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EFFECT OF CORE GEOMETRY AND SIZE ON CONCRETE COMPRESSIVE STRENGTH

Submitted to

The Alabama Department of Transportation

Prepared by

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15. Abstract
To evaluate the in-place concrete strength for acceptance for a structural member with potentially substandard strength, the compressive strength of cores may be required for assessment. Depending on the geometry and size of the core specimen, the compressive test results may need adjustment to characterize the in-place concrete strength. The comprehensive experimental study performed examines core test results for factors including: three targeted strengths (6,000, 8,000, and 10,000 psi), two coarse aggregate sizes (No. 67 and 57), five core length-to-diameters (1.0, 1.25, 1.5, 1.75, and 2.0), two core diameter sizes (3 and 4 in.), and two coring directions (parallel and perpendicular). The data represent 390 core specimens obtained from 12 separate concrete castings.

The data indicate that the core diameter significantly affects the strength correction factors for various length-to-diameters (l/d). For 4 in. diameter cores, only a slight difference from the currently recommended core l/d strength correction factors in AASHTO T 24 (2007) is observed. However, 3 in. diameter cores do not behave the same as 4 in. diameter cores when evaluated for core l/d effects on compressive strength. The analyzed data indicate that as the volume of the core specimen decreases, the compressive strength results become less reliable. Additionally, AASHTO T 24 (2007) recommends a core diameter of at least 3.75 inches. Based on the analysis, cores having a l/d less than 2.0, should not have a core diameter less than 3.75 inches.

For cores having l/d of 2.0, the data indicate that the average strength of 3 in. diameter cores is 94 percent of the average strength of a 4 in. diameter core. Results also indicate the average strength of cores drilled perpendicular to the placement direction is 96 percent of the average strength of cores drilled parallel to the placement direction.

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DISCLAIMERS

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ABSTRACT

To evaluate the in-place concrete strength for acceptance for a structural member with potentially substandard strength, the compressive strength of cores may be required for assessment. Depending on the geometry and size of the core specimen, the compressive test results may need adjustment to characterize the in-place concrete strength. The comprehensive experimental study performed examines core test results for factors including: three targeted strengths (6,000, 8,000, and 10,000 psi), two coarse aggregate sizes (No. 67 and 57), five core length-to-diameters (1.0, 1.25, 1.5, 1.75, and 2.0), two core diameter sizes (3 and 4 in.), and two coring directions (parallel and perpendicular). The data represent 390 core specimens obtained from 12 separate casts of concrete.

The data indicate that the core diameter significantly affects the strength correction factors for various length-to-diameters (*l/d).* For 4 in. diameter cores, only a slight difference from the currently recommended core *l/d* strength correction factors in AASHTO T 24 (2007) is observed. However, 3 in. diameter cores do not behave the same as 4 in. diameter cores when evaluated for core *l/d* effects on compressive strength. The analyzed data indicate that as the volume of the core specimen decreases, the compressive strength results become less reliable. Additionally, AASHTO T 24 (2007) recommends a core diameter of at least 3.75 inches. Based on the analysis, cores having a *l/d* less than 2.0, should not have a core diameter less than 3.75 inches.

For cores having *l/d* of 2.0, the data indicate that the average strength of 3 in. diameter cores is 94 percent of the average strength of a 4 in. diameter core. Results also indicate the average strength of cores drilled perpendicular to the placement direction is 96 percent of the average strength of cores drilled parallel to the placement direction.

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Chapter 1

INTRODUCTION

1.1 BACKGROUND

For over a century, engineers and researchers have desired the ability to know the in-place strength of concrete structures. Evaluating the strength of in-place concrete is a challenge but a necessity in determining the degree of safety for a structure. The quality of fresh concrete depends on the material proportions and the batching, mixing, and handling procedures. Quality of hardened concrete depends on placement, consolidation, and curing practices.

In the United States, the most common practice for evaluating in-place concrete strength is by drilling core specimens from the structure and performing compression test on each. Required compressive strengths are specified based on the characteristics of the structure and are specifically designed to meet structural requirements. The analysis of core test data can be challenging and can lead to uncertain interpretations and conclusions (ACI 214 2010).

At this time, there are no standard specifications in the state of Alabama for evaluating core strength results under various conditions. However, the Alabama Department of Transportation (ALDOT) is interested in a procedure that converts the obtained core strength results to determine the acceptability of the in-place concrete. Acceptance of in-place concrete and the payment exchanged between owner and contractor can be based on core strength results.

During new construction, in-place concrete tests or core testing are not always needed. In accordance with American Concrete Institute (ACI) 318, if both of the following criteria are met for standard cylinders, then the strength level of an individual class of concrete shall be considered satisfactory:

(a) Every arithmetic average of any three consecutive strength tests must equal or exceed the specified compressive strength of concrete, f'_c and

(b) No strength test falls below f'_c by more than 500 psi when $f'_c \leq 5000$ psi; or by more than $0.1f'_c$ when $f'_c > 5000$ psi.

When criterion (a) is not met, steps must be taken to increase strength of subsequent concrete. However, when criterion (b) is not met, in addition to the requirement to increase the strength of subsequent concrete, in-place strength must be investigated (ACI 318 2011).

This investigation is executed by testing three or more cores from the area in question. When the average core strength is greater than or equal to $0.85f'_c$ and no single strength of three cores is less than $0.75f'_c$, then the concrete in question is deemed acceptable. When the test results fail to meet these requirements, the placement can be rejected or further investigated by load testing.

Recognizing that delivery of high-quality concrete does not ensure high-quality in-place concrete, some project specifications require minimum core compressive strength results for concrete acceptance (Ontario Ministry of Transportation 1998). The core test results do not always represent the quality of concrete as delivered to the site. For instance, results may be questionable if mixing water was added during placement or if poor placement, consolidation, or curing practices are used (ACI 214 2010). The ALDOT only pays the contractor 100% of the price for the investigated concrete when the average core strength is equal to or exceeds the required 28-day compressive strength, as shown in Figure 1-1.

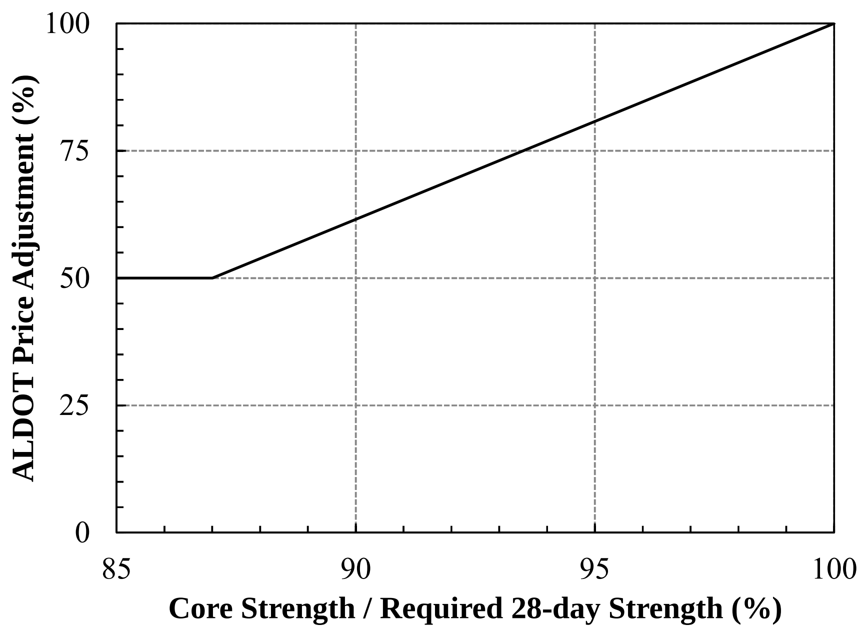


Figure 1-1: ALDOT Item 501.05 price adjustment

The price adjustment chart used by the ALDOT, shown in Figure 1-1, demonstrates that ALDOT does agree with ACI 318 (2011) in accepting an average core strength of $0.85f'_c$; however, ALDOT applies a price adjustment as the core strength decreases relative to the required 28-day strength. For core strength between 85 and 87 percent of the required 28-day strength, the price adjustment is 50 percent.

Variables that may affect core strength include mixture proportions, concrete age, core length-to-diameter ratio (l/d), core diameter, aggregate type and size, moisture condition, coring orientation, and damage from cutting operations (ACI 214 2010; Arioz et al. 2007a; Khoury et al. 2014) . If specimen size affects strength, then correction factors should be considered. In many standards and guidance documents, correction factors are listed for various specimen geometries, but this effect is not acknowledged in all standards. Due to areas of highly congested reinforcement, ALDOT commonly cuts cores smaller than the minimum core diameter of 3.75 in. required by American Association of State Highway Transportation Officials (AASHTO) T 24 (2007). Additionally, AASHTO T 24 (2007) does not recommend l/d strength correction factors for strengths above 6,000 psi. However, ALDOT constructs many structures with strengths above 6,000 psi.

1.2 PROJECT OBJECTIVES

This project has been developed so that ALDOT can implement a reliable and specific procedure for evaluating core strength results. The procedure will account for the most significant variables affecting the in-place strength for apply strength adjustment factors to calculate a value that can be directly compared to the specified 28-day compressive strength. The experimental work and research described in this report has been performed to address the following primary objectives:

- Evaluate the effect of core l/d on concrete strengths greater than 6,000 psi
- Evaluate the effect of core l/d on concrete strengths based on core diameter size
- Assess the effects of core diameter on core strength
- Assess the effects of coring orientation relative to the concrete placement direction on core strength
- Evaluate the effects of coarse aggregate size on core strength based on the core geometry
- Evaluate the damage due to drilling and trimming core specimen
- Evaluate variables affecting concrete strength (moisture conditioning, microcracking, and temperature)

The findings will be used as part of a larger study to develop a procedure for calculating the in-place strength that can be directly compared to the specified 28-day compressive strength and provide recommendations for ALDOT core testing.

1.3 RESEARCH APPROACH

The research approach consisted of two primary phases of experimental work. The first experimental phase consisted of ready-mixed concrete delivered to the Auburn University Structural Laboratory to evaluate the effects of l/d on core strength. The second experimental phase was performed in the field to assess the effect of numerous variables and test methods for in-place concrete strength. However, this report only covers the procedures and findings for the laboratory-testing phase of this work.

Experimental core drilling and testing conformed to current ALDOT practices. All the test equipment purchased matched what ALDOT uses. Additionally, at the start of the project, a meeting was held at Auburn University with ALDOT representatives to demonstrate and ensure acceptable coring practice.

1.4 ORGANIZATION OF REPORT

Chapter 2 of this report discusses published literature that addresses multiple variables affecting in-place core strength. Chapter 3 documents the experimental plan developed for this study. Chapter 4 presents the experimental results and discussion. Chapter 5 summarizes the report and offers recommendations resulting from the experimental results. Appendix A contains the raw data collected including all average cylinder strengths and core strengths. Appendix B contains additional tables and figures used in analysis.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

Cores are generally taken from structural members to assess whether the concrete of a new structure complies with strength-based acceptance criteria or to establish the quality of in-place concrete (ACI 214 2010). Core testing is the most direct method to determine the in-place compressive strength of concrete in a structure (ACI 214 2010). Although the procedure for testing compressive strength is fairly straightforward, the factors affecting the strength results can be very complex. Numerous factors can affect the measured strength; thus, the following survey of literature focuses primarily on the effects directly related to core preparation, core l/d, core diameter, and core orientation in relation to placement direction. Knowledge regarding these topics is reviewed in this chapter.

2.2 CORE PREPARATION EFFECTS ON STRENGTH

The strength of concrete is driven by the water-cement ratio (*w/c*). Mehta and Monteiro (2014) conclude that as the *w/c* decreases, strength increases. The in-place strength of concrete is commonly estimated by testing standard 6 x 12 in. molded cylinders. When cylinder strengths are low, as per ACI 318 (2011), and the strength of a structure is in question, cores are retrieved to further investigate. Variety of variables may affect concrete strength. Microcracks in a core reduce strength (Szypula and Grossman 1990). Microcracks can occur when the structure is exposed to thermal and moisture changes while also being restrained against movement. Additionally, improper or rough handling of the core specimen can also cause microcracking (ACI 214 2010).

Theoretically, concrete gains strength over time. At early ages, the strength development is rapid, but at later ages the strength gain is much slower. However, there are many factors that affect strength development. The following subsections cover effects of materials and core preparation procedures used for this project on strength.

2.2.1 AGGREGATE TYPE AND SIZE

The nominal maximum size of the coarse aggregate in a concrete mixture is selected based on a design criteria and availability. Test results have shown that larger sizes of coarse aggregates can cause a gradual decrease in relative core strength, but this effect is less significant at later ages (Arioz et al. 2007a). This may be caused by the effects of cutting operations and the presence of the interfacial transition zone (ITZ). Due to bleed water, the *w/c* surrounding the coarse aggregate is marginally increased creating a weakened membrane around the coarse aggregate (Mehta and Monteiro 2014). The ITZ is one of three components of concretes microstructure and the effects that the ITZ has on core strength is discussed in greater detail in Section 2.4.1.

For specimens that have large aggregate particles in relation to the size of the specimen, the effects of any aggregate loosened by cutting will be increased (Bungey 1979). Larger aggregates will also create larger ITZ's, thus, potentially creating pop-outs and weaker areas within the specimen. In general, the larger the aggregate size and greater the local *w/c* in the ITZ, the weaker and more permeable the concrete will be (Mehta and Monteiro 2014).

2.2.2 Compressive Strength Testing Conditions

Controlling testing conditions is very important for getting accurate and precise measurements of strength. Some of the most important factors affecting compressive strength are consolidation, curing method, specimen size, capping method, and rate of loading. ACI 318 (2011) recognizes that core strengths are potentially lesser in strength than molded cylinders, which are cast to represent the quality of concrete used in a structure. Thus, it is desirable to convert a measured core strength to a value that accurately predicts the equivalent in-place compressive strength. For a given core strength result, the equivalent in-place strength can be computed using the following equation from Bartlett and MacGregor (1995) and ACI 214 (2010).

$$f_c = F_{l/d} F_{dia} F_{mc} F_d f_{core} \qquad \textbf{Equation 2-1}$$

Where,

f_c = equivalent in-place compressive strength (psi),

$F_{l/d}$ = strength correction factor accounting for core l/d effects (Table 2-3),

F_{dia} = strength correction factor accounting for core diameter size (Table 2-4),

F_{mc} = strength correction factor accounting for core moisture condition (Table 2-1),

F_d = strength correction factor accounting for effects of damage due to core drilling (Section 2.5.2), and

f_{core} = core compressive strength (psi).

2.2.2.1 Consolidation

Consolidation is performed to expel entrapped air. It is achieved by the use of vibration during placement of conventional concrete and rodding while making molded cylinders. After sufficient consolidation, strength is reduced by approximately 7 percent for each percent of volume of entrapped air (Popovics 1969). However, excessive consolidation can lead to segregation, causing a non-uniform amount of coarse aggregates to gravitate towards the bottom of the structure. This leads to higher consolidation pressures and an increase in strength for the lower portions of vertical members (Toossi and House 1981). Consolidation uniformity can be determined by visually inspecting a core specimen for segregation or by measuring the density of various cores from the same batch of concrete obtained from different elevations in the structure.

2.2.2.2 CURING CONDITIONS

The two main factors that impact strength during curing are the humidity and temperature. Controlling curing conditions is critical for minimizing shrinkage and microcracking. When high initial temperatures are generated during the hydration of cement, a non-uniform thermal gradient may be present throughout the thickness of the structure. These high initial temperatures can significantly reduce the strength of the interior regions of elements (ACI 305 2010). In Figure 2-1, Cook (1989) provides an example where concrete core strength varies between interior and exterior specimens recovered from 30 x 30 in. columns.

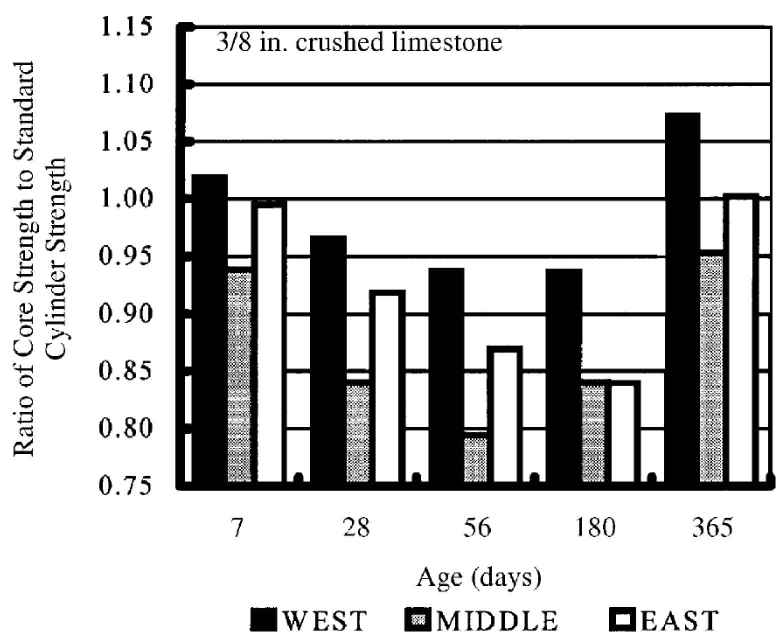
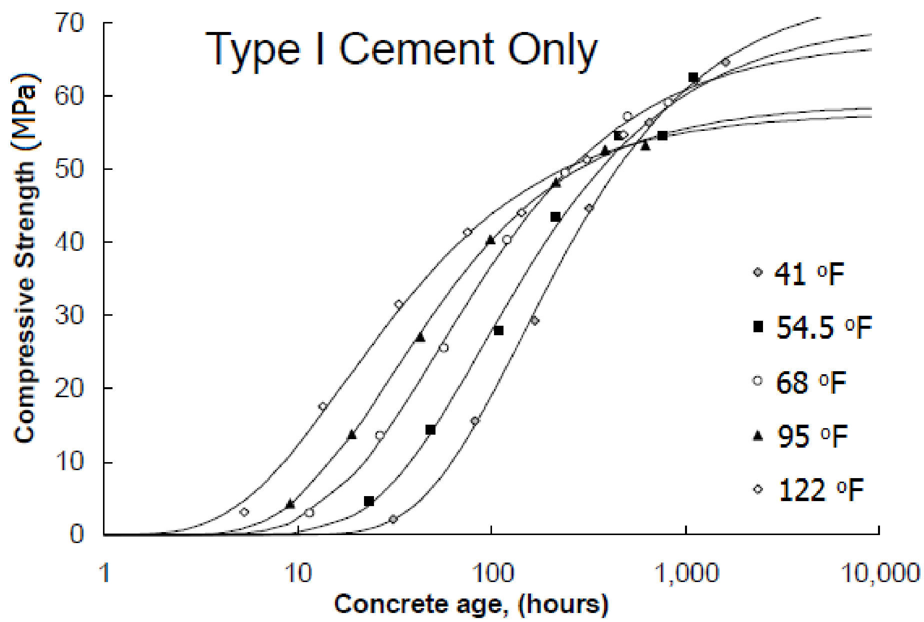


Figure 2-1: Relationships between compressive strengths of column core samples and standard-cured specimens cast with high-strength concrete (Cook 1989)

As shown in Figure 2-1, the ratio of core strength to standard cylinder strength of the middle is, in general, noticeably less than the exterior faces of the columns examined. This suggests that exterior curing methods create variation in temperature conditions throughout a structure. Based on Figure 2-1, exterior faces have greater strengths than interior faces because exterior faces experience more optimal curing conditions.

Similarly, the presence of moisture has a more significant effect on the in-place strength of slabs or beams than the in-place strength of walls or columns because the unformed top surface is a relatively large fraction of the total surface area (ACI 214 2010). Through a collection of data from four studies, Bartlett and MacGregor (1996) found that the core strength from poorly cured, shallow elements averages 77 percent of the core strength from properly cured elements at concrete ages of 28, 56, 91, and 365 days. Loss of water slows down the hydration process, thus decreasing strength. Controlling the temperature is especially important when ambient temperatures are high. Shown in Figure 2-2 are the effects that temperature has on compressive strength.



*Note: 1 MPa = 145 psi

Figure 2-2: Effects of temperature on compressive strength (adapted Carino 1981)

As shown in Figure 2-2, the compressive strength gain begins at an earlier age for higher temperature concretes. Higher concrete temperatures also result in lower overall compressive strength gain.

The effects that curing can have on strength are evident when comparing core strength to standard cured cylinder strength. In accordance with AASHTO T 22 (2007) cylinders are kept in a moist curing environment at 73°F (±3 °F). However, cores are retrieved from various locations in a structure. Therefore, only the exposed surface may have directly benefited from the curing treatment on the structure. In other words, cylinder specimens receive optimal curing while cores receive variable curing conditions that depend on the structure’s exposure condition. For this reason, standard cured cylinders generally fail at greater compressive strengths.

2.2.2.3 MOISTURE CONDITIONING

In 2007, general moisture conditioning practices for drilled cores were revised in AASHTO T 24. The current standard treatment for moisture conditioning requires that the cores be wiped dry and placed into sealed bags or nonabsorbent containers no later than 1 hour after drilling and remain in sealed bags for at least 5 days after last being wetted. AASHTO T 24 (2007) requires any core to be tested within 7 days after drilling. Therefore, cores can be kept in sealed bags for 5 to 7 days. However, other common practices are to soak the core in water for 48 hours or allow the core to air-dry. To account for the effects due to these different moisture conditions, Table 2-1 from Bartlett and MacGregor (1995) and ACI 214 (2010) provides the strength correction factor that is applied to the measured core strength.

Table 2-1: Strength correction factors accounting for effects of different moisture conditioning, f_{mc} (ACI 214 2010)

Factor	Correction Factor, f_{mc}
Standard Treatment*	1.00
Soaked 48 hours in water	1.09
Dried**	0.96

*Standard treatment specified in AASHTO T 24 (2007)

**Dried in air at 60 to 70 ^{o}F and relative humidity less than 60% for 7 days

The strength correction factors provided in Table 2-1 are part of the ACI 214 (2010) standard based on findings from Neville (1981) and Bartlett and MacGregor (1994d) that suggest air-dried cores are 10 to 14 percent stronger on average than soaked cores. For soaked cores, the test specimen shall be completely submerged for 48 hours and compression tested immediately afterward. Additionally, “drying the surface causes shrinkage that, when restrained, creates a favorable residual stress distribution that increases the measured strength” (ACI 214 2010). Conversely, soaked concrete cores swell at the surface, which creates self-equilibrated stresses on the interior region that reduce the measured compressive strength (Popovics 1986).

The use of sealed bags is the standard moisture conditioning procedure and is “intended to preserve the moisture of the drilled core and to provide a reproducible moisture condition that minimizes the effects of moisture gradients introduced by wetting during drilling and specimen preparation” (AASHTO T 24 2007). A study conducted by Bartlett and MacGregor (1994a) indicated that “moisture gradients across the cross section of the test specimen appreciably affect its strength.” Bartlett and MacGregor (1994a) provide the plot of core strength versus moisture gain shown in Figure 2-3.

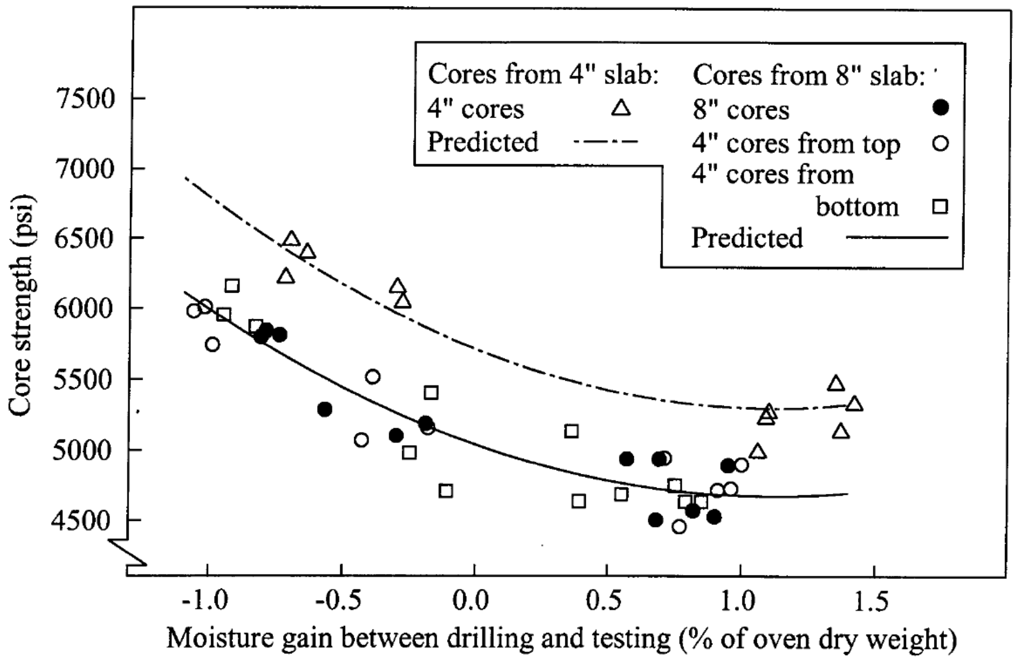


Figure 2-3: Partial regression plot of core strength versus moisture gain (Bartlett and MacGregor 1994a)

From Figure 2-3, it can be concluded that cores from the 4 in. slab were noticeably stronger than those from the 8 in. slab. This suggests that a marginal increase in moisture gain during moisture conditioning decreases the compressive strength of a core specimen. There is also an observed difference between the strengths of the cores from the top and bottom of the 8-in. slab. The figure presents the data for 4 in. diameter specimens trimmed in the following four categories: 8 in. cores, 4 in. cores from the top of the 8 in. slab, 4 in cores from the bottom of the 8 in. slab, and 4 in. cores from the 4 in. slab.

2.2.2.4 SULFUR CAPPING

To ensure that concrete specimens meet AASHTO T 22 (2007), specimen ends must be perpendicular to the axis by 0.5° and plane within 0.002 in. If specimen ends are not perpendicular to the axis, then this will lead to load eccentricities. If specimen ends are not plane, then it can lead to the development of stress concentrations within the specimen. Common methods for preparing ends are to (a) saw and then grind, (b) cap using sulfur capping compound, or (c) cap using neoprene pads.

2.2.2.5 Rate of Loading

The rate at which a load is applied during the compressive strength test is controlled by the machine operator. AASHTO T 22 (2007) states “the load shall be applied at a rate of movement corresponding to a stress rate on the specimen of 35 ± 7 psi/s.” The required rate of movement will depend on the size of the test specimen, the elastic modulus of the concrete, and the stiffness of the testing machine (AASHTO T 22 (2007). To get the most precise test results, it is best to use as few machine operators as possible.

2.3 Size Effects on Core Strength

As introduced in Section 2.2.2, ACI 214 (2010) has adopted a method for evaluating core strength based on various size, moisture, and core damage parameters. The following subsections will explain the strength correction factors accounting for effects due to core l/d and core diameter. However, the method in ACI 214 (2010) was derived empirically from test results (Bartlett and MacGregor 1994b), therefore, is not universally accepted (ACI 214 2010). Thus, additional references are reviewed in this section to further investigate the effects that core size has on the measured compressive strength.

2.3.1 Effects of Length-to-Diameter on Core Strength

The measured strength of a core taken from a given concrete structure depends on its l/d (Munday and Dhir 1984). As per AASHTO T 24 (2007), the preferred l/d of the capped or ground specimen is between 1.9 and 2.1. In thin elements or regions congested with reinforcement, it can be difficult to obtain a core with l/d between 1.9 and 2.1. AASHTO T 24 (2007) states “core specimens with l/d less than 1.75 require corrections to the measured compressive strength.” In addition, “a core having a maximum length of less than 95 percent of its diameter before capping or a length less than its diameter after capping shall not be tested” (AASHTO T 24 2007). Since core specimens can vary in geometry and size, strength correction factors have been developed to account for cores with l/d ranging from 1.0 to 1.75. A l/d strength correction factor converts any measured core strength with a l/d between 1.0 and 1.75 to the predicted core strength if that specimen’s l/d was 2.0. Strength correction factors for l/d were first recommended in 1927, and Table 2-2 presents the revised factors that have been used since in the American Society for Testing and Materials (ASTM) C42 (2012).

The current values shown in Table 2-2 are also the values used in AASHTO T 24 (2007). Based on the values provided in this table, the effect of the l/d on strength is more pronounced for stockier cores. Thus, the measured strength actually decreases, as the *l/d* increases, which is due to the effect of specimen shape on stress distributions (Khoury et al. 2014). Suggested core *l/d* strength correction functions are plotted in Figure 2-4.

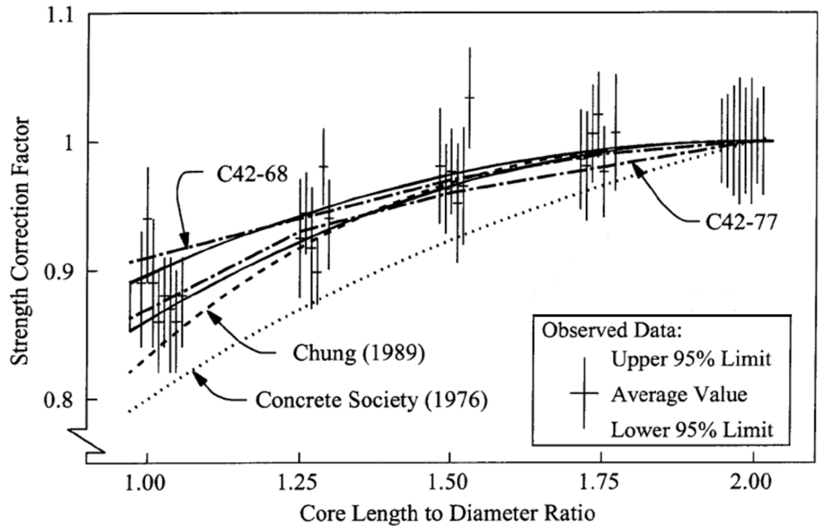
In Figure 2-4, the observed and predicted core *l/d* strength correction factors from various sources are plotted together on two graphs for either dry or wet cores. The figure presents the strength correction factor data collected by Bartlett and MacGregor (1994b). The strength correction factors suggested by ASTM C42-77 are also the values used in AASHTO T 24 (2007) and are the most present factors suggested by ASTM C42 (2012), as shown in Table 2-2.

The most current core *l/d* strength correction factors used in AASHTO T 24 (2007) were developed under a cooperative research study between the North Carolina Department of Transportation (NCDOT), the National Sand and Gravel Association (NSGA), and the National Ready Mixed Concrete Association (NRMCA). All of the cores of this study were 4 in. in diameter. The core strength test results averaged a coefficient of variation of approximately 5 percent for the project (Meininger et al. 1977). The correction factors provided in AASHTO T 24 (2007) are widely used; however, the standard states that these are only appropriate for concrete strengths between 2,000 and 6,000 psi.

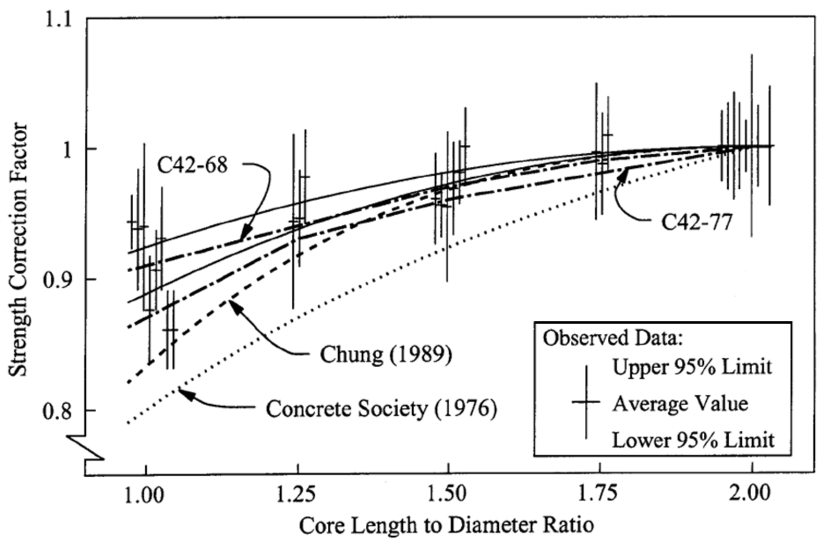
Table 2-2: Core ***l/d*** strength correction factors recommended by ASTM C42

Edition of ASTM C42	**Specimen length-diameter ratio, *l/d***			
	1.0	**1.25**	**1.5**	**1.75**
1927	0.85	0.94	0.95	0.98
1949	0.85	0.94	0.96	0.98
1961	0.89	0.94	0.96	0.98
1968	0.91	0.94	0.97	0.99
1977-present	0.87	0.93	0.96	0.98

Note: Interpolate between values



(a): Observed and predicted correction factors for dry cores



(b): Observed and predicted correction factors for wet cores

Figure 2-4: Observed and predicted correction factors (adapted from Bartlett and MacGregor 1994b)

2.2.3.1 LENGTH-TO-DIAMETER CORRECTION FACTORS FOR HIGH-STRENGTH CONCRETE

There are few published documents that explore core *l/d* strength correction factors for high-strength concretes. A project was conducted by Bartlett and MacGregor (1994b) to establish correction factors for concrete strengths between 2,000 and 14,000 psi. In their study, Bartlett and MacGregor (1994b) tested core diameters of 4 inches. Bartlett and MacGregor (1994b) collected the raw data used by Meininger et al. (1977), as discussed in Section 2.3.1, and additional data from the University of Alberta for their analyses. Figure 2-5 and Figure 2-6 provides the core location for the specimens used in the analysis.

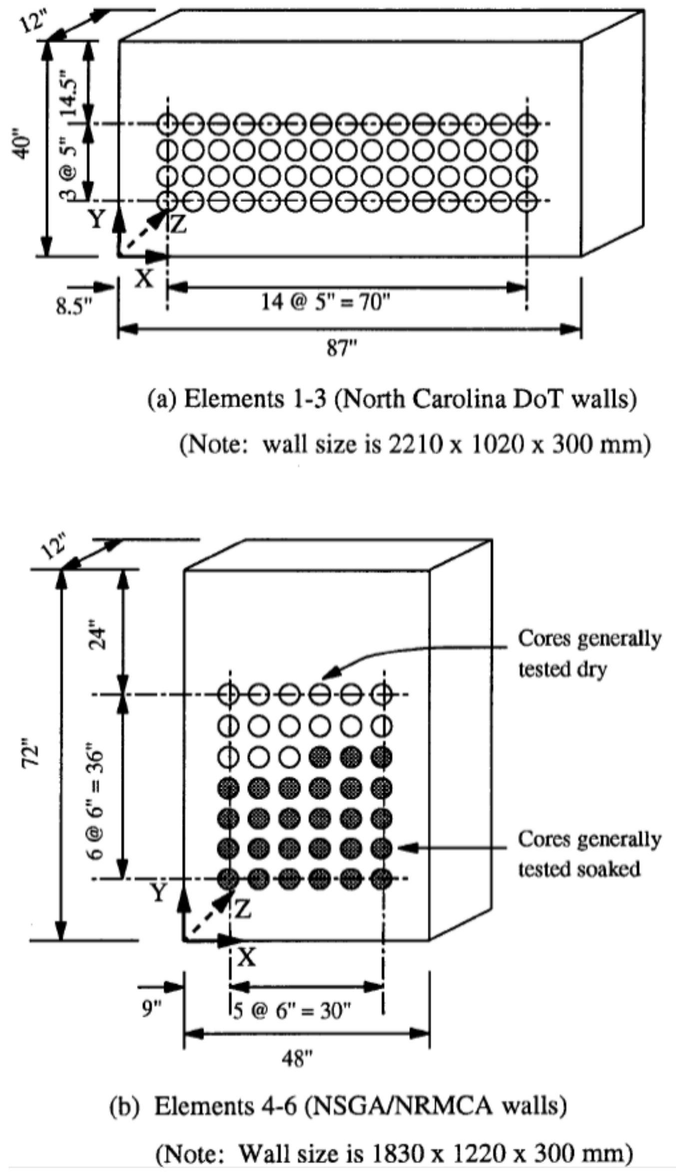
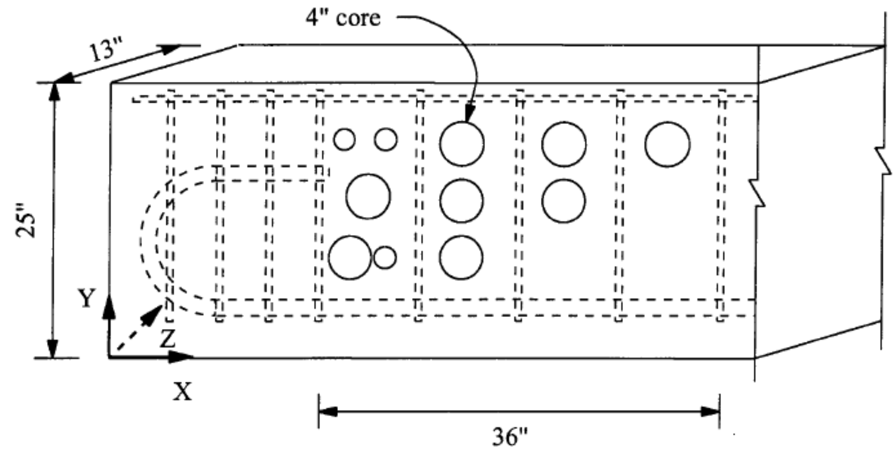


Figure 2-5: Element dimensions and core locations (Bartlett and MacGregor 1994b)

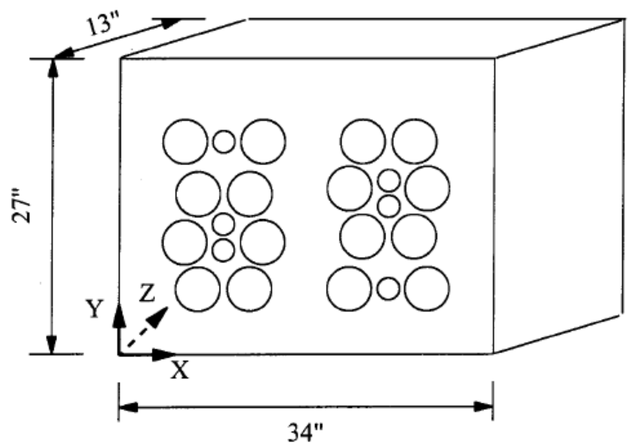
Each element was laid on its side, relative to original casting position and cores were drilled perpendicular to the casting direction, vertically through the 12 or 13 in. thickness. In a later publication, Bartlett and MacGregor (1995) developed a procedure for evaluating core strength and derived strength correction functions that are shown in Table 2-3.

The functions accounting for the effects due to core *l/d* in Table 2-3 are valid for concrete strengths between 2,000 and 14,000 psi and were adopted by ACI 214 (2010). Based on these functions, Bartlett and MacGregor (1994b) conclude that as the concrete strength increases, correction factors closer to 1.0 are appropriate.



(c) Elements 7 and 8 (University of Alberta beams)

(Note: Region cored is 910 x 640 x 330 mm)



(d) Elements 9 and 10 (University of Alberta blocks)

(Note: Block size is 860 x 690 x 330 mm)

Figure 2-6: Element dimensions and core locations (Bartlett and MacGregor 1994b)

Table 2-3: Core strength correction factors accounting for effects due to $\boldsymbol{l/d}$, $f_{l/d}$ (ACI 214 2010)

Factor	Correction Factor, $f_{l/d}$
Standard Treatment*	$1 - \{0.120 - \alpha f_{core}\}(2 - l/d)^2$
Soaked 48 hours in water	$1 - \{0.117 - \alpha f_{core}\}(2 - l/d)^2$
Dried**	$1 - \{0.144 - \alpha f_{core}\}(2 - l/d)^2$

*Standard treatment specified in AASHTO T 24 (2007)

**Dried in air at 60 to 70 °F and relative humidity less than 60% for 7 days

+Constant α equals $3(10^{-6})$ 1/psi for f_{core} in psi

2.2.3.2 SHORT CORES

In practice, there may be advantages or favoritism given to testing short specimens. For instance, short specimens take less time to drill, are easier to handle, and leave a smaller void to be patched. As mentioned in Section 2.3.1, AASHTO T 24 (2007) requires cores have a capped l/d greater than or equal to 1.0. However, when analyzing core strength data, it should be noted that short specimens fail at greater loads due to the end restraint caused by the steel loading platens of the testing machine (Ottosen 1984). This means almost the entire specimen is in a state of triaxial compression (Ottosen 1984). This is possibly the reason for such pronounced effects on l/d of short cores, as mentioned in Section 2.3.1.

2.3.2 EFFECTS OF CORE DIAMETER

When concrete is subject to stress, it is generally accepted that the larger the volume is, the more probable it is to contain a component of an extreme low strength (Neville 1995). This concept is known as the weakest link theory (Bartlett and MacGregor 1994c). Thus, as the specimen size is increased, its measured compressive strength decreases. However, concrete cores differ from molded specimens because their surfaces may be damaged during removal from the hardened concrete; therefore, small cores should be weaker and more variable than large cores (Bartlett and MacGregor 1994c). However, in core testing, it has been found that as the diameter decreases, the compressive strength of the core gradually decreases (Arioz et al. 2007b). Khoury et al. (2014) state that “as the diameter decreases, the ratio of cut surface area to volume increases, and hence the possibility of strength reduction due to cutting damage increases.” This behavior is evident in Figure 2-7 and Figure 2-8.

Another concept commonly paired with strength effects due to specimen diameter is systematic bias caused by testing procedures. The notion behind systematic bias from testing is that small specimens are experiencing more stiffness relative to large specimens. This may cause a greater ultimate strength for small specimens because a relatively stiff machine will tend to release energy at a rate that the specimen can tolerate (Neville 1981). However, the data investigated by Bartlett and MacGregor (1994c) “indicate that the effect of damage to the cut surface of the core counteracts and overwhelms any effect that might be inferred by the weakest link theory or attributed to systematic bias caused by testing procedures.”

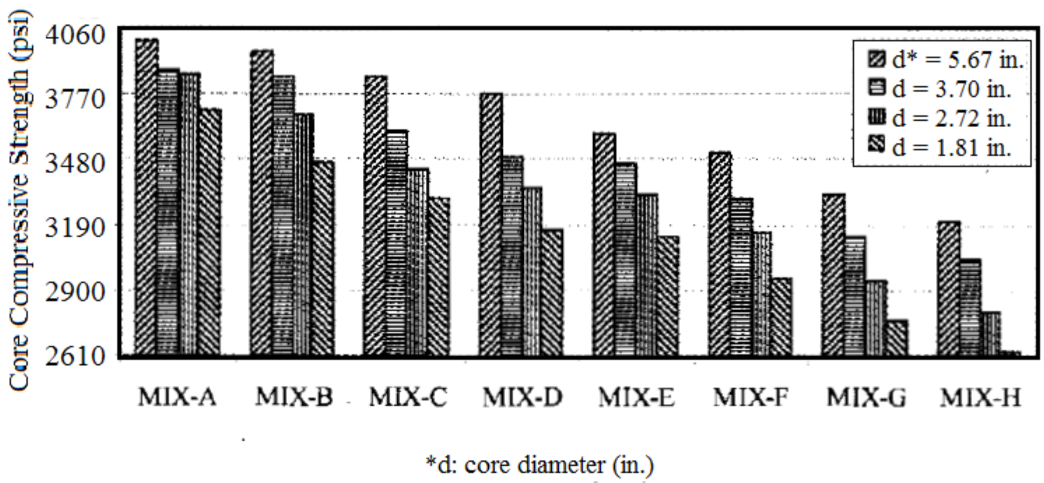


Figure 2-7: Compressive strengths of different diameter cores with ***l/d*** of 2.0 (adapted from Arioz et al. 2007a)

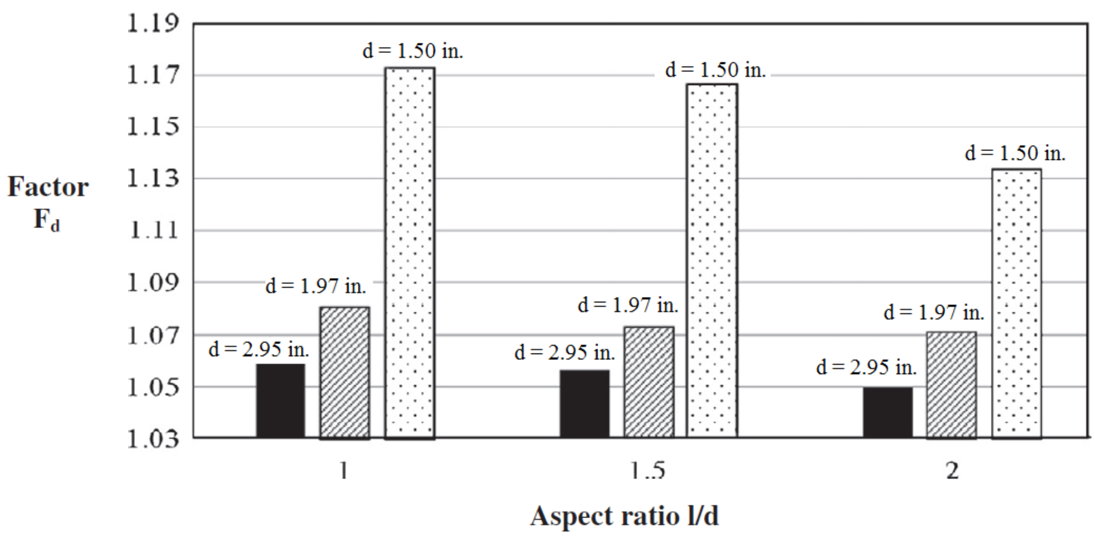


Figure 2-8: Effect of core diameter on core strength for different aspect ratios (adapted from Khoury et al. 2014)

It can be seen in Figure 2-7 that the core compressive strength decreases as the core diameter size decreases. In Figure 2-8, Factor F_d, on the vertical axis is the suggested value required to correct the measured strength. The average strength correction ranges from 1.05 to 1.08 in for core diameters 1.97 and 2.95 in. For the 1.50 in. diameter cores, the strength correction ranges from 1.13 to 1.17. Therefore, as the core diameter decreases, the measured strength decreases. In contrast, Meininger (1968) and Lewis (1976) have concluded that core diameter does not have an effect on core strength. In any case, careful alignment of the specimen in the testing machine is necessary when testing small-diameter cores (ACI 214 2010).

2.3.2.1 Applying Core Diameter Correction Factors

To convert a compressive strength test result to an equivalent strength for standard core size, ACI 214 (2010) recommends applying a correction factor to account for the effects of core diameter. The strength correction factors from ACI 214 (2010) are provided in Table 2-4. Take note that there is a strength correction factor of 1.00 needed for a core diameter of 4 inches, as this is the assumed standard core diameter for ACI 214 (2010). In addition, the difference in correction factor as the core diameter is greater than 4 inches is much more pronounced than when the core diameter is less than 4 inches. Plotted descriptions of the above statements are provided in Figure 2-9.

Table 2-4: Strength correction factors accounting for effects of core diameter, f_{dia} (ACI 214 2010)

Factor	Correction Factor, f_{dia}
2 in.	1.06
4 in.	1.00
6 in.	0.98

Note: Interpolate between values

Figure 2-9 displays regression results comparing the normalized average core strength for core diameters of 2, 4, and 6 in. cores with standard cylinder strengths between 1,440 and 13,400 psi, all having l/d of 2. The 2 in. diameter data has more dispersion than the 6 in. diameter data. The plot suggests that the normalized average strength increases as the core diameter increases. All values were forced to go through normalized average core strength of 1.0 for 4 in. diameter cores by dividing the average strength of cores of each diameter by the average strength of companion cores with 4 in. diameter (Bartlett and MacGregor 1994c). Figure 2-9 compares very well to Table 2-4, suggesting "the strength of a 2 in. diameter core with l/d of 2 is predicted to be 94 percent of the strength of a 4 in. diameter core or 92 percent of the strength of a 6 in. diameter core" (Bartlett and MacGregor 1994c).

A study conducted by Arioz et al. (2007b) suggests core l/d strength correction factors should be different depending on the core diameter. The investigation included correction factors for l/d = 0.75, however, AASHTO T 24 (2007) requires no specimen shall have a capped l/d less than 1.0, as mentioned in Section 2.3.1.2. The strength correction factors from Arioz et al. (2007b) for core diameters of 5.66 in., 3.70 in., 2.71 in., and 1.81 in. for various mixtures are shown in Figure 2-10 and Figure 2-11. The mixture proportions used for the study by Arioz et al. (2007b) are provided in Table 2-5. A total of 1,876 core specimens were tested in this investigation by Arioz et al. (2007b).

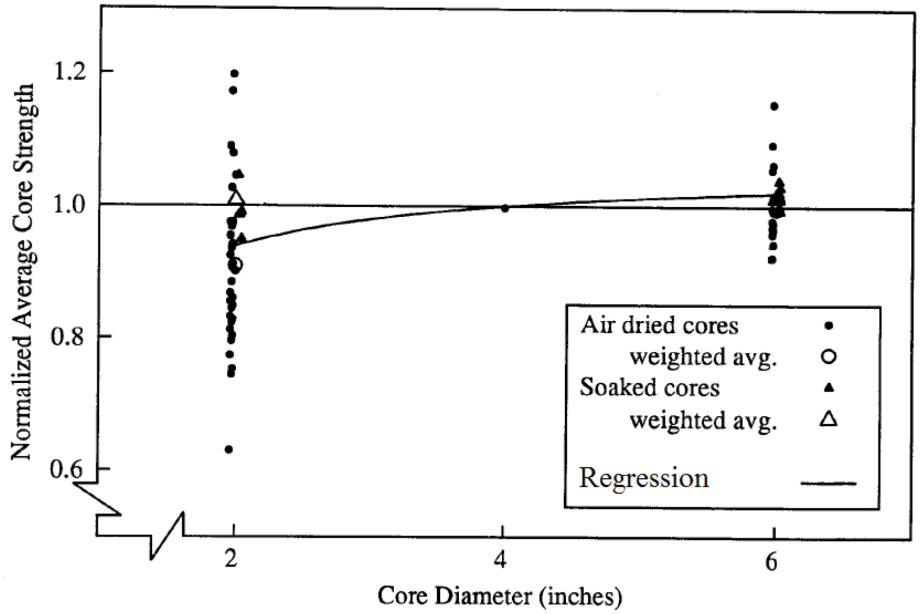
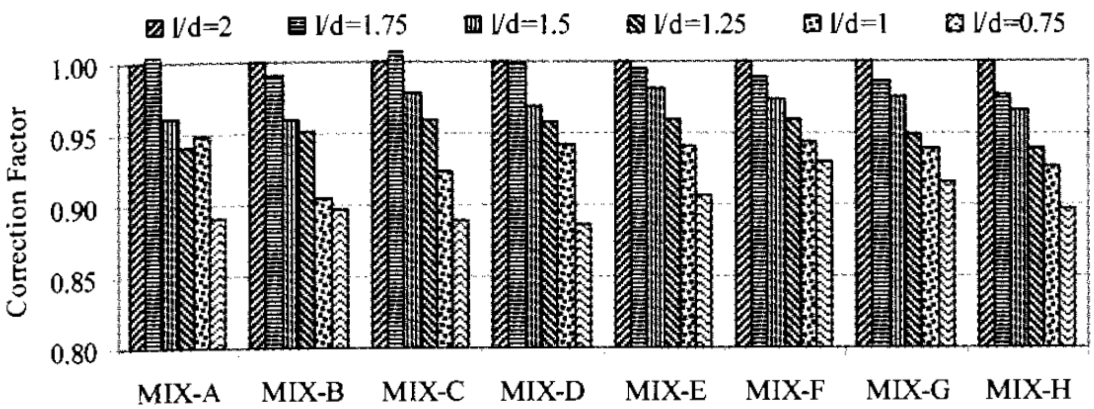
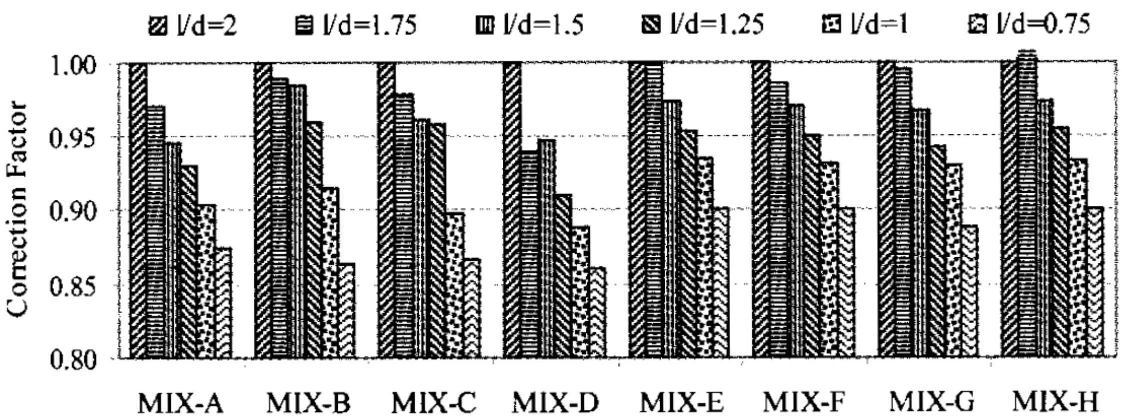


Figure 2-9: Normalized average core strength versus core diameter (adapted from Bartlett and MacGregor 1994c)

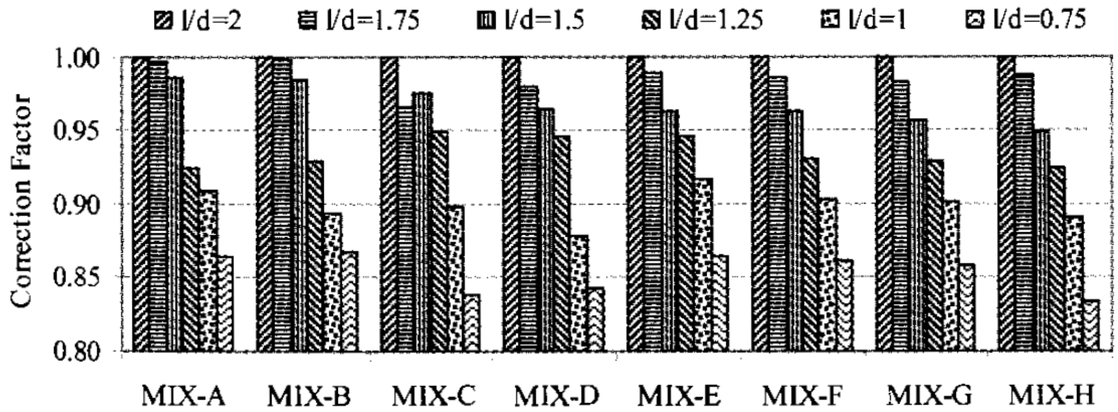


a) 5.66 in. diameter cores

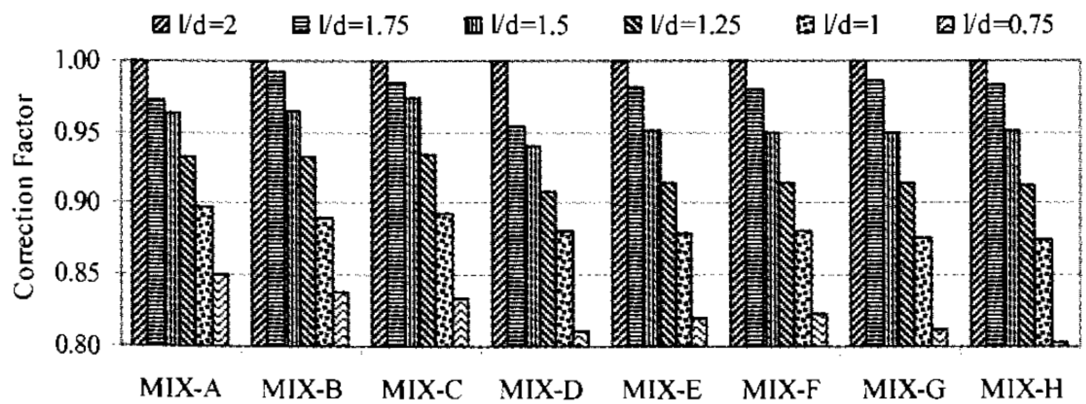


b) 3.70 in. diameter cores

Figure 2-10: Core strength correction factors for ***l/d*** ratios for a) 5.66 in., b) 3.70 in. diameter cores (Arioz et al. 2007b)



a) 2.71 in. diameter cores



b) 1.81 in. diameter cores

Figure 2-11: Core strength correction factors for ***l/d*** ratios for a) 2.71 in., and b) 1.81 in. diameter cores (Arioz et al. 2007b)

Table 2-5 provides the 28-day cube compressive strength of each mixture used in the study by Arioz et al. (2007b). The strength range is approximately 3650 to 4120 psi. In general, the data in Figure 2-10 and Figure 2-11 show that for each mixture, the correction factor decreases as the core *l/d* decreases. To minimize error introduced by the strength correction factors, it is preferable to obtain specimens with nominal diameters of 4 and 6 in. and *l/d* between 1.5 and 2.0 (Neville 2001).

Table 2-5: Proportions, some properties, and designations of concrete mixtures (adapted from Arioz et al. 2007a and Arioz et al. 2007b)

Mixture	Mixture Proportions, lb/yd^3						Some Properties	
	SSD[a] Coarse Agg.[b]	SSD[a] Fine Agg.[b]	Cement	Water	*w/c*	Agg.[b] Type	MSA[c] (in.)	28-day cube compressive strength (psi)
MIX-A	1173	1758	600	362	0.60	Crushed L.S.	0.39	4118
MIX-B	1229	1844	558	337			0.59	4075
MIX-C	1743	1426	531	320			0.87	3973
MIX-D	1901	1268	531	320			1.18	4031
MIX-E	855	2122	600	329	0.55	Natural Agg.[b]	0.39	3857
MIX-F	1404	1675	558	305			0.59	3799
MIX-G	1952	1190	531	292			0.87	3712
MIX-H	2191	952	531	292			1.18	3654

[a]SSD = Saturated surface dry

[b]Agg. = Aggregate

[c]MSA = Maximum size of aggregate

In a study by Bartlett and MacGregor (1994c), data reported by Yip and Tam (1988) were investigated to determine whether the diameter effect is constant for various l/d's on cores. Average values for 2 in. and 4 in. diameter cores trimmed to l/d of 1.0, 1.5, and 2.0 from 12 different concretes were examined. A histogram of the observed ratios of the average 2 in. diameter core strength to average 4 in. diameter core strength is shown in Figure 2-12 and the linear relationship that fits the average values is provided in Equation 2-2.

$$R = 1.091 - 0.102\,(l/d)$$ **Equation 2-2**

Figure 2-12 presents a wide scatter of data but based on the average values at each l/d analyzed, a linear relationship has been established. Equation 2-2, R, is a linear fit of the observed ratios of the average 2 in. diameter core strength to average 4 in. diameter core strength. The analyzed data suggest that the effect of diameter on strength may be negligible for short cores and more significant for cores with l/d of 2.0. Equation 2-2 implies that the effect of l/d on core strength is more significant for 2 in. diameter cores than for 4 in. diameter cores. For 2 in. diameter cores, Equation 2-2 predicts the strength at l/d of 1 to be about 20 percent larger than the strength at l/d of 2. In comparison, for 4 in. diameter cores, the strength at l/d of 1 is about 12 percent larger than the strength at l/d of 2 (Bartlett and MacGregor 1994b).

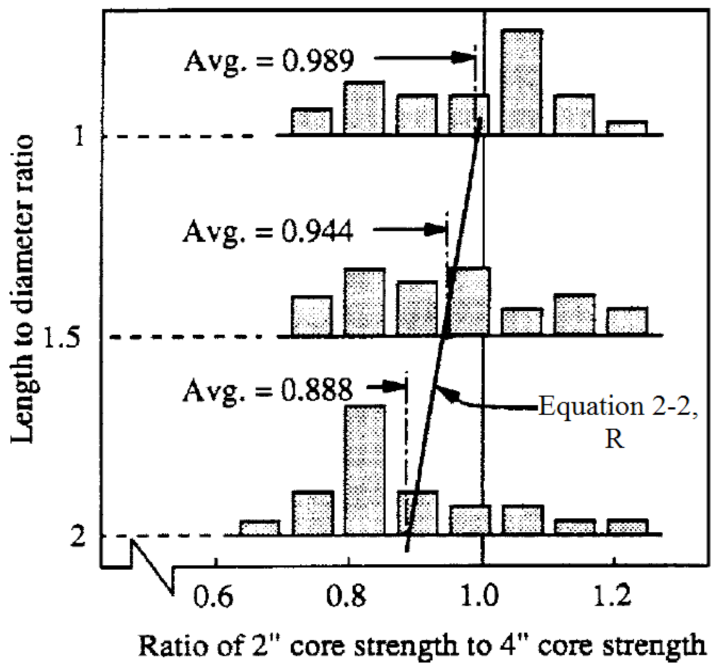


Figure 2-12: Diameter effect for cores with different ***l/d*** (Bartlett and MacGregor 1994c)

2.3.2.2 Minimum Core Diameter

The most common criticism of small-diameter cores is that they yield unreliable strength results (Bartlett and MacGregor 1994c). An example of this is provided in Figure 2-13. AASHTO T 24 (2007) specifies that the nominal diameter of core specimens for the determination of compressive strength shall be at least 3.75 in. Additionally, “core diameters less than 3.75 in. are permitted when it’s possible to obtain cores with *l/d* greater than or equal to 1 for compressive strength evaluations in cases other than load bearing situations” (AASHTO T 24 2007). In comparison, ASTM C42 (2012) requires the core diameter be “at least 3.70 in. or at least two times the nominal maximum size of the coarse aggregate, whichever is larger.” The minimum core diameter suggested by ASTM C42 (2012) is most likely recommended because of damage that may be inflicted during drilling, handling, and storing (Bartlett and MacGregor 1994c). In contrast, Munday and Dhir (1984) claim that a core diameter of 100 mm (3.93 in.) tends to be overcautious in respect to strength effects on minimum core diameter, meaning smaller diameter cores may be employed with little effects on strength.

In Figure 2-13, the coefficient of variation (COV) generally increases as the core diameter decreases. This agrees with Bartlett and MacGregor (1994c) that while the variance in force seems to be constant, the relative effect on the overall core strength is certainly more pronounced for cores with small diameters.

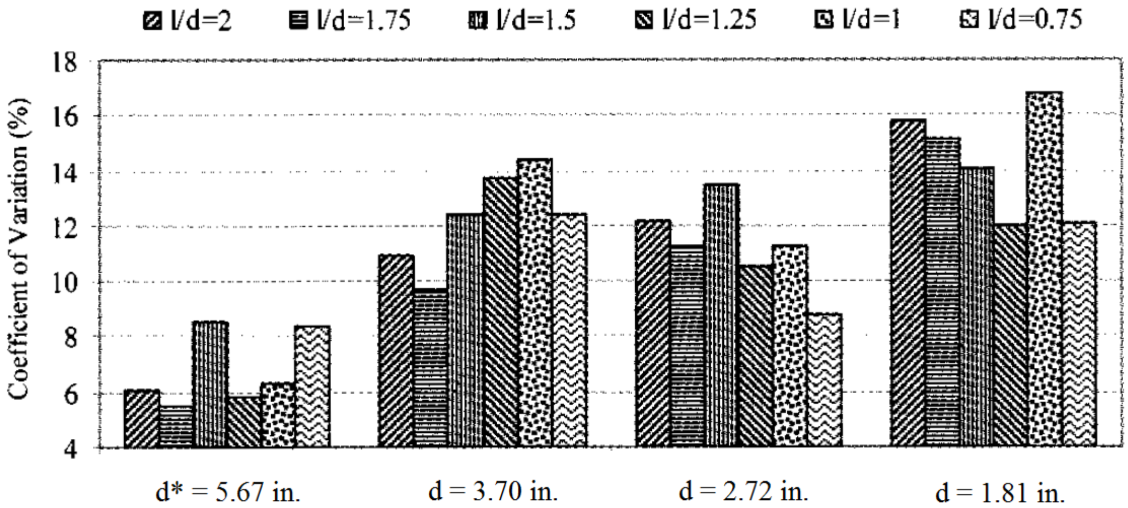


Figure 2-13: Coefficient of variation value of the core strengths (adapted from Arioz et al. 2007b)

Aggregate size may have a larger effect on small cores because any weakened zone due to core damage is proportionally larger for small-diameter cores than for large-diameter cores. In the study by Arioz et al. (2007a), cores having crushed limestone coarse aggregate with a maximum sizes of 0.39, 0.59, 0.87, and 1.18 in. were tested at 7, 28, and 90 days. Results of this analysis are shown in Figure 2-14.

From Figure 2-14, as the maximum aggregate size increases, the core strength generally decreases. It can also be observed from this figure that as the core diameter decreases, the strength ratio slightly decreases. Small-diameter cores are also more sensitive to the spatial variability of the in-situ concrete strength (Bartlett and MacGregor 1994c).

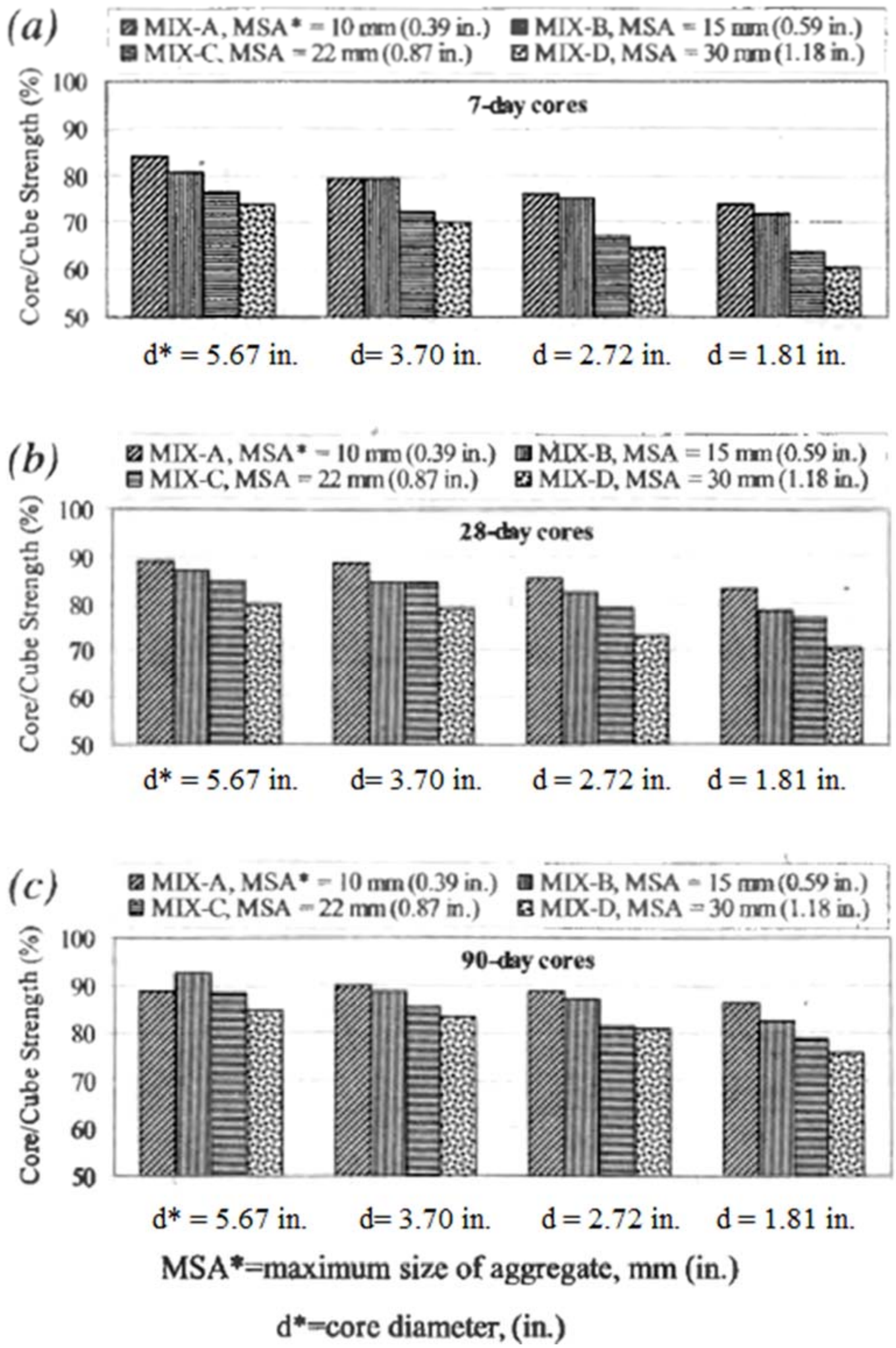


Figure 2-14: Relative strengths of cores having various core diameter and maximum aggregate size (adapted from Arioz et al. 2007a)

2.4 CORE ORIENTATION RELATIVE TO CONCRETE PLACEMENT DIRECTION

Cores can be taken from any angle but are most commonly taken either parallel or perpendicular to the casting direction in which the concrete was placed. This presents the question of whether concrete core specimens are anisotropic or isotropic? Anisotropic is the property of being directionally dependent, whereas, isotropic is the property of being identical in all directions. Information regarding the anisotropic behavior of concrete with respect to its compressive strength has been found in published documents since 1940 or earlier (Johnston 1973). The conclusions expressed by different investigators are not unanimous. In fact, there are various opinions, some being directly opposite regarding the effect of coring orientation on compressive strength.

Depending on the geometry of a structure and the direction a core is taken, it may not be possible to core all the way through the structure. In that case, the core must be drilled to a sufficient depth and then broken out using a coresnap or core retrieving tool. In a study by Meininger (1968), six 4 in. diameter cores were drilled 10 in. into a wall and then broken out and trimmed to have l/d of 2. All cores were soaked 40 to 44 hours before testing. An additional six cores were drilled through the wall, three were removed from the front half and three cores were removed from the rear half of the wall. The compressive strength values for these cores are presented in Table 2-6.

Table 2-6: Effect of breaking out cores on strength (Meininger 1968)

Compressive Strength, psi		
Cores Drilled 10 in. and Broken Out	Cores Drilled Through	
	Front Half	Rear Half
2170	2275	2285
1855	1975	1905
2115	2220	2210
2075		
2275		
2130		
Average = 2105	2155	2135

From Table 2-6 it is observed that the broken-out core tested only slightly weaker than the corresponding cores drilled through. Therefore, it is concluded that the process of breaking out cores does not affect the measured strength significantly (Meininger 1968).

2.4.1 INTERFACIAL TRANSITION ZONE

The interfacial transition zone (ITZ) is one of the three phases to concrete's microstructure. This zone is formed when water films surround large coarse aggregate, which serves as a bridge between the mortar matrix and coarse aggregate particles (Mehta and Monteiro 2014). Due to the increased *w/c* surrounding the coarse aggregate particles, the ettringite and calcium hydroxide (CH) that form are relatively larger crystals than in the bulk cement paste (Mehta and Monteiro 2014). After hydration, poorly crystalline calcium silicate hydrate (C-S-H) and additional small crystals of ettringite and CH fill the empty space of the ITZ, as shown in Figure 2-15.

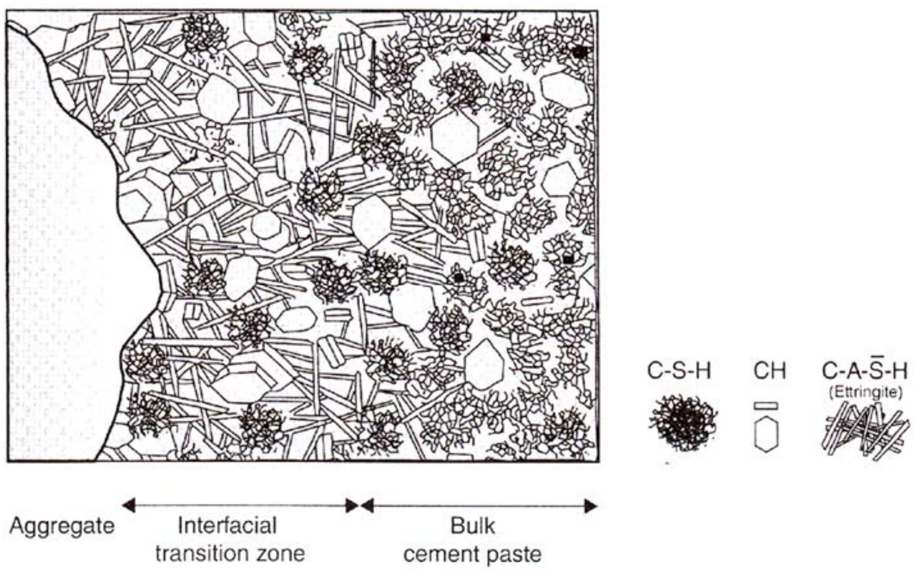


Figure 2-15: Diagrammatic representation of the ITZ and bulk cement paste in concrete (Mehta and Monteiro 2014)

Voids and microcracks in the ITZ do not permit stress transfer; therefore, the stiffness of the composite material is reduced and the ITZ is generally known as the weakest link or strength-limiting phase in concrete (Mehta and Monteiro 2014). In regards to core strength, the difference between parallel and perpendicular cores is "generally attributed to bleeding in fresh concrete, which creates weak paste pockets underneath coarse aggregates particles resulting in weak paste-to-coarse aggregate bond" (Khoury et al. 2014). A schematic illustrating the internal bleed water that develops under coarse aggregate particles is provided in Figure 2-16.

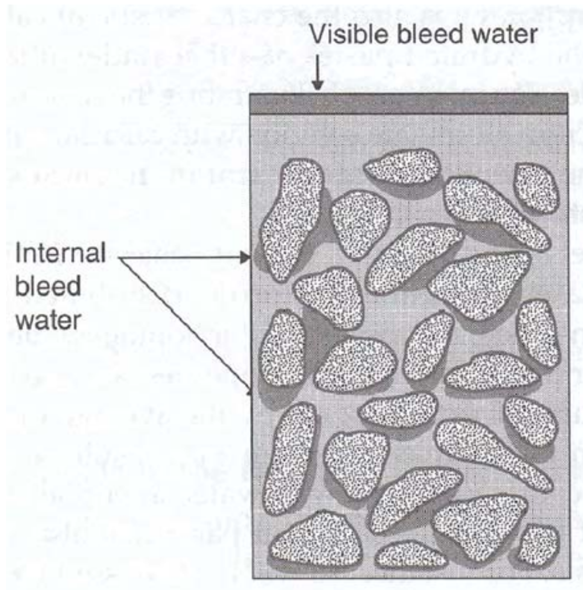


Figure 2-16: Internal bleed water that develops below coarse aggregate particles (Mehta and Monteiro 2014)

The bleed water that develops below the coarse aggregate particles in Figure 2-16 is shown for concrete that is placed vertically downward from the top of the figure. The amount of internal bleed water affects the volume and size of voids within the ITZ, affecting the overall strength of the ITZ (Mehta and Monteiro 2014). The decrease in apparent strength for cores drilled perpendicular to the concrete placement direction is attributed to moisture forming under aggregate particles, which increases stress when loaded transverse to the placement direction (Johnston 1973). Figure 2-17 illustrates the relationship between the drilled orientation and developed plane of weakness.

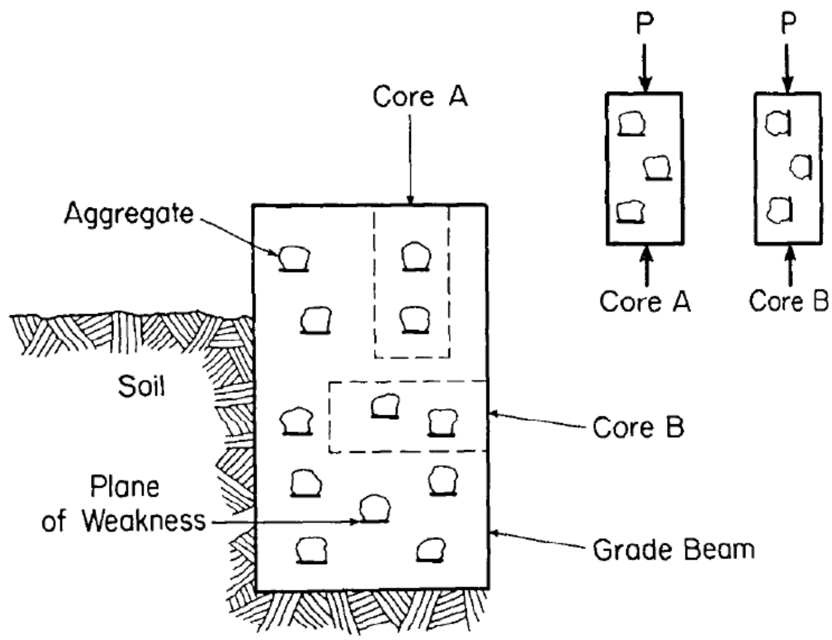
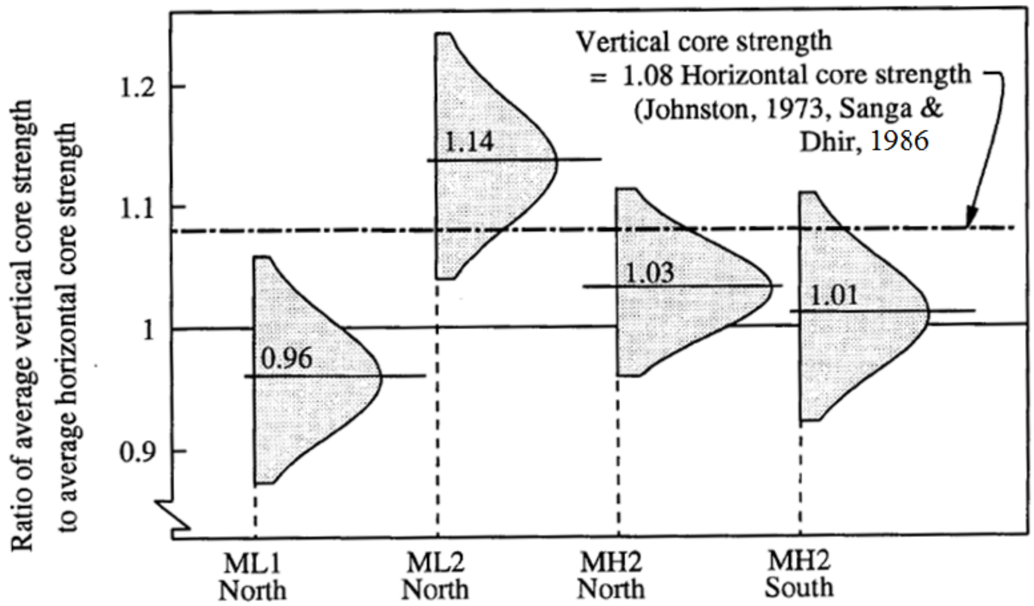


Figure 2-17: Effect of coring relative to casting direction (Suprenant 1985)

The difference in Core A and Core B in Figure 2-17, is the direction in which the plane of weakness will be tested. In a compression test, longitudinal cracks develop. Therefore, a core that was drilled perpendicular (Core B) to the concrete placement direction is tested with its plane of weakness parallel to the force being applied. In regards to compression testing Core B, the weakest interface is primarily aligned with the longitudinal cracks, thus, inducing failure (Johnston 1973). For this reason, the ITZ is commonly identified as decreasing the strength of perpendicular cores. In high-strength concrete, the matrix-aggregate bond is greater and the transition zone is more cohesive; therefore, the damage in the core specimen is low (Khoury et al. 2014).

2.4.2 LITERATURE OPPOSING ANISOTROPY

The Guide for Obtaining Cores and Interpreting Compressive Strength Results, ACI 214 (2010), does not recognize anisotropy of concrete as a significant strength influence. According to Bungey (1979), “the orientation seems to have little influence upon the variability of core results.” Bungey (1979) also found that where 10 mm (0.39 in.) maximum size aggregates are used, the relative orientation of casting and testing have an effect upon measured strength, but concluded that was likely only a reflection of the weakening of the cut surface. Bartlett and MacGregor (1994d) performed an experiment on high-performance concrete beams to investigate anisotropy. Findings from their analyses are presented in Figure 2-18.



vertical core = parallel core

horizontal core = perpendicular core

Figure 2-18: Approximate 95% confidence limits on ratio of average parallel core strength to average perpendicular core strength (Bartlett and MacGregor 1994d)

Approximate 95 percent confidence limits of the ratios of the average strength of parallel cores to the average strength of perpendicular cores are shown in Figure 2-18. The figure summarizes data from four beams. The beams are designated using two letters and one number, which are defined as

- The first letter is M for medium-sized beams (9.25 x 17.71 x 230.71 in.)
- The second letter is
    - o L for beams cast from from 7,250 psi concrete with a maximum aggregate size of 0.75 in. or
    - o H for beams cast from 13,050 psi concrete with a maximum aggregate size of 0.55 in.
- The number indicates whether the beam is the first or second cast.

The strength suggested by Johnston (1973) and Sanga and Dhir (1986) is also plotted on Figure 2-18. For the data plotted by Bartlett and MacGregor (1994d), the ML2 data set suggests that the parallel cores are approximately 14 percent stronger than the perpendicular cores. However, ML2 was cast from a ready-mixed suppliers “standard 7250 psi” product, which is the only concrete mix containing fly ash and air-entraining admixtures (Bartlett and MacGregor 1994d). Therefore, Bartlett and MacGregor (1994d) concluded that three of four cases do not differ significantly, but it is possible the strength difference of beam ML2 may be attributed to the use of either fly ash or air-entraining admixture.

2.4.3 Literature Supporting Anisotropy

The literature reviewed presenting a statistical difference in compressive strength, relative to core orientation, showed greater compressive strength results for cores drilled parallel to casting direction. The observed difference in strength shows greater average values for cores taken parallel to the cast direction ranging between 8 percent (Johnston 1973; Munday and Dhir 1984) and 18 percent (Bloem 1958). Khoury et al. (2014) also found a noticeable difference in strength, which is illustrated in Figure 2-19.

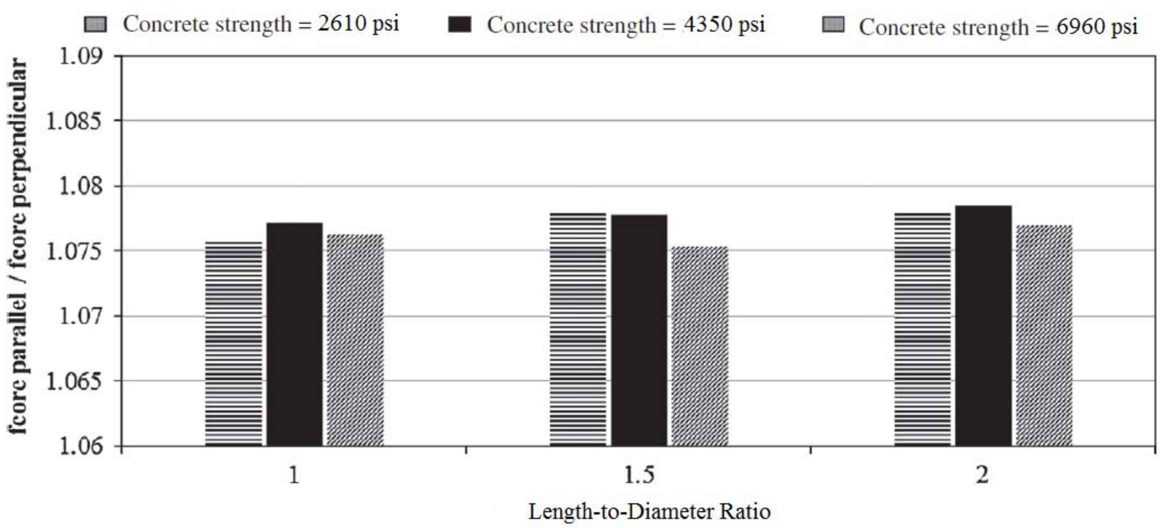


Figure 2-19: Effect of coring direction on core strength for different ***l/d*** (adapted from Khoury et al. 2014)

The ratio of strength between the parallel and perpendicular cores observed by Khoury et al. (2014) is shown Figure 2-19. The results indicate the range between the ratios is between 1.075 and 1.08. Thus, there is a noticeable difference in strength of cores taken parallel and perpendicular to the concrete placement direction. The strength difference is possibly attributed to inadequate compaction (Johnston 1973) or possibly SCMs or AEA (Bartlett and MacGregor 1994d). Additionally, the magnitude of the strength difference is independent of aggregate size, *w/c*, and slump (Johnston 1973). In Figure 2-20, the strength difference observed by Johnston (1973) and Bloem (1958) is presented. For these figures, parallel core orientation is referred to as vertical cores, and perpendicular core orientation is referred to as horizontal.

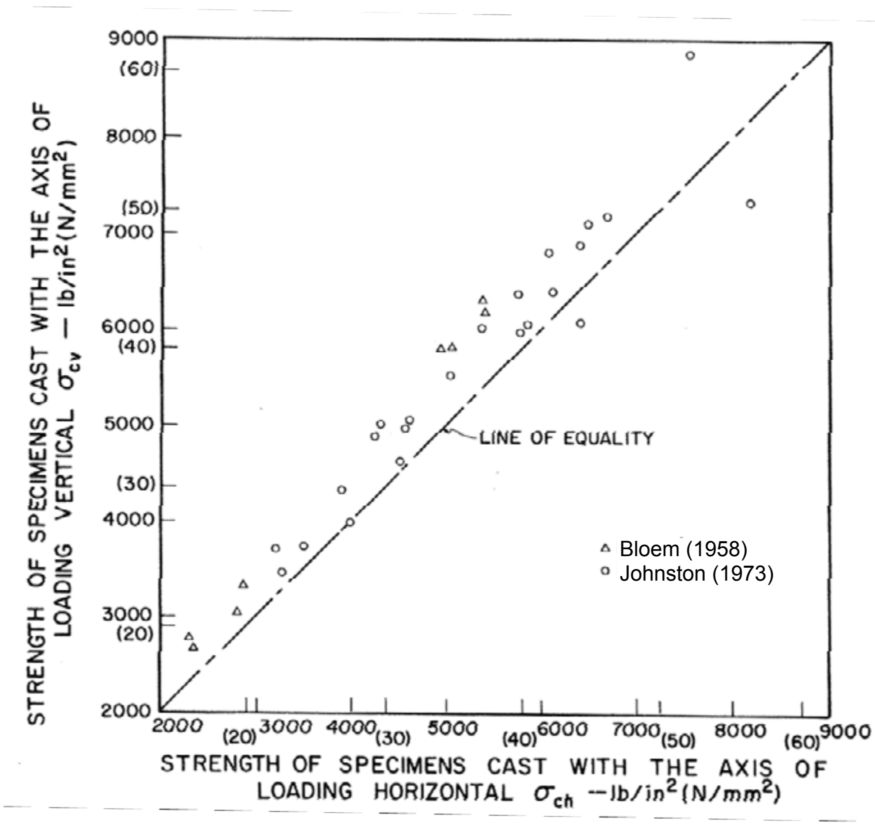


Figure 2-20: Comparative compressive strengths of specimens cast vertically (parallel) and horizontally (perpendicular) (Johnston 1973)

In Figure 2-20, almost all of the data suggest the strength of parallel cores is approximately 8 percent stronger than cores taken perpendicular to the concrete placement direction. Johnston (1973) suggests that the ITZ or capping of test specimens may be responsible for the difference between strength values.

2.5 Testing Concerns for Core Specimens

There are many reasons that compressive strength results for cores are impacted by testing conditions. As explained in Section 1.1, ACI 318 (2011) considers the average strength of three cores exceeding 0.85*f'c,* and no individual strength less than 0.75*f'c*, to be structurally adequate. Therefore, ACI 318 (2011) recognizes variability in core strength results and accepts that core strengths may be significantly less than the specified compressive strength of concrete. ACI 318 (2011) possibly accepts this decrease in apparent strength because in comparison to laboratory-cured cylinders, cores are more likely to experience insufficient curing and damage from drilling and transport. Standard cured cylinders are placed in an environment having optimal temperature and humidity, which should be optimal for strength gain. However, core specimens are retrieved from a structure; therefore, the environments and curing conditions may vary and be less optimal for strength development. In Figure 1-1 from Section 1.1, the ALDOT applies a price adjustment as the core strength per required 28-day strength decreases from 1.0*f'c* towards 0.85*f'c*. Findings from Meininger (1968), state that the average core compressive strength of 2, 4 and 6 in. diameter cores having *l/d* of 2 are 77 percent of the 28-day standard 6 x 12 in. cylinder strength. At 93 days, Meininger (1968) reports the overall average core strength was only 67 percent of the standard cylinder strength. Additionally, Bloem (1965) reports cores taken from a slab to have average strengths of approximately 88 percent of standard cylinder strengths and only 82 percent for cores taken from a column. Findings from Bollin (1993) comparing cylinder to core strength are provided in Figure 2-21 and Table 2-7.

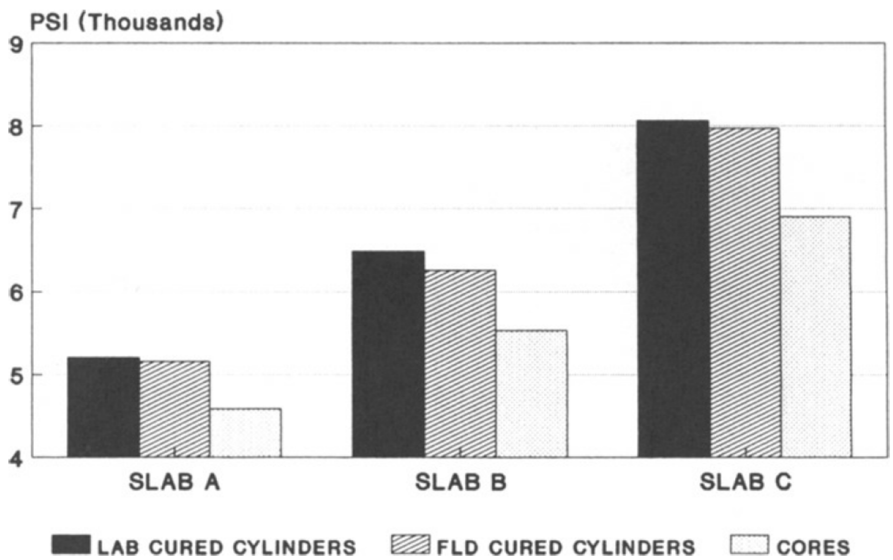


Figure 2-21: Comparison of cores with cylinders: compressive strength at 56 days (Bollin 1993)

Table 2-7: Compressive strength core/cylinder relationship (Bollin 1993)

Slab	psi
Slab A	4590/5210 = 88%
Slab B	5530/6480 = 85%
Slab C	6910/8060 = 86%

Results discussed by Bollin (1993) show that the 56-day core-to-cylinder strength relationship is reasonably close to the 85 percent core-to-cylinder relationship recommended by

ACI 318 (2011). For each slab analyzed for strength in Figure 2-22, the lab-cured cylinders have the greatest strength. This compares well to the other findings mentioned in this section and based on the reviewed literature, cores should be expected to have lower compressive strength than standard cylinders.

For the remaining subsections, additional concerns that are typically correlated with testing and analyzing cores are discussed.

2.5.1 VARIABILITY OF IN-PLACE STRENGTH

In practice, in-place concrete strength variations are unavoidable (Bartlett and MacGregor 1994c). For instance, due to effects of bleeding, the strength at the top of in-place concrete is less than the strength at the bottom (Bloem 1965). Even within the same area of a structure, strength can vary. This is most noticed in tall structures. In Figure 2-22 and Figure 2-23, the effect that the depth of a structure may have on strength is shown.

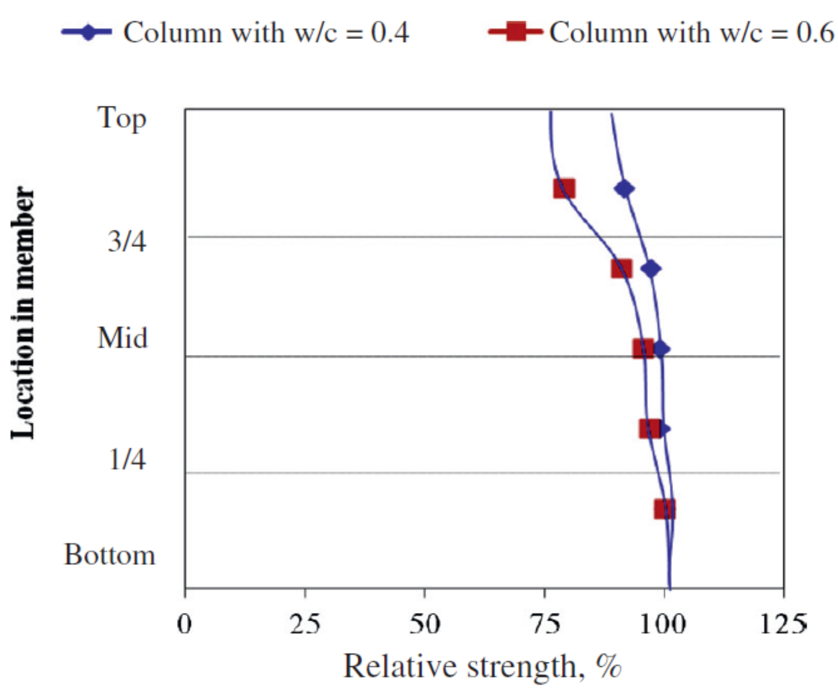


Figure 2-22: Strength variation through column’s height (Khoury et al. 2014)

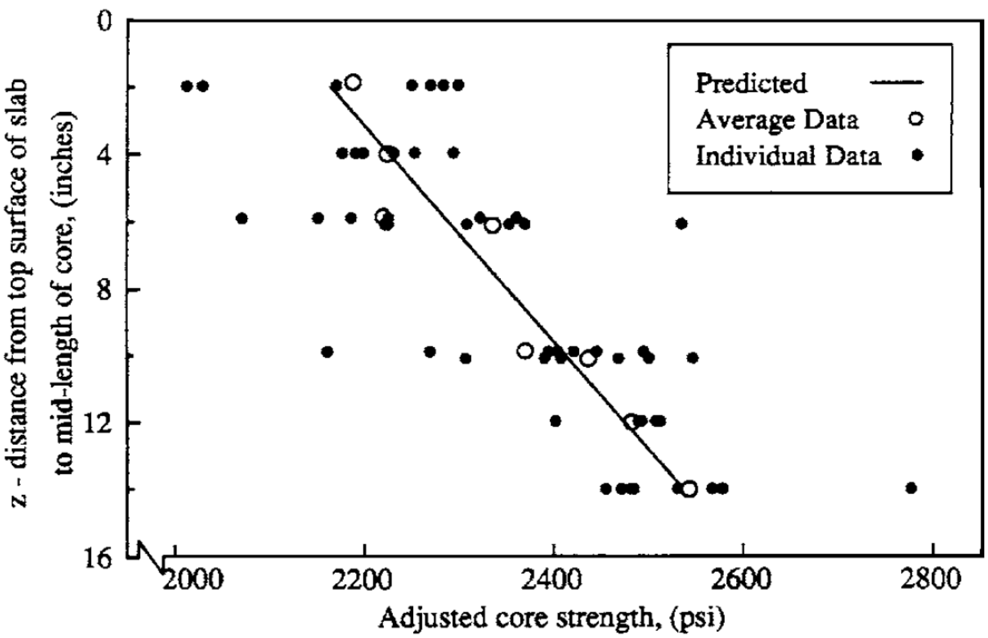


Figure 2-23: Core strength variation through slab depth (Meininger 1968)

Data shown in Figure 2-22 and Figure 2-23 suggest that the adjusted core strength increases with depth. Statistically evaluating concrete strength results is difficult to quantify due to the spatial correlation or scatter of concrete strength. Within a structure, there may be numerous batches of concrete and areas of weakness may be present. ACI 214 (2010) estimates the overall variability of in-place concrete strengths, which is presented in Table 2-8.

Table 2-8: Coefficient of variation due to in-place strength variation within a structure (ACI 214 2010)

Structure composition		**One member**	**Many members**
One batch of concrete		7%	8%
Many batches of concrete	Cast-in-place	12%	13%
	Precast	9%	10%

To limit bias in test samples, the locations from which the cores are obtained should be randomly selected (Bartlett and MacGregor 1995). Also note, as the sample size increases, the accuracy of the results improve. However, taking more cores taken a structure also increases the risk of weakening the structure (ACI 214 2010). Other factors creating variability in concrete strength are consolidation, curing conditions, and moisture conditioning, which are discussed in Sections 2.2.2.1, 2.2.2.2, and 2.2.2.3, respectively.

2.5.2 Specimen Damage on Cores Due to Cutting Operations

To account for the effect of damage sustained during drilling, ACI 214 (2010) recommends a strength correction factor F_d = 1.06, when applicable. In addition to drilling damage, this correction factor includes effects from microcracking, undulations at the drilled surface, and coarse aggregate that has been cut through and may have subsequently popped out during testing (Bartlett and MacGregor 1994a). The drilling operation weakens the bonds between the aggregate and the surrounding matrix (Khoury et al. 2014). Unfortunately, in practice, determining the magnitude of damage on a core specimen is subjective and difficult to quantify. Using a water-cooled bit to drill a core results in a moisture gradient between exterior and interior of the core that adversely affects the compressive strength (Fiorato et al. 2000). Bungey (1979) states that since “the ratio of cut surface area to volume increases as core diameter decreases, the potential influence of drilling damage upon measured strength will be greater with ‘small’ cores.” The aggregate type is commonly identified as the variable affecting the amount of damage during drilling. Since aggregates have different amounts of hardness, it is speculated that harder aggregates result in more damage during drilling.

Findings from Khoury et al. (2014) suggest that the core l/d has minimal affects on core damage but the concrete strength level has a pronounced effect on the damage occurred in core samples due to the cutting process. The matrix-aggregate bond is stronger in high-strength concrete, therefore, the transition zone is more cohesive and the damage in core specimens is low (Khoury et al. 2014). Pronounced shearing forces between the coring bit and the concrete surface are developed during coring operations, which cause greater damage to low-strength concrete as compared to high-strength concrete (Khoury et al. 2014).

2.6 Material Properties

The following subsections provide background information for the specific materials used for this project.

2.6.1 Silica Fume

Silica fume, also referred to as microsilica or condensed silica fume, is a supplementary cementing material (SCM) most often used to enhance the hardened concrete properties. It is typically used as a partial replacement, or in addition to, portland cement in amounts between 5 and 10 percent by mass of the total cementitious material (Kosmatka and Wilson 2011). Silica fume results from the reduction of high-purity quartz with coal in an electric-arc furnace as an industrial by-product of the manufacture of silicon or ferrosilicon alloy. It is noncrystalline, containing 85 to 95 percent silicon dioxide (Mehta and Monteiro 2014). The cost of SCMs is typically driven by the local availability, but in general, silica fume is 115 to 130 percent of the cost of cement. Although silica fume is more expensive than portland cement, it can still be economical when used in small proportions because of its unique physical properties. Silica fume is approximately 100 times finer than average portland cement particles (Kosmatka and Wilson 2011). Its extreme fineness significantly improves the quality of the ITZ because particles are more tightly packed, which reduces permeability and bleeding. Being a pure pozzolan, silica fume contributes to both early- and late-age strength and is commonly used in high-strength concrete mixtures. However, high-strength concretes require low *w/c* and silica fume dramatically increases the water demand. To account for the water demand, a high-range water-reducing admixture (HRWRA) is typically required.

2.6.2 Chemical Admixtures

A chemical admixture is a "material other than water, aggregates, cementitious materials, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing" (ACI 2013). Chemical admixtures can be added to the concrete batch before or during mixing, as per manufactured specifications. Types of chemical admixtures are classified in ASTM C494 (2010). The three types of admixtures associated with this project are Type B: retarding, Type D: water-reducing and retarding, and Type F: high-range water-reducing.

2.6.2.1 Water-Reducing Admixtures

Water-reducing admixtures (WRAs) are surfactants, or wetting agents, that lower the interfacial tension between two liquids. Classification of water-reducing admixtures include conventional WRA, mid-range WRA, and high-range WRA. High-range water-reducing admixtures (HRWRAs) were first developed in the 1970s as long-chain, high-molecular-weight anionic surfactants. In the 1990s, a new generation using polycarylates, polycarboxylates, and polyethylene-based copolymers redeveloped the product into a comb-like molecular structure (Malhotra 2000). These HRWRAs, also known as superplasticizers, can reduce the amount of water required to produce a certain slump on the range of 20 to 30 percent (Mehta and Monteiro 2014). The use of HRWRAs allows a low *w/c* concrete to have sufficient workability.

2.6.2.2 Retarding Admixtures

A retarding admixture is a set-controlling admixture used to increase the dormant period, which is the period that concrete retains its workability. ACI (2013) Concrete Terminology defines a retarding admixture as “an admixture that causes a decrease in the rate of hydration of the hydraulic cement and lengthens the time of setting”. For high-strength concretes, the high amount of cement increases the heat of hydration. Retarding admixtures are most commonly used to offset the effects of hot weather on hydration. Set retarder is also commonly paired with silica fume since silica decreases the set time. Additionally, a hydration-control admixture is an admixture that can significantly delay setting of concrete and is often used to obtain normal setting times when mixing concrete in hot-weather conditions.

2.6.3 AIR-ENTRAINING ADMIXTURES

Air voids, or entrapped air, are unavoidable in concrete; thus, air is a percentage of the volume in concrete. Pockets of entrapped air are irregular in size and shape that are present due to the lack of consolidation. Entrained air is chemically induced, microscopic air bubbles that are near perfectly spherical in shape. By increasing the amount of microscopic air bubbles present in concrete, air-entraining admixtures (AEA) make concrete more resistant to freezing and thawing (Mindess et al. 2003). Air content is sensitive to AEA, so AEA is typically used in small dosages.

Chapter 3

EXPERIMENTAL PLAN

3.1 INTRODUCTION

The experimental plan for this project was developed by studying previous research pertaining to the objectives of this project, which are listed in Section 1.2. Based on the findings from Chapter 2, few projects address the effects of core *l/d* on high-strength concrete cores. The effect that core drilling orientation has on strength is controversial. From literature, the effects of core diameter and coarse aggregate size may have an effect on apparent strength. Based on these observations from literature and the capabilities and resources available to the Auburn University research team, an experimental plan was developed to fully assess the project objectives, which were established to improve the interpretation of core strength results for the ALDOT. This chapter contains a description of the experimental plan, protocols used, testing equipment used, mixture proportions, and raw material details.

3.2 OVERVIEW OF EXPERIMENTAL PLAN

The experimental work performed for this research took place within the Auburn University (AU) Structures Engineering and Materials Laboratory. In order to evaluate the effects that core *l/d*, core diameter, drilling orientation, and coarse aggregate size have on core strength, the experimental plan designated 12 separate casts of concrete. All concrete was batched at a local ready-mixed plant, then delivered to the laboratory, and cast into full-scale slab and wall specimens. Mixture proportions targeted three 28-day strength classes: moderate strength (6,000 psi), intermediate strength (8,000 psi), and high strength (10,000 psi). A moderate strength of 6,000 psi was selected because the AASHTO T 24 (2007) core *l/d* strength correction factor is limited to concrete strengths between 2,000 and 6,000 psi. The high-strength class of 10,000 psi was selected based on the typical maximum strength used in ALDOT construction. An intermediate strength of 8,000 psi was implemented in order to bridge the strength data and more closely represent strength commonly targeted by the ALDOT.

For each strength class, four batches of concrete were cast, two using Number (No.) 57 crushed dolomitic limestone and two batches using No. 67 crushed dolomitic limestone as the coarse aggregate. Dolomitic crushed limestone was used for this project because it is a soft aggregate. Therefore, theoretically, less damage is induced during drilling operations, as this variable is not under evaluation in this study. Number 57 and No. 67 coarse aggregate are commonly used in ALDOT applications and thus were the agreed size of coarse aggregates used. Based on the three selected concrete strengths and two coarse aggregate sizes, there is a total of six mixtures, each batched twice.

Each mixture was batched twice, once to analyze 3 in. diameter cores for core *l/d* strength effects, and once to analyze 4 in. diameter cores for core *l/d* strength effects. Three-inch diameter cores were selected because the ALDOT commonly uses 3 in. diameter cores due to reinforcement congestion or core *l/d* geometry limitations of a structure. AASHTO T 24 (2007) recommends a minimal core diameter of 3.75 in., and ACI 214 (2010) suggests a benchmark core diameter of 4 inches. From these two standards, 4 in. diameter cores were established as the other core diameter size used in the experimental plan.

The *l/d*'s to be tested were selected based on the values commonly tested in previous work. As per core *l/d* strength correction factors listed in AASHTO T 24 (2007), the core *l/d* strength correction factors evaluated in this research project are 1.00, 1.25, 1.50, 1.75, and 2.00. Five cores were recovered for each of the five *l/d* groups listed to increase the sample size and account for possible outliers within any group. ASTM C823 (2007) recommends a minimum of five core test specimens be obtained for each concrete category with a unique condition or each test procedure.

For evaluating the effect of core *l/d* on concrete strength, all cores were taken from slab specimens and cored all the way through the slab. However, in order to assess the effects of cores taken parallel and perpendicular to the concrete placement direction on core strength, a separate wall specimen was required. Using a wall specimen, cores were recovered from the same area of the wall specimen and could be easily taken parallel and perpendicular to the cast direction. A general overview summarizing the experimental plan is provided in Table 3-1.

Table 3-1: Overview for experimental plan

Variable	Range Evaluated				
No. of Concrete Batches:	12 batches of concrete				
Concrete Strength:	6,000 psi		8,000 psi		10,000 psi
Size of Coarse Aggregate (Limestone):	No. 67			No. 57	
l/d	1.00	1.25	1.50	1.75	2.00
Core Diameter:	3 in.			4 in.	
Direction of Drilling:	Parallel to casting			Perpendicular to casting	

To organize the data presented by the 12 batches of concrete, a specimen identification system has been developed and is explained in Figure 3-1.

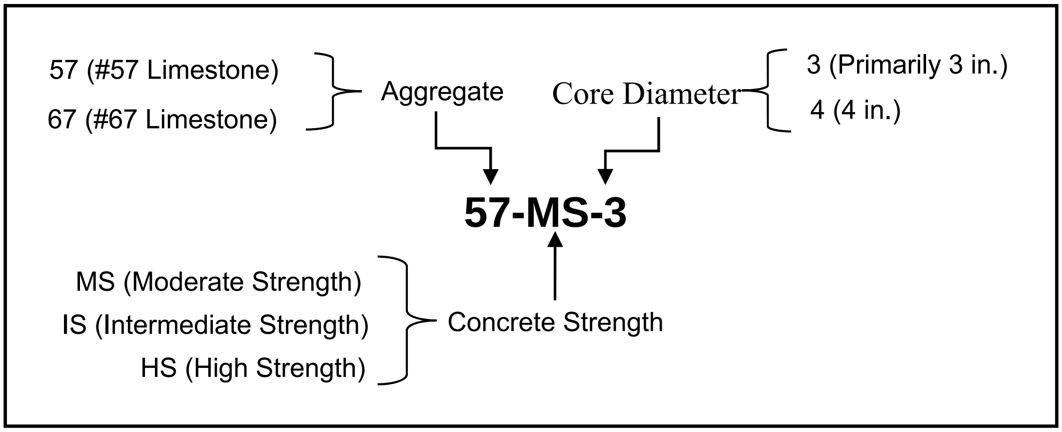


Figure 3-1: Specimen identification system for mixtures and core specimens

In Figure 3-1, an example of how a mixture or the representation of core data are labeled in this report is provided. The core label represents the aggregate size, core diameter, and concrete strength of the specified mixture.

In addition to evaluating 3 and 4 in. diameter cores for effects of core *l/d* on concrete strength, a separate analysis was implemented to directly compare the strength of 3 and 4 in. diameter cores having the same *l/d* and cast within the same batch. As discussed, for the six batches analyzing primarily 3 in. diameter cores for the effect of core *l/d* on concrete strength, there are five 3 in. diameter cores having an *l/d* of 2. Thus, for these six batches, an additional five 4 in. diameter cores were recovered and trimmed to have *l/d* of 2 as well. From this, a strength comparison within the same batch of concrete can be made between the 3 and 4 in. diameter cores. These data are labeled as having core diameter of primarily 3 in., as shown in Figure 3-1. Table 3-2 shows the overview for the number of cores taken for this analysis, in addition to the core *l/d* analysis on 3 in. diameter cores.

Table 3-2: Number of cores taken for primarily 3 in. diameter cores

Variable		**Number of Core Specimens**					
∅	*l/d*	**67-MS-3**	**57-MS-3**	**67-IS-3**	**57-IS-3**	**67-HS-3**	**57-HS-3**
4 in.	2.00	5	5	5	5	5	5
	2.00	5	5	5	5	5	5
	1.75	5	5	5	5	5	5
3 in.	1.50	5	5	5	5	5	5
	1.25	5	5	5	5	5	5
	1.00	5	5	5	5	5	5
	Total	30	30	30	30	30	30

Similarly, in addition to the evaluation of *l/d* on core strength for 4 in. diameter cores, a separate analysis directly comparing the strength of cores drilled parallel and perpendicular to the concrete placement direction was implemented in this project. The cores taken to evaluate drilling orientation all have 4 in. diameters and *l/d* of 2. These data are labeled as having core diameter of 4 in., as shown in Figure 3-1. Table 3-3 shows the overview for the number cores taken for this analysis, in addition to the core *l/d* analysis on 4 in. diameter cores.

Table 3-3: Number of cores taken for 4 in. diameter cores

Variable		**Number of Core Specimens**					
Specimen	***l/d***	**67-MS-4**	**57-MS-4**	**67-IS-4**	**57-IS-4**	**67-HS-4**	**57-HS-4**
Wall	2.00	10*	10*	10*	10*	10*	10*
Slab	2.00	5	5	5	5	5	5
	1.75	5	5	5	5	5	5
	1.50	5	5	5	5	5	5
	1.25	5	5	5	5	5	5
	1.00	5	5	5	5	5	5
	Total	35	35	35	35	35	35

* 5 cores recovered parallel and 5 cores recovered perpendicular to the casting direction

Two identical slab specimens were constructed for evaluating effects of core *l/d* on concrete strength and one wall was constructed for evaluating the effects of core drilling orientation on core strength. The targeted core locations for the slab and wall are shown in Figure 3-2 and Figure 3-3.

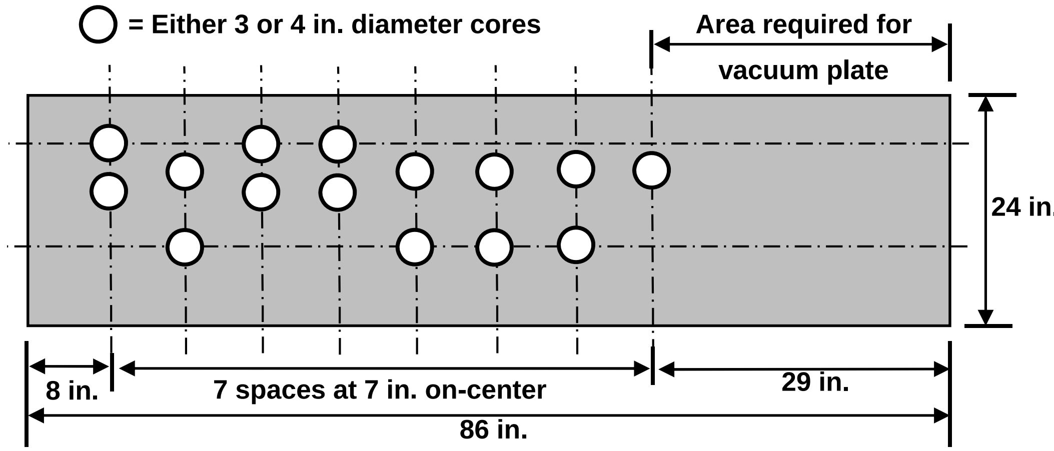


Figure 3-2: Plan view for slab with approximate on-center core locations

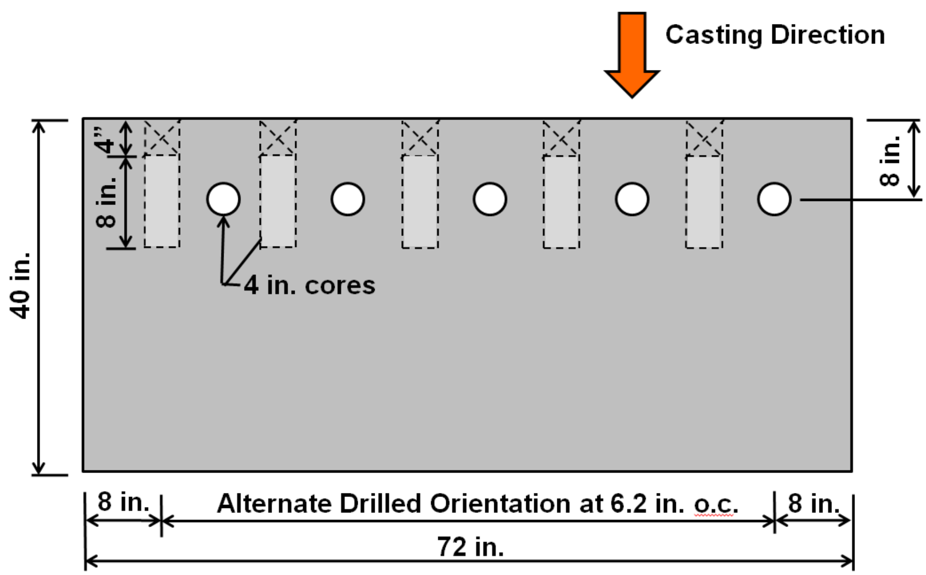


Figure 3-3: Elevation view for wall with approximate parallel and perpendicular core locations

Two slabs were necessary for construction so that each core recovered would essentially have equal amounts of restraint, while casting a specimen that can be safely moved and managed throughout the laboratory. Since a vacuum plate was attached to the core rig, there must be a flat surface to suction to directly behind the core location. This is necessary to keep the core rig stable during coring. Therefore, one long slab could have been constructed. However, this is not ideal for transporting the slab element throughout the laboratory. Furthermore, the slab specimen was not widened – so that each core would essentially experience equal amounts of restraint from the formwork. For example, doubling the width of the slab would create four rows of cores: two interior rows and two exterior rows. To minimize the difference in restraint between core specimens, the design shown in Figure 3-2, used for two slabs, is most appropriate.

Only one wall was necessary because the wall was only constructed to directly compare cores taken parallel and cores taken perpendicular to the concrete placement direction. Only five parallel cores and five perpendicular cores were recovered for this analysis. By casting a separate wall, all parallel perpendicular cores can be taken from the same region of the specimen, as shown in Figure 3-3. This minimizes in-place variability between core specimens.

3.3 EXECUTING EXPERIMENTAL PLAN

3.3.1 SCHEDULE

Preliminary work included selecting mixture proportions by trial batching for the intermediate- and high-strength mixtures, designing the elements to be cast, building the formwork for slabs and wall, and scheduling the work. The schedule was developed based on a typical timeframe in which ALDOT might perform core testing. In standard practice, cured cylinders are tested at an age of 28 days. If the cylinder strengths are low, as per ACI 318 (2011), then further investigation is required by retrieving and testing core specimens. Therefore, a common practice would be to core directly after receiving poor cylinder strengths, store the core specimens in sealed bags for 5-7 days, and then test for compressive strength. Thus, the schedule for this experimental plan is modeled after this assumed practice.

The curing method for this project included wetted burlap sealed in plastic. The burlap was routinely checked and rewetted as needed. Curing mats were left on the slab and wall specimens until forms were ready to be removed. Forms were removed at a concrete age of 6 days so that preparation for another mixture to be cast on a weekly cycle of 7 days could be achieved. Testing procedures were scheduled for a 7-day cast cycle and 37-day core compressive strength test cycle. Standard 6 x 12 in. molded cylinders were tested at 7 and 28 days to verify the predicted strength of each mixture. Due to the length of time required to core 30-35 specimens, the scheduled coring date was set at a concrete age of the 30 or 31 days. AASHTO T 24 (2007) requires the retrieved cores remain in sealed bags for 5 days and that a cored specimen be tested within 7 days after being cored. Therefore, by testing compressive strength on the 37th day, the stated flexible core dates still satisfied AASHTO standard requirements. Having a fixed schedule makes the concrete age an independent variable in this study. The schedule developed for this project, which is discussed in greater detail in the remaining sections of this chapter, is summarized in Table 3-4.

Table 3-4: Summarized schedule following a cast date

Action	Concrete Age
Remove Curing Mats and Strip Forms	6^{th} day
Test Compressive Strength of Cylinders	7^{th} and 28^{th} days
Retrieve Cores	30^{th} or 31^{st} day
Cores Sealed in Plastic Bags	for 5-6 days
Sulfur Cap Cores	36^{th} day
Test Compressive Strength of Cores	37^{th} day

3.3.2 Slab and Wall Specimen Requirements

The following subsections discuss the parameters controlling the design and layout for the slab and wall specimens.

3.3.2.1 Geometry Requirements

The dimensions of each element, as well as the location of reinforcement and hoist anchors permanently cast into them, were selected primarily in consideration of the desired coring location. It was preferred that the circumference of any drilled core not be within 4 inches of any element edge. Thus, each core experienced a comparable amount of restraint from the formwork. Additionally, no core was taken within 2 inches of any other drilled core. This was done as a precaution to minimize the amount of damage inflicted during coring or from coarse aggregate pop-outs, as discussed in Sections 2.5.2 and 2.2.1, respectively.

The largest core specimen tested had a 4 in. diameter and l/d of approximately 2.0. Therefore, the maximum length required for any core used in this project was approximately 8 inches. Based on this, the thickness for each slab and wall specimen was 9.5 in. to provide an allowance to trim each end of all core specimens. Furthermore, it was desired to test the middle portion of each core retrieved, as this would be representative of current ALDOT practices. Therefore, each end of the core was trimmed to the desired length. An example for a drilled and trimmed core is shown in Figure 3-4.

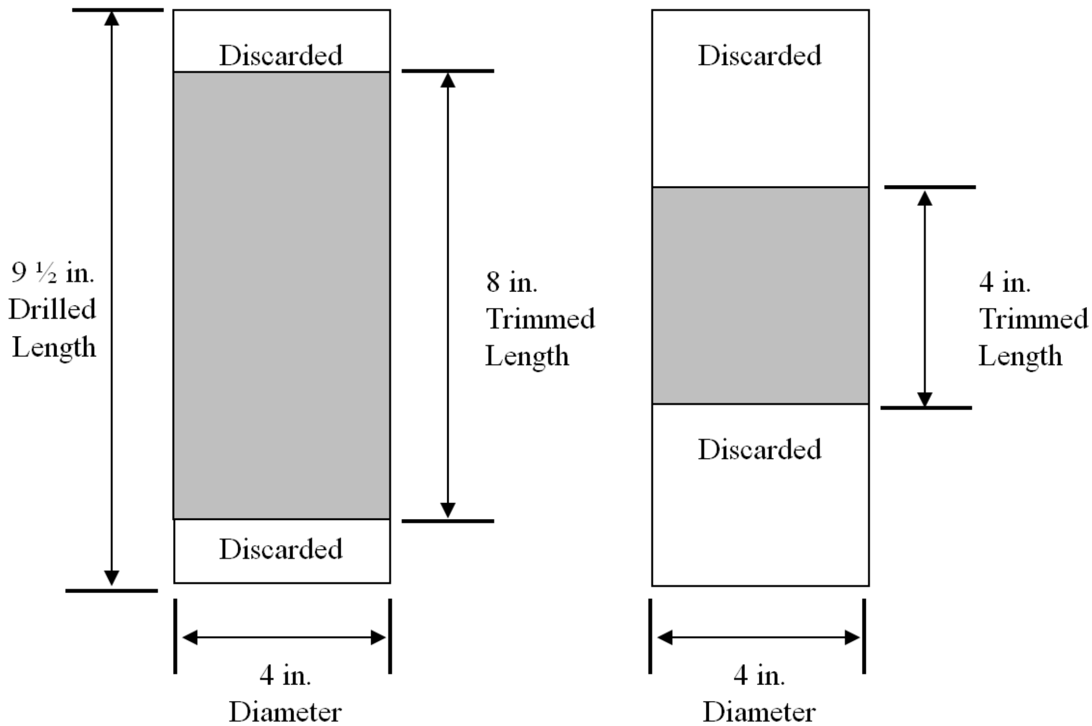


Figure 3-4: Example of drilled and trimmed core

In Figure 3-4, the shaded area represents the area of the core specimen to be tested. The core specimen on the left represents the largest core and the specimen on the right represents the smallest core tested for 4 in. diameter cores.

3.3.2.2 FORMWORK PREPARATION

Formwork was made of wood and constructed to be easily stripped and reassembled. For the area of formwork that would be exposed to concrete, all adjoining pieces of wood were lined with waterproof caulk. Caulk was placed at least one day prior to casting to allow proper set. The use of caulk helped eliminate paste leaking from the forms. Additionally, form release agent was sprayed onto the wood that would be exposed to concrete. This created a quick and easy release when stripping the forms away from the hardened elements. The release agent was typically sprayed onto the formwork on the day of casting, just prior to setting the reinforcement in place. The caulk and release agent helped to improve the durability and reusability of the forms.

3.3.2.3 STEEL REINFORCEMENT AND HOIST ANCHOR REQUIREMENTS

Steel reinforcement was provided for the slab and wall elements primarily to ensure safety during lifting operations. Elements were transported throughout the AU Structures Engineering

Laboratory using an overhead bridge crane. Slabs and beams were typically stored on top of one another with *4 x 4* in. wooden blocks separating elements from one another. Thus, reinforcement was only designed to meet minimum flexural, shrinkage, and temperature requirements as per ACI 318 (2011). Figure 3-5 and Figure 3-6 provide the reinforcement layout for the slab and wall specimens. Note that wall reinforcement was modified with no reinforcing bars near the upper portion of the wall, as shown in Figure 3-6. This was desired for coring purposes. Figure 3-7 and Figure 3-8 show the tied reinforcement cages placed into their forms.

Hoist anchors were placed in each element to provide an easy and safe method for moving the element throughout the lab. The anchors used were hoop-shaped pick-up inserts rated to carry 4000 lbs each. Although the slabs weighed approximately 1670 lbs and the wall weighed approximately 2380 lbs, inserts were placed in pairs to reduce undesired movement such as swiveling and spinning during transport. The slabs used two anchors, spaced on the top surface. However, the wall used two anchors on the top surface but also two centrally located on the ends. The top anchors were used for lifting the wall out of the form. Note that there is approximately a 2.2 in. clearance distance between the top anchors and the edge of any cored recovered. This allowance is assumed to be large enough that any damage experienced to the concrete around the hoist during lifting is negligible within the core specimen. The anchors on the ends were used so that the wall was more easily capable of being rotated onto its side. Figure 3-5 and Figure 3-6 also show the location of each hoist anchor.

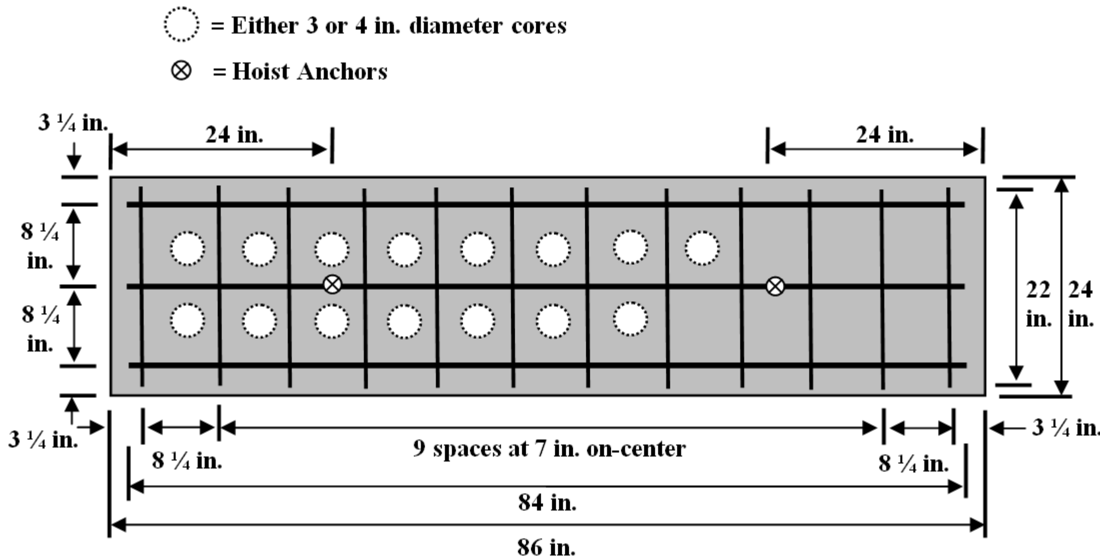


Figure 3-5: Steel reinforcement layout for slabs (plan view)

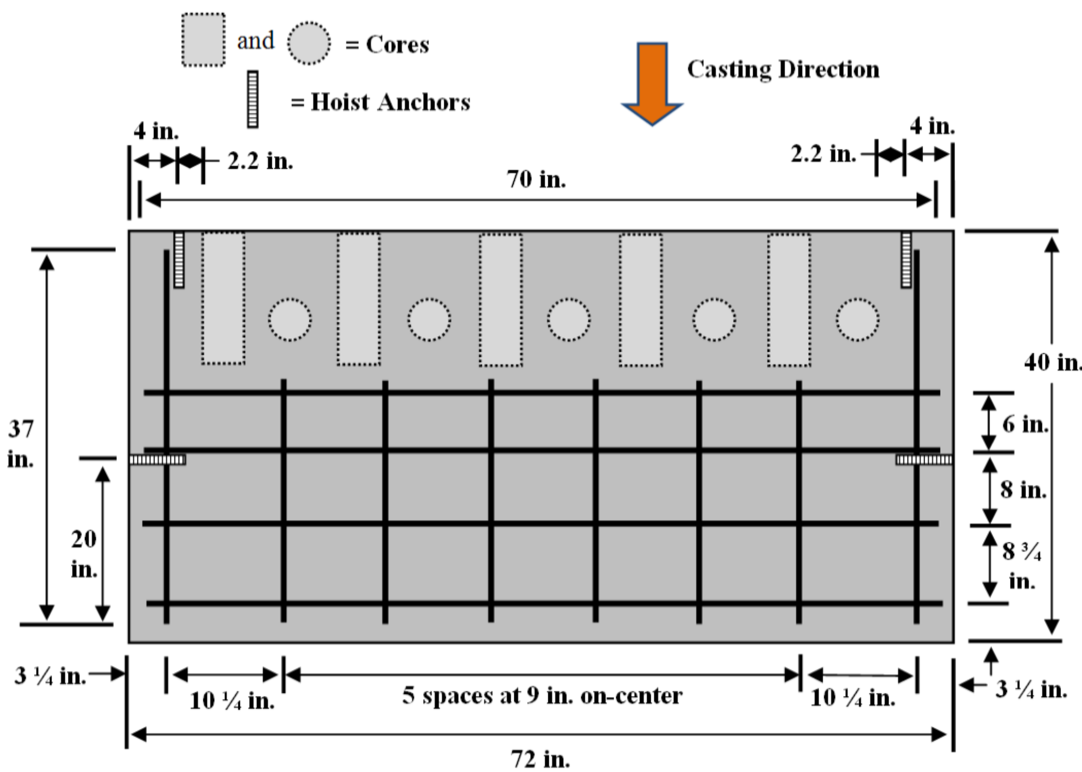


Figure 3-6: Steel reinforcement layout for wall (elevation view)

Figure 3-7: Tied reinforcing bars for a slab element

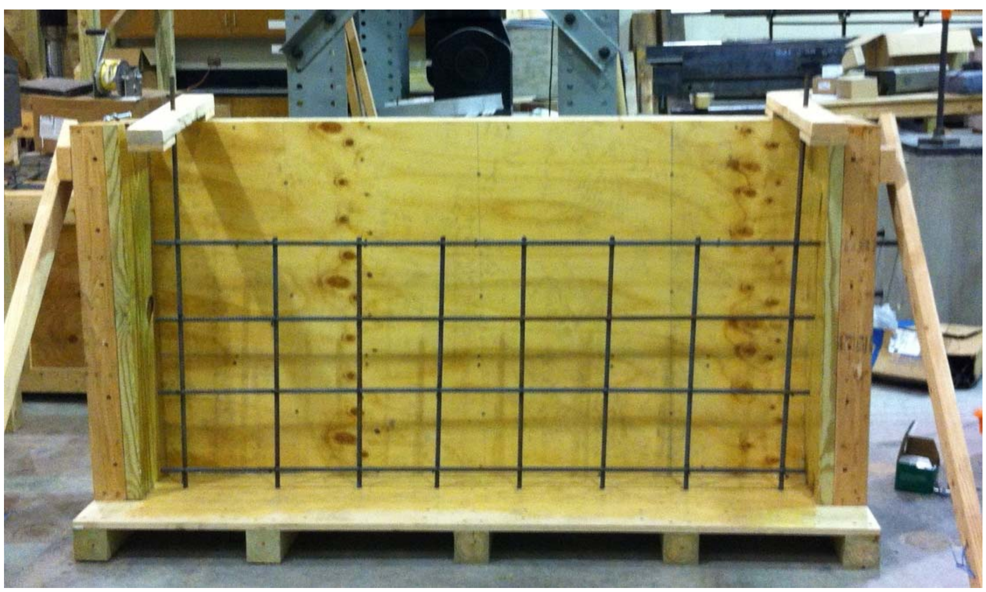


Figure 3-8: Tied reinforcing bars for the wall element

3.4 MIXTURE PREPARATION

This section describes the procedures for developing mixture proportions and mixture preparation prior to placing concrete delivered from the ready-mixed concrete plant. The moderate-strength mixture proportions were provided by Sherman Industries Ready Mixed Concrete Plant in Auburn, Alabama but the intermediate- and high-strength mixture proportions were developed by trial batching in the laboratory.

3.4.1 Raw Materials

All materials used for this project were locally available. Cement, Type C fly ash, sand, and No. 57 crushed limestone were taken from the ready-mixed concrete plant's general supply. Cement came from Lehigh Portland Cement Company Plant in Leeds, Alabama. Type C fly ash came from Headwaters Resources in Birmingham, Alabama. The fine aggregate used for this project was well-graded Type I natural sand obtained from Foley Materials Company in Shorter, Alabama (ALDOT ID: 1481). Number 57 limestone came from APAC Midsouth of Opelika, Alabama (ALDOT ID: 1604). Number 67 limestone was delivered to the ready-mixed plant for project use, as needed. Over the course of this project, No. 67 limestone was delivered from both Martin Marietta in Auburn, Alabama (ALDOT ID: 0048) and APAC Midsouth in Opelika, Alabama (ALDOT ID: 1604). Silica fume, Grade 970D, from Elkem Materials Inc. from Pittsburgh, Pennsylvania was delivered to the AU Structural Engineering Laboratory and added manually to the ready-mixed truck upon arrival to the laboratory.

The chemical admixtures used in this project include AEA, MRWRA, HRWRA, water reducing and set retarding admixture, and hydration-control admixture. All chemical admixtures used are defined in Table 3-5 are products of BASF, The Chemical Company.

Table 3-5: Chemical admixtures used

Chemical Admixture	BASF Product
AEA	MB-AE™ 90
MRWRA	Polyheed® 1025
HRWRA	Glenium® 7500
Water Reducing and Retarding Admixture	Pozzolith 322N
Hydration-Control Admixture	Delvo® Stabilizer

3.4.2 Moisture Corrections

Prior to batching, moisture corrections were performed on both fine and coarse aggregates. This procedure was conducted using a small digital scale and two hot plates. Each aggregate was sampled as approximately 35.3 oz. (1000 g). The raw materials were initially weighed and then heated to an oven-dry state and weighed again. From this, the amount of moisture present in each aggregate can be calculated. Moisture corrections were then applied to the batch proportions.

3.4.3 Trial Batching Mixture Proportions for Intermediate- and High-Strength Concretes

Trail batching was conducted in an enclosed, air-conditioned concrete laboratory in a 5 ft^3 mixer. All raw materials used to produce the concrete were stored in the laboratory. Fine and coarse aggregates were retrieved from the large stockpiles at the ready-mixed concrete plant and stored in sealed 55-gallon drums. Although this project used both No. 57 and 67 dolomitic limestone, trial batching was only conducted using No. 57. The portland cement used was Type I and was received and stored in standard 94 lb bags.

Chemical admixtures were batched into the concrete using 2.02 oz. (60 ml) syringes. The total quantity batch for each trail was approximately 4 ft^3. Three 6 x 12 in. cylinders were molded for both 7- and 28-day breaks. A table of the mixture proportions used in this experimental work is shown in Table 3-6. The mixtures batched with the proportions shown in Table 3-6 were delivered to the AU Structural Engineering Laboratory in a quantity of 2.5 yd^3 in a ready-mixed concrete truck.

Table 3-6: Mixture proportions for each targeted strength

Mixture Proportions			
Material	**6,000 psi**	**8,000 psi**	**10,000 psi**
Water (lb/yd^3)	287	265	265
Type I Cement (lb/yd^3)	602	955	1,030
Class C Fly Ash (lb/yd^3)	150	-	-
Silica Fume (lb/yd^3)	-	-	85
Fine Aggregate SSD (lb/yd^3)	1040	1,130	950
Coarse Aggregate SSD (lb/yd^3)	1957	1,800	1,800
w/cm	0.38	0.28	0.24
Admixtures Dosage (fl. oz./cwt)			
Air Entraining Admixture	0.8	-	-
MRWRA	5	-	-
HRWRA	-	6	12
Water-Reducing and Retarding Admixture	-	3	-
Hydration-Control Admixture	-	-	5

Due to the low *w/c*'s used and mixing primarily during the summer months, chilled water was used in mixing to decrease the temperature rise due to heat of hydration. This simultaneously improved the workability of the fresh concrete.

3.4.3.1 Mixing Procedure When Using Silica-Fume

Small laboratory mixers are not as efficient for mixing as truck mixers or central plant mixer (Silica Fume Association 2013). In order for silica fume to be effective, the agglomerations that make up the densified silica fume must be broken up. As mentioned in Section 2.6.1, silica fume is a very fine powder. Therefore, it is more difficult to uniformly distribute throughout the concrete during mixing. According to the Silica Fume Association (SFA), ASTM C192's recommended mixing times are not long enough to break down the agglomerations and disperse the silica fume. Thus, SFA has suggested a modified remedy for mixing silica-fume concrete in the laboratory, which is provided below and was used for this project:

- Place 75 percent of water in mixer
- Add coarse aggregate
- Add silica fume slowly into the revolving mixer
- Mix 1.5 minutes
- Add cement slowly into the revolving mixer
- Mix for 1.5 minutes
- Add fine aggregate
- Wash-in all ingredients using the remaining 25 percent of water and add any admixtures being used
- Mix for the five minutes, rest for three minutes, and mix again for five minutes

3.4.4 Mixing Procedures at Ready-Mixed Concrete Plant

For each testing cycle, materials were added to a ready-mixed concrete truck and truck-mixed. The concrete was then initially mixed at the plant and during transit to the AU Structural Engineering Laboratory, a trip that took approximately 15 minutes. In cooperation with the Twin City concrete staff, the following operations were conducted for each mixture:

1. *AU staff:* Collect fine and coarse aggregate samples from the large stockpiles at the concrete plant for determining the moisture content of each.
2. *AU staff:* Calculate the moisture-corrected batch weights and deliver batch information to the concrete plant.
3. *Plant staff:* Batch coarse aggregate, fine aggregate, cement, Type C fly ash (when used), and water into a ready-mixed concrete truck.

4. *AU staff:* Add hydration controlling admixture (when needed) directly onto the mixed concrete prior to leaving the ready-mixed plant.
5. Ingredients were then mixed during delivery to the AU Structural Engineering Laboratory.

3.4.5 Mixing Procedures Upon Arrival at the Laboratory

Once the ready-mixed concrete truck arrived at the laboratory, several additional steps were taken to add chemical admixtures and silica fume before placing the concrete. All materials added to the truck were added by bringing the concrete to the front of the drum and placing the material directly onto the fresh concrete. The following summarizes the typical procedure used at the laboratory:

1. Add predetermined amount of silica fume (when necessary) using 5-gallon buckets
2. Add an initial dose of HRWRA
3. Mix the concrete in the ready-mixed concrete truck for 30 revolutions at half of the truck's maximum rotational speed
4. Allow the mixture to sit, without any rotation of the ready-mixed truck for 2 minutes to allow the admixture to take effect
5. Rotate the mixer two full revolutions and bring the concrete up to a visible level in the truck. Based on visible consistency, add additional HRWRA or dispense a small sample for acceptance testing

Prior to placing the concrete, several tests were conducted to ensure sufficient quality. Acceptance was primarily based on the slump test in accordance with AASHTO T 119 (2007). In order to perform this test, initial sampling was conducted. Concrete was dispensed down the ready-mixed truck's chute into a waste container. Once the initial concrete was dispensed as waste, a 5-gallon bucket was used to capture a sufficient sample for acceptance testing. For moderate-strength mixtures, the target slump was 3 to 5 inches with a maximum acceptable slump of 6 in. For intermediate- and high-strength mixtures, the target slump was 7 to 9 inches with a maximum acceptable slump of 9 inches.

3.5 Fresh Concrete Test Procedures

The following subsections address the fresh concrete test procedures used directly following acceptance testing.

3.5.1 Sampling

Sampling for assessing fresh concrete properties and making cylinders was conducted by positioning the truck's chute over a 1.5 yd^3 placement bucket and filling it. An example of this procedure is shown in Figure 3-9. The bucket was then lifted using the overhead bridge crane, and a sample was placed directly into a wheelbarrow.

Figure 3-9: Placing concrete into placement bucket

3.5.1.1 Assessment of Fresh Concrete Properties

As mentioned in Section 3.4.5, the slump test was performed according to AASHTO T 119 (2007) and primarily used to determine acceptance. The following tests were additionally conducted to assess fresh concrete properties according to the standards indicated:

- Unit weight according to AASHTO T 121 (2009)
- Air content according to AASHTO T 152 (2005)
- Temperature according to AASHTO T 309 (2006)

3.5.1.2 MAKING AND CURING CYLINDERS

All test specimens were made in accordance with ASTM C 192 (2007). A total of six 6 x 12 in. cylinders were made for each mixture. Three cylinders were tested at 7 and 28 days. Each cylinder comprised three equal lifts of concrete, and each lift was tamped 25 times with a 5/8 in. tamping rod. For each lift, the sides of the molds were also slightly tapped with a rubber mallet. A wooden trowel was then used to strike off the surface of the concrete cylinder. Lastly, the cylinders were covered with plastic lids to prevent moisture loss. Once the concrete age reached 24 hours, in accordance with ASTM C192 (2010), cylinders were stripped, labeled, and transferred to the moist curing room.

3.5.2 PLACEMENT PROCEDURES

Concrete was placed into the forms using the 1.5 yd^3 placement bucket, as primarily described in Section 3.5.1. The placement bucket was initially placed on one end of formwork and uniformly placed from that end to the other, as shown in Figure 3-10. The slabs were placed in one lift and vibrated as soon as the forms were full. However, the wall was placed in two equal lifts and vibrated between lifts.

Figure 3-10: Images showing placement from one end of a slab to the other

3.5.2.1 FINISHING

Initial finishing was performed once the forms were completely full and vibrated. Using a *2 x 4* piece of lumber, the excess concrete was struck off. This was conducted by placing the lumber across the width of the forms and pulling the strikeoff board from one end to the other, constantly moving the board in a sawing motion. Wooden trowels were then used to apply a roughened finish, allowing bleed water to rise to the surface. Once the concrete approached final set, a final finish was applied using a metal trowel.

3.5.2.2 CURING ELEMENTS

Once final set of the concrete was reached, the elements were cured by completely covering the exposed surface with dampened burlap. The burlap was then covered with plastic and weights were placed on top of the plastic to reduce moisture loss, as shown in Figure 3-11. The burlap was checked on a daily basis and water was added, as needed. In order to prepare for a cast the following week (7 days later), formwork was stripped on the sixth day. Therefore, the elements were cured for the first six days after casting.

Figure 3-11: Slabs covered in burlap and wrapped in plastic

3.6 CORE PREPARATION AND OPERATIONS

3.6.1 CHECKING CYLINDER STRENGTH

As mention in Section 3.5.1.2, standard 6 x 12 in. cylinders were tested for compressive strength at 7 and 28 days. These measured values were primarily used as a reference, to conclude whether the concrete represented the targeted strength. Additionally, the break type, in accordance with AASHTO T 22 (2007), was also recorded for reference. The average 7- and 28-day cylinder strength results are presented in Appendix A.

3.6.2 CORING

Cores were recovered using a Hilti DD200 core rig with an attached vacuum rig. The two core barrels used for this project were Hoffman Diamond Products, Pro 1200 core bits. The “3 in.” barrel used for this project had an inside diameter of 2.975 in. and an outside diameter of 3.230 inches. The “4 in.” barrels used for this project had an inside diameter of 3.975 in. and an outside diameter of 4.220 inches.

As discussed in Section 3.2, there is a specific specimen identification system used for distinguishing the number of cores taken and core diameter, as shown in Figure 3-1. For the six batches of concrete shown in Table 3-2, there were primarily 3 in. diameter cores taken, 25 had a diameter of 3 inches and five cores had a diameter of 4 inches, as shown in Figure 3-12.

Figure 3-12: Cores taken when primarily testing 3 in. core diameters

For the six batches presented in Table 3-3, only 4 in. diameter cores were taken. Twenty-five were taken between the two slabs, and an additional ten were cored from the wall. In Figure 3-13, the arrangement where cores were taken from all six batches is shown. As outlined in Table 3-4, coring was conducted at a concrete age of 30 or 31 days. The following will present the procedures used for retrieving cores.

Figure 3-13: Cores taken from mixtures only testing 4 in. core diameters

3.6.2.1 LABORATORY CLEANLINESS DURING CORING

Coring concrete requires that the drill bit be wet to cool the bit. Therefore, the running water mixes with the concrete micro-particles formed from drilling to create a slurry. In order to retain the slurry and maintain a clean laboratory, the cored element was placed over a small temporary structure, which will be referred to as the *coring bath*. This bath was made of wood and lined with several sheets of plastic. The *coring bath* was sized to accommodate one slab or the wall, when laid on its side.

3.6.2.2 Retrieving Drilled Cores

Specimens were drilled all the way through the concrete section, with the exception of the parallel cores taken from the wall. As mentioned, to drill the parallel cores from the wall, the core rig was mounted to the wall of the loading dock in the AU Structural Engineering Laboratory, as shown in Figure 3-14. These cores were drilled approximately 14 in. deep into the top surface of the wall and retrieved using a coresnap, as shown in Figure 3-15. For all other cores, the slab or wall were placed on stacked *4 x 4* pieces of lumber to provide an access point for recovering the cores.

Figure 3-14: Core rig mounted to AU Structural Engineering Laboratory loading dock

Figure 3-15: Retrieving cores using a coresnap

3.6.2.3 HANDLING CORES

Once the cores were removed, several operations were conducted. In accordance with AASHTO T 24 (2007), the following information was recorded:

- time and date cored,
- drilled length to the nearest ¼ in.,
- average diameter of core to the nearest 0.01 in.,
- time trimmed,
- length of trimmed specimen to the nearest 0.1 in.,
- weight of trimmed core (for calculating density), and
- time placed into plastic bags.

Cores were trimmed using a wet saw. Once all information was recorded, the core was placed into two plastic bags and wrapped with rubber bands, as demonstrated in Figure 3-16. Cores remained in the plastic bags for 5 to 7 days and stored vertically in large plastic bins. The bags were then labeled using the nomenclature presented in Figure 3-17.

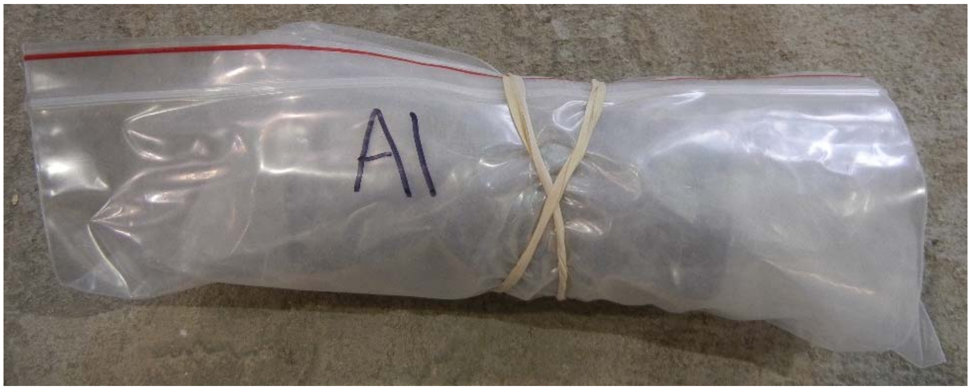


Figure 3-16: Core that has been bagged, rubber banded, and labeled

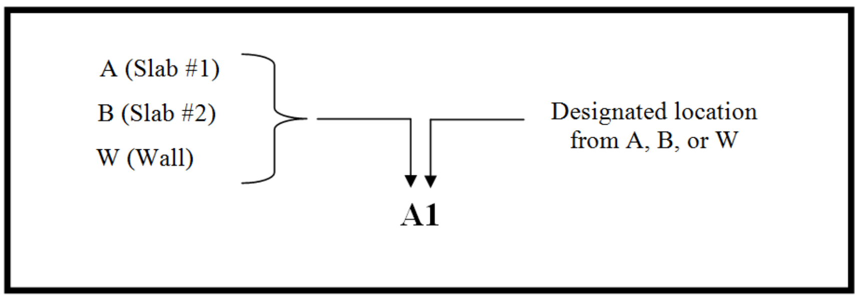


Figure 3-17: Nomenclature for labeling each core

3.6.2.4 Number of Cores Taken Per Core Barrel

The efficiency for a core barrel to effectively drill through each concrete specimen was recorded throughout this project. The core barrels used for this project had approximately 3 or 4 in. inside diameter. With each core drilled, the sharpness of the core barrel is decreased. As the barrel becomes more dull, coring can become significantly more difficult which may result in damaging the core as discussed in Section 2.5.2. In order to try and quantify a level of difficulty and establish an average number of cores that should be taken per core barrel, quantities of cores taken per barrel and notes were recorded. Table 3-7 provides the approximate number of cores taken per barrel throughout coring for this project.

It can be seen from Table 3-7 that 80 to 85 cores were taken for 4 in. diameter core barrels and only 50-55 were taken with each 3 in. core barrel. It should be noted that 4 in. diameter cores were recovered more often in the earlier stages of this project. There was no particular reason that 4 in. diameter cores were taken earlier, however, the core machine operators were still learning the degree of difficulty to core based on the number of cores taken from each barrel. In time, the core machine operators determined the level of difficulty was noted to become most apparent after approximately 50 cores were cut per barrel.

Table 3-7: Number of cores taken per core barrel

Core Barrel Diameter	Approx. # of Cores Taken
3 in. Diameter - #1	52
3 in. Diameter - #2	55
3 in. Diameter - #3	50
4 in. Diameter - #1	85
4 in. Diameter - #2	80
4 in. Diameter - #3	85

3.6.3 SULFUR CAPPING

Sulfur capping was used because it is the current capping method used by ALDOT. Sulfur capping was conducted in accordance with AASHTO T 231 (2005). Since the project focused on concrete strengths of 6,000 psi or greater, sulfur capping must be completed at least 16 hours prior to testing, as per AASHTO T 231 (2005). Therefore, cores were capped the day prior to testing compressive strength. Prior to capping, each end of each core was roughened using a wire brush and dust was then removed using a towel. This helped create a better bond between surfaces. The sulfur compound was heated to approximately 260 ^{o}F and placed into a mold, followed by the concrete specimen. To illustrate this operation, a core that has just been capped in the capping stand is shown in Figure 3-18. To accommodate our shorter cores, the capping stand was modified, as shown in Figure 3-19.

For quality assurance, the hardened caps were inspected during compressive strength testing the core specimens. A minimum of three random sulfur capped cores were selected for quality assurance measurements. Prior to testing compressive strength, both ends were visually inspected to make sure there were no hollow areas, and then each end was inspected for planeness. Planeness was checked by using a straightedge and feeler gauge, measuring in three locations to check whether the caps departed from a plane by more than 0.002 in. After compressive strength tests were conducted on the specimens, six pieces of the capping material were recovered and their thickness was measured. As per AASHTO T 231 (2005), the maximum average thickness of capping material allowed is 0.125 in. and the maximum allowance for any part of the cap is 0.1875 inches.

Figure 3-18: Example of sulfur capping

Figure 3-19: Modified capping stand for short cores

3.6.4 COMPRESSIVE STRENGTH TEST ON CORES

Compressive strength tests were performed using the Forney compression machine rated to have a 400,000 lb capacity. The rate of loading for compressive strength testing was conducted in accordance with AASHTO T 22 (2007), being 35 ± 7 psi/s. To accommodate for various heights of cores testing within the machine, solid spacing blocks were added to the bottom platen as needed.

3.7 RAW MATERIALS

Laboratory testing was performed on coarse aggregates used throughout this project to ensure their properties met ALDOT standards. The following tests were conducted:

- sieve analysis (ASTM C136 2006),
- bulk density (ASTM C29 2009), and
- absorption (ASTM C127 2007).

Coarse aggregates came from the following two sources: Martin Marietta Materials in Auburn, Alabama and APAC Midsouth in Opelika, Alabama. The bulk specific gravity and absorption are shown in Table 3-8. The results for the sieve analysis are shown in Figure 3-20 through Figure 3-22.

Table 3-8: Properties of crushed limestone

Source/Location	Bulk Specific Gravity (SSD)	Absorption Capacity (%)
Martin Marietta Materials Auburn, Alabama	2.851	0.3
APAC Midsouth Opelika, Alabama	2.836	0.2

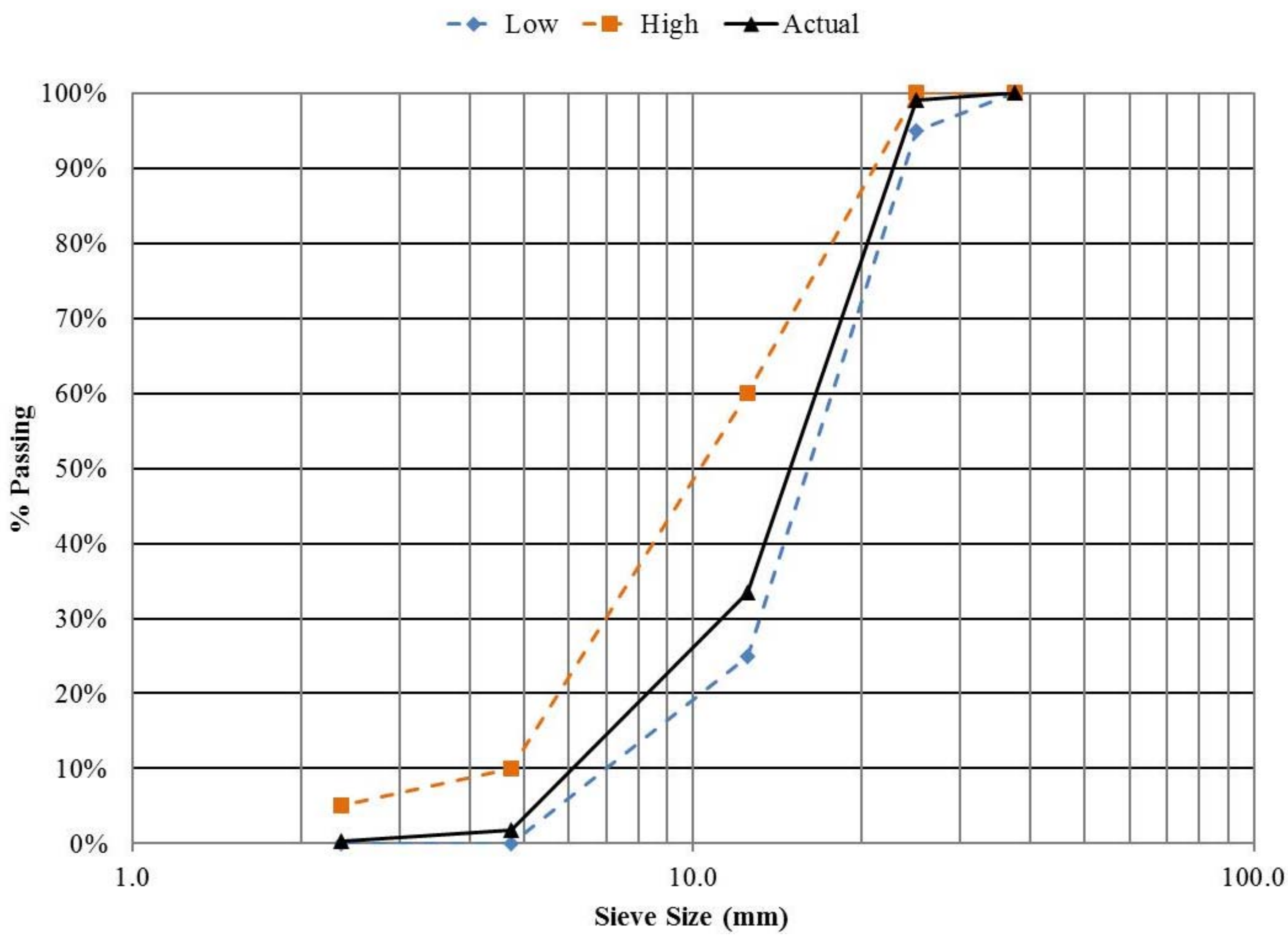


Figure 3-20: Gradation for No. 57 limestone from Martin Marietta in Auburn, Alabama

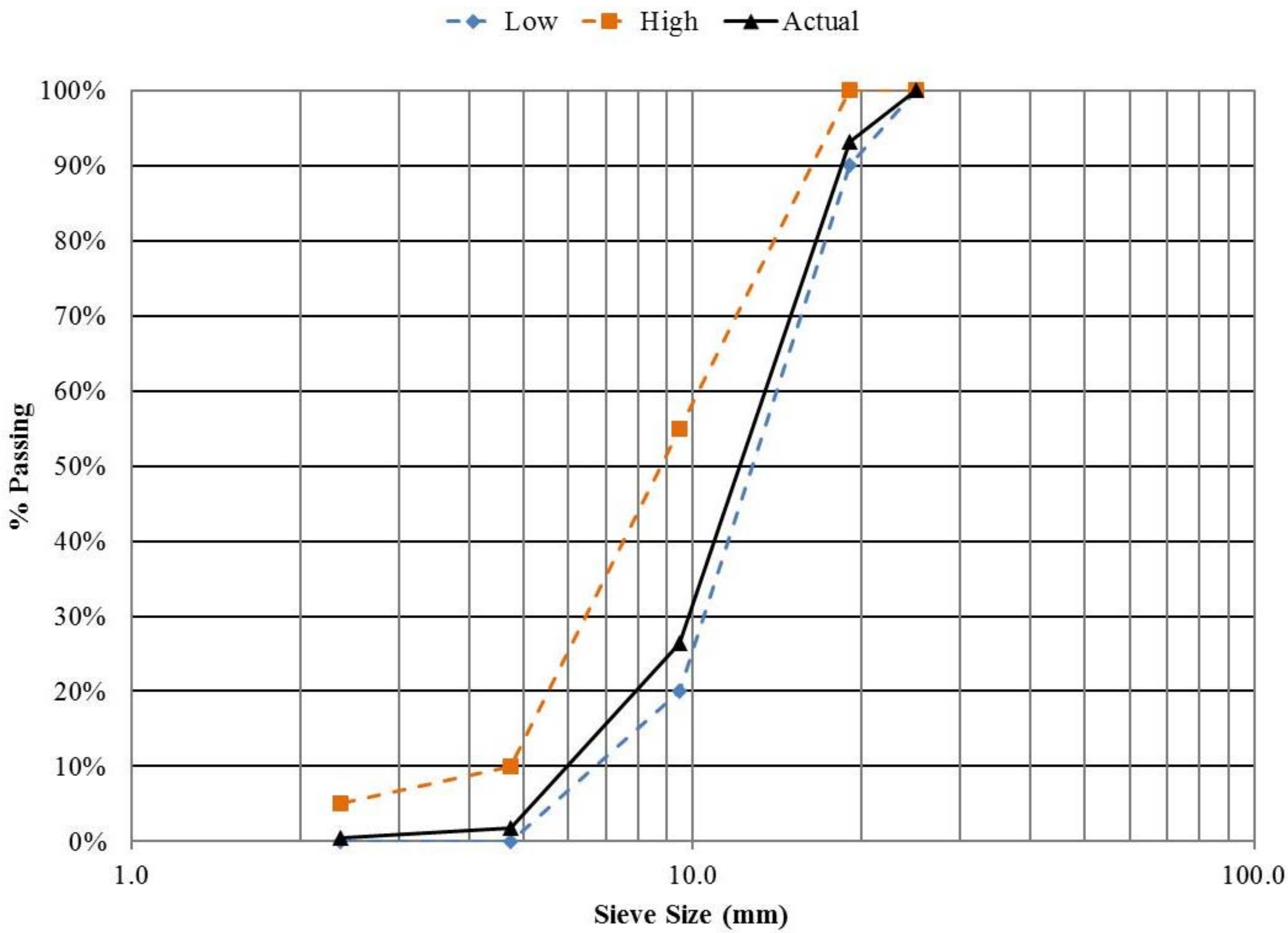


Figure 3-21: Gradation for No. 67 limestone from Martin Marietta in Auburn, Alabama

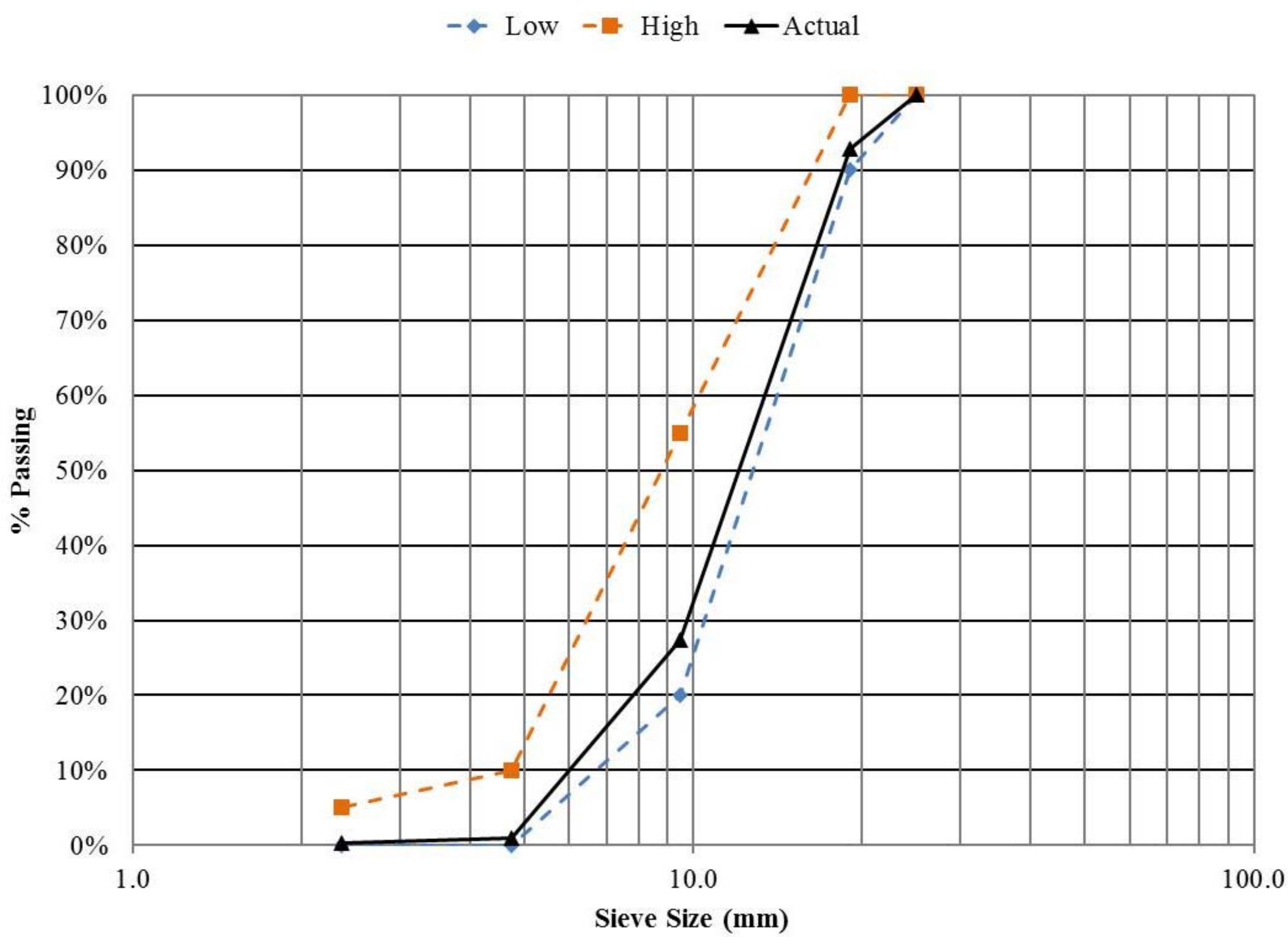


Figure 3-22: Gradation for No. 67 limestone from APAC Midsouth in Opelika, Alabama

Chapter 4

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 INTRODUCTION

The laboratory testing results of the core strength data collected are presented in this chapter. The compressive strength results were statistically analyzed to determine the observed correlations in strength, in accordance with the project objectives listed in Section 1.2. This chapter presents the results and discusses the significance between core strength values of various core *l/d*'s, core diameters, and drilled orientation.

4.2 SUMMARY OF COLLECTED DATA

Compressive strength data on cores and cylinders were collected for this project. As discussed in Section 3.6.1, 28-day cylinder strengths were collected as a reference for checking the strength for each mixture. The range for these averaged values has been grouped by strength class and is presented in Figure 4-1.

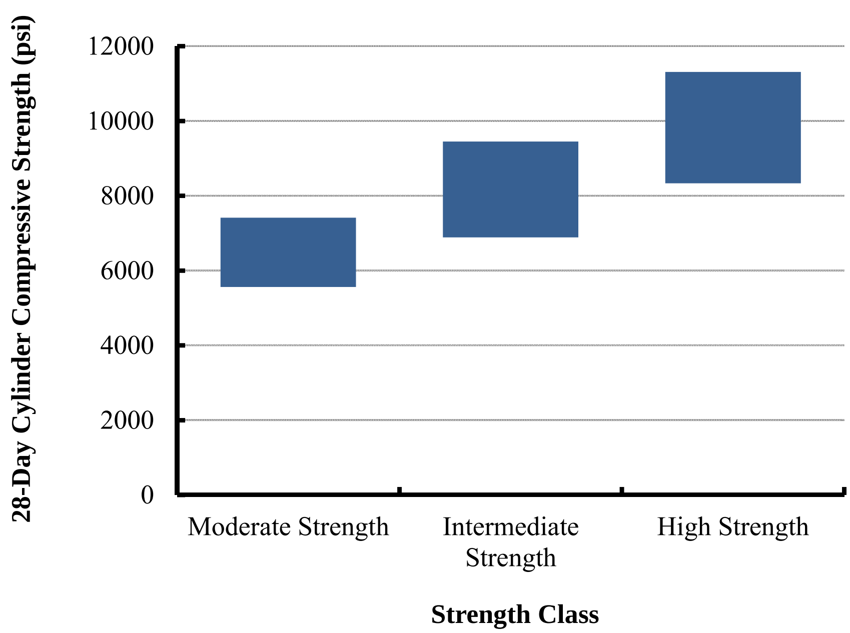


Figure 4-1: Range of the average 28-day cylinder strengths measured for all data

All core strength data were collected with the intentions of being statistically analyzed for the objectives listed in Section 1.2. Data was inputted into Microsoft Excel® and all data analysis was performed using Excel®. The specific information recorded for each core specimen is listed in Section 3.6.2.3. Additionally, the capped length and compressive force were recorded. All data specifying a core *l/d* use the sulfur capped length as the final end preparation length, as specified in AASHTO T 24 (2007). All core and cylinder strength data collected are presented in Appendix A.

4.3 PRELIMINARY DATA REVIEW

Prior to carrying out any type of analysis for the collected data, an analysis to identify outlying values for each separate mixture was conducted. Outliers may be present within a set of core specimens due to the low- or high-strength observations caused by imperfect drilling, handling, capping, or testing procedures (Bartlett and MacGregor 1994b). Outliers were identified in accordance with ASTM C42 and C670. The precision for testing was considered to be conducted under a single operator and used a coefficient of variation on cores of 3.2 percent. Although there were two operators, training procedures were taught under the same supervisor, therefore, the operator practice has been considered to be the same. The analysis using the single-operator coefficient of variation shows that "two properly conducted tests of single cores by the same operator on the same sample of material should not differ from each other by more than 9 percent of their average" (ASTM C42 2012). The single-operator coefficient of variation was multiplied by another coefficient based on the number of tests results under consideration. This coefficient can be found in ASTM C670 and established a maximum range that each value must be within to not be removed as an outlier. The complete data set contained 390 values with seven being identified as probable outliers and removed, and one value not being recorded due to a compression machine malfunction.

When outliers were detected, further investigation was conducted. In two cases, notes had been made by the original investigators that the compression machine load rate was not dialed in correctly or there was some type of operator error. This provided credible explanations for these observed low strengths. In one instance, there was an identified outlier that had previously been noted to have been insufficiently capped. In another instance, a note had been made that the core had not been trimmed in accordance with the other cores for that specific *l/d*. For this particular specimen, too much was trimmed from one end, in comparison to its other end, which does not follow the experimental plan for trimming as shown in Figure 3-4.

4.4 CORE LENGTH-TO-DIAMETER RATIO STRENGTH CORRECTION FACTOR ANALYSIS

The effect of l/d on core strength was determined by evaluating the core compressive strength for l/d of 2.0, 1.75, 1.5, 1.25, and 1.0. When evaluating the data for various core l/d values, it is important to recognize which variables may be creating variation in the results other than the l/d. For this specific investigation, each data set has the same core diameter and mixture proportions. However, the objective in analyzing the strength difference in various core l/d values is to quantify strength corrections that can be used for various core diameters and concrete strengths. Therefore, the analysis is conducted to see if various core diameters and mixture proportions can be grouped together when applying a strength correction factor.

To evaluate the core l/d data, the values have been compared to the strength correction factors provided by AASHTO T 24 (2007) and ACI 214 (2010). AASHTO T 24 (2007) states that the specimen must have a core l/d of at least 1.0 and if the l/d is less than 1.75, then the strength correction factors shown in Table 4-1 should be used. The strength correction factor using ACI 214 (2010) is provided in Table 4-2.

Table 4-1: Correction factors for l/d (AASHTO T 24 2007)

l/d	Strength Correction Factor
1.75	0.98
1.50	0.96
1.25	0.93
1.00	0.87

Note: Interpolate between values

Table 4-2: Magnitude and accuracy of strength correction factors for converting core strengths into equivalent in-place strengths (ACI 214 2010)

	Factor	Mean value	Coefficient of variation V, %
$F_{\ell/d}$: ℓ/d ratio†	Standard treatment‡:	$1-\{0.130-\alpha f_{core}\}\left(2-\frac{\ell}{d}\right)^2$	$2.5\left(2-\frac{\ell}{d}\right)^2$
	Soaked 48 hours in water:	$1-\{0.117-\alpha f_{core}\}\left(2-\frac{\ell}{d}\right)^2$	$2.5\left(2-\frac{\ell}{d}\right)^2$
	Dried§:	$1-\{0.144-\alpha f_{core}\}\left(2-\frac{\ell}{d}\right)^2$	$2.5\left(2-\frac{\ell}{d}\right)^2$
F_{dia}: core diameter	2 in. (50 mm)	1.06	11.8
	4 in. (100 mm)	1.00	0.0
	6 in. (150 mm)	0.98	1.8

*To obtain equivalent in-place concrete strength, multiply the measured core strength by appropriate factor(s) in accordance with Eq. (9-1).

†Constant α equals $3(10^{-6})$ 1/psi for f_{core} in psi, or $4.3(10^{-4})$ 1/MPa for f_{core} in MPa.

Note the correction factor equations used in ACI 214 (2010) are a function of the core strength. For this reason, the suggested correction factors based on the collected data are presented for each of the three strength classes used in this experiment. Figure 4-2 through Figure 4-4 show the strength correction factors determined according to each mixture. Equation 4-1 explains how the core *l/d* strength correction factor (S.C.F.) is calculated. For Figure 4-2 through Figure 4-4, the values shown are the averaged strength correction factors values calculated at *l/d*'s of 1.00, 1.25, 1.50, 1.75, and 2.00 for each mixture.

$$\text{Core } l/d \text{ S.C.F.} = \frac{\text{Average } f'_c \text{ (for } l/d = 2.0)}{\text{Individual } f'_c \text{ (for } l/d = 1.0 \text{ to } 1.75)} \qquad \textbf{Equation 4-1}$$

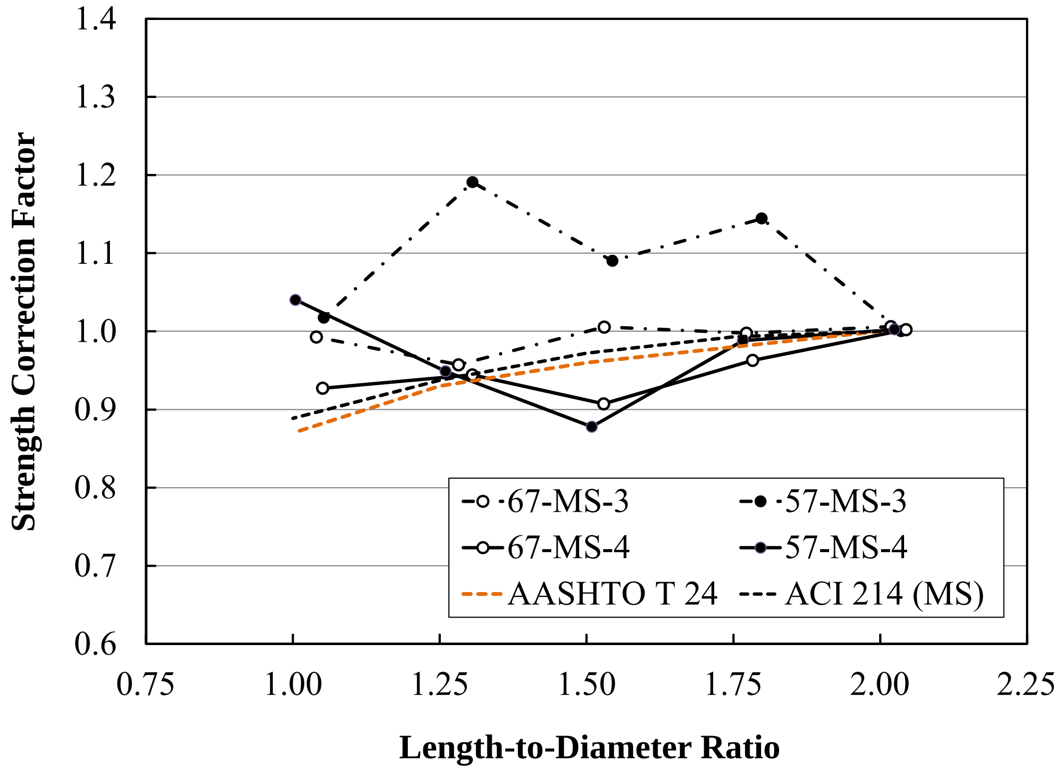


Figure 4-2: Initial strength correction factors for moderate-strength mixtures

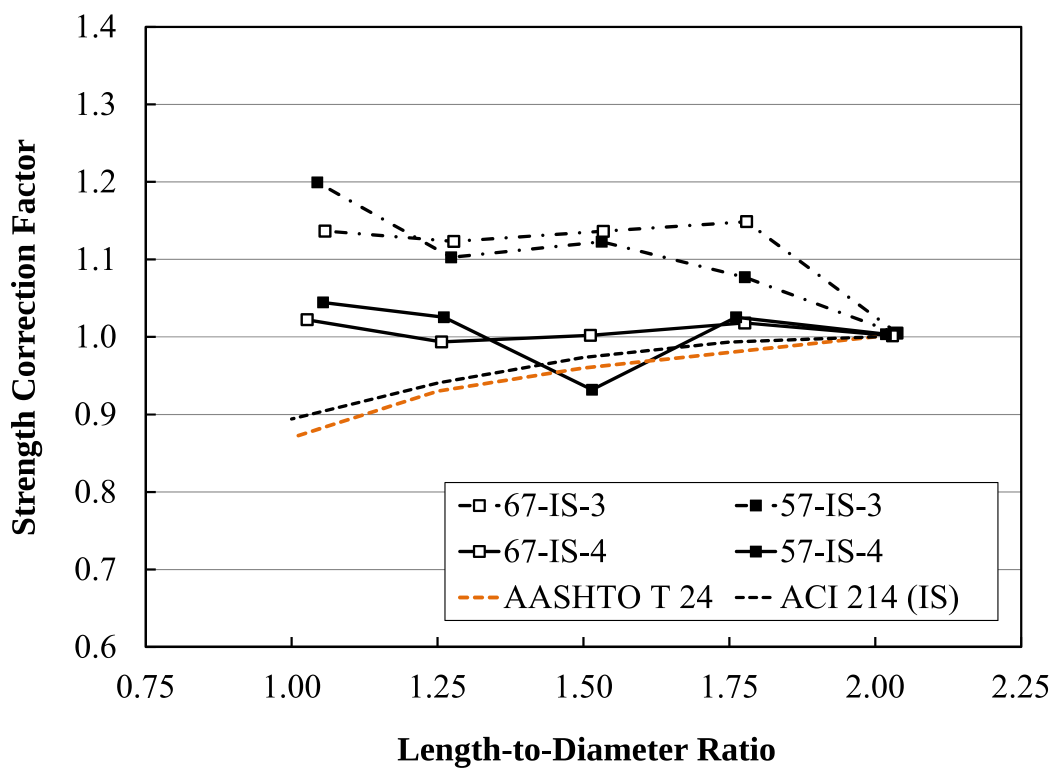


Figure 4-3: Initial strength correction factors for intermediate-strength mixtures

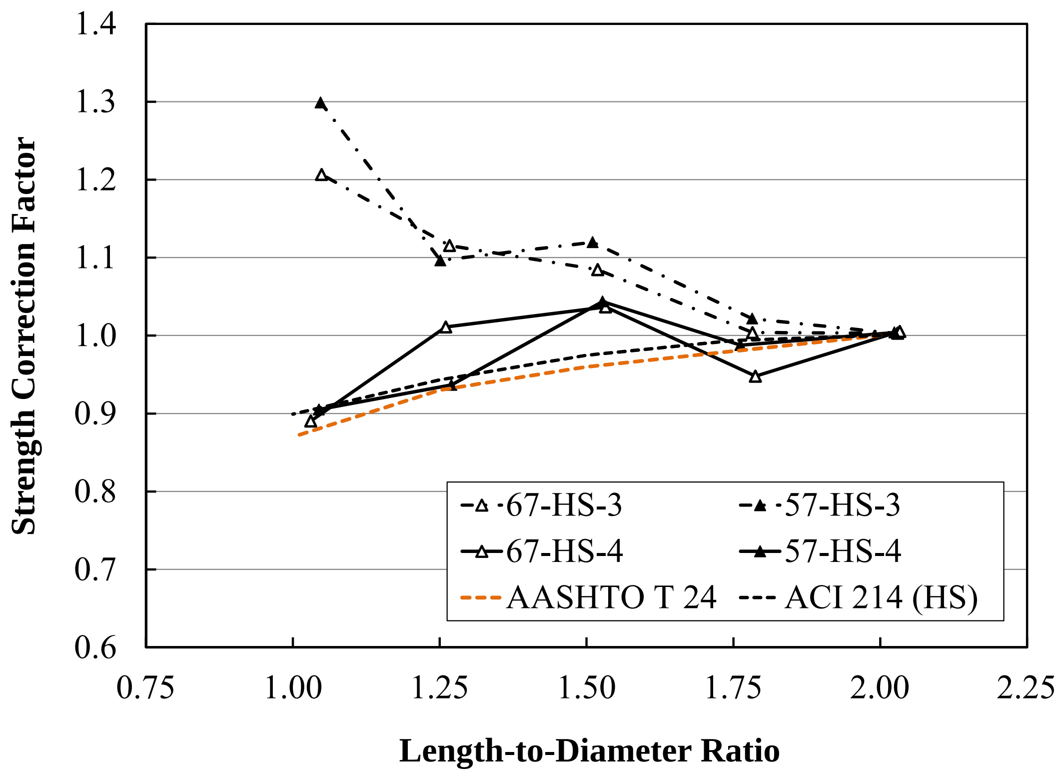


Figure 4-4: Initial strength correction factors for high-strength mixtures

The collected data from this experiment illustrates that the correction factors suggested by AASHTO T 24 (2007) and ACI 214 (2010) do not correlate well with all of the different batches of concrete. From observing Figure 4-2 through Figure 4-4, it is apparent that the correction factors suggested for the specimens having 3 in. diameters are less accurate than for the 4 in. diameter specimens in comparison to AASHTO T 24 (2007) and ACI 214 (2010).

To further investigate the strength correction factors for the collected data, each individual measured value was plotted as a ratio of the average strength of the cores having *l/d* of 2.0 divided by the measured strength for each individual value, as per Equation 4-1. These core strength ratios are shown by the scatter in Figure 4-5. The correction factor suggested by AASHTO T 24 (2007) is also plotted for reference.

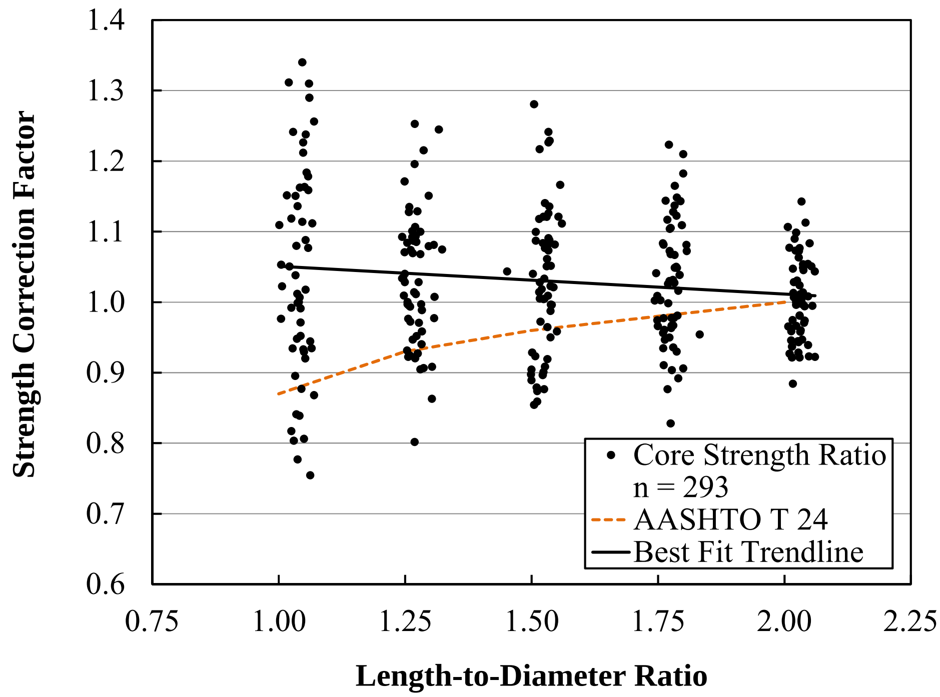


Figure 4-5: All core-strength-ratio values for core ***l/d*** strength correction factor analysis

In Figure 4-5, the vertical axis is the strength correction factor. As defined in Section 2.3.1, the core *l/d* strength correction factor converts any measured core strength with a *l/d* between 1.0 and 1.75 to the predicted core strength of that specimen if it had a *l/d* of 2. Thus, the scatter of the core-strength-ratio values represent the average strength of all measured core-strengths values having a *l/d* of 2 (five values within a data set) divided by each individual measured core-strength value (within that same data set). From Figure 4-5, the data is clearly heteroskedastic, meaning the scatter is unequal at various core *l/d* values. This means there is not a constant error, which is shown by the “trumpet” shape of the scatter. For this reason, the data were closely investigated to determine which, if any, variables are creating uneven variance in the data. By separating the analysis by the core diameter size, a significant observation can be seen in the scatter plot. Figure 4-6 and Figure 4-7 illustrate the difference in scatter between 3 and 4 in. diameter specimens, respectively.

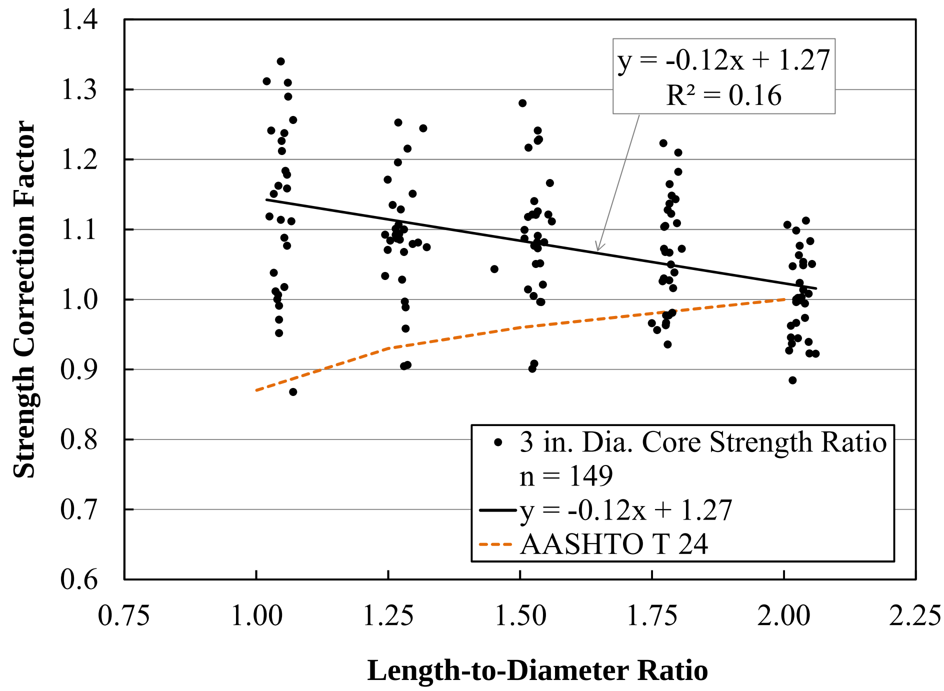


Figure 4-6: Core-strength-ratio values for all 3 in. diameter cores used for ***l/d*** strength correction factor analysis

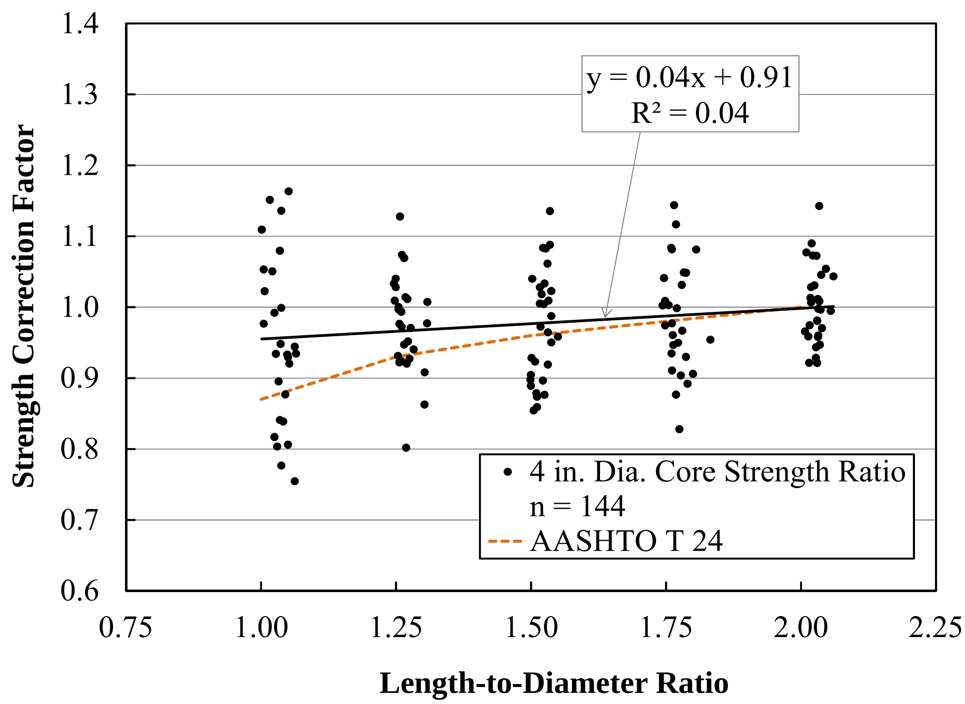


Figure 4-7: Core-strength-ratio values for all 4 in. diameter cores used for ***l/d*** strength correction factor analysis

The observed trends in Figure 4-6 and Figure 4-7 appear to be of significant difference. The trend shown for the 4 in. diameter cores is more consistent with the trend provided by AASHTO T 24 (2007). However, the trend shown for the 3 in. diameter ratios appear to be nearly the reciprocal of the correction factors suggested by AASHTO T 24 (2007). Based on the regression equations shown in Figure 4-6 and Figure 4-7, the suggested correction factors calculated are compared to the correction factors of AASHTO T 24 (2007) in Table 4-3.

Table 4-3: Correction factors suggested from 3 and 4 in. diameter core data and from AASHTO T 24 (2007)

l/d	Strength Correction Factor		
	3 in. Diameter Cores	**4 in. Diameter Cores**	**AASHTO T 24 (2007)**
1.75	1.06	0.98	0.98
1.50	1.09	0.97	0.96
1.25	1.12	0.96	0.93
1.00	1.15	0.95	0.87

From Figure 4-6, Figure 4-7, and Table 4-3, it can be hypothesized that these values are of significant statistical difference. In addition to observing the plotted data, the coefficient of variation (COV) should be evaluated. The coefficient of variation for all the core *l/d* data is provided in Appendix B.

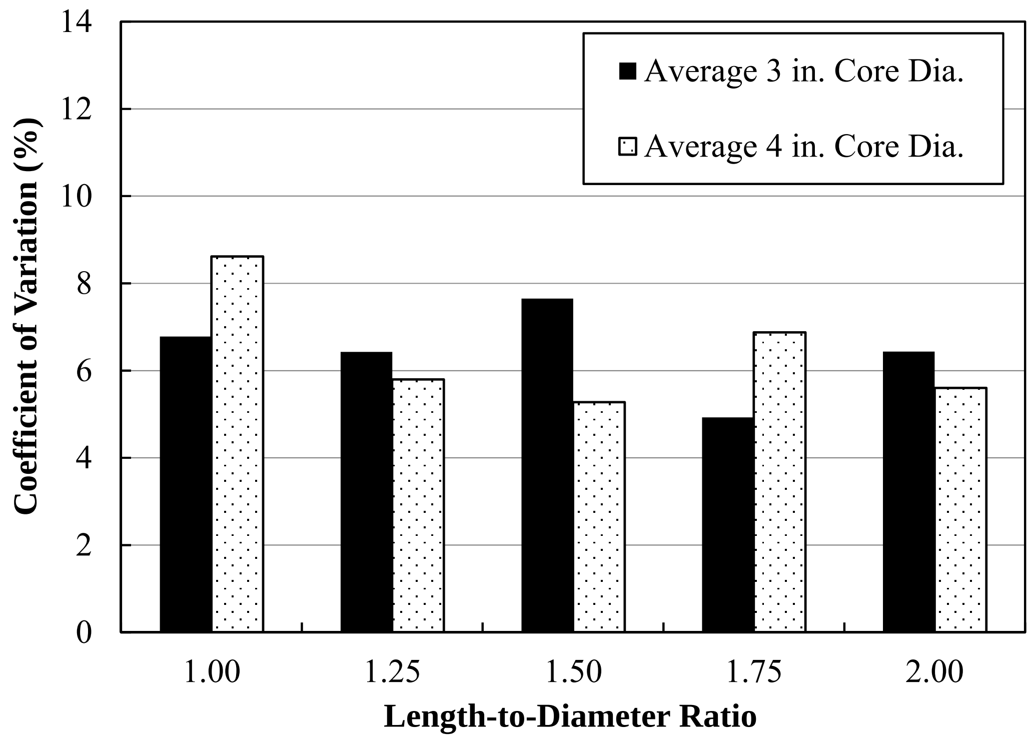


Figure 4-8: Coefficient of variation between 3 and 4 in. core diameter cores

Figure 4-8 shows the difference in COV between 3 and 4 in. diameter cores. By observing this figure and the tables in Appendix B, it can be concluded that the COV is not impacted by core diameter or core *l/d*.

In order to validate any conclusions from the data, the collected values must be statistically analyzed. The Central Limit Theorem is the most important result in statistics and says that if "we draw a large enough sample from a population, then the distribution of the sample mean is approximately normal, no matter what population the sample was drawn from" (Navidi 2010). However, the sample size for this project is small, thus, the Central Limit Theorem does not apply and the Student's t-distribution test can be used. For analyses that had two populations, a two-sample, assuming equal variance, t-test was conducted. This procedure assumes that the null hypotheses of the two means are equal. The following figure outlines the approach used in distinguishing which factors were significantly different in evaluating the strength correction factors at various core *l/d*'s.

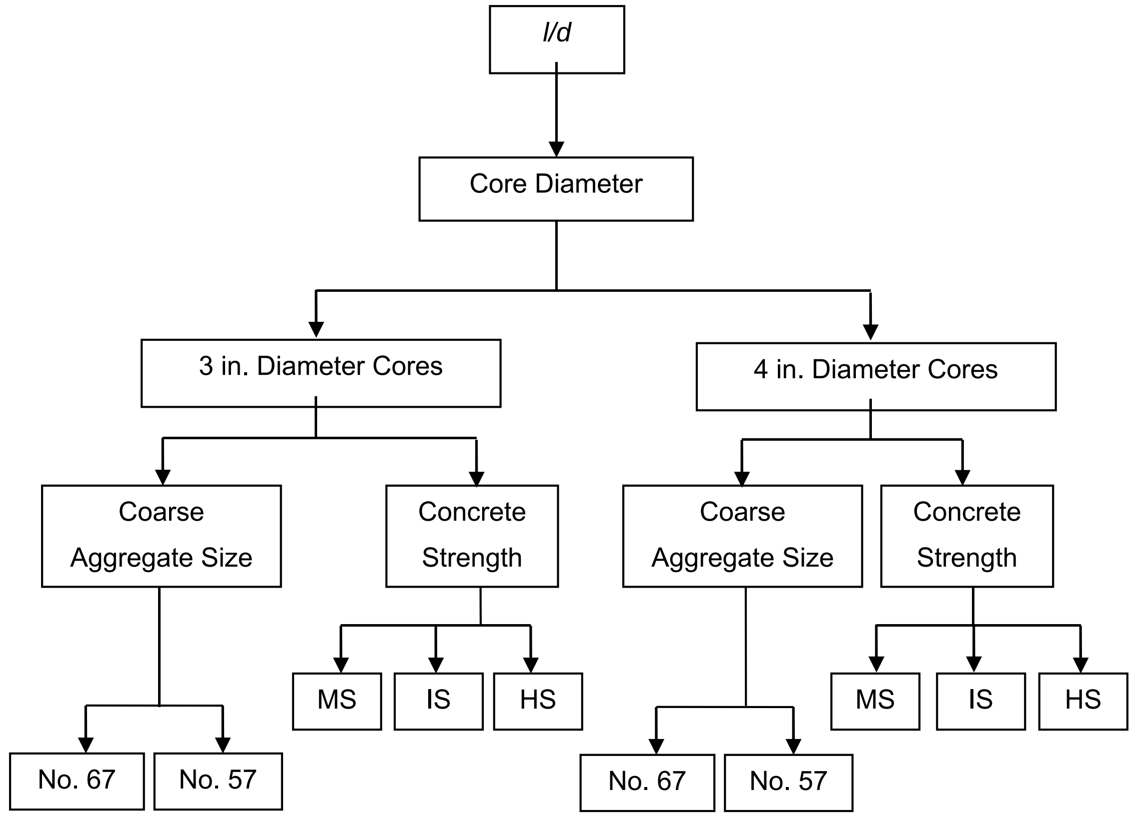


Figure 4-9: Outline for statistical analysis

For analyses comparing two variables, the Student's t-test was used. However, since there are three strength levels, a single factor analysis of variance (ANOVA) statistical test was used for comparing strength levels. ANOVA is a procedure for statistically assessing whether the null hypothesis of the means for two or more populations are equal (El Mogazy 2001). Table 4-4 shows the P-values for all t-distribution and ANOVA tests performed for the core l/d analysis.

The P-value indicates the probability associated with the conclusion to accept or reject the null hypothesis (El Mogazy 2001). At a 95 percent confidence level, any P-value below 0.05 indicates the there is a significant difference. Based on the statistical values presented in Table 4-4, it can be concluded that there is a significant difference in core strength correction factors between core diameter. The P-value calculated for the analysis between 3 and 4 in. diameter cores is extremely small, as shown in Table 4-4. For this reason, core diameter is a critical factor in the core l/d strength correction factor analysis. This agrees with the results presented in Section 2.3.2 from Arioz et al. (2007b) and Khoury et al. (2014). Therefore, the analysis results for 3 and 4 in. diameter cores should be kept separate. For each core-diameter size, further investigation was performed to see whether the coarse aggregate size, the concrete strength, or both were also of any significant statistical difference. Based on the statistics shown in Table 4-4, the core *l/d* strength correction factor analysis results for 3 in. diameter cores are significantly affected by the coarse aggregate size and strength. For 4 in. diameter cores, the *l/d* strength correction factor is only affected by the strength.

Table 4-4: Summary of P-values for core ***l/d*** analysis

Variables Compared	Test Used	P-value*
Core Diameter (3 vs. 4 in.)	t-test	7.92×10^{-18}
3 in. Core Diameter Coarse Aggregate Size (No. 67 vs. No. 57)	t-test	0.034
3 in. Core Diameter Strength Class (MS vs. IS vs. HS)	ANOVA	0.00186
4 in. Core Diameter Coarse Aggregate Size (No. 67 vs. No. 57)	t-test	0.410
4 in. Core Diameter Strength Class (MS vs. IS vs. HS)	ANOVA	0.0022

*At a 95% confidence level, a P-value of 0.05 or less indicates that there is a significant difference in variables

4.4.1 Analysis for 3 in. Diameter cores

As shown in Table 4-4, there are significant statistical differences observed within the 3 in. diameter data set. The P-values prove that coarse aggregate size and strength class create a significant variance for the 3 in. diameter data at a 95 percent confidence level. The following subsections will discuss the analysis for evaluating cores with 3 in. diameters for coarse aggregate size and core strength.

4.4.1.1 Coarse Aggregate Size

The statistical analysis results in Table 4-4 indicate that the core *l/d* strength correction factor is affected by the coarse aggregate size for 3 in. diameter specimens. The two coarse aggregates contained within the observed specimens are No. 67 and No. 57 crushed dolomitic limestone. Number 67 coarse aggregate has a nominal maximum aggregate size (NMAS) of 0.75 inch. Number 57 coarse aggregate is specified to have a NMAS of 1.0 inch. The best fit trends in Figure 4-10 and Figure 4-11 suggest that as the coarse aggregate size increases for 3 in. diameter cores, the calculated strength correction values less accurately represent the strength correction factors suggested by AASHTO T 24.

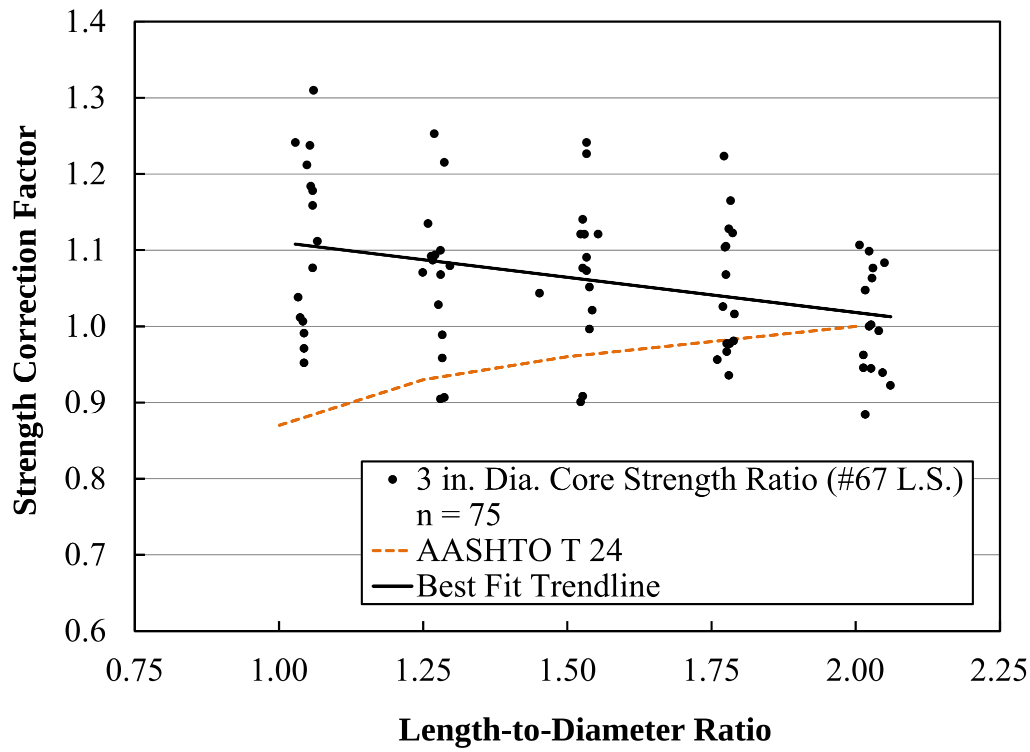


Figure 4-10: Core-strength-ratio values for all 3 in. diameter cores with No. 67 limestone

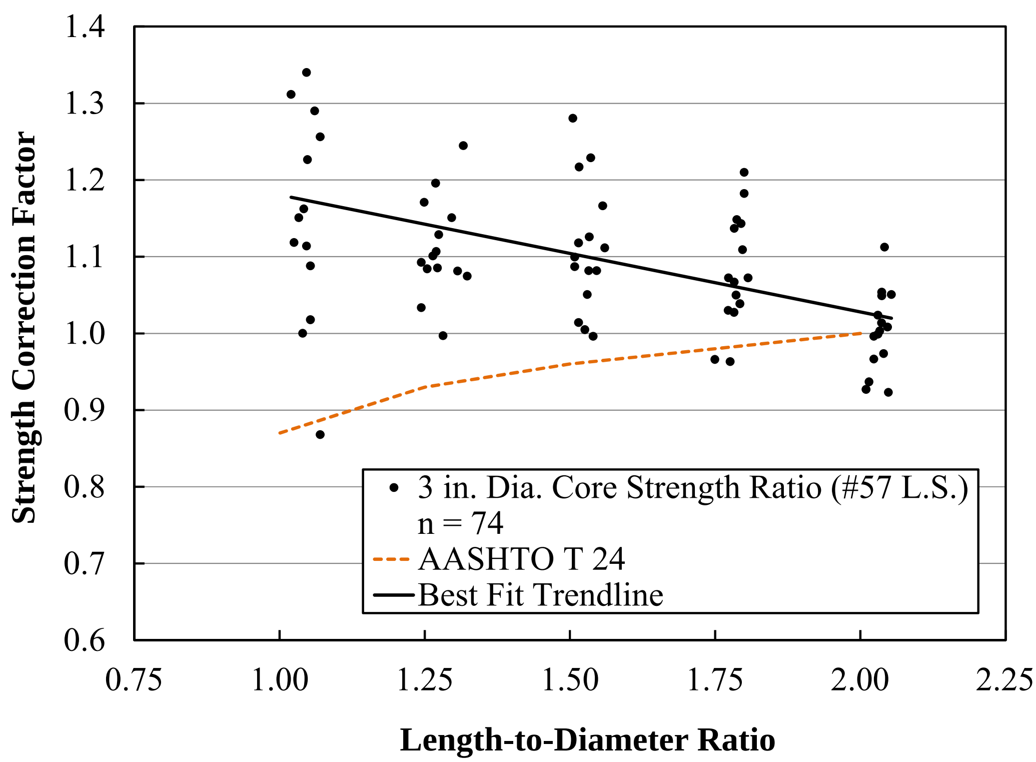


Figure 4-11: Core-strength-ratio values for all 3 in. diameter cores with No. 57 limestone

In order to quantify the percentage of error between the plotted data and the suggested correction factors from ASTM C 42, the unbiased estimate of the standard deviation, S_j, for the error has been calculated. Equation 4-2, taken from McCuen (1985), was used to estimate the standard deviation for the absolute error.

$$S_j = \sqrt{\frac{1}{n-1}\sum_{i}^{n}(\Delta_i^2)}$$

Equation 4-2

where,

S_j = unbiased estimate of the standard deviation (percent),

n = number of data points (unitless), and

Δ_i = absolute error (percent).

The absolute error was calculated using the following equation:

$$\Delta_i = [(S_i)_{est} - (S_i)_{meas}]/(S_i)_{meas} \times 100$$ **Equation 4-3**

where,

Δ_i = absolute error (percent),

$(S_i)_{est}$ = value of the estimated compressive strength (psi), and

$(S_i)_{meas}$ = value of the measured compressive strength (psi).

For calculating the absolute error, the estimated value was considered to be the specified core *l/d* correction factor as per AASHTO T 24 (2007). Since the values are very similar for both AASHTO T 24 (2007) and ACI 214 (2010), only the S_j for AASHTO T 24 (2007) will be presented. The values have been calculated at *l/d* values of 2.00, 1.75, 1.50, 1.25, and 1.00. Table 4-5 presents the difference in S_j for No. 67 and 57 crushed dolomitic limestone.

This table clearly shows that the S_j for specimens containing No. 57 crushed limestone are significantly greater as the core *l/d* gets smaller. As suggested by Arioz et al. (2007a), larger coarse aggregates can cause a gradual decrease in relative core strength, as shown in Figure 2-14. Tuncan et al. (2008) state that as the maximum aggregate size increases, the strength of core decreases. It is concluded from these analysis results, that the effects due to larger coarse aggregates may be significantly magnified as the core *l/d* is decreased.

Table 4-5: Unbiased estimate of the standard deviation of No. 67 and 57 crushed limestone for 3 in. diameter cores to AASHTO T 24 (2007) strength correction factors

l/d	S_j	
	No. 67	**No. 57**
2.00	1.9%	1.0%
1.75	2.9%	3.5%
1.50	4.4%	5.3%
1.25	4.1%	6.6%
1.00	6.6%	11.9%

4.4.1.2 CORE STRENGTH

The data collected has been separated into three strength classes, based on the mixture proportions used for each cast: moderate strength (MS), intermediate strength (IS), and high strength (HS), which have targeted strengths of 6,000, 8,000, and 10,000 psi, respectively. Based on the statistical analysis results shown in Table 4-4, there is a significant difference in core l/d strength correction factor when evaluating between strength classes. Figure 4-12 through Figure 4-14 show the plotted 3 in. diameter core data for each strength class.

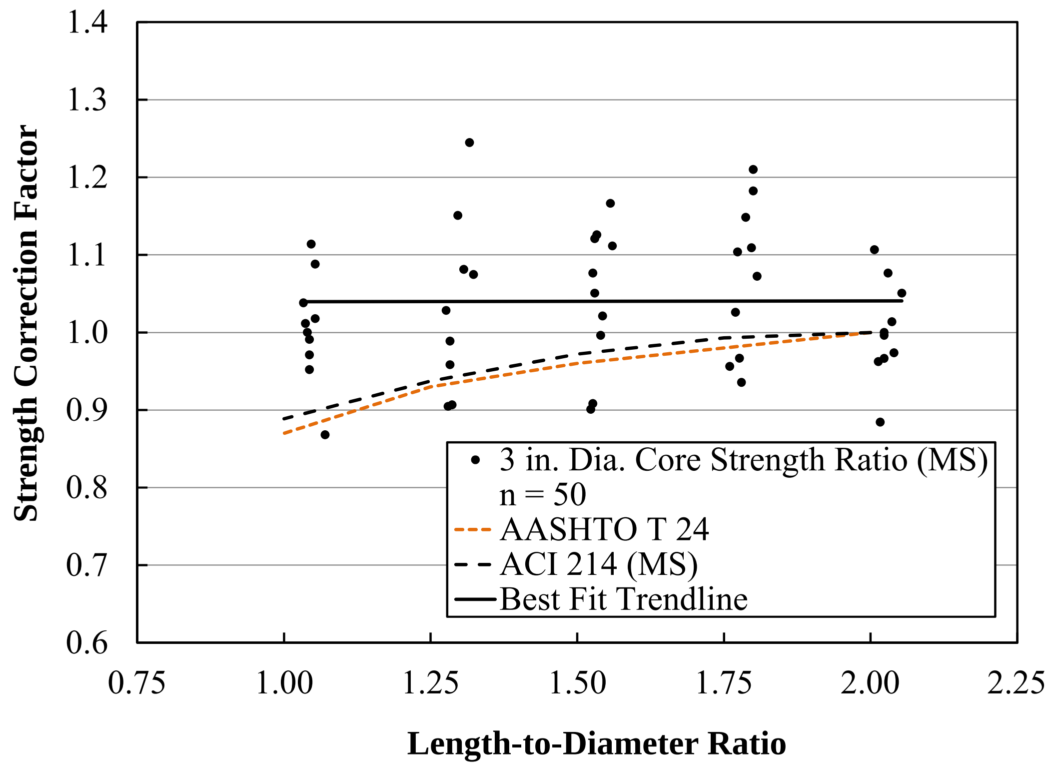


Figure 4-12: Core-strength-ratio values for all 3 in. diameter cores for MS mixtures

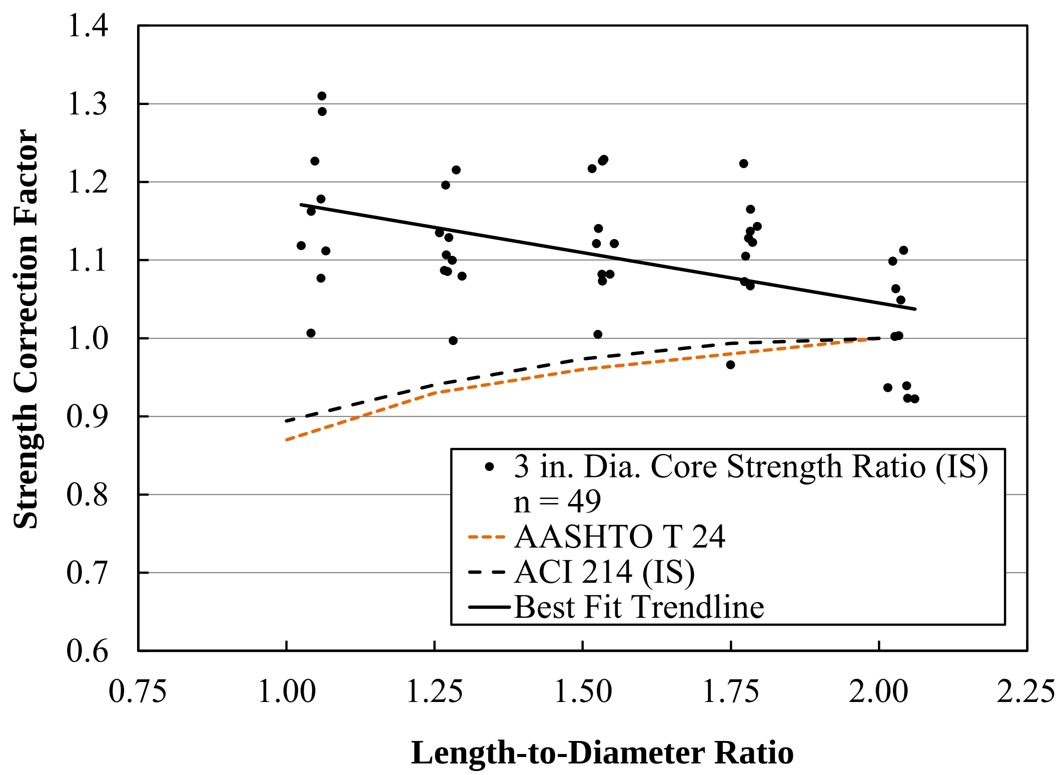


Figure 4-13: Core-strength-ratio values for all 3 in. diameter cores for IS mixtures

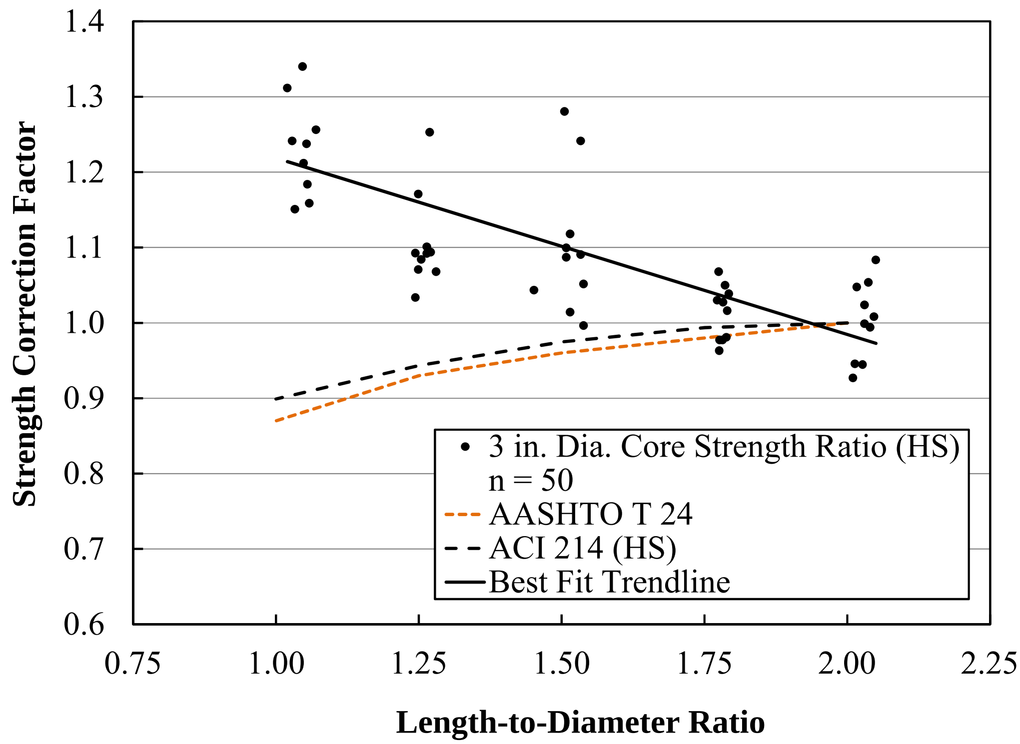


Figure 4-14: Core-strength-ratio values for all 3 in. diameter cores for HS mixtures

From Figure 4-12 through Figure 4-14, it is apparent that the core *l/d* strength correction factor for 3 in. diameter cores is a function of the concrete strength level. Table 4-6 shows the S_j for MS, IS, and HS mixtures for 3 in. diameter cores.

Table 4-6: Unbiased estimate of the standard deviation of MS, IS, and HS mixtures for 3 in. diameter cores to AASHTO T 24 (2007) strength correction factors

l/d	S_j		
	MS	**IS**	**HS**
2.00	1.2%	1.6%	0.8%
1.75	3.4%	4.2%	0.4%
1.50	2.8%	5.2%	4.1%
1.25	5.8%	4.0%	3.6%
1.00	1.5%	7.4%	14.0%

Based on the values presented, it can be concluded that, in general, as the core *l/d* decreases, the unbiased estimate of the standard deviation for 3 in. diameter cores becomes greater as the strength increases. This suggests that for high-strength mixtures having 3 in. diameter specimens, AASHTO T 24 (2007) strength correction factors may not be valid.

4.4.2 Analysis for 4 in. Diameter Cores

Four-inch diameter cores are commonly used as the benchmark diameter size in core testing. Based on the statistical results presented in Table 4-4, the 4 in. diameter core data is only a function of the strength level. Since no significant difference was observed for coarse aggregate size, it can be concluded that for larger diameter specimens, the difference between the size of No. 67 and 57 limestone does not affect the core *l/d* strength correction factor. Figure 4-15 through Figure 4-17 show the difference in scatter based on strength class for 4 in. diameter cores.

Comparing Figure 4-15 through Figure 4-17, there is a noticeable difference in the distribution. However, the values correlate more accurately with the AASHTO T 24 (2007) correction factors. Table 4-7 presents the unbiased estimate of the standard deviation values summarizing the difference in the plotted data to the AASHTO T 24 (2007) correction factors.

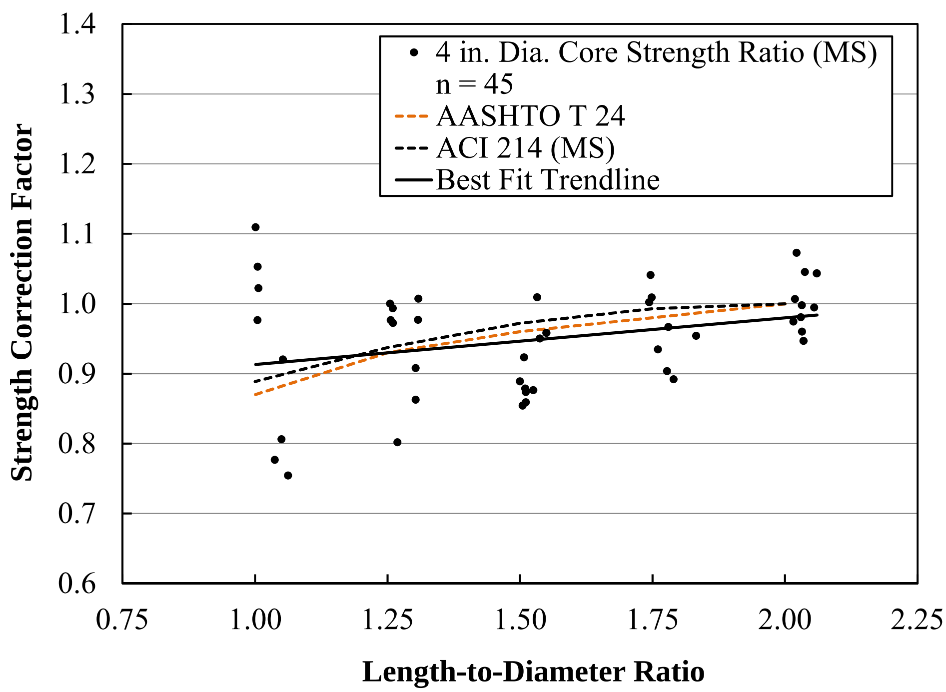


Figure 4-15: Core-strength-ratio values for all 4 in. diameter cores for MS mixtures

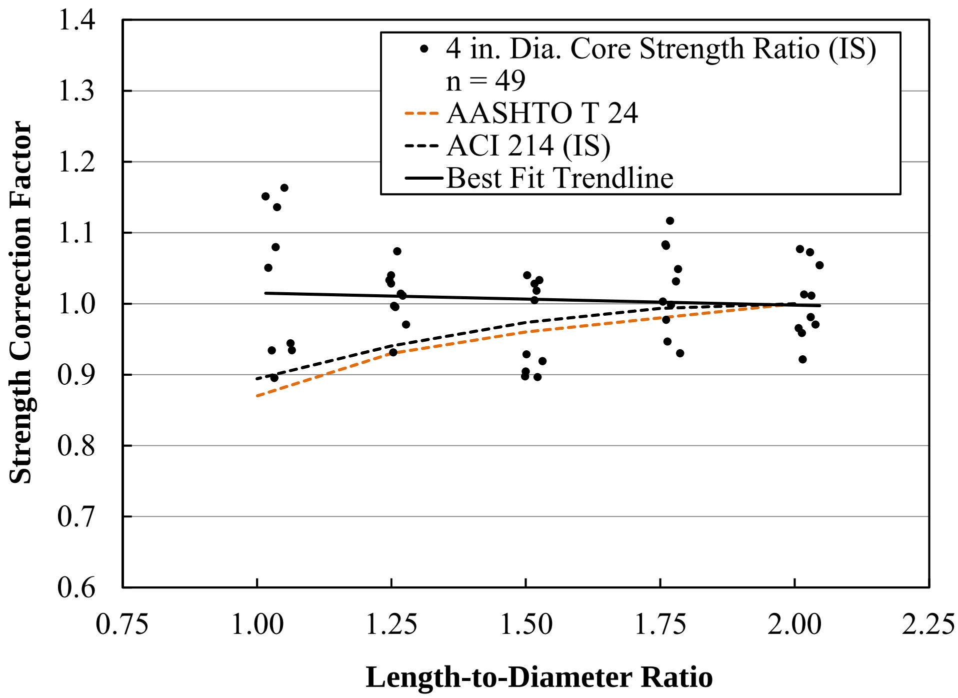


Figure 4-16: Core-strength-ratio values for all 4 in. diameter cores for IS mixtures

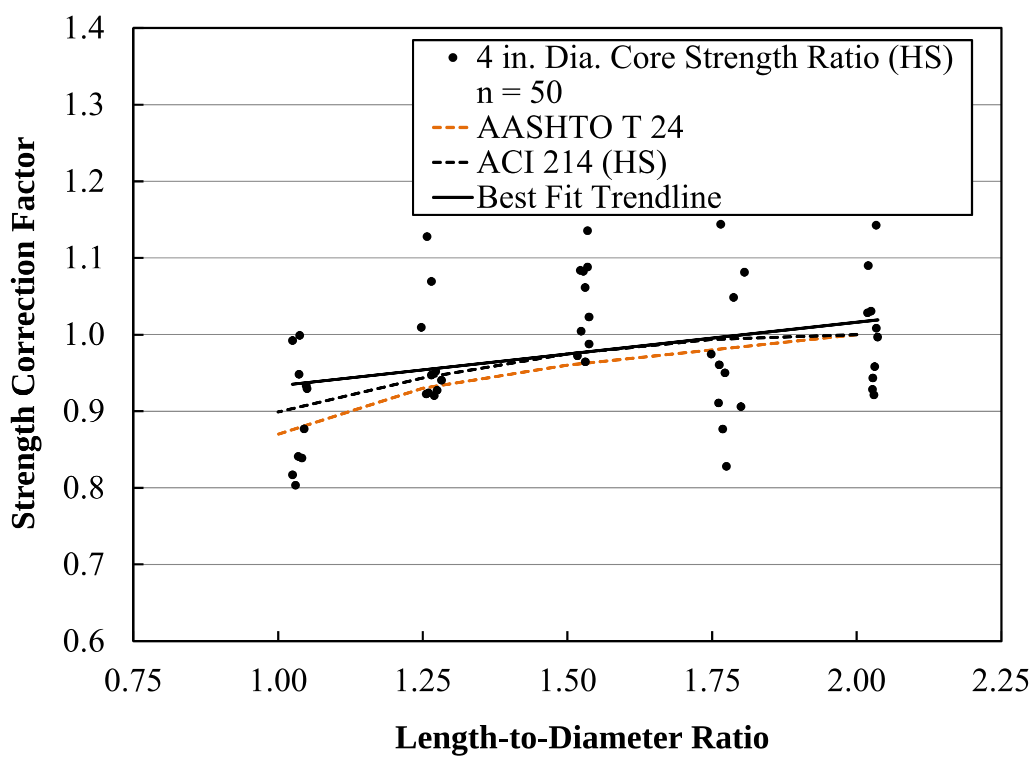


Figure 4-17: Core-strength-ratio values for all 4 in. diameter cores for HS mixtures

Table 4-7: Unbiased estimate of the standard deviation of MS, IS, and HS mixtures for 4 in. diameter cores to AASHTO T 24 (2007) strength correction factors

l/d	S_j		
	MS	**IS**	**HS**
2.00	0.5%	0.8%	1.4%
1.75	1.4%	1.2%	3.7%
1.50	4.8%	1.8%	1.3%
1.25	3.5%	0.5%	1.8%
1.00	10.1%	3.0%	7.2%

Comparing Table 4-7 to Table 4-6, the values are generally less, indicating that the AASHTO T 24 (2007) core *l/d* strength correction factors are more applicable to the 4 in. diameter cores having a *l/d* closer to 2.0. Thus, the information in Table 4-7 agrees with Neville (2001) that nominal diameters of 4 in. and *l/d* between 1.5 and 2.0 minimize the error introduced by the strength correction factors. As reported in Section 2.3.2.1, Bartlett and MacGregor (1994c) indicate that the effect of *l/d* on core strength is more significant for 2 in. diameter cores than for 4 in. diameter cores, indicating that this may be a trend as the diameter decreases from 4 inches.

4.4.3 Evaluation of *L/D* on Small Diameter Cores

Small-diameter cores create unreliable strength results (Bartlett and MacGregor 1994c). From the data presented and from the statistical analysis results, it can be concluded that 3 in. diameter cores behave differently compared to 4 in. diameter cores as the *l/d* decreases. Arioz et al. (2007b) suggest there should be different core *l/d* strength correction factors depending on the core diameter. The observed strength effects for various *l/d* values on small diameter cores is most likely due to the damage from drilling and trimming relative to the volume of concrete being tested. As discussed in Sections 2.5.2 and 2.3.2, the ratio of cut surface area to volume increases as core diameter decreases, thus, the potential influence of drilling damage will become more significant as the core diameter decreases (Bungey 1979 and Khoury et al. 2014). This statement has proved to hold true for the collected data as the *l/d* decreases for 3 in. diameter cores. This is possibly why AASHTO T 24 (2007) and ASTM C42 (2012) require a minimum core diameter of 3.75 and 3.70 inches, respectively. Figure 4-18 illustrates the potential damage inflicted onto a typical trimmed core.

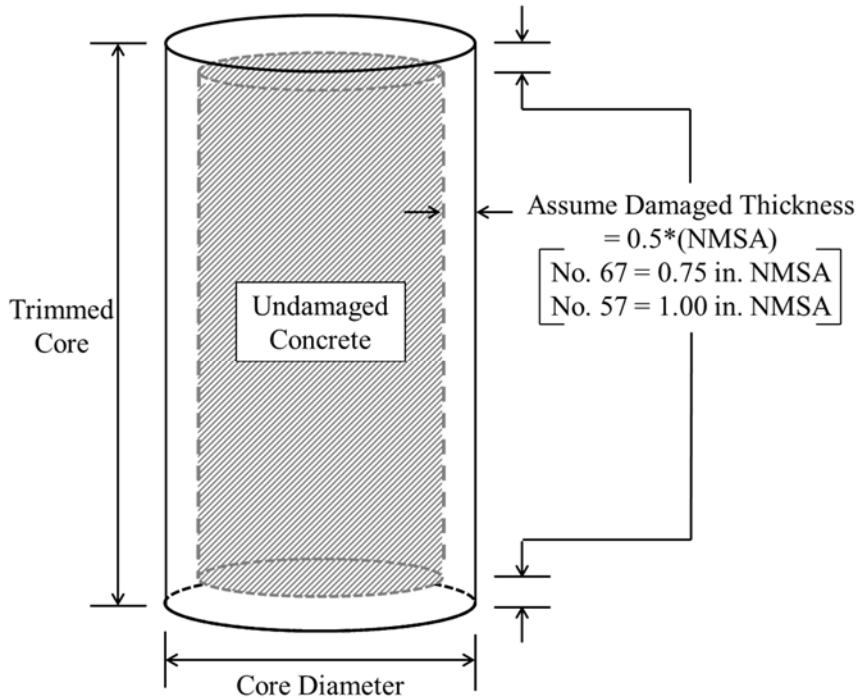


Figure 4-18: Typical illustration of assumed damage on a trimmed core

It is assumed that the damaged thickness inflicted from trimming and coring is approximately the nominal maximum size of the coarse aggregate. Bartlett and MacGregor (1994a) suggest that damage during drilling is partially attributed to the coarse aggregate that has been cut through and may have subsequently popped out during testing. This means that each trimmed core specimen has a surrounding exterior volume that may be influenced by the damage from cutting operations, as shown in Figure 4-18. From Figure 4-19, Figure 4-20, and Figure 4-21, the larger the coarse aggregate, the larger this effect is.

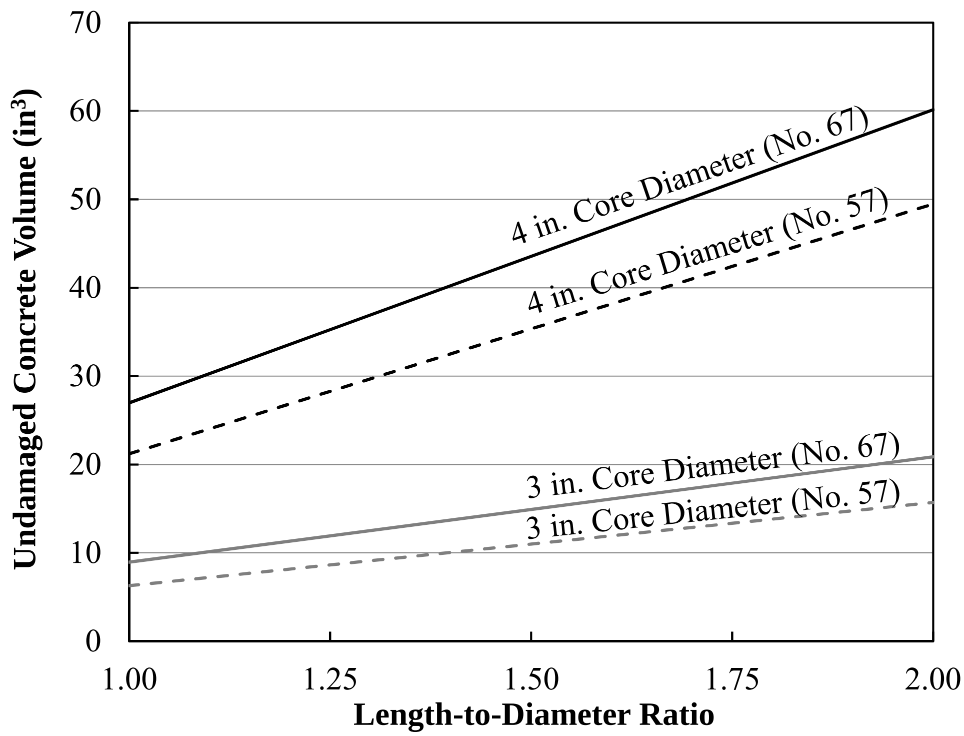


Figure 4-19: Volume of undamaged concrete for 3 and 4 in. diameter cores having No. 67 or 57 limestone

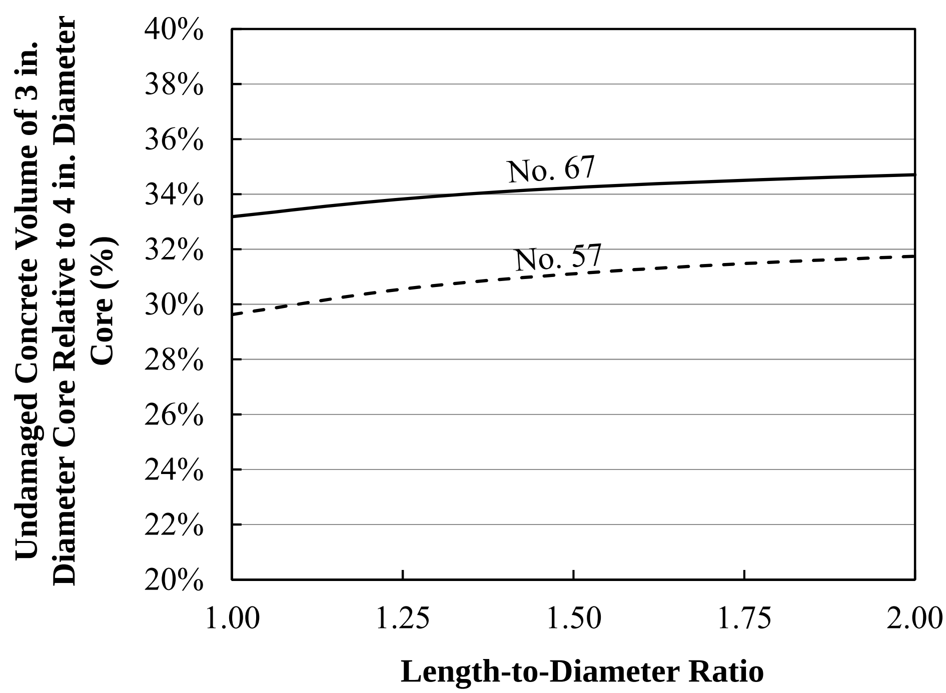


Figure 4-20: Percentage of undamaged concrete volume between 3 and 4 in. diameter cores for No. 67 or 57 limestone

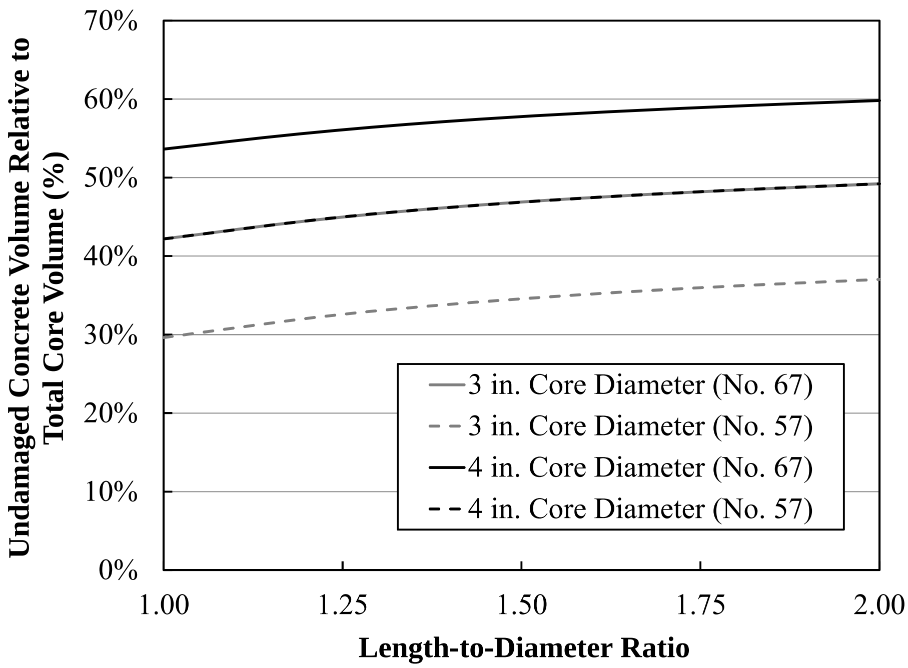


Figure 4-21: Percentage of undamaged concrete relative to total core volume

Figure 4-19 through Figure 4-21 indicate that the volume of undamaged concrete is significant as the core diameter decreases and as the core *l/d* decreases from 2. An increase in NMSA creates an even more pronounced effect on the volume of undamaged concrete tested. In Figure 4-21, there is an approximate 20 percent difference in the undamaged concrete relative to the total volume of the core tested when comparing a 4 in. diameter core with No. 67 limestone to a 3 in. diameter core with No. 57 limestone. As discussed in Section 2.3.22, as the maximum aggregate size increases, there is a noticeable decrease in core strength (Arioz et al. 2007a). Additionally, it is suggested that small diameter cores are more sensitive to damage not only from cutting operations but also from handling and storing (Bartlett and MacGregor 1994c). Due to the lesser amount of volume being tested on short cores having small diameters, they may also experience more effects from spatial variability (Bartlett and MacGregor 1994c). As stated by Neville (1995), when concrete is subject to stress, it is generally accepted that the larger the volume is, the more probable it is to contain a component of an extreme low strength. While this may be true, the findings of this research indicate that that a component of extreme low strength is magnified in small specimens and lead to a decrease in apparent strength.

4.4.4 PRECISION OF SUGGESTED CORE *L/D* STRENGTH CORRECTION FACTORS TO STANDARD STRENGTH CORRECTION PROCEDURES

For this study, an analysis using standard correction procedures was conducted to compare the unbiased estimate of the standard deviation, S_j, of the absolute error found between these data and the core *l/d* strength correction factors from AASHTO T 24 (2007) and ACI 214 (2010). For each of these procedures there is a suggested core *l/d* strength correction factor. The AASHTO T 24 (2007) core *l/d* strength correction factors are provided in Table 4-1 and the core *l/d* strength correction functions required by ACI 214 (2010) are shown in Table 4-2. Based on the collected data the calculated core *l/d* strength correction values are compared to the values recommended when using AASHTO T 24 (2007) and ACI 214 (2010). Figure 4-22 through Figure 4-25 present this comparison for both 3 and 4 in. diameter cores. Note that the individual calculated core *l/d* strength correction factors are obtained from the ratio values presented in Figure 4-6 and Figure 4-7. The data is plotted with ±10 percent difference and the line of equality (L.O.E.).

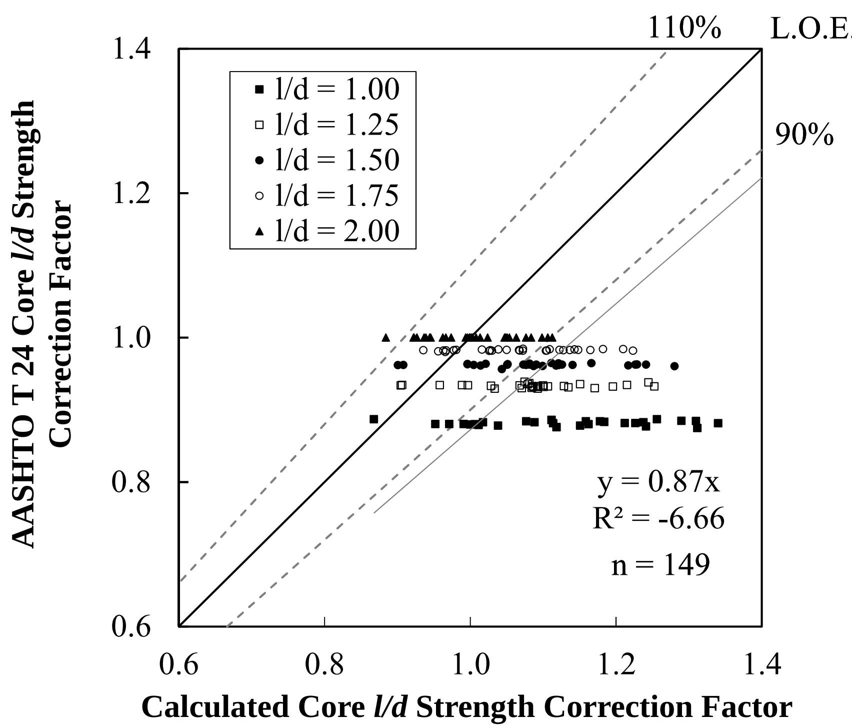


Figure 4-22: Individual calculated core ***l/d*** strength correction factors versus AASHTO T 24 (2007) recommended core ***l/d*** strength correction factors for 3 in. diameter cores

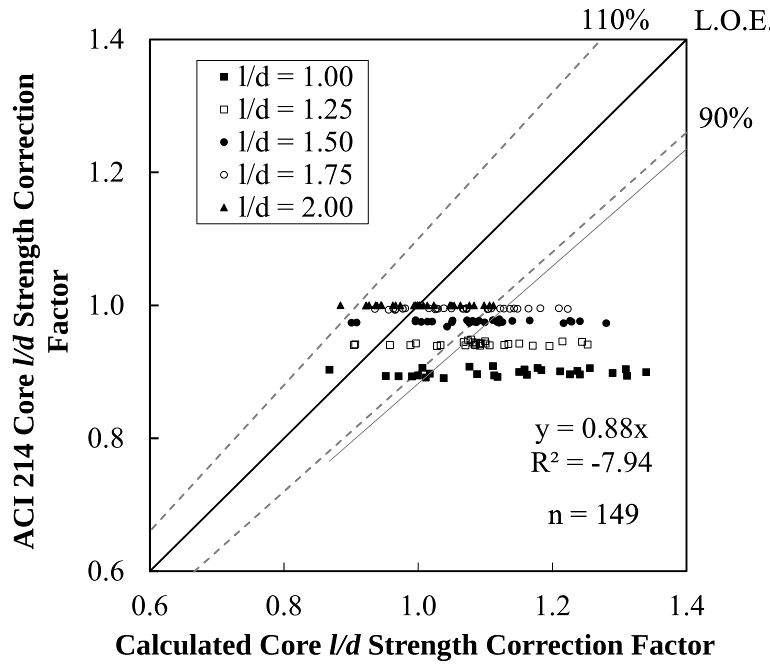


Figure 4-23: Individual calculated core ***l/d*** strength correction factors versus ACI (2010) recommended core ***l/d*** strength correction factors for 3 in. diameter cores

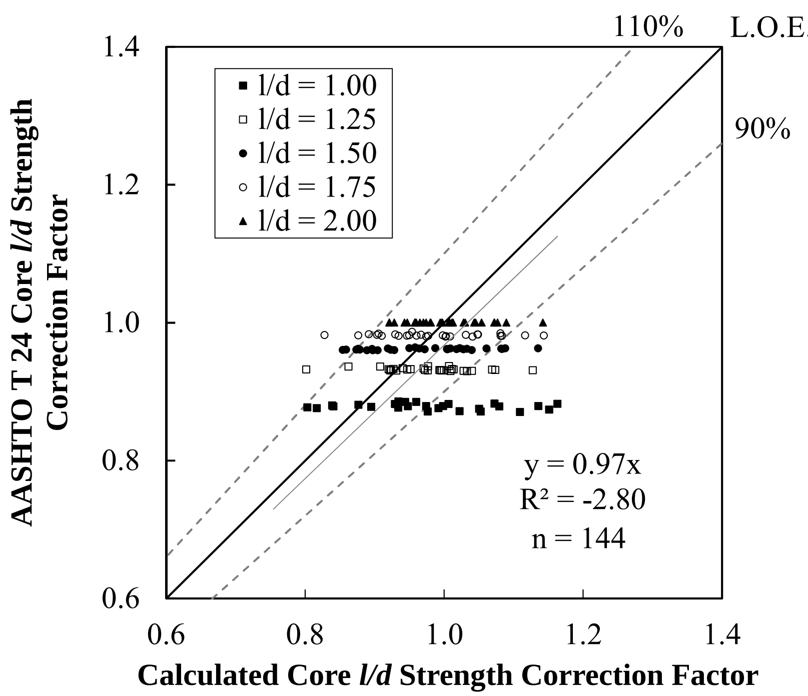


Figure 4-24: Individual calculated core ***l/d*** strength correction factors versus AASHTO T 24 (2007) recommended core ***l/d*** strength correction factors for 4 in. diameter cores

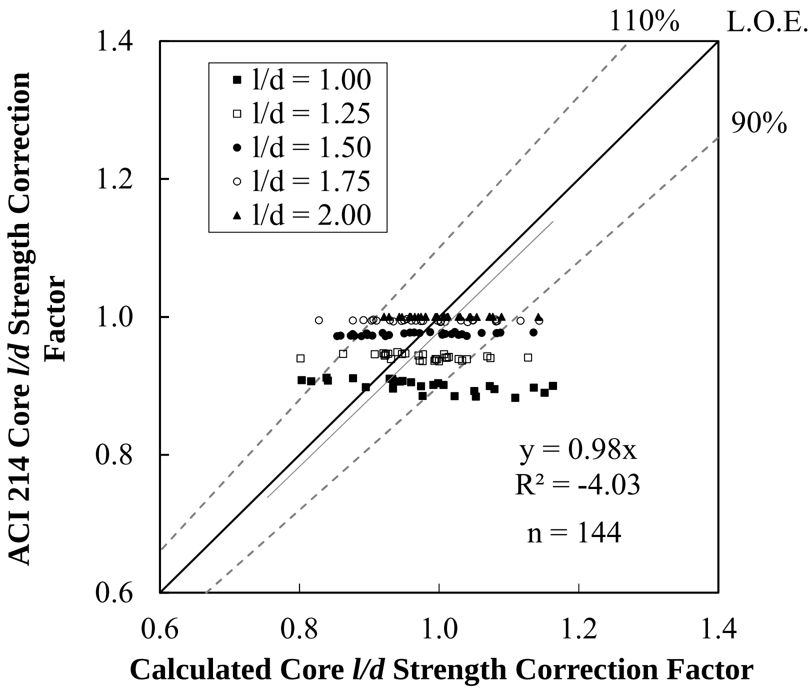


Figure 4-25: Individual calculated core ***l/d*** strength correction factors versus ACI (2010) recommended core ***l/d*** strength correction factors for 4 in. diameter cores

Based on these scatter plots, it can be concluded that for 3 in. diameter cores, AASHTO T 214 (2009) and ACI 214 (2010) underestimate the core *l/d* strength correction values by more than 10 percent in comparison to the core *l/d* strength correction factors suggested by the analyzed data. For 4 in. diameter cores, both AASHTO T 24 (2007) and ACI 214 (2010) slightly underestimate the core *l/d* strength correction values in comparison to the core *l/d* strength correction factors suggested by the analyzed data. Overall, the core *l/d* strength correction factors from ACI 214 (2010) are marginally closer to the suggested core *l/d* strength correction values of this data, in comparison to AASHTO T 24 (2007).

A statistical evaluation to determine the unbiased estimate of the absolute error for the comparison between AASHTO T 24 (2007) and ACI 214 (2010) core *l/d* strength correction factors to the calculated core *l/d* strength correction was performed. Equation 4-2 from Section 4.4.1 was used for this calculation. The unbiased estimate of the standard deviation, S_j, of the absolute error for the AASHTO T 24 (2007) and ACI 214 (2010) core *l/d* strength correction factor is shown in Table 4-8.

Table 4-8: S_j for 3 and 4 in. diameter calculated core ***l/d*** strength correction factors in comparison to AASHTO T 24 and ACI 214 core ***l/d*** strength correction factors

Core Diameter	S_j	
	AASHTO T 24 (2007)	**ACI 214 (2010)**
3 in.	27.5%	24.6%
4 in.	9.0%	8.8%

From Table 4-8, it can be concluded that the S_j is noticeably less for 4 in. diameter cores than for 3 in. diameter cores. Therefore, the calculated core *l/d* strength correction factors for 4 in. diameter cores correlate more accurately with both AASHTO T 24 (2007) and ACI 214 (2010) than the 3 in. core *l/d* strength correction factors. Additionally, S_j for the error using the ACI 214 (2010) more closely represents the core *l/d* strength correction factors calculated using the collected data for this study.

4.5 CORE DIAMETER ANALYSIS

Numerous publications discuss the difference in strength between various core diameters. In direct comparison to this study, ACI 214 (2010) has a strength correction factor established for 3 and 4 in. diameter specimens. These correction factors are presented in Table 2-4.

All specimens evaluated for the core diameter analysis were trimmed to have a *l/d* of approximately 2.0. For six batches of concrete, the average of five 3 in. diameter specimens were compared to the average of five 4 in. diameter cores. A regression analysis was then performed on the average values. For each average, there are 10 data points, five strength values for 3 in. diameter cores and five strength values for 3 in. diameter cores. The results from the regression calculated at a 95 percent confidence level are shown in Figure 4-26. To illustrate the normal distribution within the averaged values, Figure 4-27 is presented. Note that in Figure 4-27, the normal distribution curve for each data set represents the ratio of 4 in. to 3 in. core diameter strengths. This data set consists of the individual 4 in. diameter core strength values divided by the average 3 in. diameter core strength.

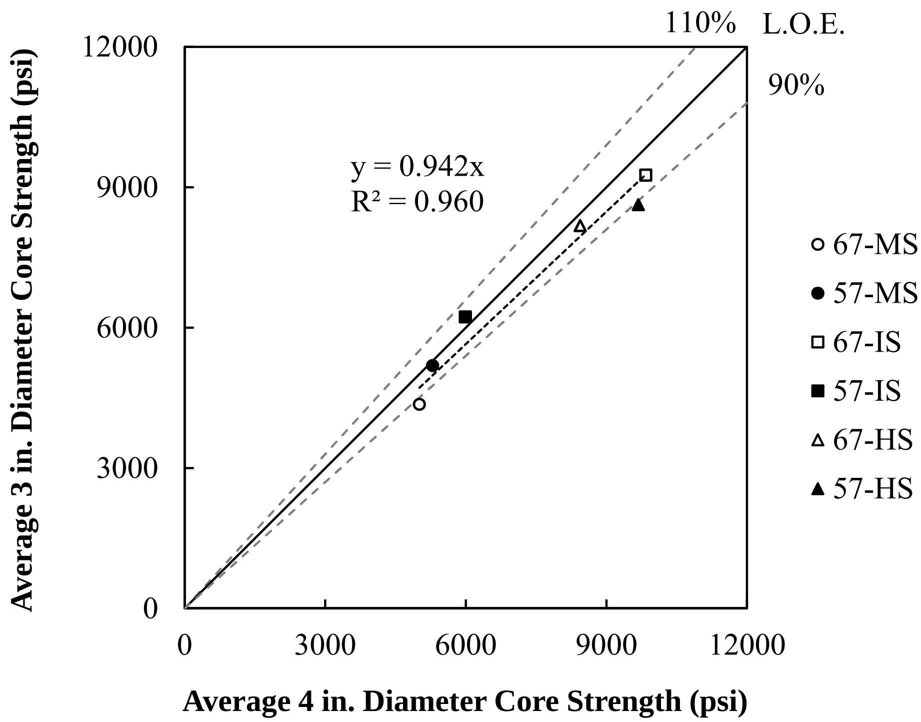


Figure 4-26: Regression analysis of average 4 in. to average 3 in. diameter core strength

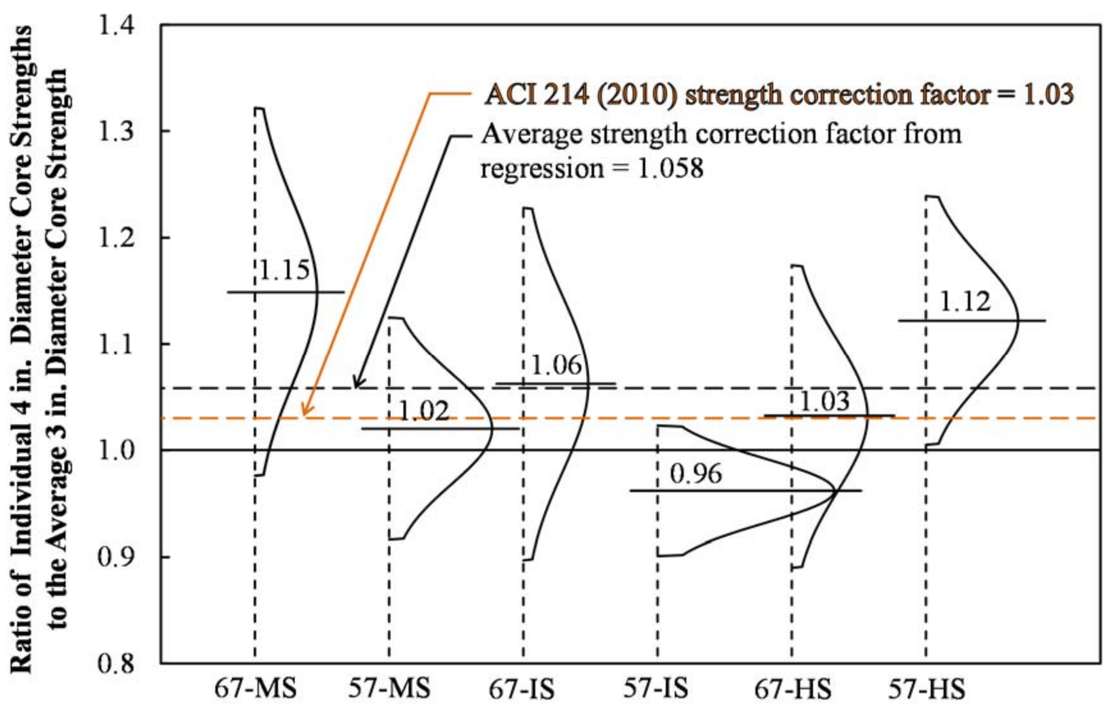


Figure 4-27: Approximate 95% confidence limits on strength ratio of 4 in. to 3 in. diameter cores

To calculate the core diameter strength correction factor (S.C.F.), Equation 4-4 is used. The strength of 4 in. diameter cores is in the numerator because 4 in. diameters are referred to as the benchmark core diameter and has a strength correction factor of 1.0 in Table 2-4 from ACI 214 (2010).

$$\text{Core Diameter S.C.F.} = \frac{\text{Average } f'_c \text{ (for 4 in. diameter cores)}}{\text{Average } f'_c \text{ (for 3 in. diameter cores)}} \qquad \textbf{Equation 4-4}$$

The P-value calculated at a 95 percent confidence level in Figure 4-26 is 1.16×10^{-7}. Therefore, there is a significant statistical difference between 3 and 4 in. core diameters. Figure 4-27 shows the approximate 95 percent confidence limit of the evaluated ratio for each mixture. The normal distribution curves presented on Figure 4-27 show the 95 percent confidence limit, or two standard deviations away from the mean, for the strength ratio of 4 in. diameter cores to 3 in. diameter cores. The regression equation presented in Figure 4-26 is the inverse of Equation 4-4; therefore, the strength correction factor accounting only for diameter is nearly 1.06 for a 3 in. diameter core. This value creates an upper-limit, strength correction factor relative to the 1.03 strength correction factor established by ACI 214 (2010) in Table 2-4, which is also shown on Figure 4-27. In Figure 2-8 of Section 2.3.2, Khoury et al. (2014) suggests a strength correction factor of 1.05 for cores having a diameter near 3 in. (2.95 in.) at l/d of 2.0.

4.6 Drilled Orientation Analysis

The reviewed literature investigating whether the drilled orientation has a significant effect on the core strength presents conflicting experimental conclusions. As discussed in Sections 2.4.2 and 2.4.3, there are some research findings opposing anisotropy and many supporting anisotropy. Table 4-9 is presented to summarize the various strength correction factors suggested by various published literature.

The specimens collected for the drilled orientation study were completely separate from the core l/d strength correction factor study. A separate wall, as shown in Figure 3-3 was cast solely for the purpose of this analysis. All cores were trimmed to have a core l/d of approximately 2.0, and all specimens had a diameter of 4 inches. Each core was taken from the top region of the wall element to minimize the difference in spatial variation. The analysis was conducted similarly to the analysis described in Section 4.5. For six mixtures, the average of five parallel orientation specimens were compared to the average of five perpendicular orientation cores. Within the analysis of these averaged values, there was one outlier found from the perpendicular cores taken from 67-HS. The results are presented in Figure 4-28 and Figure 4-29.

Table 4-9: Summary of strength correction factors for cores drilled perpendicular to the concrete placement direction relative to parallel cores

Source of Data	Strength Correction for Perpendicular Cores Relative to Parallel Cores
Bloem (1958)	1.18
Petersons (1964)	1.12
Meininger (1968)	1.10
Graham (1969a) and Graham (1969b)	1.07-1.09
Johnston (1973)	1.08
Munday and Dhir (1989)	1.08
Yip and Tam (1988)	1.04-1.08
Khoury (2014)	1.075
Bartlett and MacGregor (1994d)*	None
ACI 214 (2010)*	None
Bungey (1979)	None

*Literature recognize perpendicular cores may be weaker but do not specify a correction factor

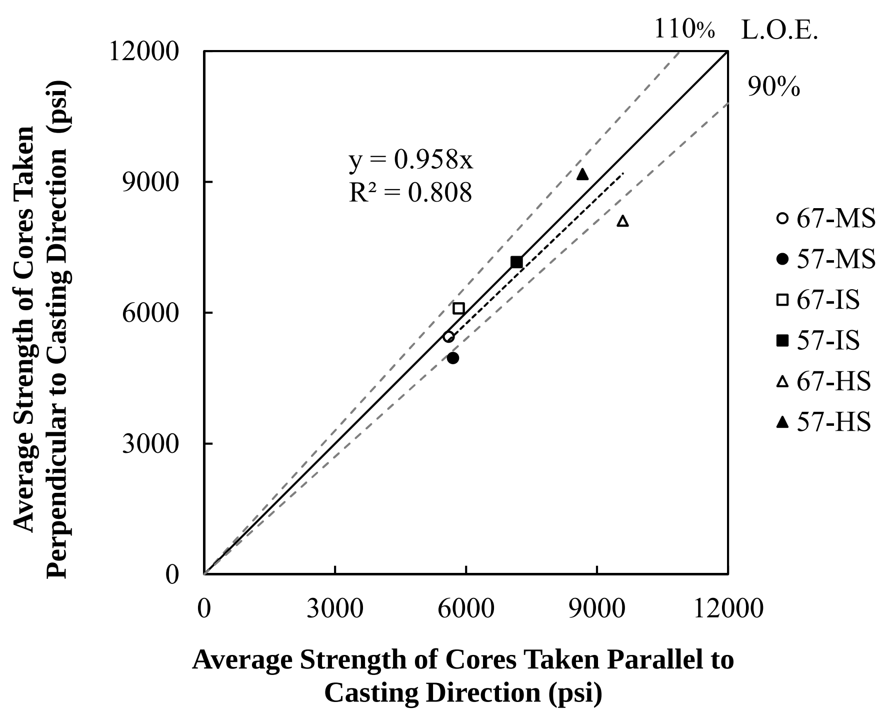


Figure 4-28: Regression analysis of average parallel to average perpendicular core strength

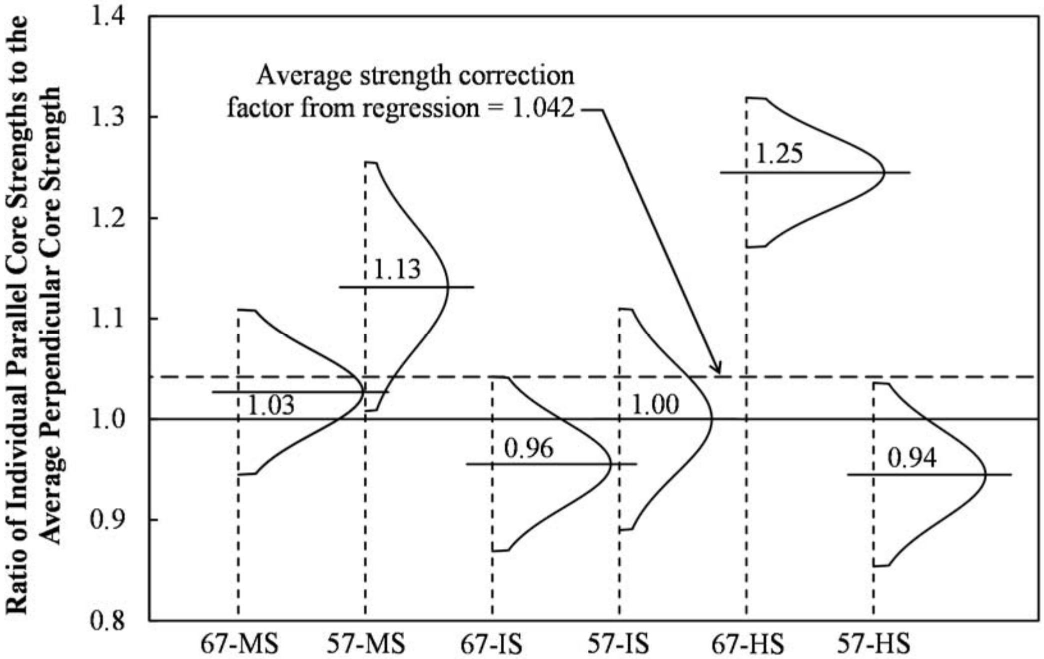


Figure 4-29: Approximate 95% confidence limits on ratio of average parallel core strength to average perpendicular strength

To calculate the core orientation strength correction factor (S.C.F.), Equation 4-5 is used.

$$\textit{Core Orientation S.C.F.} = \frac{\textit{Average } f'_c \textit{ (for parallel cores)}}{\textit{Average } f'_c \textit{ (for perpendicular cores)}} \qquad \textbf{Equation 4-5}$$

Based on the inverse of the regression equation provided in Figure 4-29 and the normal distribution curves shown on Figure 4-29, the collected data suggests a correction factor of approximately 1.04 for cores drilled perpendicular to the cast direction. The P-value calculated at a 95 percent confidence level in Figure 4-28 is 2.38 x 10^{-6}. Therefore, there is a significant statistical difference between cores drilled parallel and perpendicular to the concrete placement direction. In comparison to previously suggested correction factors, a strength correction factor of 1.04 is similar to the smallest value listed in Table 4-9. This is most likely due to the high-strength level used in the analyzed concrete as compared to that used by the previous researchers in Table 4-9. For high-strength concrete mixtures, the strength of the ITZ should be increased relative to the rest of the concrete; thus, the effects from drilling perpendicular to the cast direction may be decreased. Khoury et al. (2014) states that in high-strength concrete, the matrix-aggregate bond is stronger and the transition zone is more cohesive; thus, the damage in the core specimen is low.

Chapter 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 PROJECT SUMMARY

The research described in this report was conducted as a part of a larger research project funded by the ALDOT to evaluate the in-place concrete strength by core testing. This phase of the project was primarily undertaken to assess the effects of various *l/d*'s on concrete core specimens having strengths above 6,000 psi. Additional observations focused on the effects of small diameter cores and the drilling direction with respect to the concrete placement direction. The information reported in this report covers the laboratory findings for the ALDOT funded project. Further information on the findings for the field phase will be reported separately.

Data were collected from 390 core specimens from 12 different casts. To incorporate the evaluation of coarse aggregate size and concrete strength, mixtures were developed to assess these effects. Six of the 12 batches of concrete used No. 67 crushed dolomitic limestone, and the remaining six batches used No. 57 crushed dolomitic limestone. Three mixture proportions were developed to evaluate the effects that strength may have on core *l/d.* The strength classes developed were moderate, intermediate, and high strength having strengths of 6,000, 8,000, and 10,000 psi, respectively. Four batches of concrete were cast for each of these targeted strengths. Procedures and scheduling was performed consistently between all mixtures and tests. This eliminated variables such as age, aggregate type, curing, coring practices, moisture condition, and end preparation as contributing factors in the analysis.

A study of the effects *l/d* has on core strength was performed on a total of 300 of the cores retrieved. In other words, 25 cores were collected for this analysis from each of the 12 batches of concrete. Cores were trimmed to have *l/d*'s of 2.0, 1.75, 1.5, 1.25, and 1.0. Half of these cores had a diameter of 3 inches and the remaining 150 cores were 4 inches in diameter. The analysis evaluated the effects core diameter, coarse aggregate size, and concrete strength has on the various core *l/d* values for various mixtures.

An additional analysis directly comparing the strengths of 3 in. diameter cores to 4 in. diameter cores within the same data set was also performed. This analysis used the average of five strengths for each diameter size. The compared cores were retrieved from the same batch of concrete. This analysis was performed on six batches of concrete and direct comparisons were grouped to draw generalized overall conclusions.

The last study performed was designed to evaluate strength difference between cores taken parallel and perpendicular to the concrete placement direction. For this analysis, a wall was cast for six batches of concrete and ten cores were retrieved from each wall. Five cores were drilled parallel, and five cores were drilled perpendicular to the cast direction. All cores were taken from the same region of the wall to minimize spatial variation. This provided a direct comparison between the two drilling orientations. Again, the orientation comparisons made within each of the six data sets were grouped to draw generalized overall conclusions.

The results of this research are aimed at providing guidance to the ALDOT when assessing parameters on concrete core specimens.

5.2 Research Conclusions

5.2.1 Conclusions from the Core *L/D* Study

- The 3 in. diameter cores do not behave the same as 4 in. diameter cores when evaluated for core *l/d* effects on compressive strength.
- For 3 in. diameter cores, the calculated core *l/d* strength correction factor increases as the coarse aggregate size increases and as the *l/d* decreases.
- For 3 in. diameter cores, the calculated core *l/d* strength correction factor increases as the concrete strength increases and as the *l/d* decreases.
- Based on the analyzed data, the core *l/d* strength correction factors used in AASHTO T 24 (2007) and ACI 214 (2010) are not accurate predictions for 3 in. diameter core specimens with coarse aggregate sizes of No. 67 or larger.
- For 4 in. diameter cores, the coarse aggregate sizes of No. 67 and 57 do not have a significant impact on core *l/d* effects on strength.
- For 4 in. diameter cores, the core *l/d* strength correction factor is closer to a value of 1.0 at each *l/d* between 1.0 and 1.75 in comparison to the core *l/d* strength correction factors recommended by AASHTO T 24 (2007) and ACI 214 (2010).
- For 4 in. diameter cores, the core *l/d* strength correction factors suggested by AASHTO T 24 (2007) and ACI 214 (2010) compare well with the analyzed data.
- The core *l/d* strength correction factors suggested by AASHTO T 24 (2007) and ACI 214 (2010) suggest a lower bound prediction of core strength in comparison to the best-fit trend line obtained from the collected data.

5.2.2 Conclusions from Core Diameter Size Study

- The data analyzed indicate that the core strength decreases as the core diameter decreases from 4 inches, which is in agreement with ACI 214 (2010) and Khoury et al. (2014).
- The data analyzed indicate that the strength correction factor for 3 in. diameter cores relative to 4 in. diameter cores is 1.06. This core-diameter, strength correction factor is greater in comparison to the value of 1.03 recommended by ACI 214 (2010) for 3 in. diameter cores.

5.2.3 Conclusions from Core Drilling Orientation Study

- The difference in strength for cores drilled parallel and perpendicular to the placement direction indicate that the apparent strength of cores taken perpendicular to the casting direction is 96 percent of the apparent strength of cores taken parallel to the casting direction. In general, this is similar to the lower bound of the results reported by the majority of previous research on core drilling orientation.

5.3 Research Recommendations

- For cores having a diameter of 3.75 in. or larger, as per AASHTO T 24 (2007), use core l/d strength correction functions suggested by ACI 214 (2010), presented in Table 2-3. The core l/d strength correction functions presented in ACI 214 (2010) are applicable for concrete strengths between 2,000 and 14,000 psi.
- Cores having a diameter less than 3.75 in. should only be used if a l/d of 2.0 can be obtained.
- For 3 in. diameter cores having a l/d of 2.0, a strength correction factor of 1.03 should be applied to account for core diameter size effects on strength. This strength correction factor is calculated by interpolating the values presented in Table 2-4, which is the core diameter correction factors suggested by ACI 214 (2010) and is valid for concrete strengths between 1,440 and 13,400 psi.
- If a core is drilled perpendicular to the concrete placement direction, a strength correction factor of 1.04 is recommended for comparison with cores drilled parallel to the concrete placement direction.

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Appendix A

RAW DATA

The following tables list the average cylinder strengths for each mixture and the specific values recorded for each core specimen. See Section 3.6.2.3 for identification of core labels. Note all cores are taken parallel to the cast direction with the exception of cores W1-W5, which were taken perpendicular to the placement direction.

Table A-1: Average cylinder strength at 7 and 28 days for each cast

Cast	Average Cylinder Strength (psi)	
	7-day	28-day
67-MS-3	3920	5970
57-MS-3	4750	5970
67-IS-3	8200	9450
57-IS-3	5480	6890
67-HS-3	8100	11310
57-HS-3	8600	10270
67-MS-4	6050	7410
57-MS-4	4610	5560
67-IS-4	5880	7290
57-IS-4	7540	8720
67-HS-4	7100	8900
57-HS-4	8190	8330

Table A-2: Collected core data for mixture 67-MS-3

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	3.00	6.0	2.01	3940
A2	3.00	6.1	2.02	4930
A3	3.00	6.1	2.03	4050
A4	3.00	6.0	2.01	4530
A5	3.00	6.1	2.02	4360
A6	3.00	5.3	1.78	4660
A7	3.00	5.3	1.76	4560
A8	3.00	5.3	1.77	4250
A9	3.00	5.3	1.77	3950
A10	3.00	5.3	1.78	4510
A11	3.00	4.6	1.54	4270
A12	3.00	4.6	1.53	3890
A13	3.00	4.6	1.53	4800
A14	3.00	4.6	1.52	4840
A15	3.00	4.6	1.53	4050
B1	3.00	3.8	1.28	4820
B2	3.00	3.9	1.28	4410
B3	3.00	3.9	1.29	4810
B4	3.00	3.8	1.28	4240
B5	3.00	3.9	1.28	4550
B6	3.00	3.1	1.03	4200
B7	3.00	3.1	1.04	4490
B8	3.00	3.1	1.04	4400
B9	3.00	3.1	1.04	4580
B10	3.00	3.1	1.04	4310
B11	4.00	8.1	2.02	5400
B12	4.00	8.0	2.01	5130
B13	4.00	8.1	2.02	4390
B14	4.00	8.1	2.02	4990
B15	4.00	8.0	2.01	5130

Table A-3: Collected core data for mixture 57-MS-3

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	3.00	6.1	2.04	5120
A2	3.00	6.1	2.02	5210
A3	3.00	6.1	2.02	5370
A4	3.00	6.2	2.05	4940
A5	3.00	6.1	2.04	5330
A6	3.01	5.4	1.80	4680
A7	3.00	5.4	1.81	4840
A8	3.00	5.4	1.80	4390
A9	3.01	5.4	1.79	4520
A10	3.00	5.4	1.80	4290
A11	3.00	4.7	1.56	4670
A12	3.00	4.6	1.53	4610
A13	3.00	4.6	1.54	5210
A14	3.00	4.7	1.56	4450
A15	3.00	4.6	1.53	4940
B1	3.00	3.9	1.31	4800
B2	3.00	4.0	1.32	4170
B3	3.00	3.9	1.30	4510
B4	3.00	4.0	1.32	4830
B5	3.00	3.9	1.29	3700
B6	3.00	3.2	1.07	5980
B7	3.00	3.1	1.04	5190
B8	3.00	3.2	1.05	5100
B9	3.00	3.1	1.05	4660
B10	3.00	3.2	1.05	4770
B11	4.00	8.1	2.04	5420
B12	4.00	8.1	2.03	5620
B13	4.00	8.2	2.04	5140
B14	4.00	8.1	2.04	4920
B15	4.00	8.1	2.03	5370

Table A-4: Collected core data for mixture 67-IS-3

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	2.98	6.1	2.06	10040
A2	2.99	6.1	2.05	9860
A3	2.99	6.1	2.03	8710
A4	3.00	6.1	2.03	9240
A5	3.00	6.1	2.02	8430
A6	3.00	5.4	1.79	8250
A7	3.00	5.3	1.78	8380
A8	3.00	5.3	1.78	8210
A9	3.00	5.4	1.78	7950
A10	3.00	5.3	1.77	7570
A11	3.00	4.6	1.53	8630
A12	3.00	4.6	1.53	8120
A13	3.00	4.6	1.52	8260
A14	3.00	4.6	1.53	7550
A15	3.00	4.7	1.55	8260
B1	3.00	3.9	1.29	7620
B2	3.00	3.9	1.30	8580
B3	3.00	3.8	1.28	8420
B4	3.00	3.8	1.26	8160
B5	3.00	3.8	1.27	8520
B6	3.00	3.1	1.04	9200
B7	3.00	3.2	1.07	8330
B8	3.00	3.2	1.06	8600
B9	3.00	3.2	1.06	7860
B10	3.00	3.2	1.06	7070
B11	3.99	8.1	2.04	10770
B12	3.98	8.0	2.01	10190
B13	3.98	8.0	2.02	8690
B14	3.99	8.0	1.99	9850
B15	3.98	8.0	2.02	9680

Table A-5: Collected core data for mixture 57-IS-3

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	2.99	6.0	2.02	6650
A2	2.99	6.1	2.05	6750
A3	2.99	6.1	2.03	6210
A4	2.99	6.1	2.04	5600
A5	2.99	6.1	2.04	5940
A6	3.00	5.2	1.75	6450
A7	3.00	5.3	1.77	5810
A8	3.00	5.3	1.78	5840
A9	3.00	5.4	1.79	5450
A10	3.00	5.3	1.78	5480
A11	3.00	4.6	1.53	6200
A12	3.00	4.6	1.55	5760
A13	3.00	4.6	1.53	5760
A14	3.00	4.6	1.54	5070
A15	3.00	4.5	1.52	5120
B1	3.00	3.8	1.27	5740
B2	3.00	3.8	1.27	5210
B3	3.00	3.8	1.27	5520
B4	3.00	3.8	1.28	6250
B5	3.00	3.8	1.27	5630
B6	3.00	3.1	1.05	5080
B7	3.00	3.2	1.06	4830
B8	3.00	3.1	1.04	2810*
B9	3.00	3.1	1.04	5360
B10	3.00	3.1	1.03	5570
B11	4.00	8.1	2.02	5690
B12	4.00	8.1	2.03	6030
B13	4.00	8.1	2.03	5970
B14	4.00	8.1	2.04	6200
B15	4.00	8.1	2.01	6070

*Value was found to be an outlier and removed from analysis

Table A-6: Collected core data for mixture 67-HS-3

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	3.00	6.0	2.01	8650
A2	3.00	6.1	2.03	8660
A3	3.00	6.1	2.02	7810
A4	3.00	6.1	2.04	8230
A5	3.00	6.2	2.05	7550
A6	3.00	5.4	1.79	8050
A7	3.00	5.4	1.79	8340
A8	3.00	5.3	1.78	8370
A9	3.00	5.3	1.78	7660
A10	3.00	5.3	1.78	8370
A11	3.00	4.6	1.53	7500
A12	3.00	4.6	1.54	8210
A13	3.00	4.4	1.45	7840
A14	3.00	4.6	1.54	7780
A15	3.00	4.6	1.53	6590
B1	2.98	3.8	1.28	7660
B2	2.99	3.7	1.25	7640
B3	2.99	3.8	1.27	7480
B4	2.99	3.8	1.26	7490
B5	2.99	3.8	1.27	6530
B6	2.99	3.2	1.06	6910
B7	2.99	3.1	1.03	6590
B8	2.99	3.1	1.05	6750
B9	2.99	3.2	1.06	7060
B10	2.99	3.2	1.05	6610
B11	3.99	8.0	2.01	8420
B12	3.99	8.1	2.02	8090
B13	3.99	8.1	2.02	9050
B14	3.99	8.0	2.00	8970
B15	3.99	8.0	2.01	7690

Table A-7: Collected core data for mixture 57-HS-3

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	2.99	6.0	2.01	9310
A2	2.99	6.1	2.05	8560
A3	2.99	6.1	2.04	8190
A4	2.99	6.1	2.03	8430
A5	2.99	6.1	2.03	8640
A6	2.99	5.3	1.78	8400
A7	2.99	5.4	1.79	8310
A8	2.99	5.3	1.77	8380
A9	2.99	5.3	1.79	8220
A10	2.99	5.3	1.78	8960
A11	2.99	4.5	1.52	8510
A12	2.99	4.5	1.51	7850
A13	2.99	4.5	1.51	7940
A14	2.99	4.5	1.51	6740
A15	2.99	4.5	1.52	7720
B1	2.99	3.7	1.25	7370
B2	2.99	3.8	1.26	7840
B3	2.99	3.8	1.25	7960
B4	2.99	3.7	1.24	7900
B5	2.99	3.7	1.24	8350
B6	3.00	3.1	1.03	7500
B7	3.00	3.1	1.02	6580
B8	3.00	3.2	1.07	6010
B9	3.00	3.2	1.07	6870
B10	3.00	3.1	1.05	6440
B11	4.00	8.1	2.02	10330
B12	4.00	8.1	2.02	9690
B13	4.00	8.2	2.04	8920
B14	4.00	8.1	2.02	9720
B15	4.00	8.0	2.01	9750

Table A-8: Collected core data for mixture 67-MS-4

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	3.99	8.2	2.06	5560
A2	3.99	8.2	2.06	5300
A3	4.00	8.2	2.04	5290
A4	3.99	8.1	2.03	5640
A5	3.99	8.1	2.04	5840
A6	4.00	7.1	1.78	5720
A7	4.00	7.2	1.81	**
A8	4.00	7.1	1.78	6120
A9	4.00	7.2	1.79	6200
A10	4.00	7.1	1.78	4510*
A11	4.00	6.1	1.53	5480
A12	4.00	6.1	1.53	6310
A13	4.00	6.2	1.55	5770
A14	4.00	6.0	1.50	6220
A15	4.00	6.2	1.54	5820
B1	3.99	5.2	1.31	5490
B2	3.99	5.2	1.30	6090
B3	3.96	5.2	1.30	6410
B4	3.99	5.3	1.32	3970*
B5	4.00	5.2	1.31	5660
B6	4.00	4.3	1.06	7330
B7	3.99	4.2	1.05	6010
B8	3.99	4.2	1.05	6860
B9	3.98	4.3	1.09	3130*
B10	4.00	4.2	1.04	7120
W1	4.00	8.3	2.06	5620
W2	3.99	8.2	2.05	5170
W3	4.00	8.2	2.06	5310
W4	4.00	8.2	2.04	6140
W5	4.00	8.2	2.04	5010
W6	4.00	8.1	2.03	5290
W7	4.00	8.1	2.02	5580
W8	4.00	8.1	2.02	5800
W9	4.00	8.1	2.02	5490
W10	4.00	8.1	2.02	5820

*Value was found to be an outlier and removed from analysis

**No value was recorded due to compression machine malfunction

Table A-9: Collected core data for mixture 57-MS-4

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	4.00	8.1	2.03	4760
A2	4.00	8.1	2.02	4260
A3	4.00	8.1	2.02	4540
A4	3.99	8.1	2.03	4580
A5	3.99	8.0	2.02	4690
A6	4.00	7.0	1.76	4890
A7	4.00	7.3	1.83	4790
A8	4.00	7.0	1.75	4390
A9	4.00	7.0	1.74	4560
A10	4.00	7.0	1.75	4530
A11	4.00	6.0	1.51	5230
A12	4.00	6.0	1.51	5350
A13	4.00	6.0	1.51	5200
A14	4.00	6.0	1.51	5320
A15	4.00	6.0	1.51	4950
B1	4.00	5.0	1.26	4600
B2	4.00	5.0	1.26	4700
B3	4.00	5.0	1.26	4680
B4	4.00	5.1	1.27	5700
B5	4.00	5.0	1.26	4570
B6	4.00	4.0	1.00	4680
B7	4.00	4.0	1.01	4470
B8	4.00	4.0	1.00	4120
B9	4.00	4.0	1.01	4340
B10	4.00	4.2	1.05	5570
W1	3.99	8.1	2.03	5400
W2	3.99	8.1	2.03	5400
W3	3.99	8.1	2.03	5060
W4	3.99	8.2	2.05	4670
W5	3.99	8.1	2.03	4690
W6	3.98	8.1	2.04	5860
W7	3.99	8.1	2.04	5960
W8	3.99	8.1	2.03	5640
W9	3.98	8.0	2.01	5860
W10	3.99	8.0	2.01	5190

Table A-10: Collected core data for mixture 67-IS-4

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	3.99	8.0	2.01	6510
A2	3.99	8.1	2.04	6430
A3	3.99	8.1	2.03	6170
A4	3.99	8.2	2.05	5920
A5	3.99	8.1	2.02	6160
A6	3.97	7.1	1.78	5950
A7	3.99	7.1	1.77	6250
A8	3.99	7.1	1.79	6710
A9	3.99	7.0	1.76	5770
A10	3.99	7.1	1.78	6050
A11	3.99	6.1	1.52	6210
A12	3.99	6.1	1.53	6040
A13	4.00	6.0	1.50	6000
A14	3.99	6.0	1.50	6900
A15	3.99	6.1	1.52	6070
B1	4.00	5.0	1.26	6260
B2	4.00	5.0	1.26	6270
B3	4.00	5.0	1.25	6700
B4	4.00	5.0	1.25	6040
B5	4.00	5.1	1.27	6170
B6	4.00	4.1	1.04	5780
B7	4.00	4.1	1.02	5420
B8	4.00	4.1	1.02	5940
B9	4.00	4.1	1.03	6680
B10	4.00	4.1	1.03	6970*
W1	4.00	7.8	1.94	6290
W2	3.98	8.1	2.03	6300
W3	3.99	8.0	2.01	6110
W4	3.99	8.1	2.03	5750
W5	3.90	8.1	2.08	6040
W6	4.00	8.1	2.02	5470
W7	4.00	8.0	2.01	6090
W8	4.00	8.0	1.99	5640
W9	4.00	8.1	2.02	5960
W10	4.00	8.0	2.00	5980

*Value was found to be an outlier and removed from analysis

Table A-11: Collected core data for mixture 57-IS-4

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	4.00	8.0	2.01	7530
A2	4.00	8.1	2.03	7410
A3	4.00	8.0	2.01	6750
A4	4.00	8.1	2.03	6780
A5	4.00	8.1	2.02	7890
A6	4.00	7.1	1.77	6510
A7	4.00	7.0	1.75	7250
A8	4.00	7.0	1.76	6710
A9	4.00	7.0	1.76	7680
A10	4.01	7.1	1.76	7440
A11	4.00	6.1	1.52	8110
A12	4.00	6.1	1.52	7140
A13	4.00	6.0	1.50	7830
A14	4.00	6.1	1.53	7910
A15	4.00	6.0	1.50	8100
B1	4.00	5.0	1.25	6990
B2	4.00	5.0	1.26	6770
B3	4.00	5.0	1.25	7070
B4	4.00	5.1	1.28	7490
B5	4.00	5.1	1.27	7170
B6	4.00	4.2	1.05	6250
B7	4.00	4.1	1.04	6400
B8	4.00	4.1	1.04	8940*
B9	4.00	4.3	1.06	7700
B10	4.00	4.3	1.07	7780
W1	4.00	8.2	2.04	6820
W2	4.00	8.1	2.03	7530
W3	4.00	8.1	2.03	7490
W4	4.00	8.0	2.01	7800
W5	4.00	8.1	2.03	8170
W6	4.00	8.2	2.05	6910
W7	4.00	8.1	2.03	7690
W8	4.00	8.1	2.02	6780
W9	3.99	8.1	2.02	7460
W10	3.99	8.1	2.03	6960

*Value was found to be an outlier and removed from analysis

Table A-12: Collected core data for mixture 67-HS-4

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	3.99	8.1	2.03	8590
A2	3.99	8.1	2.03	7580
A3	3.99	8.1	2.04	8690
A4	4.00	8.1	2.03	9040
A5	3.99	8.1	2.03	9400
A6	4.00	7.1	1.77	9880
A7	4.00	7.2	1.81	8010
A8	4.00	7.2	1.80	9560
A9	4.00	7.1	1.78	10460
A10	4.00	7.2	1.79	8260
A11	4.00	6.2	1.54	8770
A12	4.00	6.1	1.53	8160
A13	3.99	6.1	1.54	7960
A14	4.00	6.1	1.53	8000
A15	4.00	6.1	1.53	8980
B1	4.00	5.1	1.28	9340
B2	4.00	5.1	1.27	8100
B3	4.00	5.0	1.26	7680
B4	4.00	5.0	1.26	9390
B5	4.00	5.0	1.25	8580
B6	4.00	4.1	1.03	10600
B7	4.00	4.1	1.03	10780
B8	4.00	4.1	1.03	8730
B9	4.00	4.2	1.04	8670
B10	4.00	4.1	1.04	10300
W1	4.00	8.1	2.01	7560
W2	4.00	8.0	2.00	7020
W3	4.00	8.1	2.01	7720
W4	4.00	8.1	2.02	8500
W5	4.00	8.1	2.03	9730*
W6	3.99	8.1	2.03	9170
W7	3.99	8.1	2.04	9670
W8	4.00	8.1	2.03	9960
W9	3.99	8.1	2.03	9550
W10	3.99	8.1	2.03	9590

*Value was found to be an outlier and removed from analysis

Table A-13: Collected core data for mixture 57-HS-4

Core	Dia. (in.)	Capped Length (in.)	*l/d*	Compressive Strength (psi)
A1	4.00	8.1	2.03	10040
A2	4.00	8.1	2.02	8690
A3	4.00	8.1	2.02	9210
A4	4.00	8.1	2.03	9190
A5	4.00	8.1	2.03	10200
A6	4.00	7.1	1.77	9970
A7	4.00	7.0	1.76	10400
A8	4.00	7.1	1.76	9860
A9	4.00	7.1	1.77	8280
A10	4.00	7.0	1.75	9720
A11	4.00	6.1	1.54	8340
A12	4.00	6.2	1.54	9260
A13	4.00	6.1	1.52	9430
A14	4.00	6.1	1.52	8740
A15	4.00	6.1	1.52	9740
B1	4.00	5.1	1.27	10000
B2	4.00	5.1	1.27	10290
B3	4.00	5.1	1.28	10070
B4	4.00	5.1	1.27	9950
B5	4.00	5.0	1.26	10250
B6	4.00	4.2	1.04	11290
B7	4.00	4.2	1.05	10150
B8	4.00	4.2	1.05	10800
B9	4.00	4.2	1.05	10190
B10	4.00	4.1	1.04	9990
W1	4.00	8.1	2.01	9450
W2	4.00	8.1	2.03	8510
W3	4.00	8.1	2.03	9940
W4	4.00	8.1	2.01	8650
W5	4.00	8.1	2.02	9350
W6	4.00	8.1	2.02	8180
W7	4.00	8.1	2.03	9210
W8	4.00	8.1	2.02	8640
W9	4.00	8.0	2.01	8950
W10	4.00	8.1	2.02	8390

Appendix B

CORE STRENGTH ANALYSIS

Additional tables and figures used in the analysis are provided on the following pages of this appendix.

Table B-1: Core strength data for l/d analysis for 3 in. diameter cores

Cast	Average l/d	n	f_c (psi)	Average f_c (psi)	s (psi)	COV (%)
67-MS-3	1.04	5	4200	4400	149	3.38
	1.28	5	4820	4570	252	5.52
	1.53	5	4270	4370	433	9.90
	1.77	5	4660	4390	287	6.54
	2.02	5	3940	4360	396	9.08
57-MS-3	1.05	5	5980	5140	519	10.10
	1.31	5	4800	4400	474	10.78
	1.54	5	4670	4780	300	6.28
	1.80	5	4680	4540	221	4.86
	2.04	5	5120	5190	173	3.33
67-IS-3	1.06	5	9200	8210	801	9.76
	1.28	5	7620	8260	392	4.75
	1.53	5	8630	8160	392	4.80
	1.78	5	8250	8070	321	3.98
	2.04	5	10040	9260	700	7.56
57-IS-3	1.04	4	5080	5210	323	6.20
	1.27	5	5740	5670	380	6.70
	1.53	5	6200	5580	480	8.60
	1.78	5	6450	5810	403	6.93
	2.04	5	6650	6230	482	7.73
67-HS-3	1.05	5	6910	6780	201	2.96
	1.27	5	7660	7360	471	6.40
	1.52	5	7500	7580	611	8.05
	1.78	5	8050	8160	309	3.79
	2.03	5	8650	8180	497	6.07
57-HS-3	1.05	5	7500	6680	553	8.28
	1.25	5	7370	7880	350	4.44
	1.51	5	8510	7750	641	8.27
	1.78	5	8400	8450	292	3.45
	2.03	5	9310	8630	419	4.85
				High	801	10.78
				Low	149	2.96
				Average	407	6.45

Table B-2: Core strength data for *l/d* analysis for 4 in. diameter cores

Cast	Average *l/d*	n	f_c (psi)	Average f_c (psi)	s (psi)	COV (%)
67-MS-4	1.06	4	7330	6830	579	8.48
	1.31	4	5490	5910	417	7.05
	1.53	5	5480	5920	342	5.78
	1.79	3	5720	6010	257	4.28
	2.04	5	5560	5530	234	4.24
57-MS-4	1.01	4	4680	4400	235	5.33
	1.26	5	4600	4850	478	9.86
	1.51	5	5230	5210	158	3.03
	1.77	5	4890	4630	204	4.40
	2.02	5	4760	4570	192	4.20
67-IS-4	1.03	5	5780	6160	646	10.48
	1.26	5	6260	6290	248	3.94
	1.51	5	6210	6240	375	6.01
	1.78	5	5950	6150	360	5.85
	2.03	5	6510	6240	236	3.78
57-IS-4	1.05	4	6250	7030	820	11.66
	1.26	5	6990	7100	264	3.72
	1.51	5	8110	7820	398	5.09
	1.76	5	6510	7120	493	6.93
	2.02	5	7530	7270	495	6.82
67-HS-4	1.03	5	10600	9820	1033	10.52
	1.26	5	9340	8620	753	8.73
	1.53	5	8770	8370	469	5.61
	1.79	5	9880	9230	1058	11.46
	2.03	5	8590	8660	683	7.88
57-HS-4	1.04	5	11290	10480	546	5.21
	1.27	5	10000	10110	151	1.49
	1.53	5	8340	9100	559	6.15
	1.76	5	9970	9650	805	8.34
	2.02	5	10040	9470	635	6.70
				High	1058	11.66
				Low	151	1.49
				Average	471	6.43

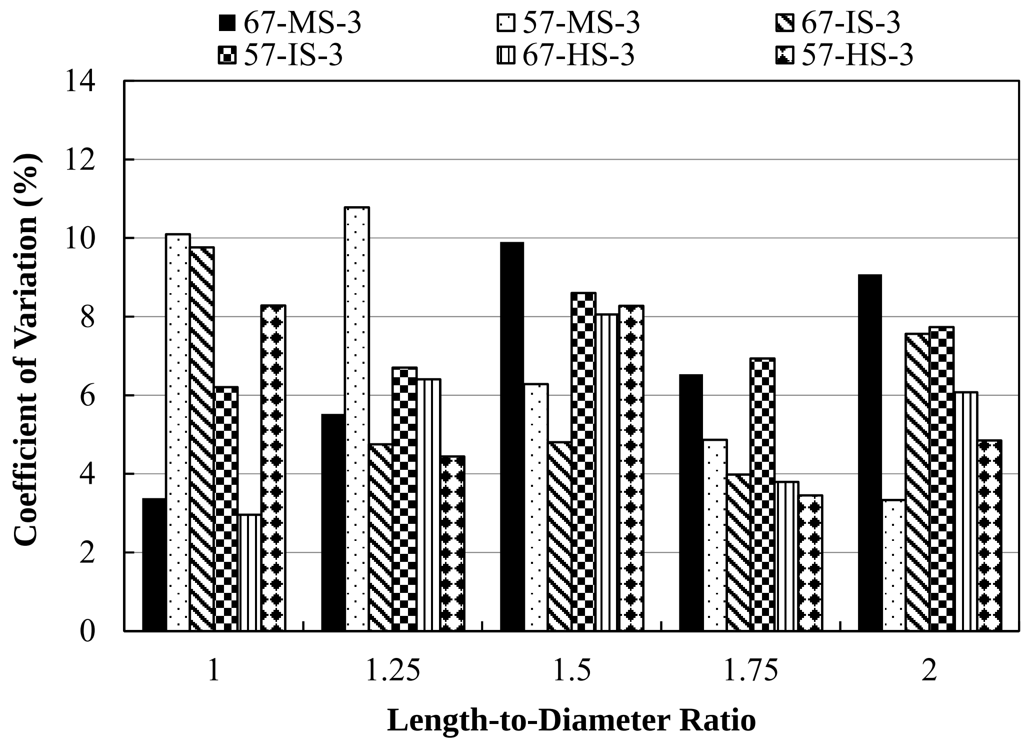

Figure B-1: COV for 3 in. diameter cores at various *l/d*'s

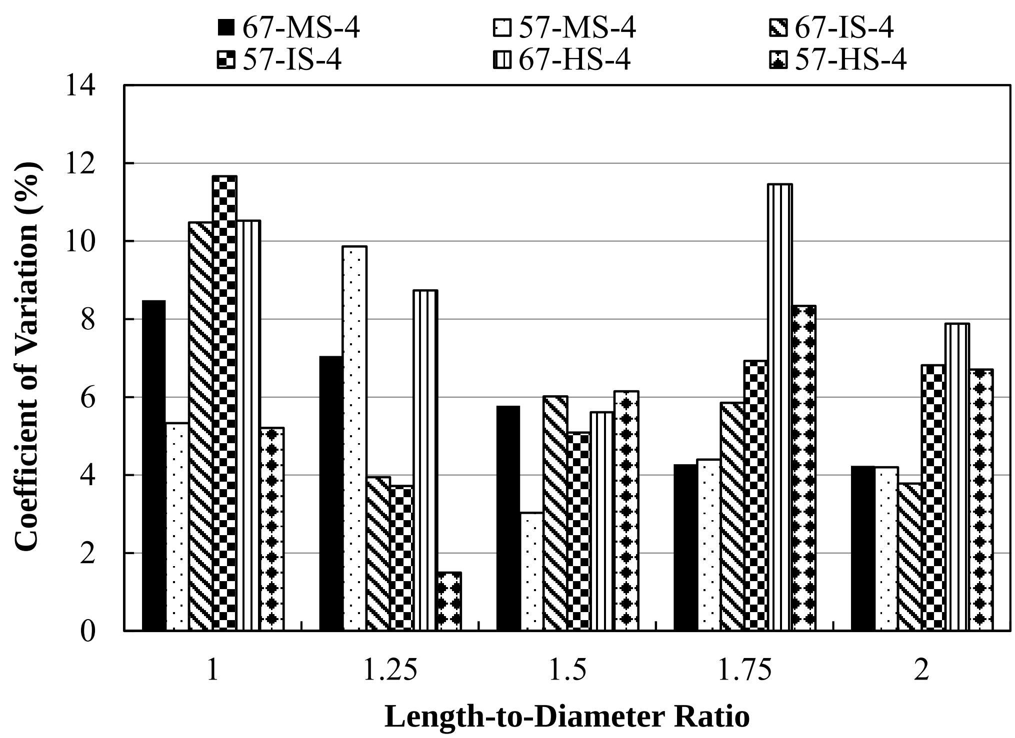

Figure B-2: COV for 4 in. diameter cores at various *l/d*'s