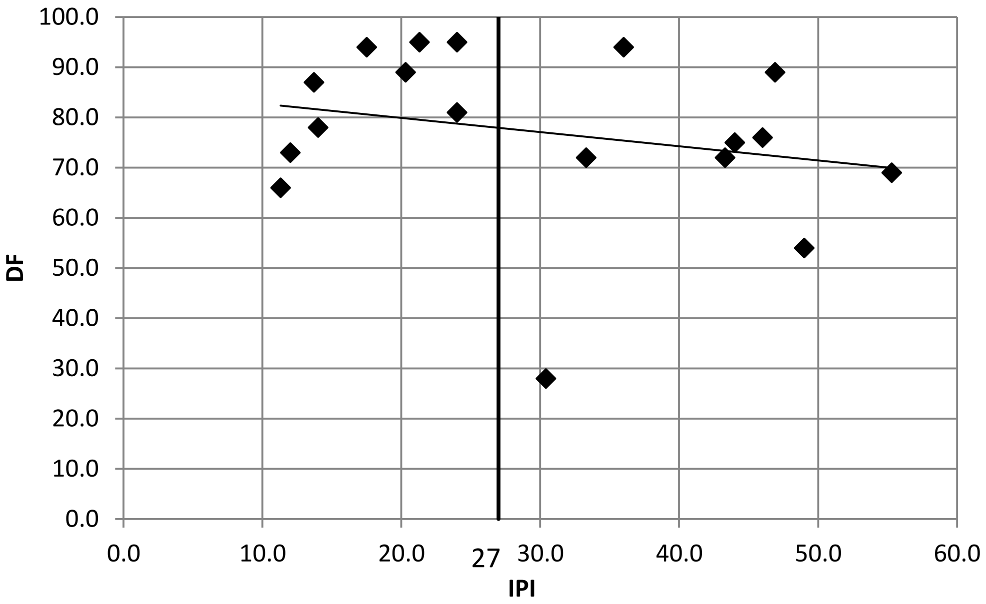

Figure 4.16. Corrected IPI vs DF (NMS less than ¾-inch)

The ability to accurately correct the IPI of a small sized aggregate to the standard size is easy and beneficial in screening aggregates for acceptance.

4.2.2. Repeated Oven Drying. All five of the 2011 aggregates were tested with the repeated oven drying procedure prior to performing the IPI test which also includes an oven drying step. The specimens were labeled with an “OD2” to indicate it had been oven dried two times. The quantity of aggregate did not allow for three replicate specimens to be performed on all five aggregate samples. There was an equipment malfunction that compromised some of the data collected for the Knox (11) aggregate so the data was not included in the analysis. Table 4.4 shows the number of replicated specimens tested for each aggregate sample and fraction size. The average of the replicates the IPI-OD2 reported. The t-tests show that there is only a 20% probability that the repeated oven drying had an effect on the IPI of the aggregate.

Table 4.4. Number of replicate specimens for repeated oven dry

	#4-⅜	⅜-½	½-¾
CQ Calif(11)	0	2	4
Knox(11)	**	**	3
Bluff City(11)	3	1	3
Bussen(11)	3	3	0
HM(11)	2	2	2

Figure 4.17 shows the relationship between the IPI of the OD2 material and the IPI of aggregate from the same quarry and ledge. The 11 data points represent all three fraction sizes of aggregate. The trend line produced has a good correlation coefficient R (0.9816) and is close to the line of equality. It is seen by the slight divergence of the trend from the line of equality that as the aggregates pore structure (as indirectly measured by the IPI) gets worse, the repeated oven drying has a somewhat greater affect.

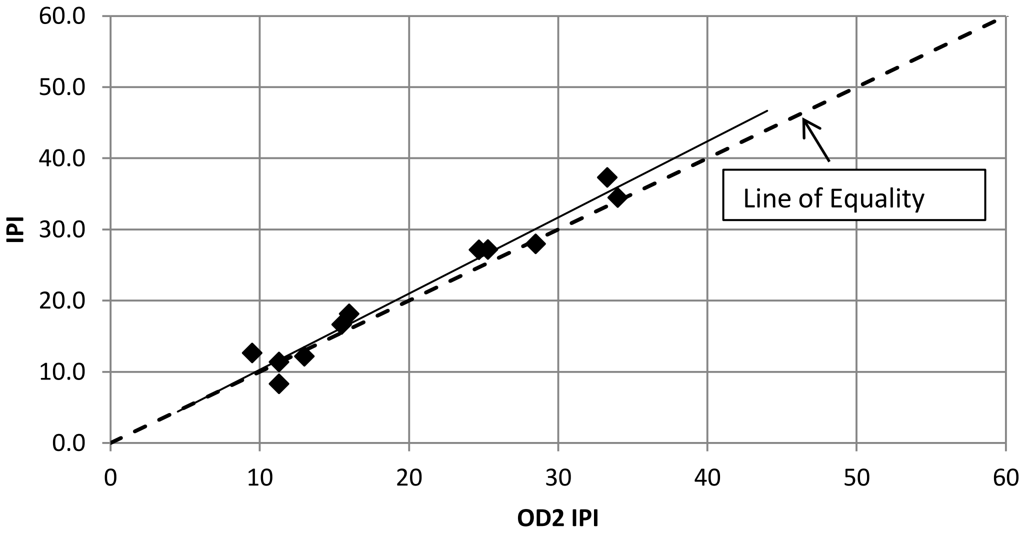

Figure 4.17. Correlation of Repeated Oven Dry IPI and IPI

However, since the probability of the oven drying having an effect on the IPI is only 20% and the trend line that represents the data has a good correlation coefficient R(0.9636), the data suggests that this testing variable is not significant. Thus, a second drying preparation (for the aggregates tested) does not affect the pore structure, or the effects are negligible for the IPI test.

4.2.3. Re-pressurization. The re-pressurization procedure was performed on the #4-⅜-inch 2008 material along with all of the available sizes of the 2011 material. The IPI obtained by the re-pressurization procedure is denoted as "IPIr" for the duration of the study. The data is presented in Table 4.5 and it can be seen that with the exception of the Joplin aggregate, the IPIr is significantly lower than the IPI, and is quite small (average =2.7). The results of the t-test confirm this with a 99.9% probability that the IPI will be affected by the re-pressurization process. These results were expected, since in the preliminary testing it was seen that after one IPI test, water remained in the pores of the aggregate. The lower IPIr is due to the fact that the capillary pore did not expel all of the water that was pushed into them therefore it cannot take in the same amount of water as the initial IPI test.

The IPI is affected by the re-pressurization procedure to only a small degree; this is shown by a poor correlation coefficient R (0.1034) is produced in Figure 4.18 when trying to correlate the data. The scattered data is expected, since different aggregates have different pore properties. Therefore the amount of water left in the aggregate would be different for each. This analysis shows that one re-pressurization by itself does not seem to disrupt the aggregate pore system. The results follow a similar trend as the re-pressurization data from the preliminary testing. One difference is that the Jefferson City dolomite from the preliminary testing had on average a re-pressurized IPI of six. This average is higher than the re-pressurized IPI average of the 2011 material tested. A possible reason for the difference is that the re-pressurization procedure on the Jefferson City dolomite followed a second IPI test whereas the re-pressurization of the 2011 material followed only one IPI test. Another reason for this difference could be that the re-pressurized IPI for the Jefferson City dolomite is specific to its geological make-up, similar to the results of Joplin (11) aggregate.

Table 4.5. Re-pressurized IPI

	IPI			IPIr		
	#4-⅜	⅜-½	½-¾	#4-⅜	⅜-½	½-¾
Bluff	13.3	--	--	3.3	--	--
WNM 029	9.5	--	--	1.0	--	--
Joplin	15.7	--	--	10.7	--	--
SEMO	12.0	--	--	2.0	--	--
CQ-Calif	28.0	--	--	4.7	--	--
Sp Und	4.0	--	--	2.0	--	--
Knox	16.0	--	--	4.0	--	--
F-H	5.7	--	--	2.0	--	--
WNM 020	8.3	--	--	2.3	--	--
Muenks	26.2	--	--	4.0	--	--
HM (11)	16.7	28.0	34.5	--	--	2.0
Capital (11)	9.3	12.7	18.2	3.0	3.3	4.0
Knox (11)	11.3	17.3	27.2	3.7	1.7	2.0
Bussen (11)	27.2	37.3	42.0	2.0	2.3	4.0
Bluff City (11)	8.3	12.2	11.4	--	1.3	2.0

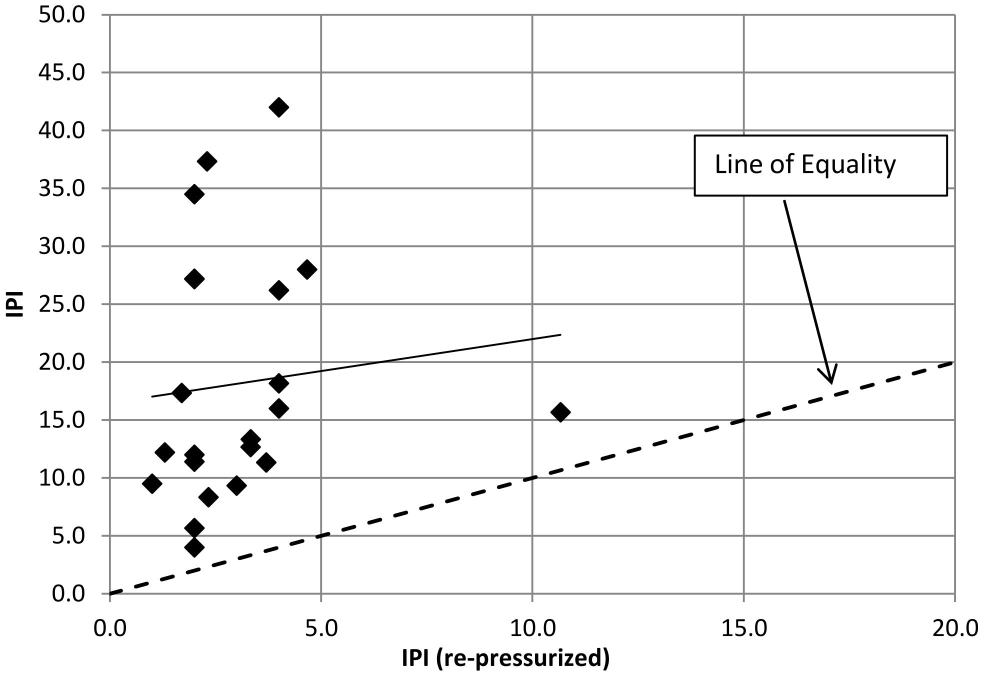

Figure 4.18. Correlation of IPIr and IPI

4.2.4. Recovery. The recovery data was collected on all three sizes of the 2011 material and the #4-⅜-inch size of the 2008 in addition to the #4-⅜ different sizes of the 2008 material were tested that related to the size of aggregate that was used to obtain the Durability Factor during the T161 test. It is noted that the “recovery volume” is total recovered minus the PE, thus, an indicator of elastic recovery of the aggregate. At first the recovery data was recorded on the 2011 aggregate and the #4-⅜-inch 2008 aggregate while collecting indices for the size correction research.

The Jefferson City Dolomite used in the preliminary testing showed that the recovered water correlated well with both the IPI and Primary index. It was expected that the use of multiple aggregates would not correlate as well as a single aggregate due to geological differences varying the data produced. The recovered water was plotted against the IPI in Figure 4.19 and only includes the 2011 and #4-⅜-inch 2008 aggregate data. As this figure shows there is not a strong relationship between the recovered water and the IPI. A poor correlation coefficient R of 0.2145 is produced with the trend line below.

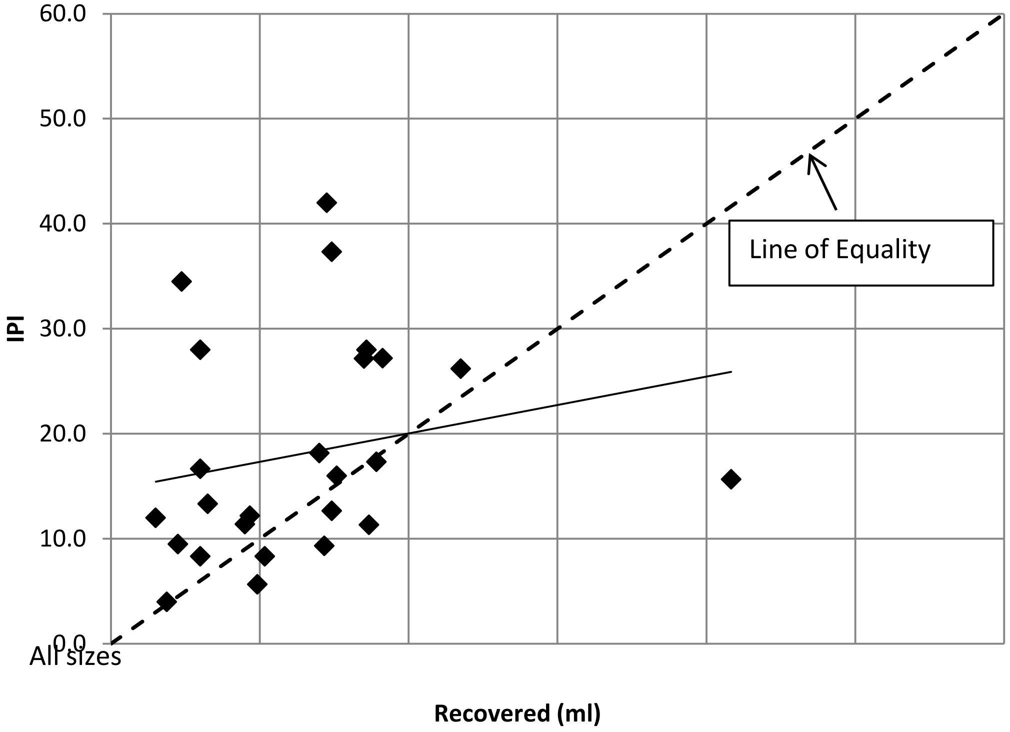

Figure 4.19. Correlation of Recovered and IPI

A future investigation of the potential of the Recovery procedure and data, the IPI with Recovery should be performed on the 2008 material. This would allow the data to be compared to the Durability Factor. The Durability Factor of the different aggregates was obtained with different nominal maximum sizes of the aggregate. In an attempt to find a better relationship between the Durability Factor and the IPI and/or the Recovered water, the IPI with Recovery procedure was performed with aggregate specimens of the same sized particles that were used in the ASTM C 666 test to calculate a DF.

The data collected during the Recovery procedure allowed for the water recovered, water retained within the aggregate, degree of saturation at different points throughout the test, and the percent of recovered and retained to be analyzed. The calculation for the water recovered from the aggregate is shown in Appendix A, while the retained water is just the total load minus the recovered. The degree of saturation was calculated using both of the absorptions from AASHTO T 85 and a Vacuum Saturated procedure. The percent of Recovered (%Rec) and percent Retained (%Ret) was calculated similarly to that of the absorption, in that the recovered or retained water was divided by the oven dry weight of the aggregate. The results of the recovery and calculated values are shown in Table 4.6. Values labeled with a "T85" were found with the absorption from the T85 method while "V.Abs" refers to the absorption from the Vacuum Saturated method. There are multiple degrees of saturation (°Sat) that were calculated, both prior to the recovery procedure and after the recovery procedure. The degree of saturation that corresponds to the water state prior to the recovery is labeled with an "IPI" at the end to indicate that it is the degree of saturation at the end of the IPI test. The "Rec" at the end of the degree of saturation refers to the degree at the end of the recovery procedure.

Table 4.6. Recovery Data

Formation	Bluff City	WNM2-4	Amaz	Joplin	SEMO	HM	Capital	SU	Knox	F-H	Muenks	APAC
C 666 size	½-¾	⅜-½	#4-⅜	⅜-½	½-¾	⅜-½	½-¾	½-¾	½-¾	½-¾	½-¾	⅜-½
IPI 2nd	15.7	16.0	26.7	17.1	14.7	32.5	34.7	8.0	35.0	11.7	45.7	23.7
Primary	25.3	23.3	36.7	112.8	12.7	30.0	54.7	15.3	59.3	28.0	78.7	56.7
Recovered (ml)	6.3	2.8	6.0	32.3	0.8	3.5	14.7	3.2	12.5	6.7	21.2	10.5
Retained (ml)	14.2	16.8	25.7	32.3	12.8	28.0	30.3	8.5	34.7	13.2	41.3	29.7
Total Load (ml)	20.5	19.7	31.7	64.5	13.7	31.5	45.0	11.7	47.2	20.0	62.5	40.2
Agg Wt. Avg. (g)	4499.8	4501.1	4500.5	4471.9	4500.4	4500.9	4501.9	4501.2	4500.0	4501.1	4501.4	4501.0
T85(%)	0.8	1.2	1.9	0.8	1.1	1.5	1.7	0.8	2.6	1.2	3.0	2.7
Vac Abs(%)	1.2	1.4	2.2	1.4	0.9	1.9	2.5	0.9	3.0	1.8	3.4	2.9
DF	95.0	95.0	94.0	81.0	78.0	76.0	75.0	73.0	72.0	66.0	54.0	28.0
°Sat IPI-T85	56.9	36.4	37.0	180.3	27.6	46.7	58.8	32.4	40.3	37.0	46.3	33.1
°Sat IPI-V.Abs	38.3	31.2	32.6	103.0	33.0	37.0	40.1	30.5	35.3	25.4	40.5	30.8
°Sat Rec-T85	39.4	31.2	30.0	90.1	25.9	41.5	39.6	23.6	29.6	24.4	30.6	24.4
°Sat Rec-V.Abs	26.5	26.7	26.4	51.5	31.0	32.9	27.1	22.2	25.9	16.7	26.8	22.7
%Rec.	0.1	0.1	0.1	0.7	0.0	0.1	0.3	0.1	0.3	0.1	0.5	0.2
%Ret.	0.31	0.37	0.57	0.72	0.29	0.62	0.67	0.19	0.77	0.29	0.92	0.66
Rec. after 1 min	5.0	1.8	4.2	21.8	0.8	2.5	11.7	2.0	9.8	5.7	17.8	8.7
Ret. after 1 min	15.5	17.9	27.5	42.8	12.8	29.0	33.3	9.7	37.3	14.3	44.7	31.5
% Ret after 1 min	0.34	0.40	0.61	0.96	0.29	0.64	0.74	0.21	0.83	0.32	0.99	0.70

The measurement of the recovered water allows for the amount of water retained in the aggregate to be calculated. Physically the amount retained is similar to the amount of water in an aggregate when an absorption test is performed. Thus, the % Retained should correlate well with the T85 and vacuum saturated absorption values. Figure 4.20 shows the relationship between the % Retained and the T85 absorption. A fairly good correlation coefficient R (0.7543) is produced when the data is compared.

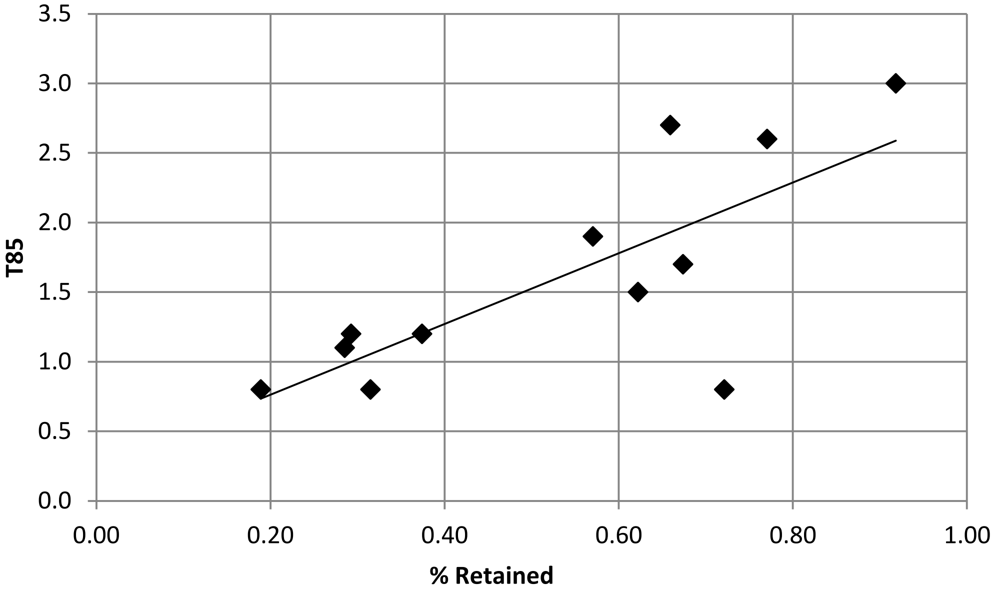

Figure 4.20. % Retained vs. T85 absorption

The % Retained is plotted against the vacuum saturated absorption values for the aggregate samples in Figure 4.21. The correlation coefficient R (0.8456) is good and better than the correlation coefficient from the T85 comparison. Both the vacuum saturated absorption and the % Retained use change in pressure to increase the amount of water that the aggregate absorbs in a given time so the better correlation between the vacuum saturated and % Retained was expected.

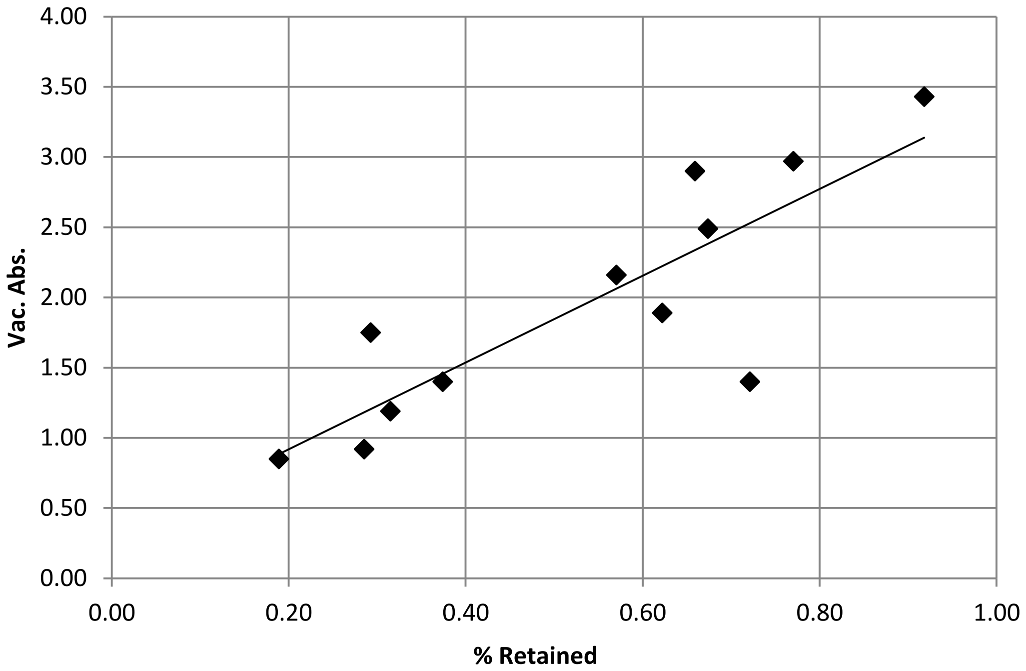

Figure 4.21.   %Retained vs. Vacuum Sat. absorption

Upon plotting the different values that were obtained from the Recovery data against the Durability Factor, only poor to zero correlations were found. Figure 4.22 shows the best correlation with the DF that was found and it is for the % Retained. A poor correlation coefficient R (0.3767) was found for this data. Although the correlation is poor, the correlation is slightly better than the DF vs IPI correlation coefficient R (0.125) Richardson found in his study (Richardson, 2009) and better than the correlation coefficient R (0.242) from the corrected IPI and DF found using the data for the 2008 aggregate. The % Retained being the best correlation to the DF is expected because it is a measure of absorption and Richardson found that out of 16 test methods, the absorption had the second highest correlation with the Durability Factor (Richardson, 2009).

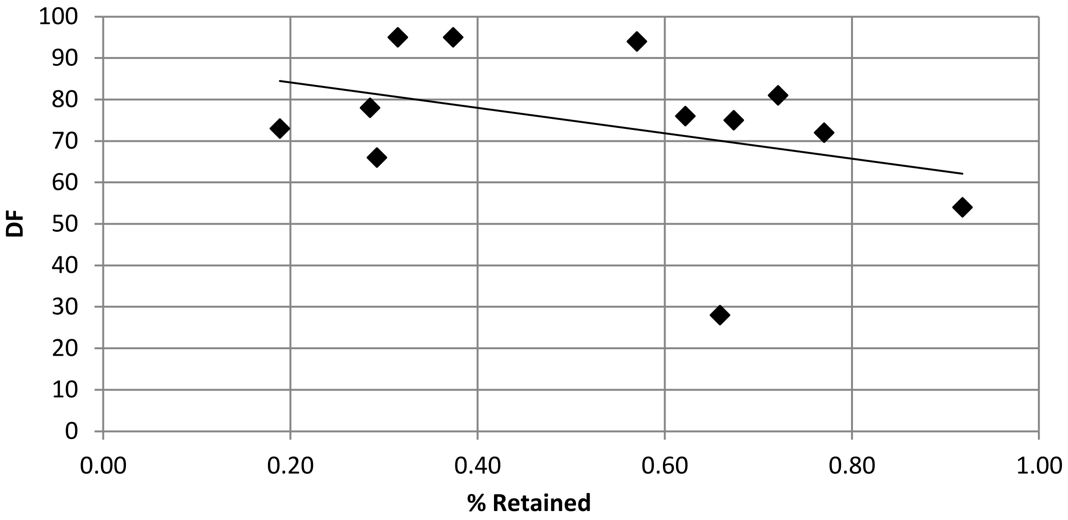

Figure 4.22. Correlation of % Retained and Durability Factor

The second highest correlation with was the %Ret after 1 minute of recovery which can be seen in Figure 4.23. The correlation coefficient R (0.3256) is poor but as previously stated, due to it being a measurement of absorption, its correlation is expected to be one of the highest.

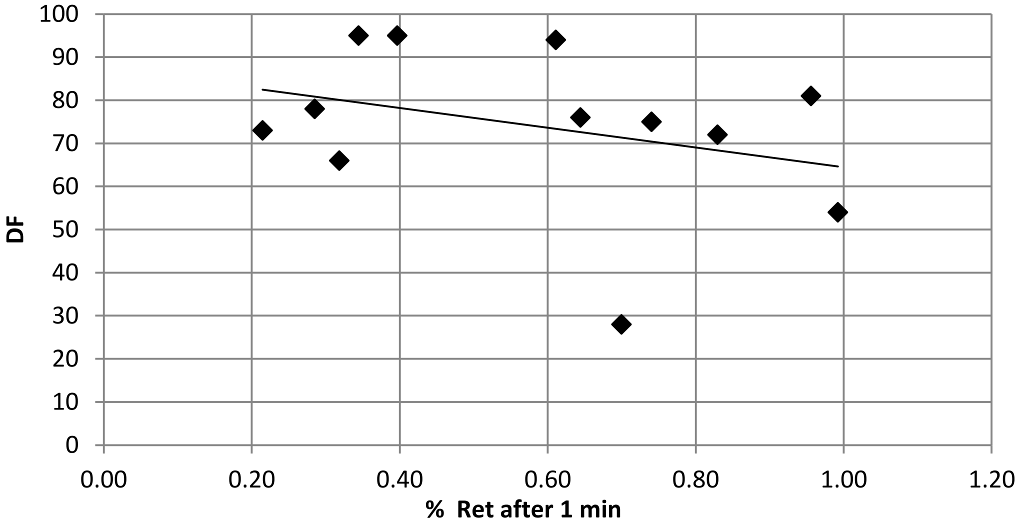

Figure 4.23. Correlation of % Ret. after 1 min. and Durability Factor

One observation about the % Retained relationship with the Durability Factor is that the % Ret at the end of the procedure had a better relationship to the Durability Factor than the % Ret after 1 min. of the recovery procedure. This comes as an unexpected trend since the degree of saturation is less at the end of the procedure. If the trend followed the theory of a critically saturated aggregate having freeze/thaw durability problems, then it would make sense for the data to correlate better with the Durability Factor as the degree of saturation became closer to the critical level.

Figure 4.24 shows that the IPI from the aggregate tested has a poor relationship to the Durability Factor. The correlation coefficient R (0.2812) is expected for this relationship since in the size correction analysis it showed that the correlation between IPI and Durability Factor decreases as the size of aggregate tested decreased. This data is from aggregate sizes that correspond to the size used in the Durability Factor test, therefore all three size fractions are represented.

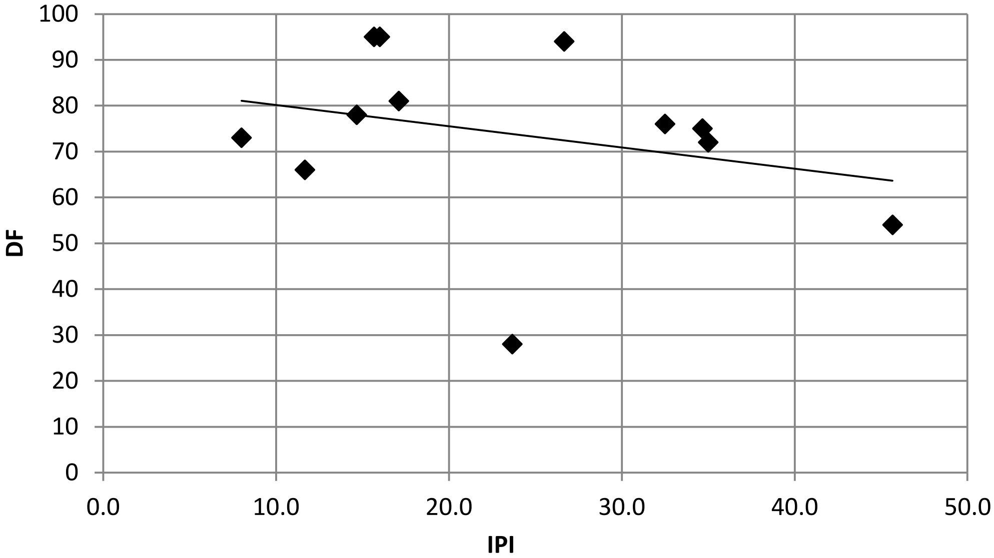

Figure 4.24.   Correlation of IPI (Recovery) and Durability Factor

Since the recovery data did not produce a good correlation with the Durability Factor, it was evaluated against the IPI and Primary index in order to determine the potential of the recovery data and what it might be representing. Figure 4.25 shows the relationship between the recovered water and the Primary index from the IPI test. A good correlation coefficient R (0.9784) suggests that the recovered water is almost directly related to the Primary index. This correlation is expected since the Primary index comes from the Primary load which represents macro sized pores. These pores in the aggregate would be too large for capillary forces to retain the water. The increasing trend is also expected due to the increased amount of water taken in by the macro pores which means there is more to “push” out once de-pressurized.

Figure 4.26 shows the relationship between the retained water and the Primary Index. A fairly good correlation coefficient R (0.7983) is produced from this data and the increasing trend is expected since not the entire Primary load is recovered from the aggregate.

Figure 4.27 shows the relationship between the % Retained and the Primary Index. A good correlation coefficient R (0.8013) is seen and as with Figure 21, the increasing trend is expected.

Figure 4.28 shows the relationship between the % Ret after 1 minute of de-pressurization and the Primary Index. A good correlation coefficient R (0.8972) is produced by the trend of the data in the figure. This correlation is expected because Primary load is a measurement of the macro pores and thus should be able to be expelled out of the aggregate with greater ease than the Secondary load.

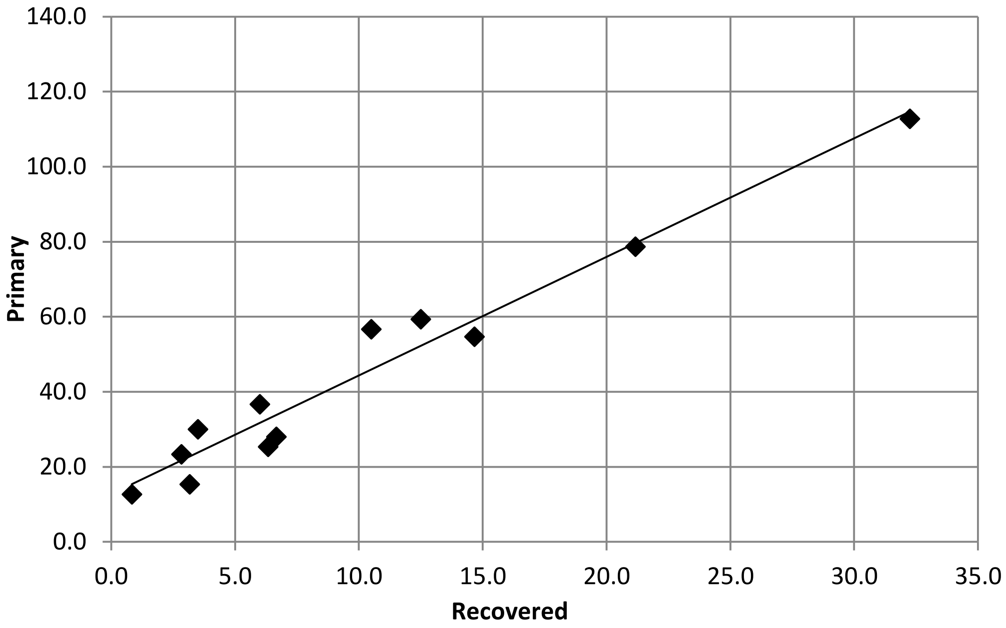

Figure 4.25. Correlation of Recovered and Primary Index

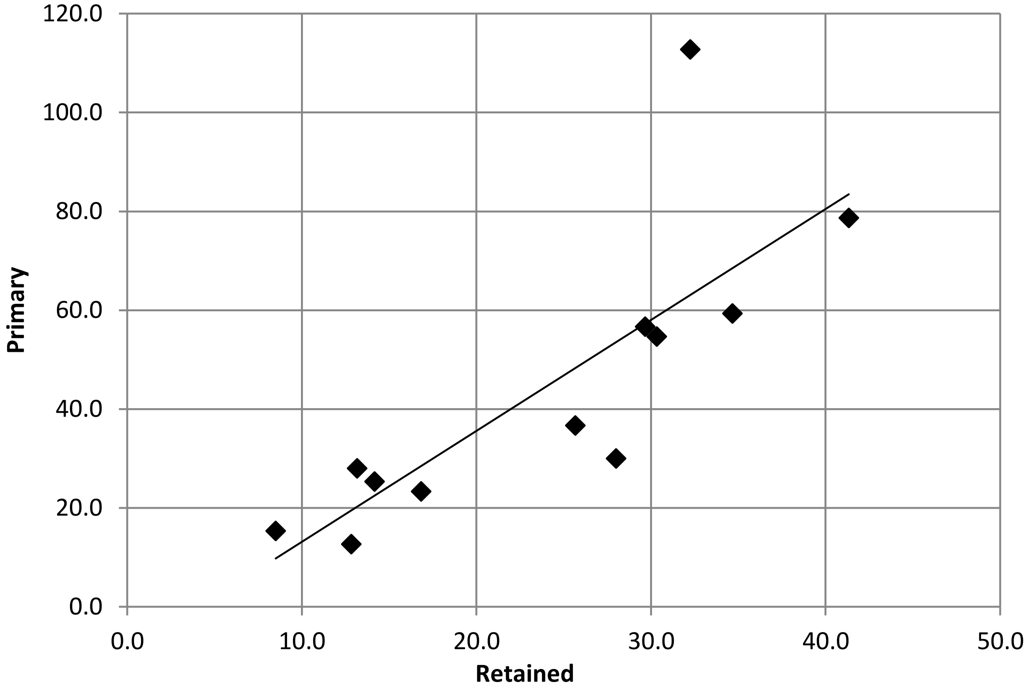

Figure 4.26. Correlation of Retained and Primary Index

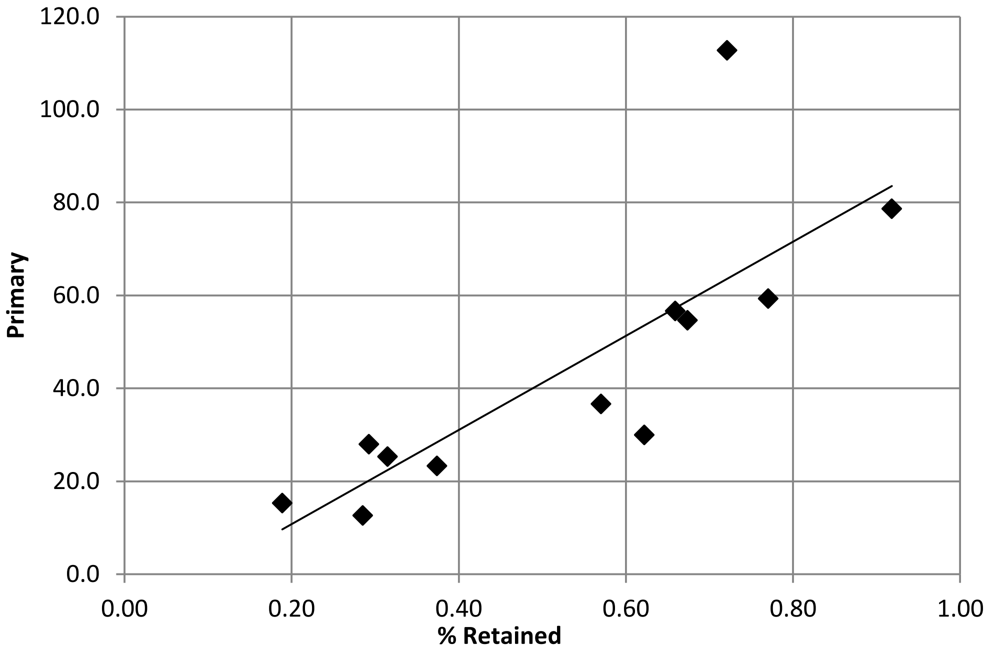

Figure 4.27. Correlation of %Retained and Primary Index

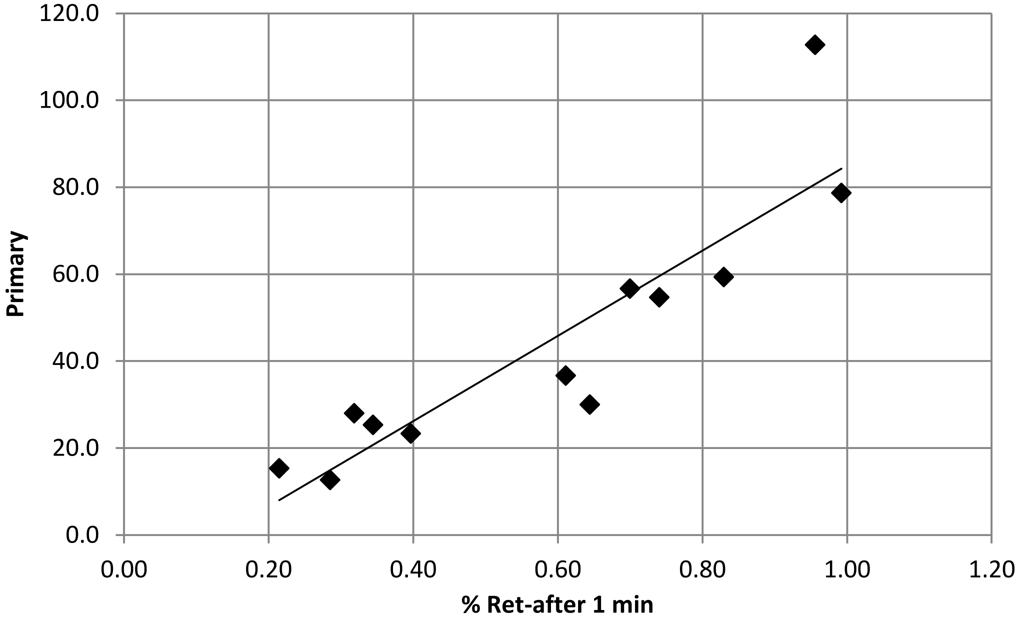

Figure 4.28. Correlation of %Retained after 1 min and Primary Index

The IPI and the recovered water did not have a good correlation. This is illustrated in Figure 4.29 and with a poor correlation coefficient R (0.3676).

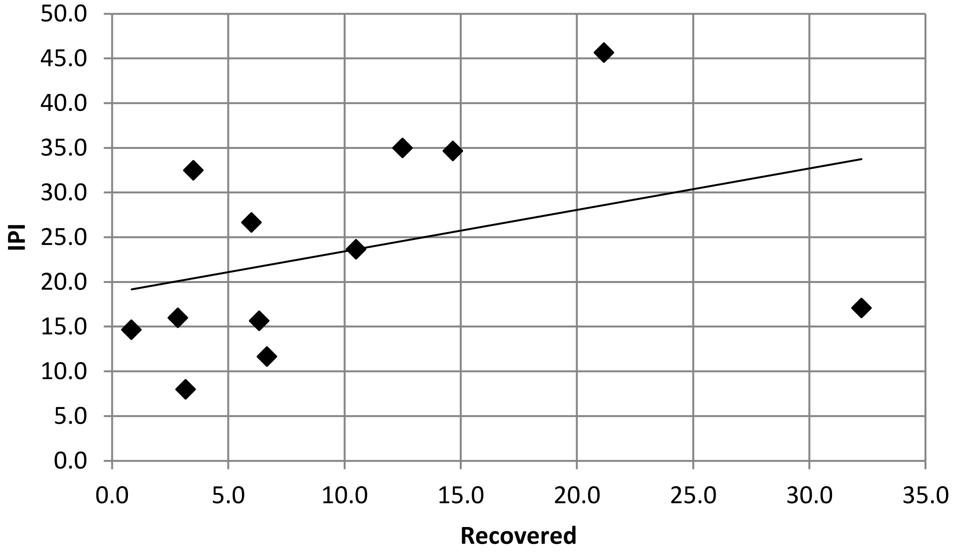

Figure 4.29. Correlation of Recovered and IPI

Figure 4.30 shows the relationship between the Retained water and the IPI. A good correlation coefficient R (0.8799) for this data is produced. It was expected that the correlation between IPI and Retained would be greater than the IPI and Recovered because the IPI represents the micro pores that would retain water via capillary forces.

Figure 4.31 shows the relationship between the % Retained and the IPI. Again a good correlation coefficient R (0.8776) is seen in the data trend. This is expected as the % Retained is a measure of absorption and Richardson has shown that the IPI has a fair correlation to the absorption of the aggregate (Richardson, 2009).

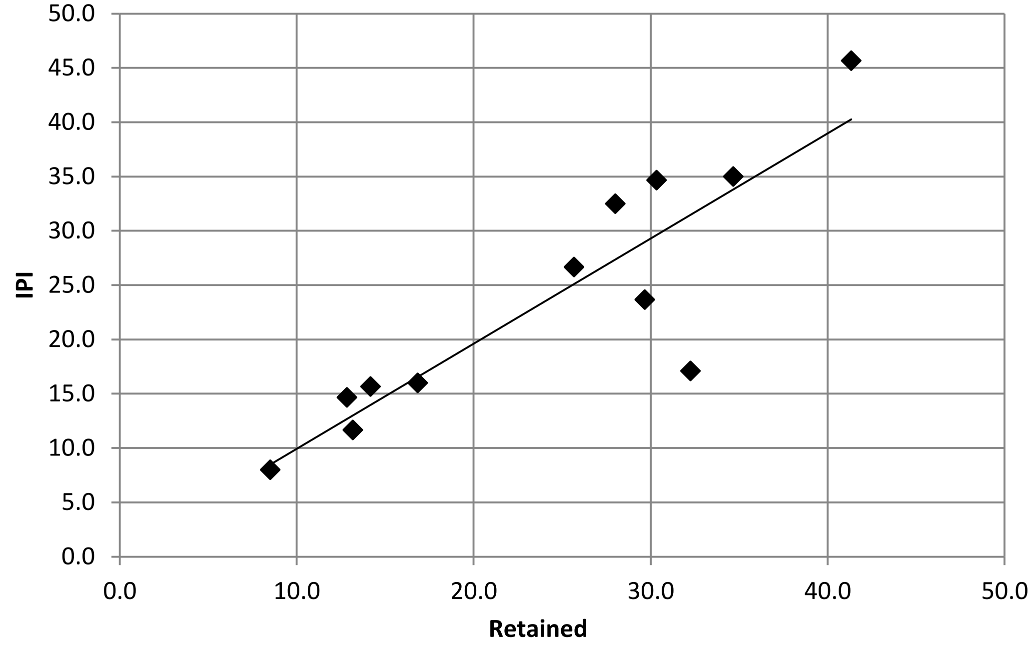

Figure 4.30. Correlation of Retained and IPI

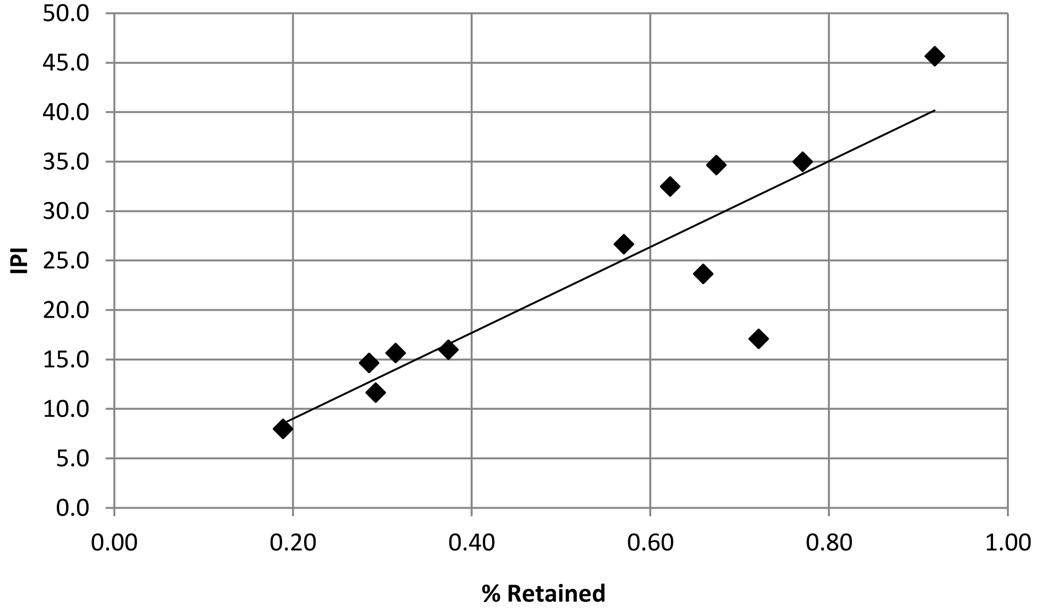

Figure 4.31. Correlation of % Retained and IPI

Figure 4.32 shows that the relationship between the % Retained after 1 min. and the IPI is fair with a correlation coefficient R of 0.7835. The trend follows the % Retained vs. IPI trend which is expected and the strength of the correlation is less than the % Retained, also expected.

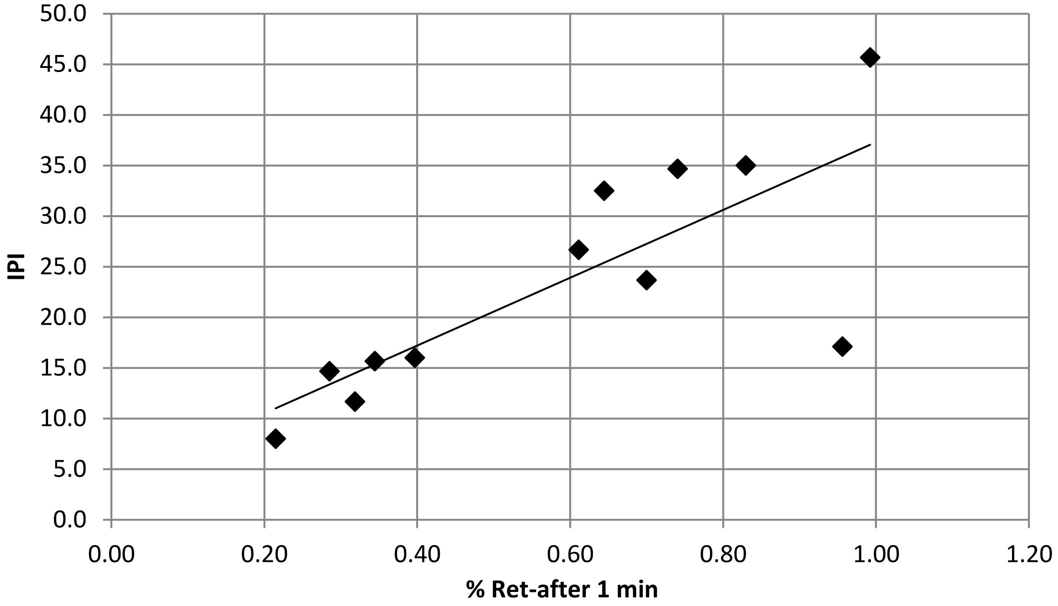

Figure 4.32. Correlation of % Retained after 1 min and IPI

4.2.5. Material Re-testability. The term re-testability is defined for this research as the ability of the IPI test to be performed on the same sample of aggregate more than once and produce similar results. The re-testability of the material with the IPI test is crucial for an organization to know so that disputes over results can be settled. In order to determine if an aggregate is re-testable using the IPI, test samples of the 2011 aggregate underwent a re-testing procedure. The samples were washed and oven dried, then tested in the IPI apparatus without the Recovery procedure. After the test was completed the aggregate was washed and oven dried then tested in the IPI apparatus a second time. The first IPI test allowed for the IPI of the sample to be determined by the first IPI test. Then the second test would check to see if a similar or same IPI could be produced. The second IPI gathered from the testing is indicated by “IPI2”.

The results of the materials re-testability are shown in Figure 4.33 with a good correlation coefficient R (0.9972). The trend does not fall exactly on the line of equality, which is similar to the repeated oven drying investigation. A t-test analysis (two tailed) was performed on the data from the material re-testability investigation and the conclusions were that the results of the IPI2 had an 82% probability to be the same as the results of an IPI test.

The re-testability procedure added a pressurization step to the repeated oven drying and since it showed that the oven drying did not have a significant effect on the

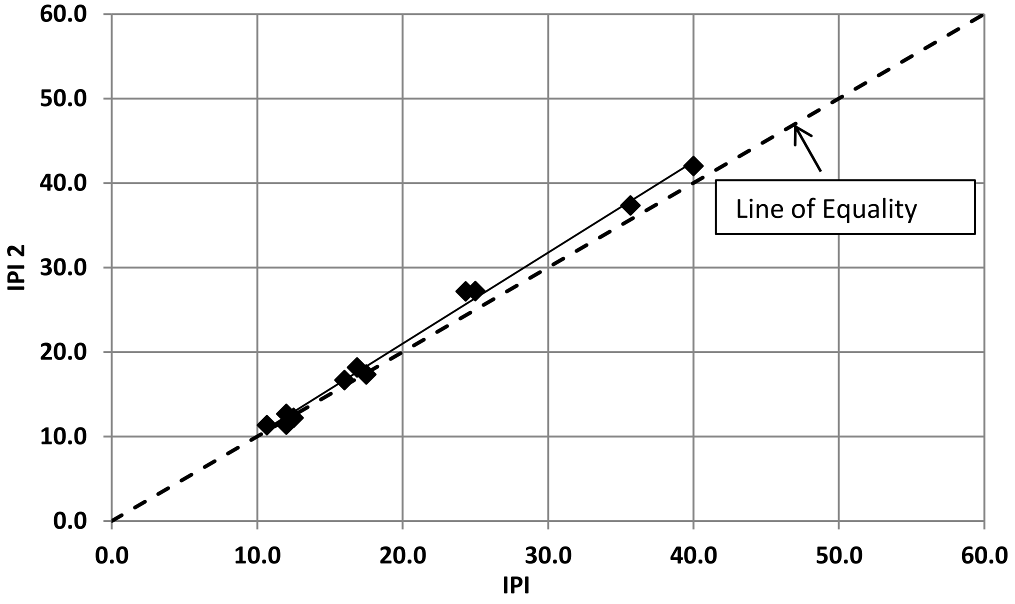

Figure 4.33. Correlation of IPI and IPI 2

material’s pore structure that is represented by the IPI, this also allows for the pressurization’s destructivity of the aggregate to be investigated. The findings of the material re-testability concur with the findings of Olsen, Janssen and Dempsey (Olsen, et al., 1983) in that the IPI test is a nondestructive test and can be performed repeatedly on the same material sample.

4.2.6. Different Operators. The testing of the 2011 material produced data that had slightly different IPIs than the IPI produced in 2008 using the 2008 aggregate. The aggregate samples came from the same quarries, ledge, and formation with the only difference being the time of collection. In order to rule out operator error in the difference of IPI, the effect of different operators was explored.

The data from the 2008 study was used in the analysis of the effect of the aggregate size on the IPI. This data was collected two years prior to the testing for this study and differences in the testing include operators, IPI apparatus, and time. A portion of the aggregate tested in 2011 was from untested material collected at the same time as the aggregate tested in 2008. This 2008 aggregate had been stored in a climate controlled room at the Missouri University of Science & Technology.

During the course of testing it was observed that some indices produced in the 2008 testing differed from the IPI produced from aggregate of the same sample when tested in 2011. The IPI data is tabulated in Table 4.7 and includes data from different sizes of aggregate that was tested. The data was collected from 2008 material and the year it was tested is indicated by the two columns. The data collected in 2011 was recorded during the Recovery part of this study.

Table 4.7. Different Operator IPI Results

		Test Year	
	Size	2008	2011
Bluff City Minerals@Alton	½-¾	21.3	15.7
Weber New Melle	⅜-½	18.0	16.0
NAP Savannah West	#4-¾	22.7	26.7
Joplin Stone- Joplin	⅜-½	19.7	17.1
SEMO at Cape Girardeau	½-¾	14.0	14.7
Hunt Martin-Greenwood	⅜-½	33.7	32.5
Capital Quarries#5@Calif.	½-¾	44.0	34.7
Springfield Underground	½-¾	12.0	8.0
Knox Co. Stone	½-¾	33.3	35.0
Fischer-Hughesville@Sedalia	½-¾	11.3	11.7
Muenks Bros at Loose Cr	½-¾	49.0	45.7
APAC-KS@Harrisonville	⅜-½	24.3	23.7

Although individually some of the aggregates IPI's differ from 2008 to 2011, a student's t-analysis showed that there is no significant difference between the two years when analyzed as a group.

4.2.7. Testing Observations. When testing aggregate it was observed once that during the System Check cycle, the water began to rise above the starting point. The applied air pressure was checked and a procedural 35psi was confirmed. Testing proceeded with more observation as to the water level in the cylinders during the test duration. With an unknown reason for this behavior, testing was ceased until further exploration could be performed. The IPI test was performed without aggregate. Only a pot full of water was tested. Upon doing so it was evident that the system was gaining water even while being pressurized to 35 psi. The three-way valve was replaced and a water-only test was conducted. The water levels of the cylinders remained constant, indicating that the system did not gain or lose water during the test. The data that was affected by this mechanical failure of the apparatus was not used in the analysis of any relationships stated above.

5. CONCLUSIONS

5.1. SUMMARY

In an attempt to determine the effect of particle size on the Iowa Pore Index of an aggregate for its use in aggregate acceptance or in a Durability Factor estimation equation and the effects of specimen preparation, a more developed understanding of the IPI was achieved. Preliminary testing of a local aggregate allowed for the test procedure to be refined so that variables that could skew the data or make the data less precise would be eliminated or controlled. A relationship was developed to convert the IPI of a nonstandard particle size into an IPI for the standard sized particle. Also, a new method of collecting additional data without adding time to the test was developed. The data did not show promise in relating to the Durability Factor but has potential to be used as an alternate method of an aggregate durability classification or acceptability tool.

5.2. CONCLUSIONS

The IPI apparatus potentially variable fill time was a problem that could lead to inconsistent results, which was a critique of the IPI. The standardization of the fill time solves this problem by allowing the same amount of absorption time prior to the start of each test. This should increase the precision of the IPI test.

Another addition to the test procedure that will increase the precision is the use of agitation with a rubber mallet while filling the apparatus. The removal of compressible air from the system removes a random error that could lead to false acceptance of an aggregate.

In IPI testing performed during 2008 at Missouri S&T, the typical Pot Expansion (PE) for the tests was 15. During the 2011 testing at Missouri S&T the PE was consistently 10 after the time to fill was set at 90 seconds and the 10 taps with the rubber mallet were applied. Without knowing the time to fill the apparatus that was used in 2008, it cannot be determined that the new procedure reduced the PE by 5-ml, but it can be concluded by the observations made that there was less air in the system using a 90-sec time to fill with 10 taps of a rubber mallet. Due to the observations made and the consistency of the PE during the 2011 testing, the time to 90 second fill time with 10 taps from a rubber mallet were successful at standardizing the filling procedure for the IPI test.

The temperature of the water ranged from 12.8°C (55°F) to 23.4°C (74°F) during the duration of the testing. The temperature seemed to have no observable effect on the PE, therefore any effect it may have had on the test is negligible. The effect of temperature differences from the start to the end of the test can produce a systematic error in the loads. Extreme variations in the testing room temperature and initial temperature of water that could lead to a change in temperature greater than 1°C during the test should be avoided. If such temperature variations exist during testing, the results could be affected.

Upon analyzing the IPI data from the three different particle sizes tested, it is determined that the two regression equations can be used to successfully convert an IPI derived from either #4-⅜-inch particle sizes or ⅜-½-inch particle sizes to an ½-¾-inch IPI equivalent. The converted IPI did correlate slightly better with the DF, than the non-corrected IPI. The correction for one aggregate was significant enough to change the evaluation of the aggregate from acceptable to non-acceptable. The main benefit from the size correction is the corrections used in screening aggregates for D-cracking. Using the actual size of particle in the aggregate should give a more accurate IPI while the correction allows for the threshold of an IPI of 27 to be used.

The effect that the oven drying procedure has on the aggregate's IPI is minimal. This variable in the IPI test looks to be insignificant in such that it does not play a role in altering the pore properties of the aggregates tested to a point that the IPI is affected. Aggregate for the IPI test can be oven dried, set aside, and then oven dried a second time.

From the given data, it appears that the index from the re-pressurization procedure (IPIr) should not be used in the event of a malfunction or procedural error while testing, but may have some other usefulness in terms of relating to durability evaluation. In the event a malfunction or procedural error does occur, the study indicated that an aggregate can be tested, set aside, oven dried and tested again. This would also be useful in settling disputes between variations in reported data.

The data obtained in the Recovery procedure did not produce any significantly strong correlations with the Durability Factor. The strongest correlation is from the % Retained. This correlation is stronger than the IPI correlation with the Durability Factor so the Recovery data does show promise in helping to predict the durability qualities of aggregate. The strong correlation of the Recovered to the Primary Index may not have too much meaning to durability prediction. The Primary Index has not been found to be correlated to D-cracking or freeze/thaw durability, so the Recovered may just be a way of determining the Retained and % Retained. The Retained, while having a fair correlation to the IPI, did not produce a correlation as strong as the % Ret so the % Ret is a value that may provide some usefulness as a way of determining the proneness to D-cracking and freeze/thaw durability as a time efficient test.

The IPI2 of a material showed no significance difference than that of the IPI from the first test procedure, so the material is re-testable without a significant change in the index produced. This will allow for the re-testing of a material to be done in order to settle disputes over data and allow for the material to be tested a second time in the case that discrepancies are suspected in the initial testing.

The use of different operators for the data used in this study produced results that had some variation. However, after the statistical analysis of the data, the different operator, different testing apparatus, and time were variables that had little effect on the IPI. There were some aggregates that had a large change in IPI, but none such that its classification as D-crackable would be changed.

5.3. FUTURE RESEARCH

Future research should focus on the Recovery data and different procedures of this testing step. The data is a form of pressurized absorption and also water expulsion. Both absorption and water expulsion are properties that relate to the aggregate's freeze thaw durability. Having a short test that produces data which could describe two aggregate properties would be beneficial to aggregate acceptance for use in a freeze/thaw environment. Research should include a large variety of aggregates that have known service records and/or known Durability Factors, so correlations can be made to a widely accepted form of predicting durable aggregates.

APPENDIX A

IOWA PORE INDEX PROCEDURE

Iowa Pore Index

Iowa 219-D

Influence of Particle Size and Specimen Preparation on the Iowa Pore Index Study

Equipment

Equipment includes an Iowa Pore Index apparatus, which includes: a chamber pot with a valve/cylinder board, and control board. Sieve Sizes: ¾”, ½”, 3/8”, #4.

Procedure

1. For aggregates following MoDOT gradations B and D, **prepare a 4500 gram sample of washed and oven-dried aggregate** passing the ¾ in. and retained on the ½ in. sieve. For materials that lack this size, use aggregate that passes the ½ in. and is retained on the ⅜ sieve, or passes the ⅜ in. and is retained on the #4 sieve. The specimen should be washed to prevent cloudiness of the water in the graduated glass tubes. The aggregate should be dried at 110 ± 5 °C (230 ± 9 °F) for 24 ± 4 hrs., then cooled to room temperature (25 ± 5 °C). Drying time may affect IPI results, thus should be kept as nearly constant as possible. Wash and dry the aggregate only once.
2. **Add the sample to the chamber pot, level the sample, and snap the lid in place** in the same position each time. **Tighten the four bolts** evenly with the small torque wrench set to 35 inch-lbs using a cross-tightening technique, similar to tightening lug nuts on a car wheel.
3. Ensure that all pressure and water lines are attached to the apparatus.
4. **Turn the power switch to On**.
5. **Turn the Mode switch clockwise from Off to Load. Push the Start button.**
6. **Feather the three-way valve on the sample pot to the Load position** (about 30 degrees clockwise from the Run direction) **until water fills all three graduated cylinders, and the menisci coincide with the zero marks**. If the marks are not at zero, **record the levels**. Fill the pot/manifold/cylinder system as quickly as possible, but not so fast as to generate excess turbulence at the bottom of the pot where the water enters. Symptoms of excess turbulence can be seen as suspended fines and/or air bubbles in the cylinders. **Tap the pot sharply with a rubber**

mallet as it is filling throughout the filling cycle. Stop tapping when the water starts to enter the glass cylinders. Be consistent in filling time-do not delay moving to the next step. The **interval between the start of the introduction of water** to the pot and the start of the testing cycle (Step 7) **should be 90 ± 5 seconds**. Water is being absorbed at this point. *NOTE: In the event that any of the graduated cylinders are overfilled with water to the degree that water may have actually entered the plastic tubing coming up out of the top of the cylinder AND drained into the aluminum manifold block on the back of the IPI device panel, 1) turn the three-way valve to the Drain position until the water level in the overfilled cylinder(s) comes back down equal to or below the zero mark, then return the three-way valve to a position that will stop the draining (Run), 2) attach a short piece of plastic tubing over the "system vent" plastic tubing (attached to the back side of the right panel leg, as one looks at the front of the panel), 3) then blow on the attached piece of tubing while simultaneously pulling (carefully) on the small toggle-valve handle (at the very bottom-left of the front of the panel), thereby draining the aluminum manifold block on the back of the panel. Once any and all water has been blown out of the manifold block, release thesmall toggle-valve, remove the short piece of tubing used to blow out the water in the manifold block, then very slowly feather the three-way valve in the Load position until all menisci are at the zero marks.*

7. Once the cylinders' menisci are at the zero marks, **switch the three-way valve to the Run position**, which will close the Secondary Load and System Check valves. **Push the Start button.**
8. The controls will ensure the appropriate valves are opened and shut at the correct times. First, the Primary Load cylinder valve will open for one minute. Next, the Primary Load cylinder valve will close and the Secondary Load cylinder valve will open for 14 minutes. Next, the Secondary Load cylinder valve will close and the System Check cylinder valve will open for 15 minutes, then close.
9. After the three testing intervals are complete, the Test Done light will switch on.

Record the Primary and Secondary load values [R_1 to the nearest whole number; i.e. ½ of a graduation mark] and [R_{14} to the nearest 0.5; i.e. ½ of a graduation mark], respectively.

10. **Record the System Check level**. If the system check graduated cylinder does not read less than 6 after the test, this indicates a leak in the pressurized system and the test is not valid.
11. **Turn the Mode switch from Run to Drain. Push the Start button**.
12. **Turn the three-way valve on the sample pot to the Drain position**, which will open all three valves. The system pressure will force the water out. After most of the water has drained (the drain line will start spitting air and water), **hit the Stop button** to stop pressurization of the pot.
13. **Check the torque** for each bolt to make sure it is still at 35 inch-lbs. If not, make a note of the torque on the data sheet. Remove the nuts and washers from the lid.
14. **Place your hand firmly on the top of the lid, turn the Mode switch to Run, and press the Start button with your other hand**. Pressure will be reintroduced to the pot and the lid will unseal. **Press the Stop button**, **turn the Mode switch to Off, and remove the lid**. An alternate method to remove the lid is to remove the air supply line in the top of the lid after the pressure has been released at the end of the test, insert a short piece of tubing into the air supply line fitting, and blow into the tubing with enough force to unseal the lid.

Determining Pot Expansion

Every day that the test is run, the pot expansion [PE] must be determined. To determine the pot expansion, **run the test (steps 2 through 7)** without adding an aggregate sample. **After the primary load indicator light switches off, record the primary load value** as the pot expansion value for the day. It should be around 14 ml. **Stop the test by pushing the Stop button.**

NOTE: When hooking up to water for the first time, run the PE several times until the PE becomes consistent for at least 2 runs.

Post-Test Effect of Re-Pressurization

In the event one desires to also determine the Post-Test Primary and Secondary load values on a specimen that has just been tested, proceed in the following manner: **Run the test as usual (steps 2 – 10).**

15. **Push the Stop button**, thereby depressurizing the system. **Using the 3-way valve, drain the cylinders, but not the pot**.
16. **Remove the chamber pot lid**. Make sure the aggregate particles remain submerged**. Re-assemble**.
17. **Finish running the test (steps 5-14)**

Recovery Data Procedure

In the event one desires to collect Recovery data on a specimen of aggregate proceed in the following manner: **Run the test as usual (steps 1-5 with or without Re-Pressurization)**

18. **Perform steps 6 – 7 except fill the cylinders to half their volumes**, eg. the 150 (Primary), 50 (Secondary) and 49 (System Check) levels instead of zero.[Note: the Missouri S&T device System Check cylinder is one mark offset from perfectly level, so 49 is the starting point instead of 50] These levels may need to be altered based on the Primary, Secondary, and Pot Expansion load values for a particular aggregate type. The levels should allow for the sum of the values to back flow into the System Check cylinder without flowing above the zero mark. After the Primary and Secondary load intervals are completed and the **System Check interval reaches 2 minutes, record the water levels, and vent the System Check cylinder (and the others) by pulling the vent toggle-valve.**
19. **As water flows back into the System Check cylinder, record the water levels at one-minute intervals.**
20. This step is similar to Step 9. **After the System Check interval is finished (15 minutes)**, the valves will automatically close. **Record all three levels.**
21. **Push the Stop button.** This will open all 3 cylinder valves. When the water levels have equilibrated. **Record the levels.**

22. **Proceed with steps 11-14**.

Calculations: Normal Procedure

Primary Load Index [PLI] = $(R_1 - PE) * (9000 / W)$

Secondary Load Index [SLI] = $(R_{14}) * (9000 / W)$

Iowa Pore Index [IPI] = SLI

Pore Index Quality Number [PIQN] = (SLI / PLI) * (PLI + SLI) * (0.055)

Calculations: Re-Pressurization Procedure

Same calculations but with Re-Pressurization steps data.

Calculate:

Gross Water In = (Primary Load + Secondary Load + System Check)

Net Water In = (Gross Water In – PE)

Gross Backflow Water = change in System Check level upon venting

Net Backflow = (Gross Backflow – PE)

Retained Water = (Net Water In – Net Backflow)

APPENDIX B

TIME TO FILL OBSERVATIONS

Initial Trial

Agg. condition	Time to fill (sec)	Observations	Valve procedure
dry	90.6	1 or 2 large bubbles, they moved to the top before cylinders were full	Valve was opened to the same location until water was half way up the cylinders then it was feathered letting water in slowly until full
wet	84.9	1 or 2 large bubbles, they moved to the top before cylinders were full	
wet	87.0	1 or 2 large bubbles, they moved to the top before cylinders were full	
wet	85.6	1 or 2 large bubbles, they moved to the top before cylinders were full	
wet	81.3	a few large bubble, more small bubbles in water but not too many	Valve was opened to the same location as the first 4 runs, but the valve was feathered to let water in quickly once the cylinders started to fill.
wet	78.4	a few large bubble, more small bubbles in water but not too many	
wet	74.7	a few large bubble, more small bubbles in water but not too many	
wet	72.0	a few large bubble, more small bubbles in water but not too many	
wet	58.2	A lot of small bubbles in water	Valve opened all the way until water was in the cylinder then feathered with water flowing quickly
wet	56.6	A lot of small bubbles in water	

Time to fill with Tapping side 10 times once water reaches cylinder

Agg. condition	Time to fill (sec)	Observations	Valve procedure
dry	88.2	Large bubbles cont. to appear through out the cylinder filling, tiny bubble visible in water	Valve was opened to the same location until water was half way up the cylinders then it was feathered letting water in slowly until full
wet	90.7	Few large bubbles, appeared after valve was feathered, some tiny bubbles in water	
wet	93	1 or 2 large bubbles, some tiny bubbles	
wet	84.3	1 or 2 large bubbles, some tiny bubbles	
wet	94.5	1 or 2 large bubbles, some tiny bubbles	

Time to fill with Tapping side 10 times as water fills the aggregate in the pot

Agg. condition	Time to fill (sec)	Observations	Valve procedure
dry	95.4	large bubbles continued up the cylinder, I taped the pot once the water was in the cylinder and more came up	Valve was opened to the same location until water was half way up the cylinders then it was feathered letting water in slowly until full
wet	89.2	Few large bubbles , some tiny bubbles in water, I tapped the pot and only a couple bubbles came up	
wet	92	Few large bubbles , some tiny bubbles in water, I tapped the pot and only 1 bubble came up	
wet	87.9	Few large bubbles , some tiny bubbles in water, I tapped the pot and only 1 bubble came up	

Time to fill with Tapping side 10 times as water fills the aggregate in the pot and 4 times once water is close to "zero" in the cylinder

Agg. condition	Time to fill (sec)	Observations	Valve procedure
dry	85	Large bubbles continued up cylinder through out loading until water was close to "zero", no bubbles came up once pot was tapped	Valve was opened to the same location until water was half way up the cylinders then it was feathered letting water in slowly until full
wet	90	Large bubbles continued up cylinder, they slowed down as the water level raised to zero	
wet	87	Large bubbles continued up cylinder while filling, non came out when tapped, but they did periodically flow up	

APPENDIX C

T-TESTS

Comparison of tested #4-⅜ IPI and ⅜-½ IPI

Table C.1
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	15.8982	22.2367
Variance	63.7287	123.5158
Observations	20.0000	20.0000
Pooled Variance	93.6222	
Hypothesized Mean Difference	0.0000	
df	38.0000	
t Stat	-2.0716	
P(T<=t) one-tail	0.0226	
t Critical one-tail	1.6860	
P(T<=t) two-tail	0.0451	
t Critical two-tail	2.0244	

Table C.2
-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	15.8982	22.2367
Variance	63.7287	123.5158
Observations	20.0000	20.0000
Hypothesized Mean Difference	0.0000	
df	34.0000	
t Stat	-2.0716	
P(T<=t) one-tail	0.0230	
t Critical one-tail	1.6909	
P(T<=t) two-tail	0.0460	
t Critical two-tail	2.0322	

Comparison of tested #4-⅜ IPI and ½-¾ IPI

TableC.3
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	15.2369	27.0963
Variance	61.0752	148.3970
Observations	18.0000	18.0000
Pooled Variance	104.7361	
Hypothesized Mean Difference	0.0000	
df	34.0000	
t Stat	-3.4765	
P(T<=t) one-tail	0.0007	
t Critical one-tail	1.6909	
P(T<=t) two-tail	0.0014	
t Critical two-tail	2.0322	

Table C.4
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	15.2369	27.0963
Variance	61.0752	148.3970
Observations	18.0000	18.0000
Hypothesized Mean Difference	0.0000	
df	29.0000	
t Stat	-3.4765	
P(T<=t) one-tail	0.0008	
t Critical one-tail	1.6991	
P(T<=t) two-tail	0.0016	
t Critical two-tail	2.0452	

Comparison of tested ⅜-½ IPI and ½-¾ IPI

Table C.5
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	22.7492	28.7016
Variance	155.6466	190.0446
Observations	21.0000	21.0000
Pooled Variance	172.8456	
Hypothesized Mean Difference	0.0000	
df	40.0000	
t Stat	-1.4671	
P(T<=t) one-tail	0.0751	
t Critical one-tail	1.6839	
P(T<=t) two-tail	0.1502	
t Critical two-tail	2.0211	

Table C.6
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	22.7492	28.7016
Variance	155.6466	190.0446
Observations	21.0000	21.0000
Hypothesized Mean Difference	0.0000	
df	40.0000	
t Stat	-1.4671	
P(T<=t) one-tail	0.0751	
t Critical one-tail	1.6839	
P(T<=t) two-tail	0.1502	
t Critical two-tail	2.0211	

Comparison of Corrected #4-⅜ IPI to tested ½-¾ IPI (Eq. 1)

Table C.7
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	27.09624	27.0962963
Variance	131.117	148.3969789
Observations	18	18
Pooled Variance	139.757	
Hypothesized Mean Difference	0	
df	34	
t Stat	-1.55E-05	
P(T<=t) one-tail	0.499994	
t Critical one-tail	1.690924	
P(T<=t) two-tail	0.999988	
t Critical two-tail	2.032244	

Table C.8
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	27.09624	27.0962963
Variance	131.117	148.3969789
Observations	18	18
Hypothesized Mean Difference	0	
df	34	
t Stat	-1.55E-05	
P(T<=t) one-tail	0.499994	
t Critical one-tail	1.690924	
P(T<=t) two-tail	0.999988	
t Critical two-tail	2.032244	

Comparison of Corrected ⅜-½ IPI to tested ½-¾ IPI Eq. 2)

Table C.9
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	28.70207	28.7015873
Variance	180.1704	190.0446085
Observations	21	21
Pooled Variance	185.1075	
Hypothesized Mean Difference	0	
df	40	
t Stat	0.000115	
P(T<=t) one-tail	0.499954	
t Critical one-tail	1.683851	
P(T<=t) two-tail	0.999909	
t Critical two-tail	2.021075	

Table C.10
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	28.70207	28.7015873
Variance	180.1704	190.0446085
Observations	21	21
Hypothesized Mean Difference	0	
df	40	
t Stat	0.000115	
P(T<=t) one-tail	0.499954	
t Critical one-tail	1.683851	
P(T<=t) two-tail	0.999909	
t Critical two-tail	2.021075	

Comparison of IPI-OD2 and IPI

Table C.11
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	21.239	20.218
Variance	100.016	84.168
Observations	11.000	11.000
Pooled Variance	92.092	
Hypothesized Mean Difference	0.000	
df	20.000	
t Stat	0.250	
P(T<=t) one-tail	0.403	
t Critical one-tail	1.725	
P(T<=t) two-tail	0.805	
t Critical two-tail	2.086	

Table C.12
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	21.239	20.218
Variance	100.016	84.168
Observations	11.000	11.000
Hypothesized Mean Difference	0.000	
df	20.000	
t Stat	0.250	
P(T<=t) one-tail	0.403	
t Critical one-tail	1.725	
P(T<=t) two-tail	0.805	
t Critical two-tail	2.086	

Comparison of IPIr and IPI

Table C.13
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	18.1514	3.0605
Variance	112.5745	3.9381
Observations	22.0000	22.0000
Pooled Variance	58.2563	
Hypothesized Mean Difference	0.0000	
df	42.0000	
t Stat	6.5575	
P(T<=t) one-tail	3.13E-08	
t Critical one-tail	1.6820	
P(T<=t) two-tail	6.26E-08	
t Critical two-tail	2.0181	

Table C.14
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	18.1514	3.0605
Variance	112.5745	3.9381
Observations	22.0000	22.0000
Hypothesized Mean Difference	0.0000	
df	22.0000	
t Stat	6.5575	
P(T<=t) one-tail	6.76E-07	
t Critical one-tail	1.7171	
P(T<=t) two-tail	1.35E-06	
t Critical two-tail	2.0739	

Comparison of material re-testability IPI vs IPI2

Table C.15
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	21.22424	20.23030303
Variance	115.6431	99.20676768
Observations	11	11
Pooled Variance	107.4249	
Hypothesized Mean Difference	0	
df	20	
t Stat	0.2249	
P(T<=t) one-tail	0.41217	
t Critical one-tail	1.724718	
P(T<=t) two-tail	0.824339	
t Critical two-tail	2.085963	

Table C.16
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	21.22424	20.23030303
Variance	115.6431	99.20676768
Observations	11	11
Hypothesized Mean Difference	0	
df	20	
t Stat	0.2249	
P(T<=t) one-tail	0.41217	
t Critical one-tail	1.724718	
P(T<=t) two-tail	0.824339	
t Critical two-tail	2.085963	

Comparison between 2008 IPI and 2011 IPI with operator, apparatus and time differing between the two.

Table C. 17
t-Test: Two-Sample Assuming Equal Variances

	Variable 1	*Variable 2*
Mean	25.275	23.43888889
Variance	150.4475	132.3811785
Observations	12	12
Pooled Variance	141.4143	
Hypothesized Mean Difference	0	
df	22	
t Stat	0.378206	
P(T<=t) one-tail	0.354451	
t Critical one-tail	1.717144	
P(T<=t) two-tail	0.708903	
t Critical two-tail	2.073873	

Table C.18
t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	*Variable 2*
Mean	25.275	23.43888889
Variance	150.4475	132.3811785
Observations	12	12
Hypothesized Mean Difference	0	
df	22	
t Stat	0.378206	
P(T<=t) one-tail	0.354451	
t Critical one-tail	1.717144	
P(T<=t) two-tail	0.708903	
t Critical two-tail	2.073873	

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During his time at Missouri S&T Chris was a member of Chi Epsilon and the Missouri S&T Semper Fi Society. Chris was the Graduate Teaching Assistant of a Construction Materials lab for two semesters. He served the community as a volunteer designing, constructing and fundraising for a Veterans Memorial park in Rolla, Missouri with the South Central Regional Veterans Group. Chris married Lesa Schnackenberg in May of 2007. They had their first child, Madison Elaine, in February of 2009. Zachary Paul, their second child, was born in March of 2011.