FINAL REPORT – Volume 1 of 2

State Project No. 872
Contract No. BC354-53

USE OF ACCELERATED FLOWABLE FILL IN PAVEMENT SECTION

Prepared
for

Florida Department of Transportation
in cooperation with
U.S. Department of Transportation

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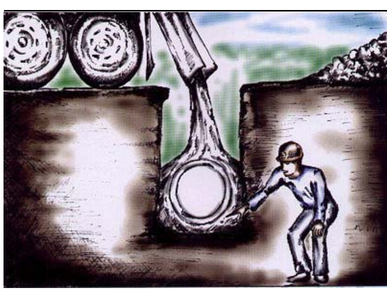

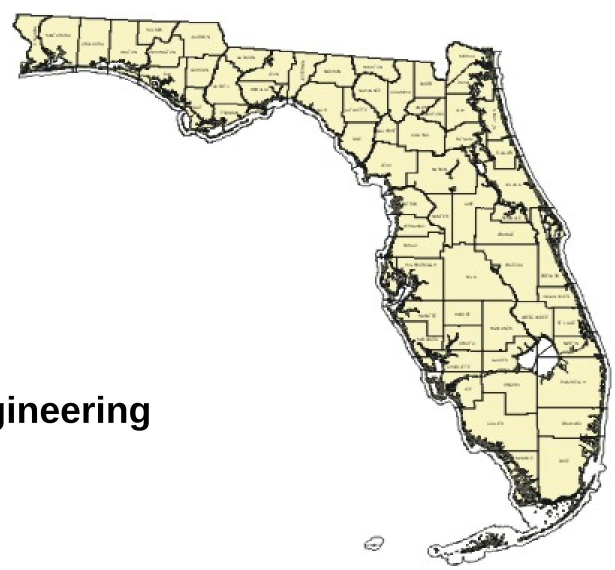

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DISCLAIMER

CONTENT

This report consists of two volumes. Volume 1 presents a background on flowable fill, objectives of the study, a literature review, response summary for flowable fill questionnaire, trial testing prior to the start of research, development of a laboratory procedure for testing flowable fill, information on materials, laboratory design mixes, laboratory results and discussions, accelerated strength testing, statistical analysis, and finally, the conclusions and recommendations. Volume 2 contains the appendices of the report.

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16. Abstract Flowable fill is a relatively new technology whose use has grown over the years. It describes a fill technology that is used in place of compacted backfill. Flowable fill is an answer for fill that allows a fast return to traffic, will not settle, does not require vibration or other means of compaction, can be excavated, is fast placing, and safer than other forms of fill. The objective of this research was to evaluate flowable fill in the pavement section using accelerated and non-accelerated mixtures. The evaluation included determination of strength, set time, and flow applicable to conditions in Florida. The unit weight, air content, and compressive strength were analyzed to establish the conformity of the contractor-provided mixes and those produced in the lab to the FDOT specifications. Further, a relationship was established between the LBR and penetrometer readings for different mix designs to help measure the strength of the underlying mix in the field. Unit weights of the mixes depicted substantial variability among different mix designs as well as among different districts within the same mix design. However, a majority of the readings did not comply with the FDOT specifications. Similar conclusions were drawn for the air content of different mixes. However, it may be noticed that air content for a majority of the districts was within the FDOT specified range for both excavatable, as well as non-excavatable design mixes. The compressive strength was above the FDOT specified range for excavatable mixes, except for Districts 2 and 5. For the non-excavatable mixes, the compressive strength did comply with the FDOT specifications but its value may be considered too high. The relationship between LBR readings and penetrometer readings was established and the models were checked for adequacy. After removing the unusual observations, pertinent regression equations relating LBR to the penetrometer data were obtained. It is recommended that more data be collected for all design mixes in a controlled environment. It is recommended that FDOT districts be provided with target values for different mixes to improve consistency. It is also recommended that the equations relating the LBR readings with those obtained from the penetrometer be validated by employing field data for strength of the underlying mixes.

17. Key Words	18. Distribution Statement
Flowable Fill, Controlled Low Strength Material, Backfill, Compressive Strength, Fast Return to Traffic, Accelerated and Non-accelerated Mixture, Unit Weight, Air Content, LBR, Penetrometer, Pogo Stick.	No restrictions. This document is available to the public through the National Technical Information service, Springfield, VA, 22161.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000L shall be shown in m^3.				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
ILLUMINATION				
Fc	foot-candles	10.76	lux	lx
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
G	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
fl	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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1. INTRODUCTION

1.1 Background

The Florida Department of Transportation (FDOT) is always searching for the most cost and time efficient means for completing its projects. Many of these projects include cutting and backfilling trenches for structure and drainage pipe installation. Often cutting and backfilling these trenches disrupts major traffic arteries. Standard practice for backfilling trenches includes soil being placed in 6-inch lifts and compacted until a minimum density threshold is achieved. The soil tests required to set and verify the density threshold in the field require several days to complete. The use of flowable fill negates the need for placing the 6-inch lifts. It also eliminates the need for all but the simplest of in-place soil tests. Research is needed to establish the minimum curing period necessary for this material. The following will be addressed:

1) Can accelerating admixtures be used to reduce the curing time to six hours or less?
2) Is curing time affected by the water table elevation and the surrounding soil where the flowable fill is placed?
3) When backfilling trenches under the roadway, how close (D_{min} shown in Figure 1.1) can the material be brought to the bottom of the asphalt without detrimental effect to the roadway?
4) How wide can a trench be opened and filled before problems can be expected to occur during construction (slippage between asphalt and flowable fill)?
5) What is the long-term strength of flowable fill (is excavatable flowable fill truly excavatable)?
6) What is the current means for field acceptance of flowable fill?

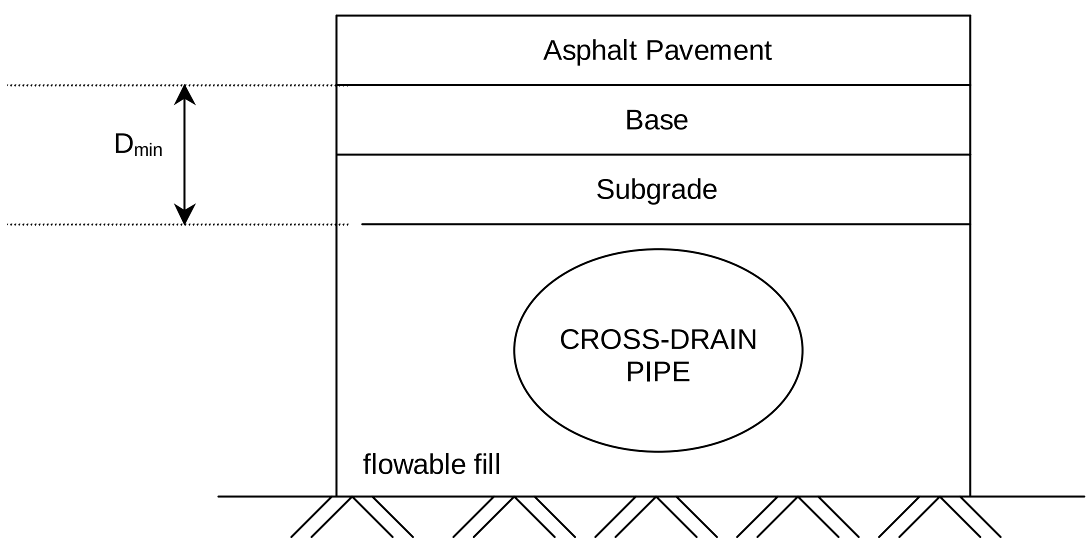

Figure 1.1 Flowable Fill Cross-drain Pipe Layout Example

Flowable fill answers the need for a fill that allows fast return to traffic, does not settle, does not require vibration or other means of compaction, can be excavated, is fast to place, and safer than other forms of fill. In general, the desired strength is the maximum hardness that can be excavated at a later date using conventional excavating equipment. The existing FDOT flowable fill specification requires field testing to verify that a minimum penetration resistance is achieved. It is critical that research be conducted at this time when large roadway construction, maintenance and rehabilitation projects are taking place throughout Florida. The expected outcomes follow:

1) Field evaluation and verification of existing flowable fill specifications for Florida conditions in relation to the use of ready-mix flowable fill as an alternative to compacted soil.
2) Verification of existing standard test methods needed for the engineer's approval for use of ready-mix flowable fill mixture.
3) To perform laboratory testing of flowable fill mixtures to determine compressive strength, Limerock Bearing Ratio (LBR) and other properties of the mix for both excavatable and non-excavatable mix.
4) A procedure to determine project acceptance based on sufficient penetration resistance and LBR values as measured using a hand-held penetrometer for excavatable and non-excavatable mix.

1.2 Objective of the Study

The objective of this research is to evaluate the performance of flowable fill in pavement section using accelerated and non-accelerated mixtures. The evaluation will include determination of strength, set time, and flow properties applicable to conditions in Florida.

1.3 Organization of Report

This report is divided into two volumes. Volume 1 includes the eleven chapters summarized below.

- Chapter 1 introduces the background and research objectives of this study.
- Chapter 2 presents basic information on the definition of flowable fill; related engineering properties; current design procedures; current applications and installation approaches; a review of test methods and current specifications used for flowable fill; and why a need for new or improved standards on flowable fill is desired.
- Chapter 3 includes the two-part questionnaire directed to FDOT Districts, counties, and cities to determine the utilization of flowable fill in Florida.
- Chapter 4 presents trial laboratory testing conducted prior to the start of the main laboratory research work on flowable fill.
- Chapter 5 details the overall testing procedure, equipment used, and sample preparation for the research.

- Chapter 6 discusses the material acquired and used in the flowable fill mixes that were tested in the laboratory.
- Chapter 7 presents laboratory design mixes for both excavatable and non-excavatable mixtures.
- Chapter 8 discusses the laboratory and field results.
- Chapter 9 details the accelerated strength testing performed in the laboratory.
- Chapter 10 presents the statistical analysis performed on data acquired from laboratory and field experiments.
- Chapter 11 emphasizes the conclusions and recommendations of the investigators for further research.

Volume 2 includes Appendices A through F.

- Appendix A is a sample of the questionnaire sent to various counties, FDOT districts and municipalities in the Florida.
- Appendix B details the chemical and physical analyses of test results conducted on type I Portland cement by the FDOT State Materials office.
- Appendix C details the chemical and physical analysis of test results conducted on fly ash by the FDOT State Materials office.
- Appendix D includes the chemical and physical analysis of test results conducted on slag by the FDOT State Materials office.
- Appendix E presents LBR data for excavatable accelerated mix, excavatable mix, non-excavatable accelerated mix and non-excavatable mix for Districts 1, 2, 4&6, and 5.
- Appendix F gives the Proctor penetrometer data obtained for all laboratory mixes.

2. LITERATURE REVIEW

2.1 Flowable Fill Technology

Flowable fill, also referred to as controlled low-strength material (CLSM), is a relatively new technology whose use has grown over the years. It describes a fill technology that is used in place of compacted backfill. Flowable fill is self-leveling with a consistency similar to pancake batter; it can be placed with minimal effort and no vibration or tamping is required.

Flowable fill, or CLSM, is a highly flowable cementitious slurry typically comprised of water, cement, fine aggregates, and often fly ash and chemical admixtures, including air-entraining agents, foaming agents, and accelerators. Other names used for this material are "flowable mortar" and "lean-mix backfill" (*1*).

Flowable fill is defined by the ACI Committee 229 as a "self compacting cementitious material that is in a flowable state at the time of placement and that has a specified compressive strength of 200 lb/in^2 [pounds per square inch] or less at 28 days." Flowable fill contains a low cementitious content for reduced strength development, which makes future excavation a possibility. This mixture is capable of filling all voids in irregular excavations and hard-to-reach places (such as under and around pipes), and hardens in a matter of a few hours without the need for compaction in layers.

2.1.1 Types of flowable fill

There are a variety of CLSM types available for various engineering purposes. The most obvious distinction between types is the possible need for future removal. Thus, the current FDOT specification divides flowable fill into two main classes: (i) excavatable fill; and (ii) non-excavatable fill.

CLSM excavatability is dependent on many factors including binder strength, binder density, aggregate quantity, aggregate gradation, and the excavating equipment used. The National Ready Mixed Concrete Association (NRMCA) recommends that excavatable CLSM mixes have a 20+ psi compressive strength at 3 days, a 30+ psi compressive strength at 28 days, and ultimate compressive strength less than 150 psi. Compliance with these recommendations is typically established with cylinder compressive strength tests (*2*).

2.1.2 Advantages of using Controlled Low-Strength Material (CLSM)

There are various inherent advantages of using CLSM over compacted soil and granular backfills. Some of these are listed below (*1*).

1) It has a fast setup time.
2) It hardens to a degree that precludes any future trench settlement.
3) The extra cost for the material, compared to compacted backfill, is offset by the fact that it eliminates the costs for compaction and labor, reduces the manpower required for close

inspection of the backfill operation, requires less trench width, and reduces the time period and costs for public protection measures.

4) There are no problems due to settlement, frost action, or localized zones of increased stiffness.
5) Flowable fill mix designs can be adjusted to meet specific fill requirements, thus making the fill more customized and efficient.
6) The flowable fill is stronger and more durable than the compacted soil or granular fill.
7) During placement, soil backfills must be tested after each lift for sufficient compaction. Flowable fill self-compacts consistently and does not need this extensive field testing.
8) It allows fast return to traffic use.
9) Flowable fill does not form voids during placement nor settle or rut under loading.
10) Since it reduces exposure to possible cave-ins, flowable fill provides a safer environment for workers.
11) It reduces equipment needs.
12) It makes storage unnecessary because ready-mix trucks deliver flowable fill to the jobsite in the quantities needed.
13) Flowable fill containing fly ash benefits the environment by making use of this industrial waste by-product.

These benefits also include reduced labor and equipment costs (due to self-leveling properties and no need for compaction), faster construction, and the ability to place material in confined spaces. The relatively low strength of CLSM is advantageous because it allows for future excavation, if required. Another advantage of CLSM is that it often contains by-product materials, such as fly ash and foundry sand, thereby reducing the demands on landfills, where these materials may otherwise be deposited.

Despite these benefits and advantages over compacted fill, the use of CLSM is not currently as widespread as its potential might warrant. CLSM is somewhat a hybrid material; it is a cementitious material that behaves more like a compacted fill. As such, much of the information and discussions on its uses and benefits are lost between concrete materials engineering and geotechnical engineering. Although there is considerable literature available on the topic, CLSM is often not given the level of attention it deserves by either group.

2.1.3 Engineering characteristics of CLSM

When a CLSM mixture is designed, a variety of engineering parameters needs to be evaluated prior to, during, and after placement in the field. Optimum conditions for each parameter depend on the application. Typically, blends will be proportioned and the desired characteristics will be tested according to the appropriate standard procedures. Although not all parameters need to be evaluated, the following are of major consequence to the effectiveness of the CLSM mixture (*2*):

i) strength development;
ii) time of set;
iii) flowability and fluidity, or consistency of the mixture;
iv) permeability;
v) consolidation characteristics;

vi) California bearing-ratio test; and
viii) freeze-thaw durability.

The performance criteria for flowable fills is outlined in ACI 229R-94. Flowable fill is a member of the family of grout material. ACI Committee 229 calls it "controlled low-strength material," and does not consider it concrete. If it is anticipated or specified that the flowable lean-mix backfill may be excavated at some point in the future, the strength must be much lower than the 1200 psi which ACI uses as the upper limit for CLSM. The late-age strength of removable CLSM materials should be in the range of 30 to 150 psi as measured by compressive strength in cylinders (*1*).

2.1.4 Uses of flowable fill

CLSM is typically specified and used as compacted fill in various applications, especially for backfill, utility bedding, void fill and bridge approaches. Backfill includes applications such as backfilling walls, sewer trenches, bridge abutments, conduit trenches, pile excavations, and retaining walls. As structural fill, it is used in foundation subbase, subfooting, floor slab base, and pipe bedding. Utility bedding applications involve the use of CLSM as a bedding material for pipe, electrical and other types of utilities and conduits. Void-filling applications include the filling of sewers, tunnel shafts, basements or other underground structures such as road base, mud jacking, sub footing, and floor slab base. CLSM is also used in bridge approaches, either as a subbase for the bridge approach slab or as backfill with other elements. Other uses of flowable fill include abandoned underground storage tanks, wells, abandoned utility company vaults, voids under pavement, sewers and manholes, and around muddy areas (*1*, *2*).

Conventional backfill in trenches and around small structures usually involves placement of aggregate material in thin layers with labor-intensive compaction. Poorly constructed backfill or lack of control of compaction often creates excessive settlement of the road surface and may produce unacceptable stresses on buried utilities and structures. Use of CLSM removes the necessity for mechanical compaction with the associated safety hazards for workers. It can also provide more efficient placement and may permit reduced trench dimensions (*2*).

2.1.5 Delivery and placement of flowable fill

CLSM can be delivered in ready-mix concrete trucks and placed easily by chute in a flowable condition directly into the cavity to be filled or into a pump for final placement. For efficient pumping some granular material is needed in the mixture (*1*). CLSM can even be transported as a dry material in a dump truck. It can be proportioned to be self-leveling thus not requiring compaction, and so can be placed with minimal effort and no vibration or tamping. It hardens and develops strength, and can be designed to meet specific strength criteria or density requirements.

Precautions against the following need to be taken into account while working with flowable fill (*1*):

1) Fluidized CLSM is a heavy material and during placement (prior to setting) will exert a high fluid pressure against any forms, embankment, or wall used to contain the fill.

2) Placement of flowable fill around and under tanks, pipes, or large containers such as swimming pools, can cause the container to float or shift.

2.1.6 Limits

Although CLSM mixtures provide numerous advantages compared to conventional earth backfilling, some limitations must be considered when these materials are used. Limitations include the following (*2*):

1) need to anchor lighter-weight pipes;
2) confinement needed before setting;
3) higher-strength mixtures may not allow excavation; and
4) lateral pressure is applied while in the fluid condition (forms or pipes must resist lateral pressures).

2.2 Specifications, Test Methods, and Practices

The Environmental Protection Agency (EPA) recommends that procuring agencies use ACI229R-94 and the ASTM Standards listed in Table 2.1 when purchasing flowable fill or contracting for construction that involves backfilling or other fill applications. More than 20 states have specifications for flowable fill containing coal fly ash. They include California, Colorado, Delaware, Florida, Georgia, Illinois, Indiana, Kansas, Kentucky, Maryland, Massachusetts, Michigan, Minnesota, Nebraska, New Hampshire, New Mexico, North Carolina, Ohio, Texas, Washington, West Virginia, and Wisconsin. The history of the current standard test methods for CLSM is rather short but quite important (*2*).

Table 2.1 Current ASTM Standards on Controlled Low Strength Material (CLSM)

ASTM Specification Number	Title
D 4832-02	Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders
D 5971-01 (PS 30)	Standard Practice for Sampling Freshly Mixed Controlled Low Strength Material
D 6023-02 (PS 29)	Standard Test Method for Unit Weight, Yield, Cement Content and Air Content (Gravimetric) of Controlled Low Strength Material (CLSM)
D 6024-02 (PS 31)	Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application
D 6103-97 (PS 28)	Standard Test Method for Flow Consistency of Controlled Low Strength Material

One or more of the following ASTM test methods listed in Table 2.1 are used primarily as a quality measure during backfilling and construction in the following areas (*1*, *2*):

1) Sampling – Obtaining samples of the flowable fill for control tests shall be in accordance with Practice D 5971.

2) Unit weight, yield (ASTM C 138) and air content (ASTM C 231) – Determining the unit weight, yield, or air content of a flowable fill mixture shall be in accordance with Test Method D 6023.
3) Flow consistency – Measuring the flowability of the flowable fill mixture shall be in accordance with Test Method D 6103.
4) Compressive strength – Preparing compressive strength cylinders and testing the hardened material for compressive strength shall be in accordance with Test Method D 4832. In addition to comparing to specification requirements, the compressive strength can provide an indication of the reliability of the mix ingredients and proportions.
5) Load application – Determining when the hardened mixture has become strong enough to support load, such as backfill or pavement, shall be done in accordance with Test Method D 6024 (*5*).
6) Penetration resistance – Tests such as ASTM C 403 may be useful in judging the setting and strength development up to a penetration resistance number of 4000 (roughly 100 psi compressive cylinder strength).
7) Density tests – These are not required since it becomes rigid after hardening.
8) Setting and early strength – These may be important where equipment, traffic, or construction loads must be carried. Setting is judged by scraping off loose accumulations of water and fines on top and seeing how much force is necessary to cause an indentation in the material. ASTM C 403 penetration can be run to estimate bearing strength.
9) Flowability of the CLSM – Flowability is important, so that the mixture will flow into place and consolidate.

Many states have developed specifications (in some cases, provisional) governing the use of CLSM. However, these specifications differ from state to state, and moreover, a variety of different test methods are currently being used to define the same intended properties. This lack of conformity, both on specifications and testing methods, has also hindered the proliferation of CLSM applications. There are also technical challenges that have served as obstacles to wide-spread CLSM use. For instance, it is often observed in the field that excessive long-term strength gain makes it difficult to excavate CLSM at later stages. This can be a significant problem that translates to added cost and labor. Other technical issues deserving attention are the compatibility of CLSM with different types of utilities and pipes, and the durability of CLSM subjected to freezing and thawing cycles (*2*).

2.2.1 ASTM standard test methods

2.2.1.1 Standard test method for preparation and testing of CLSM test cylinders (ASTM D 4832-02). Cylinders of CLSM are tested to determine the compressive strength of the material. The cylinders are prepared by pouring a representative sample into molds, curing them, removing the cylinders from the molds, and capping the cylinders for compression testing. The cylinders are then tested on a testing machine to obtain compressive strengths by applying the load until the specimen fails. Duplicate cylinders are required (*2*).

The compressive strength of the specimen is calculated as follows,

$$f_c = \frac{P}{A}$$

where f_c = compressive strength in pounds per square inch (lb/in^2)
P = maximum failure load attained during testing in pounds (lb)
A = load area of specimen in square inches (in^2).

This test is one of a series of quality control tests that can be performed on CLSM during construction to monitor compliance with specification requirements.

2.2.1.2 Standard practice for sampling freshly mixed CLSM (ASTM D 5971-96). This practice explains the procedure for obtaining a representative sample of the freshly mixed flowable fill as delivered to the project site for control and properties tests. Tests for composite sample size shall be large enough to perform so as to ensure that a representative sample of the batch is taken. This includes sampling from revolving-drum truck mixers and from agitating equipment used to transport central-mixed CLSM (*2*).

2.2.1.3 Standard test method for unit weight, yield, cement content and air content (gravimetric) of CLSM (ASTM D 6023-96). The density of the CLSM is determined by filling a measure with CLSM, determining the mass, and calculating the volume of the measure. It is calculated by dividing mass by volume. The yield, cement content and the air content of the CLSM are calculated based on the masses and volumes of the batch components (*2*).

(a) Yield:

$$Y = \frac{W_1}{W}$$

where Y = volume of CLSM produced per batch in cubic feet (ft^3)
W = density of CLSM in pounds per cubic foot (lb/ft^3)
W_1 = total mass of all materials batched, lb.

(b) Cement content:

$$N = \frac{N_t}{Y}$$

where N = actual cement content in pounds per cubic yard (lb/yd^3)
N_t = mass of cement in the batch, lb
Y = volume of CLSM produced per batch in cubic yards (yd^3).

(c) Air content:

$$A = \frac{T - W}{T} * 100$$

where A = air content (% of voids) in the CLSM
T = theoretical density of the CLSM computed on an air free basis, lb/ft^3
W = density of CLSM, lb/ft^3.

2.2.1.4 Standard test method for ball drop on CLSM to determine suitability for load application (ASTM D 6024-96). This test method is used primarily as a field test to determine the readiness of the CLSM to accept loads prior to adding a temporary or permanent wearing surface. A standard cylindrical weight is dropped five times from a specific height onto the surface of in-place CLSM. The diameter of the resulting indentation is measured and compared to established criteria. The indentation is inspected for any free water brought to the surface from the impact (*2*).

2.2.1.5 Standard test method for flow consistency of CLSM (ASTM D 6103-96). This test method determines the fluidity and consistency of fresh CLSM mixtures for use as backfill or structural fill. It applies to flowable CLSM with a maximum particle size of 19.0 mm (3/4 in.) or less, or to the portion of CLSM that passes a 19.0 mm sieve. An open-ended cylinder is placed on a flat, level surface and filled with fresh CLSM. The cylinder is raised quickly so the CLSM will flow into a patty. The average diameter of the patty is determined and compared to established criteria (*2*).

2.2.2 Other currently used and proposed test methods

The American Concrete Institute (ACI) classifies CLSM as a mixture design having a maximum 28-day compressive strength of 1200 lb/in^2. A CLSM mixture that is considered to be excavatable at a later age using hand tools should have a compressive strength lower than 101.5 psi at the 28-day stage (*2*). This is used to minimize the cost of excavating a mix at a later stage. Two field requirements that should be specified to ensure quality control and ease of placement are a minimum level of flowability or consistency and a specified method of measuring it. Measuring flowability with the flow cone method is most applicable for grout mixtures that use no aggregate filler. A maximum flow cone measurement of 35 seconds or a minimum slump of 9 inches would be two practical design parameters. Other methods to specify CLSM consistency have also been suggested. One such method is very similar to the ASTM Standard Test Specification, "Flow Table for Use in Tests of Hydraulic Cement" (C 230), for determining the consistency or flow of mortar mixtures (*2*).

Permeability of the CLSM mixtures has been measured using the ASTM "Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter" (D 5084). Loss on ignition of CLSM mixtures, and mineralogy of the hardened CLSM has been determined on the basis of similar tests for cement. It has been determined that aggregate containing up to 21% finer than 0.075 mm could be used to produce a flowable fill mix meeting National Ready Mixed Concrete Association (NRMCA) performance recommendations (*2*).

The gradation has been determined per ASTM C136-01, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates and ASTM C117, Standard Test Method for Materials Finer than 75 μm (No. 200) Sieve in Mineral Aggregates by Washing." Also, AASHTO M43

#10 screening aggregate specifications (AASHTO 1995) have been used to determine the suitability of utilizing the compliance of aggregates used with these standards (*2*).

A new ASTM standard "Standard Practice for Installing Buried Pipe Using Flowable Fill" has been proposed, which describes how to use flowable fill for installing buried pipe. ASTM Committee C 3 on Clay Pipe has already initiated mentioning the use of flowable fill in the Standard C 12 that covers installation of clay pipe (*2*).

A summarized overview of the test standards currently in use and that of provisional test methods is as follows (*2*):

- Provisional Method of Tests:

1) AASHTO Designation: X7 (2001) – Evaluating the Corrosion Performance of Samples Embedded in Controlled Low Strength Material (CLSM) via Mass Loss Testing
2) AASHTO Designation: X8 (2001) – Determining the Potential for Segregation in Controlled Low Strength Material (CLSM) Mixtures
3) AASHTO Designation: X9 (2001) – Evaluating the Subsidence of Controlled Low Strength Materials (CLSM).

- Other ASTM Test Methods used in CLSM Technology:

1) ASTM C231-97 – Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
2) ASTM C403/C 403M-99 – Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
3) ASTM D560-96 – Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures
4) ASTM D5084-90 (Reapproved 1997) – Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter
5) ASTM G51-95 (Reapproved 2000) – Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing.

2.2.2.1 Limerock Bearing Ratio test (Florida Test Method 5-515). The Limerock Bearing Ratio (LBR) test was adopted by the Florida Department of Transportation (FDOT) as a standard strength test for subgrade and base materials in the 1960's. The LBR test is a modified version of the California Bearing Ratio (CBR) test. This test defines the ability of a soil to support a load. As part of this test, the maximum density of the soil is determined by the standard method ASTM D-1557. CBR was renamed LBR because the standard strength for the CBR test was changed to more closely represent Florida materials. Some minor procedural changes to the LBR test have also evolved over the years. The LBR test as used in flexible pavement design in Florida is a measure of the bearing capacity of soil. The test consists of measuring the load required to cause a standard circular plunger (an area of 3 in^2) to penetrate the soil specimen at a specified rate (refer to Figures 2.1 and 2.2). The LBR test measures the unit load, in psi, required to force the plunger into the soil 0.1 inch, expressed as a percentage of the unit load in psi, required to force the same plunger to the same depth in a standard sample of crushed limerock.

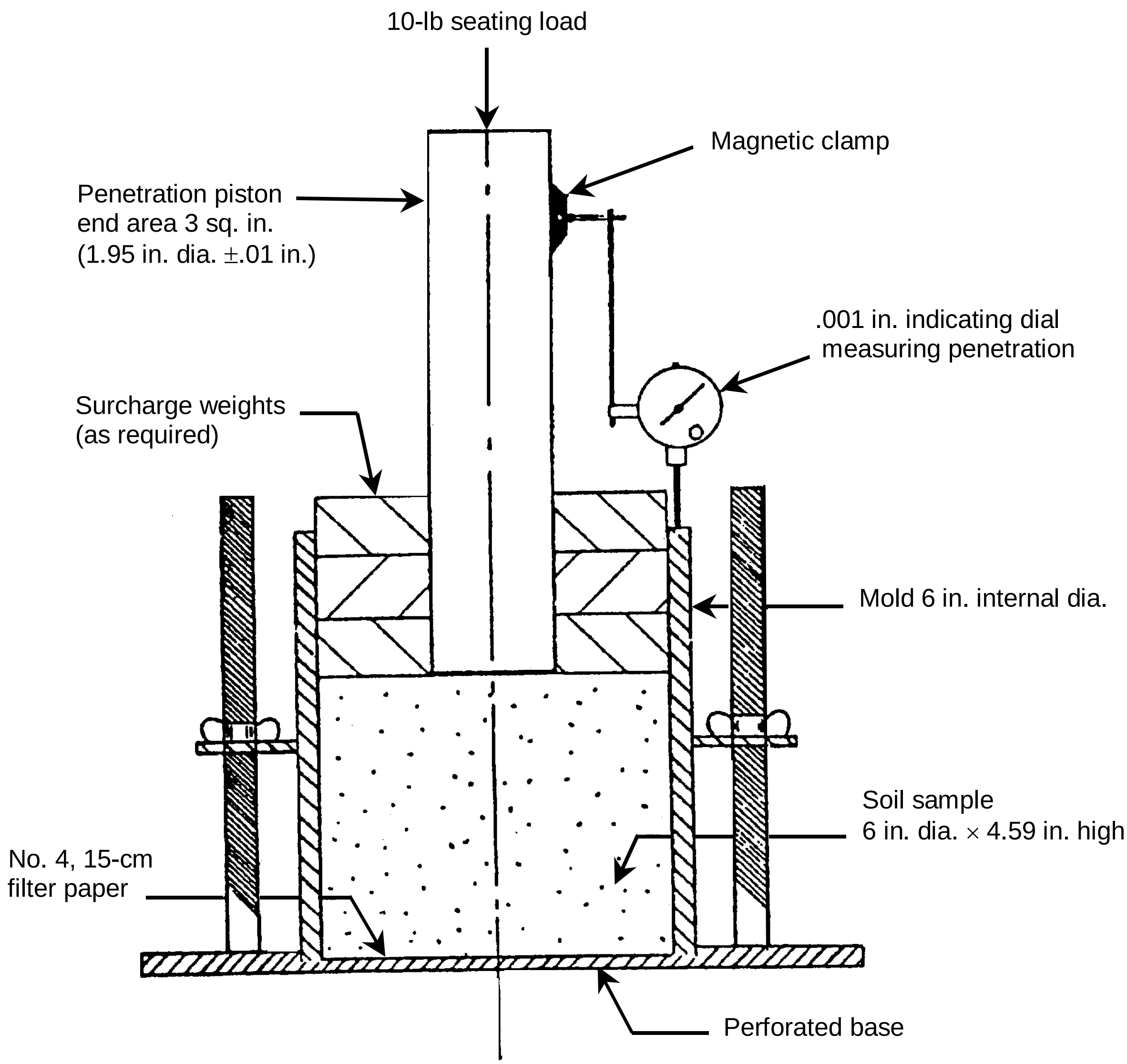

Figure 2.1 Cross Section of Seated LBR Penetration Piston

Figure 2.2 LBR Machine

The average penetration unit load for a typical crushed limerock found in Florida has been standardized to 800 psi. The resulting ratio multiplied by 100 is known as the Limerock Bearing Ratio (with percentage omitted). The test results are intended to provide the relative bearing value of base and stabilized materials (*5*).

2.2.2.2 Soil pocket penetrometer. The hand-held soil penetrometer (ST) is a tool developed for usage by field engineers to check visually the classification of soils. SOILTEST©, the manufacturer of the ST, compiled data on about a thousand unconfined compressive strength tests of silty clays and clayey soils against the penetrometer reading, which led to the development of the penetrometer scale. The scale reading is in tons per square foot (ton/ft^2). Figure 2.3 is a portrait of the soil pocket penetrometer used in the trial stage of the research study (*6*).

In order to classify soils on a consistent basis, there exists a close relationship between the penetrometer device scale reading and the type of soil unconfined compressive strength. The pocket penetrometer is a tool used primarily as an aid for classifying soils uniformly. It can be used in the laboratory or in the field to determine shear strength of cohesive soils (*6*).

Figure 2.3 Soil Pocket Penetrometer

The pocket penetrometer design is based on the work of Bucchi, and is meant to be used on soil to estimate the unconfined compressive strength, cohesion, c, and angle of internal friction, Φ. Bucchi assumes that when the circular tip of the penetrometer is pushed into soil to a quarter of an inch, the soil undergoes bearing capacity failure, and therefore the Terzaghi bearing capacity equations can be used. Using Terzaghi's equation for a circular footing thus yields,

$$q_f = 1.3 \times 5.7\ c_u = 7.41\ c_u = 3.71\ q_u$$

where q_f = ultimate bearing capacity;
c_u = undrained cohesion; and
q_u = unconfined compressive strength.

Therefore, by taking the reading from the soil pocket penetrometer and multiplying the reading by 3.709, the soil pocket penetrometer value can be back calculated.

2.2.2.3 Proctor penetrometer. The Proctor penetrometer is used for determining the moisture-penetration resistance relationship of fine-grained soils (ASTM D 1558-99). The unit consists of a special calibrated spring dynamometer with a pressure-indicating scale on the stem of the handle. The pressure scale is calibrated to 130-lb by 1-lb subdivisions. There is a major division located at each 10-lb interval. A sliding ring on the stem indicates the maximum load obtained during the test. Figure 2.4, shown below, depicts the Proctor penetrometer device in its carrying case with its complete set of penetrometer needles. The needles have end areas of 1, 3/4, ½, 1/3, 1/5, 1/10, 1/20, 1/30, and 1/40 in^2 (*6*).

Figure 2.4 Proctor Penetrometer (Pogo Stick)

2.2.3 Specifications by the state departments of transportation

From a survey of six southeastern states (shown in Table 2.2) carried out by Riggs and Keck (*2*), it is apparent that all of the specifications were issued after 1990, and so the use of CLSM is relatively new to standard transportation road construction. Tables 2.3 and 2.4 show the comparison of various requirements for similarities and differences, based on the survey.

Table 2.2 States Surveyed and Their Specification on Flowable Fill

State	Specification and Title of Section	Issue Date
Alabama	Section 260 Low Strength Cement Mortar	1996
Florida	Section 121 Flowable Fill (rev 1996)	1997
Georgia	Section 600 Controlled Low Strength Flowable Fill	1995
North Carolina	Controlled Low Strength Material Specification	1996
South Carolina	Specification. 11 Specification for Flowable Fill	1992
Virginia	Special Provisions for Flowable Backfill	1991

Table 2.3 Specified Acceptance Strengths and Ages

State	Age (days)	Strength, psi (MPa in parentheses)
Alabama	28	80 (0.55); 200 (1.4);
Florida	28	100 (0.7) (maximum); 125 (0.9);
Georgia	28	100 (0.7) (maximum); 125 (0.9)
N. Carolina	28;56	125 (0.9); 150 (1.0) (maximum)
S. Carolina	28;56	80 (0.55); 125 (0.86)
Virginia	28	30 - 200 (0.2 - 1.4)

Note: Maximum strengths are restricted to enable excavation at later stages, if desired or needed.

Table 2.4 Suggested Mixture Proportions, lb/yd^3 (values in kilograms per cubic meter, kg/m^3, are in parentheses)

State	Cement	Pozzolan	Fine Aggregate	Water	Air Range
Alabama	61 (36)	331 (196)	2859 (1696)	509 (302)	Not given
	185 (110)	0	2637 (1586)	500 (297)	″
	195 (116)	572 (339)	2637 (1586)	488 (290)	″
	195 (116)	572 (339)	2673 (1586)	488 (290)	″
	517 (307)	0	413 (245)	341 (202)	″
Florida	75-100 (44-89)	0	(a)	(b)	5-35
	75-150 (44-89)	150-600 (89-356)	(a)	(a) (b)	15-35
Georgia	75-100 (44-89)	0	(a)	(b)	15 – 35
	75-150 (44-89)	150-600 (89-356)	(a)	(a) (b)	5 - 15
N. Carolina	40-100 (24-59)	(a)	(a)	(b)	0 – 35
	100-150 (59-89)	(a)	(a)	(a) (b)	0 – 35
S. Carolina	50 (30)	600 (356)	2500 (1483)	458 (272)	None (c)
	50 (30)	600 (356)	2500 (1483)	541 (321)	None (c)
Virginia	Contractor must submit his own mixture (“ mix design”)				

(a) Proportion to yield 1 yd^3 (1 m^3)
(b) Proportion to produce proper consistency
(c) Air up to 30% may be used if required.

According to the survey, the general acceptance age is 28 days with two states having 56-day requirements (Table 2.3). As a result of the high levels of pozzolans in many CLSM mixtures, there can be significant strength increases after 28 days. Several states have both excavatable and non-excavatable mixtures. If the CLSM is to be removed at a later date, its strength must be limited to less than 300 psi, which can be assured only if later age strengths are evaluated (*2*).

2.2.4 Use of flowable fill in the state of Florida

Flowable fill has been used throughout the state of Florida as a construction material. The Florida Department of Transportation (FDOT) has used the material for bedding, encasements, tank enclosures, pipes, and general backfill for trenches. Occasionally, the use of flowable fill has been specified for placement under a base with a set time of four hours or more, prior to the placement of the base materials (*3*).

The current specification divides the flowable fill into two classes: excavatable and non-excavatable. The maximum allowable 28-day compressive strength of excavatable flowable fill is 100 psi. The minimum compressive strength for non-excavatable flowable fill is 125 psi. The suggested range of cement and fly ash has been specified for each class of excavatable and non-excavatable. Prior to use on projects, flowable fill mix designs must be approved by FDOT. The approval of the mix design is based on the specified range of material and laboratory test data, such as air content, compressive strength, and unit weight (*3*).

2.2.4.1 Material specifications: (Section 121-2). According to Section 121 of the FDOT Standard Specifications for Roadway and Bridge Construction, the material requirements that a flowable fill mix design must meet in order to be approved by FDOT are shown in Table 2.5 below (*3*).

Table 2.5 FDOT Materials Specifications Requirements

Fine Aggregate*	Section 902
Portland Cement (Types I, II, or III)	Section 921
Fly Ash, Slag and other Pozzolanic Materials	Section 929
Air Entraining Admixtures**	Section 924
Water	Section 923

*Any clean fine aggregate with 100% passing a 3/8-inch [9.5-mm] mesh sieve and not more than 15% passing a No. 200 [75 µm] sieve may be used.

**High air generators or foaming agents may be used in lieu of conventional air entraining admixtures and may be added at jobsite and mixed in accordance with manufacturer's recommendation.

All materials used should meet other specification requirements on a consistent basis (see Section 2.2.4.3 below).

2.2.4.2 Construction requirements and acceptance (Sections 121-5, 121-6). Department specifications require the ambient air temperature to be 40° F (4° C) or higher, and the mix be delivered at a temperature of 50° F (10° C) or higher. FDOT does not permit placement during rain or when the temperature is below 40° F. Specification requires that the material should remain undisturbed until it reaches a penetration resistance of 35 psi or higher. A soil penetrometer (ASTM C 403, Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance) is used to measure setting time (*3*).

2.2.4.3 Mix design (Section 121-3). To assist in designing a flowable fill mix, Section 121 of the specifications provides a guideline shown in Table 2.6 for one to use in preparing a mix design (*3*).

Table 2.6 FDOT Flowable Fill Mix Design

	Excavatable	Non-excavatable
Cement Type I	75 – 100 lb/yd^3 (45 – 60 kg/m^3)	75 – 150 lb/yd^3 (45 – 90 kg/m^3)
Fly Ash	None	150 – 600 lb/yd^3 (90 – 335 kg/m^3)
Water	*	*
Air**	5 – 35%	5 – 15%
28 Day Compressive Strength**	Maximum 100 psi (690 kPa)	Minimum 125 psi (860 kPa)
Unit Weight ** (wet)	90 – 110 lb/yd^3 (1440 –1760 kg/m^3)	100 –125 lb/yd^3 (1600 – 2000 kg/m^3)

*Mix design shall produce a consistency that will result in a flowable self-leveling product at a time of placement.

**The requirements for percent air, compressive strength and unit weight are for laboratory designs only and are not intended for jobsite acceptance requirements. Fine aggregate shall be proportioned to yield 1 yd^3 (1 m^3).

3. SUMMARY OF QUESTIONNAIRE RESPONSES

A two-part questionnaire (Parts A and B) was prepared. Part "A" questionnaire was sent to 67 counties and four large cities in Florida. Only four counties (Palm Beach, Leon, Bay, and Lee) and two cities (Jacksonville and Sarasota) responded. Appendix A presents this two-part questionnaire and the corresponding responses. Part "B" questionnaire was e-mailed to all seven FDOT districts. The maintenance engineers from all of these districts responded. The following two sections detail the responses received for Parts "A" and "B" of the questionnaire, respectively.

3.1 Part "A" Questionnaire Responses

1) The use of flowable fill can primarily be found in the following areas:
   a. Backfill over and around culverts, behind retaining walls, under driveways, behind bridge support walls, inside old stormwater pipes for closure.
   b. Trench fill (backfill), thin layer sub base, pipe plugging, narrow void around foundation structure (backfill), annular space filling, rapid road repair sub base for asphalt and concrete slab replacement / repair.
   c. To repair open cuts in roadway.
   d. Used on the average about once every two years to restore backfill areas that are difficult to compact conventionally such as under bridge abutments where washouts occur. Used as backfill to the haunches of pipe to ensure good compaction up to the spring line. Used to fill abandoned pipes and manholes.
   e. Roadway open cuts on existing roads; storm drain backfill on new roads.
   f. Backfill and base replacement.

2) The total estimated volume of flowable fill used by respondents varies. Figure 3.1 presents estimated flowable fill usage. The highest amount of usage within a year was 2500 yd^3.

3) It has not been long since various agencies started using flowable fill. According to the response that was received from these agencies, it is evident that most have been using flowable fill for 6 to 10 years.

4) The advantages of flowable fill as purported by various counties are summarized below. It is a cost effective alternative to excavation, compaction and equipment cost.
   a. It is readily available (ready-mix), is a consistent quality, manufactured product (approved design mix), is easily placeable (flowing, filling smallest of voids, self-leveling, workable), and it provides for trench safety (place in confining / collapse prone space without workers / equipment in same space).
   b. In its liquid state, it flows easily to fill all voids. One can pave the open cut sooner due to the accelerator. When flowable fill is used, the repair takes about half as long as it does when using backfill and limerock.
   c. The advantage over concrete is that it can be removed with standard excavation equipment if required, years down the road.

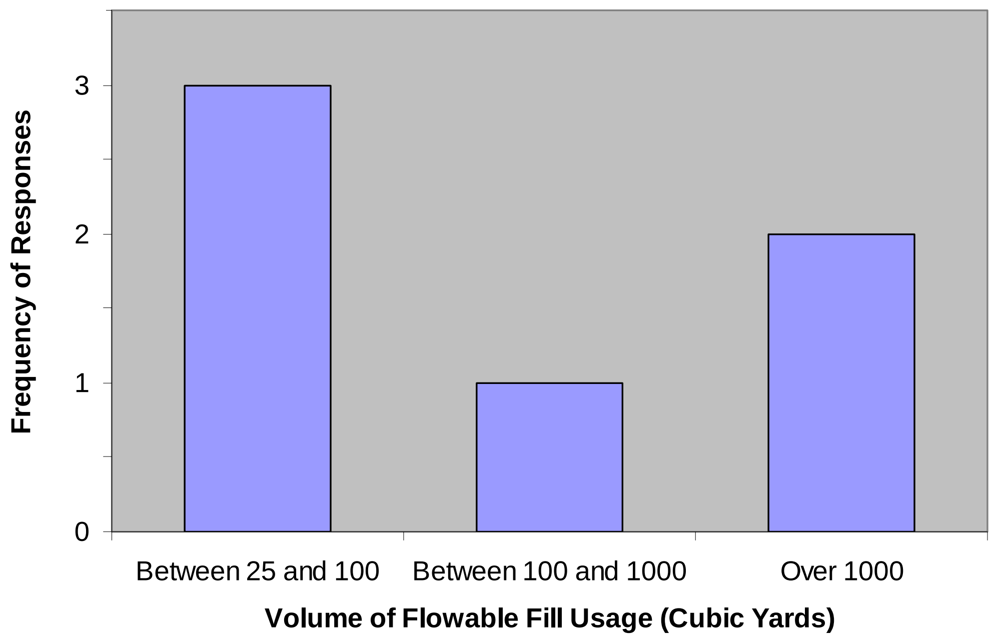

Figure 3.1 Part “A” Questionnaire Responses – Estimated Flowable Fill Usage

d. Reduces backfill errors.
e. It provides for quick settlement, does not require density testing and saves on labor costs.

5) Comments concerning the disadvantages of flowable fill as cited by public works departments in the state of Florida are as follows:
a. It requires estimation of quantity to be used, scheduling and proper preparation of area.
b. It causes shrinkage, water bleed, and puddling at surface. Involves a long-time to set-up. A repair subbase-contractor wants to put travel onto surface temporarily before finished structural surface. He has to wait for extended period for settlement, hardening, strength gain, and bearing.
c. It is not approved for use as the base course of the roadway and it is still required to use limerock or asphalt as base. Sometimes, when needed, it is not available and the repair of the roadway has to be done immediately to protect the safety of the motoring public.
d. Even though it can be removed, it is still more difficult than good select dirt backfill.
e. It is extremely difficult to shovel it around utilities.

6) At the time of use, the following were the common problems faced by workers of public works departments in the state of Florida in regard to flowable fill:
a. It is not pumpable.
b. It is difficult to fill entire pipe annular space.
c. It undergoes segregation (when attempted to pump – pump / hoses clogging).

d. It lacks body/volume (probably due to high air content), undergoes shrinkage, the surface bleed water, and it takes a long time to set-up to travel upon.
e. There is too much water in the mix, when it arrives, and the hole that is being filled is already wet. It takes longer to get the water out and set up.
f. When pumping longer lengths of pipe (filling abandoned pipe), there are problems with the low cement content mix. It is sometimes necessary to go for a mix with the higher cement content to pump further into the lines.
g. Inconsistent set time to allow traffic back on the patch.
h. The flowable fill usually does not set up in two to three hours. When it does set in two hours, it cannot be excavated.

7) Most of the users follow Florida DOT's design specifications as purported in Section 121. However, some are using a mix that provides for strength of 800-1000 psi.

8) In order to ensure short- and long-term quality control, the following test methods are currently used in the field:
   a. For short-term, the penetrometer (bearing) test is the most widely used test, if available, otherwise pocket/heel/probe test is used to check for firmness to travel upon without marring surface (tire marks), etc.
   b. Load tickets are received and matched to the material data sheet to see if the material complies with the specifications, for example: a 700 or 1200-psi requirement for compressive strength. As cited by one of the counties, Ardaman and Associates (Test Lab) has not been used to test flowable fill in the limited places that they have used it.

9) Following are the criteria used by respondent as a way to ensure that flowable fill will be excavatable at a later stage:
   a. Separate design mixes are used for each type. It is ensured that the mix falls within the minimum and maximum compressive strength and unit weight specifications. However, such measurements have never been taken in the field, and are rarely used for design mix computation. Prior to specification development, the cementitious content, air percent, etc., are established by demonstration with toothed backhoe.
   b. Some of the counties refrain from using anything above the 250 psi as they think that this is usually what is needed for road repairs.
   c. For some, standardized mix design is used throughout the county.
   d. Some of the counties were not aware of any such criteria.

10) There were almost no environmental concerns mentioned by any of the respondents in reference to flowable fill usage.

11) As for the durability, however, some said that the mix underwent considerable shrinkage post placement. Thin layer cracking was observed when traveled upon, prior to structural applied surfacing.

12) The following are some of the suggestions provided by the respondents:
   a. Color enhancement/addition provided for identification of embedded piping, etc.
   b. Heat-sink materials added for insulating embedded pipes from perimeter materials.

c. Admixtures (that are not cement quantity dependent) be used to reduce shrinkage, control bleed and promote setting.
d. Use (by the Sarasota stormwater crews) of flowable fill on a large (two 24″ RCP) double barrow storm line is effective when there is only 12″ of separation between each pipe, and there is an inability to reach in between and get proper compaction.

3.2 Part "B" Questionnaire Responses

The following questions were e-mailed to the seven FDOT districts:

1) Have you used flowable fill to backfill a trench out in the pavement?
2) How high did you bring the flowable fill?
   a. Top of Embankment ______________________
   b. Top of Sub grade ______________________
   c. Top of Base ______________________
3) How wide was the trench?
4) Was it longitudinal or transverse to the pavement?
5) How did it perform?

Appendix A contains the detailed responses to Part "B" of the questionnaire. The following summarizes the responses. In response to question 1 above, a majority of the districts confirmed use of flowable fill in backfilling trenches out in the pavement. Concerning question 2, most of those responding indicated they bring flowable fill to the top of the subgrade and the top of the base. According to responses to question 3, trenches backfilled with flowable fill have varied in width between 2 feet and 20 feet in most districts. Responses to question 4 indicate that flowable fill has been used by the districts in trenches both longitudinal and transverse to the pavement. Regarding the final question above, most of those responding were satisfied with the performance of the flowable fill.

4. TRIAL TESTING PRIOR TO START OF RESEARCH

Running a trial mix was necessary to prepare and plan the research activities, which consisted of:

1) approach;
2) setup;
3) sample preparation;
4) tools for testing flowable fill samples; and
5) materials acquisition.

Most of the planned activities came from meetings and discussions among the UF/FDOT team members. In the meetings, everyone agreed that the knowledge gained from the trial mix would benefit sample preparation and the making of tools for testing of flowable fill samples.

4.1 Research Team

The preliminary stage for this study began with the first meeting between the University of Florida (UF) team (Najafi, Tia, Javed, and Lovencin) and the FDOT team (Ruelke, Horhota, and Bergin). After the first meeting, the same team met four times to discuss the work progress. The meetings were highly constructive and provided valuable suggestions and advice to the research group.

4.2 Trial Test Specimens and Equipment

To initiate the research project, several items were acquired in preparation for starting a trial experimental flowable fill mixing. Mold specimens were constructed using the following:

- 2″ × 8″ × 10′ lumber (approximately 40 sets of 10′ long),
- 2 sets of plywood (3/4-inch thickness),
- filter fabric,
- screws,
- Industrial oil,
- filter fabric liner, and
- plastic viscoline liner.

The above materials were taken to the FDOT State Materials Laboratory where flowable fill samples were prepared.

4.2.1 Wooden mold

Open, perforated wooden molds were constructed to simulate field trench conditions. The molds were constructed using 2″ × 8″ lumber. The mold dimensions were constructed in accordance with the standards of AASHTO and ASTM for such testing. Figure 4.1 is a schematic drawing of the wooden mold. The inside portion of the mold is lined with woven materials such as filter geotextile fabric or plastic liner. One-quarter inch diameter perforations were drilled on the sides and the bottom of the wooden molds to allow some degree of bleeding through the sidewalls.

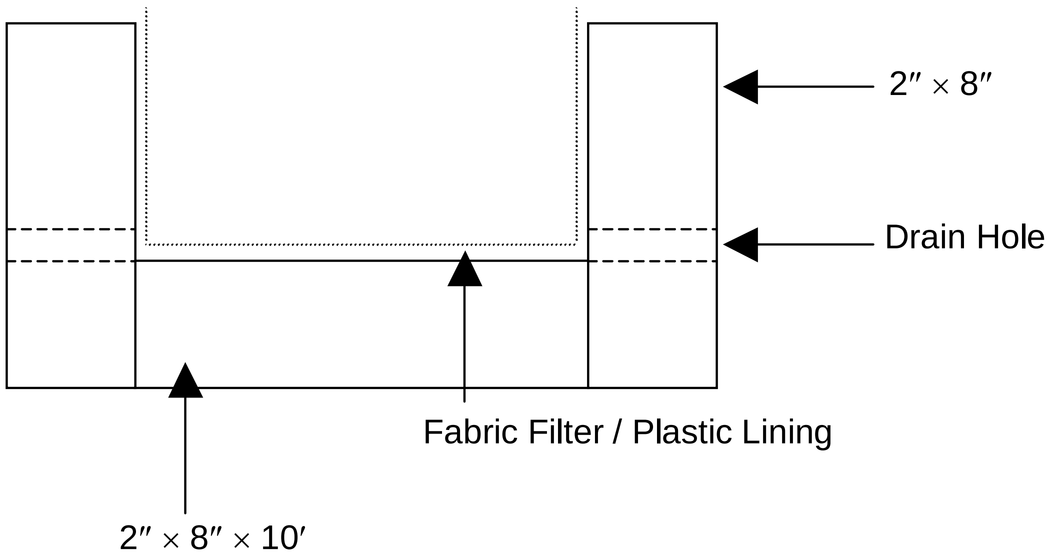

Figure 4.1 Wooden Mold Cross-section View

The purpose of lining the inside of the box is to simulate various drained and undrained conditions one might experience on construction sites during placement of flowable fill in various earthen trenches throughout Florida. The inside perimeter of the drained wooden mold specimens was lined with filter fabric designed to gradually drain out the water from the flowable fill. The undrained samples were set up to retain the water.

Since the mixing to be performed was a trial experimental test, only seven wooden molds were prepared.

4.2.2 Limerock Bearing Ratio (LBR) mold

Six Limerock Bearing Ratio (LBR) specimen molds were obtained for making the trial mix. The molds were prepared for use as samples in accordance with drained and undrained conditions.

4.2.3 Trial mixing

On the day of the trial mix, the wooden molds were constructed and they also required some finishing touches prior to placement or pouring of flowable fill. For trial mixing, filter fabric and plastic liners were cut and placed into the molds. Filter fabric was used for drained condition molds. Plastic liner was used for undrained condition molds. Quarter-inch (¼″) holes were drilled into the drained condition molds. These quarter-inch holes were drilled on both sides of the molds, 3 inches apart. Six LBR molds were also used for the trial mix. Three LBR molds were used for drained and the remaining three were used for undrained conditions. The plastic liners were placed only at the bottom of the LBR mold, while the filter fabric liners were placed at the bottom as well as around the perimeter of the mold. After preparing the molds, the materials for the excavatable flowable fill were mixed and poured into each mold as shown in Figure 4.2. Each wooden mold was filled with flowable fill to its top. The LBR specimen molds were filled up to 5.5 inches of their depth. Figure 4.2 shows the wet flowable fill in the bin after mixing. The design mix used was an excavatable flowable fill.

Figure 4.2 Flowable Fill Wet Mix in Large Bin

Field conditions were adequately represented due to hot (92^{o} F) and humid conditions on the day of trial mixing. As a result, it was decided that placing the samples in a steam-curing room was not necessary. Figures 4.3 and 4.4 show the flowable fill cast for the trial mixing.

The plastic air content properties obtained for excavatable flowable fill mix resulted in 17% air.

4.2.4 Tests performed

After curing, samples were tested. The Proctor penetrometer (Pogo Stick), pocket penetrometer (hand-held soil penetrometer), and the LBR machine were used for testing. In addition, unconfined compressive tests were run on two 6″ by 12″ cylinders. Tests were taken at intervals of 6 hours, 24 hours, and 28 days. Table 4.1 presents the test data from the Proctor penetrometer tests, while Table 4.2 displays the results from the hand-held penetrometer tests.

Figure 4.3 Cast Drained Samples

Figure 4.4 Cast Undrained Samples

Table 4.1 Results from Proctor Penetrometer (Pogo Stick)

Sample Type	Test Duration (hrs)	Tip Area in^2	Penetrometer (Pogo Stick) Reading(s) (lb)			Stress Conversion (lb/in^2)			Average (lb/in^2)
Drained	6.0	1.0	78	71	61	78	71	61	70.0
Drained	24.0	1.0	92	112	95	92	112	95	99.7
Drained	6.0	0.05	2	3.5	4	40	70	80	63.3
Undrained	6.0	1.0	49	45	41	49	45	41	45.0
Undrained	6.0	0.05	3	1	3	60	20	60	46.7

Table 4.2 Results from Pocket Penetrometer

Sample Type	Test Duration (hrs)	Tip Area in^2	Penetrometer (Hand-held) Reading(s) (ton/ft^2)			Stress Conversion (lb/in^2)			Average (lb/in^2)
Drained	6.0	–	0.60	0.50	0.70	8.33	6.94	9.72	8.3
Undrained	6.0	–	0.50	0.30	0.40	6.94	4.17	5.56	5.6

The Proctor penetrometer and soil pocket penetrometer are presented in Chapter 2, "Literature Review." As seen from the results of the Proctor penetrometer (Pogo Stick) and the pocket penetrometer, the average strength value differs. The Proctor penetrometer has only one needle to read as compared to the Proctor penetrometer having several needles to select from. The variation in readings between the two pieces of equipment is relevant to the needle sizes and pressure scales (*4*).

After casting, the LBR samples were tested using the LBR machines. Since the LBR machine is stationary, and not movable, LBR samples could not be tested at the same location as the other samples. As a result, the LBR samples were transported on a cart to the LBR machine. Figures 4.5 and 4.6 show load versus penetration for two LBR samples. In Figure 4.5, the drained sample exhibited an LBR of 2, while the undrained sample exhibited an LBR of 0 due to its wetness. Figure 4.6 presents LBR values for both drained and undrained conditions at 24 hours. It can be seen from these figures that the values of drained LBR increased from 2 to 9 (from 6 hours to 24 hours). In addition, the LBR values for undrained conditions increased from 0 to 4 (from 6 hours to 24 hours).

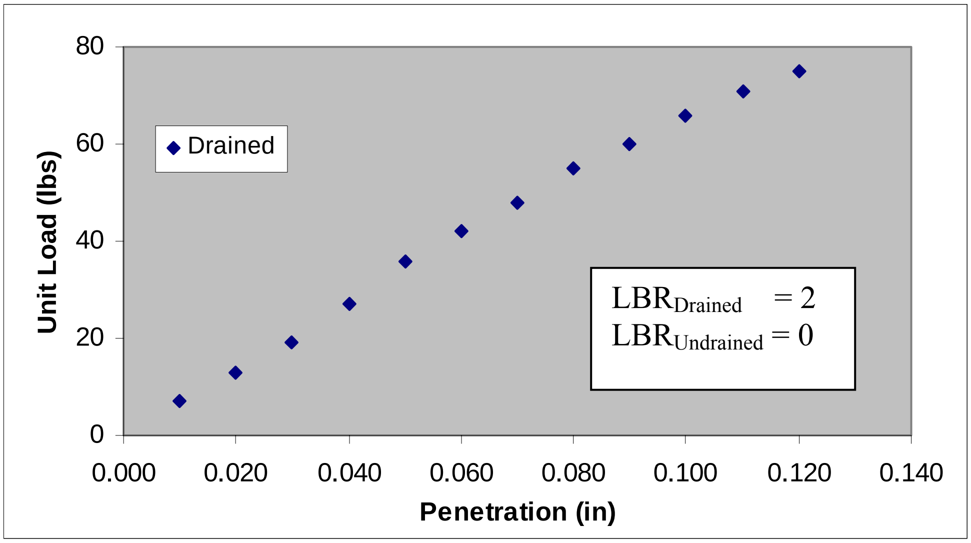

Figure 4.5 LBR Results for Drained and Undrained Conditions at 6 Hours

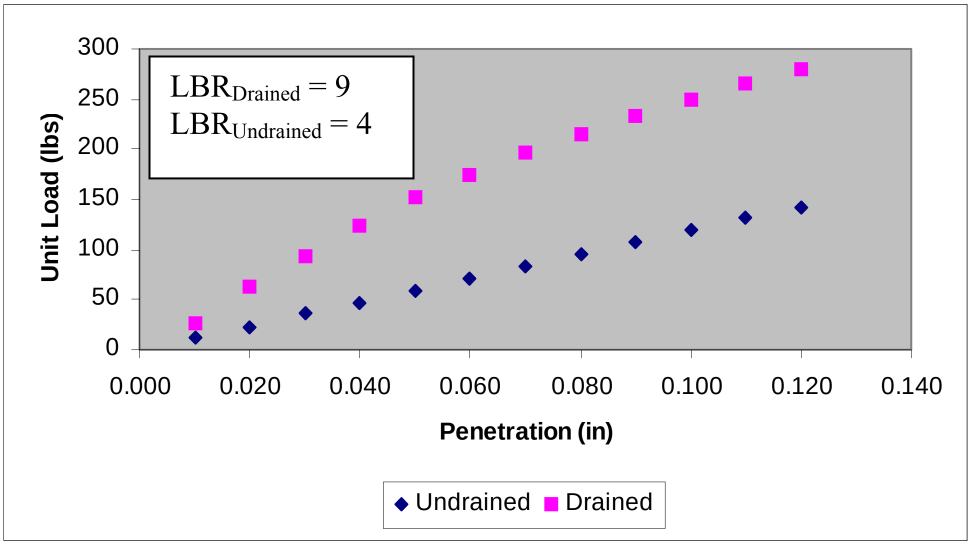

Figure 4.6 LBR Results for Drained and Undrained Conditions at 24 Hours

4.2.5 Problems encountered

Several lessons were learned during trial mixing. The undrained samples leaked from the bottom crack and side joints of the wooden molds and the LBR samples. To remedy the water leakage problem, it was suggested that we use some plastic lining, such as "Saran Wrap®" on the wooden box mold. Latex spray paint was suggested for painting the corners of the wooden molds. Both options were considered but the option which showed maximum potential was the Saran Wrap® plastic liner.

4.3 Suggestions

The following is a list of suggestions made by the team members:

- Wooden molds should be rebuilt to increase volume.
- More data were needed to establish relationships between the LBR and the Proctor penetrometer.
- No need to use surcharge weight for the LBR when performing the LBR test.
- Samples should be oven-dried to accelerate the hydration (for undrained and drained mix conditions).
- A relationship between oven curing and normal curing is needed (oven would be set at 120° F or higher).
- Proctor penetrometer should be adopted as the main piece of equipment for collecting data for the wooden mold samples in accordance to ASTM standard.
- Plastic should not be cut, keeping it whole for undrained samples.
- Approved FDOT contractor mix designs are needed from all FDOT districts.

4.4 Solicitation of FDOT Approved Mix Design

Although various departments of transportation provide guidelines for designing flowable fill mixes, there is no existing national standard for the design of flowable fill. There is, however, literature that provides some guidelines for designing a mix of flowable fill. Because the nature of flowable fill is defined as a cementitious material, it is recommended that its design mix consist of sand, fly ash (class F), and cement.

In preparing flowable fill mixes for this study, it was concluded that existing approved design mixes used on current FDOT projects would be used for this study. Table 4.3 presents a list of the FDOT District contact personnel who were contacted during the research to obtain their approved flowable fill design mixes. Typical approved mixes of excavatable and non-excavatable flowable fill were requested. Each district submitted design mixes. Each of the

Table 4.3 FDOT District Personnel Contacts

Name	District	Phone Number	Ext.	Suncom
Bobby Ivery	2	386-758-3700	7742	881-7742
Daniel F. Haldi	5	386-736-5465	--	383-5465
James R. Ward	1	863-519-4261	--	557-4261
Keith A. West	1	863-519-4264	--	557-4264
Winellen B. Marshall	3	850-921-2195	--	291-2195
Roger M. Marshall	3	850-484-5055	--	690-5055
Leigh Markert	4 & 6	N/A	--	N/A
Charlie McQue	7	N/A	--	N/A

design mixes received was carefully scanned and evaluated for adherence to the FDOT specifications. All the design mixes submitted were accepted with the exception of the design mix received from District 3, which did not concur with current FDOT specifications on flowable fill. The design mixes used in the lab for each district are presented in Chapter 7.

5. DEVELOPMENT OF LABORATORY PROCEDURE FOR TESTING FLOWABLE FILL

5.1 Introduction

Once the approved mix designs from various FDOT districts were selected, a laboratory procedure was developed for executing the research study. The laboratory procedure was designed based on the suggestions made by the research team. A total of eight mix designs were selected for the study. Four of them were classified as excavatable and the remainder as non-excavatable.

5.2 Experimental Design

The objective of this study was to evaluate flowable fill in the pavement section using excavatable, excavatable accelerated, non-excavatable and non-excavatable accelerated mixes. The evaluation included determination of strength, set time, and flow properties applicable to conditions in Florida.

Table 5.1 summarizes the overall specimen samples required for each lab mix. As shown, the total number of samples required for collection per mix is 52. The number of samples needed per mix and the type of specimen samples (i.e., 32 LBR and 20 wooden mold) helped determine the design of the experiment. The 52 samples collected per mix provided the basis for total volume of flowable fill needed for each mix.

Table 5.1 Summary of Sample Specimens Collected Per Mix

Samples for each of the 4 Districts:

	Excavatable		Non-excavatable	
	Accelerated	Non-accelerated	Accelerated	Non-accelerated
Drained - Wooden	12	12	12	12
Drained - LBR	12	12	12	12
Undrained - Wooden	8	8	8	8
Undrained - LBR	8	8	8	8
Oven Drained - LBR	12	12	12	12
TOTAL	52	52	52	52

TOTAL PER DISTRICT: 208

TOTAL FOR ALL 4 DISTRICTS: 832

Mold Requirements per Mix

LBR	32
Wooden	20

TOTAL NUMBER OF MIX: 16

Tables 5.2 and 5.3 show the curing durations used for all the samples collected per batch of mix. The volume of mix per batch was based on the total number of samples needed per mix. As illustrated in Table 5.4, an approximate volume of 15.90 ft^3 of flowable fill was required per batch of mix.

Table 5.2 Drained/ Undrained Design Test Intervals

Drained		
Number of Molds	Duration (hours)	Duration (days)
2	6	0.25
2	24	1
2	168	7
2	336	14
2	672	28
2	2160	90

Undrained		
Number of Mold	Duration (hours)	Duration (days)
4	672	28
2	672	28
2	672	28

Table 5.3 Oven Drained/ Undrained Design Test Intervals

Oven Drained		
Number of Molds	Duration (hours)	Duration (days)
2	48	2
2	96	4
2	192	8

Oven Undrained		
Number of Molds	Duration (hours)	Duration (days)
2	48	2
2	96	4
2	192	8

5.3 Test Equipment

5.3.1 Specimen molds

The specimen molds employed for the research can be categorized as rectangular wooden molds and cylindrical LBR molds.

5.3.1.1 Rectangular wooden molds. The rectangular wooden molds were made to cast flowable fill samples cured in the laboratory for 6 hours, 1 day, 2 days, 7 days, 14 days, 28 days, and 90 days. The dimensions for the molds are shown in Table 5.4. Twenty wooden molds were used in each mix, twelve were for drained condition and eight were for undrained condition.

5.3.1.2 Circular (metal) LBR molds. The circular molds were used to carry flowable fill samples for LBR testing. Thirty-two circular molds were used in each mix. The mold samples were cured for 6 hrs, 1 day, 2 days, 4 days, 7 days, 8 days, 14 days, 28 days, and 90 days.

Table 5.4 Volume Computations for Each Mix

LBR Mold			Wooden Mold		
Configurations:			Configurations:		
Diameter	6.00	in	Length	16.00	in
Depth	6.00	in	Width	7.25	in
			Height	9.50	in
Area =	28.27	in^2	Area =	116.00	in^2
Volume of each LBR Mold			Volume of each Wooden Mold		
Volume =	169.65	in^3	Volume =	1102.00	in^3
	0.10	ft^3		0.64	ft^3
Total LBR molds per mix =	32		Total wooden molds per mix =	20	
Total Volume required to fill LBR molds per mix:			*Total Volume required to fill wooden molds per mix:*		
Volume =	5428.67	in^3	Volume =	22040.00	in^3
	3.14	ft^3		12.75	ft^3

Total volume of flowable fill needed per mix =	
27468.67	in^3
15.90	ft^3
0.59	yd^3

5.3.1.3 Filter fabric. Filter fabric was used as a draining material in the molds. The fabric was placed inside the wooden and LBR specimen molds designated as drained samples. Once the flowable fill was dispensed inside the molds, water drained through the fabric over time. The purpose of the filter fabric was to stop the fine aggregates from seeping through the small corner cracks and small openings of the molds. The filter fabric not only stops the leaching of the fine aggregate, it also aids the drainage of the water from specimen samples.

5.3.1.4 Plastic sheets. Plastic sheets were placed in the interior of LBR and wooden molds designated as undrained samples. The purpose of the plastic sheets was to stop drainage of water from the samples.

5.3.1.5 Aluminum foil. Aluminum foil was used only in the circular molds, which were designated for undrained oven samples. These samples were placed inside a large oven for accelerated curing. The aluminum foil was used as a replacement for plastic sheets in the undrained LBR samples placed in the oven.

5.3.2 Fabrications of flowable fill specimen

Each mix required several steps to be undertaken before specimens could be prepared, they are:

5.3.2.1 Preparation of molds. The wooden molds and the circular molds were always prepared two days prior to the start of the mix to be performed. The process of preparing for a mix required proper cleaning of each wooden and LBR mold, and greasing them with mineral oil. The oil was used to help prevent the filter fabric from sticking to the molds, after casting the flowable fill sample. This practice was necessary in order to promote best practice and to reuse the molds after casting. Fabric cloth was placed in the molds designated as drain samples. Plastic sheeting was placed in molds designated as undrained samples. Aluminum foil was placed in eight LBR molds for undrained oven samples.

5.3.2.2 Mixing of flowable fill. All mixes were made during early morning hours. Prior to the start of each mix, all constituent materials were carefully weighted. This step was taken to ensure appropriate adherence to the FDOT field district's replicate design mix.

All flowable fill mixtures were prepared using a 17-ft^3 rotating concrete drum mixer. The batching sequence consisted of placing the sand into the mixer and making sure that it was spread evenly inside the mixer. After the fine aggregate was placed into the mixer, the mixer was turned on to homogenize the fine aggregate, then 80% of the mixing water was added followed by the addition of cement, and any other dry materials (i.e., fly ash, blast furnace slag). After placement of the dry materials into the mixer, the mixer was kept rotating for three minutes, followed by a two-minute rest period. After the rest period, the remaining mixing water was added along with any required admixtures. The mixing was resumed for three additional minutes.

Immediately after mixing, flowable fill was poured into a large bin container for transportation and subsequent transfer into specimen molds. Prior to pouring into specimen molds, a sample of the fresh mix was taken so that plastic property measurements such as flow, unit weight, and air content tests could also be performed on the mix. Each specimen mold was properly marked and labeled for identification and testing purposes.

5.3.3 Proctor penetrometer

Penetration resistance on each wooden molded flowable fill specimen was obtained using the Proctor penetrometer testing method outlined in ASTM D 1558-99 (*6*). In this test, the cylindrical needle tip is pressed one inch into the flowable fill, and the resistance offered by the flowable fill is measured in pounds. This value (in lb) is divided by the cross sectional area of the tip, and is taken as the penetration resistance. Since different needle tip diameters exist, the choice of the needles that one selects depends on the strength of the material being tested.

5.3.4 Compressive strength test

Compressive strength tests were performed according to ASTM Standard Test Method C-39-02 for Compressive Strength of Cylindrical Concrete Specimens. A computerized testing machine with load-control loading at a rate of 35 psi per second was used. A total of four 4-in. ×

8-in. (152.4 × 304.8 mm) cylindrical specimens per batch per curing condition was used for this test. Figure 5.1 shows the set up for the compressive strength test.

Figure 5.1 Compressive Strength Test

Initially compressive strength testing was not part of the laboratory testing design. It was added as a result of not being able to obtain an accurate strength for samples aged more than 28 days using the Proctor penetrometer and the LBR machine. Four plastic cylindrical molds were added to the sample specimen collection scheme after the addition of this test.

For mixes performed prior to the above recommendation, a technique was devised for obtaining the compressive strength. This technique involved using the wooden mold samples already tested and coring them in order to obtain a cylindrical specimen, as shown in Figure 5.2. The cores were approximately 3 inches by 6 inches.

5.3.5 Drying oven

A standard laboratory oven with approximately 6 ft^3 of capacity was used for curing of oven drained and undrained specimen samples. Samples were stored inside the oven at a set temperature of 120° F. The oven shown in Figure 5.3 is equipped with a thermostat and sensor to control the temperature of the oven. Prior to the start of every mix, the oven was turned on to ensure that it would be warm enough to place specimens inside. Information acquired from specimens cured in the oven would help predict in-service aging.

Figure 5.2 Core Drilling of Wooden Mold Sample

Figure 5.3 Oven Used to Dry Samples

5.3.6 Water bath

A water bath was used to saturate undrained LBR specimens. The water bath, as shown in Figure 5.4, was filled with potable water and covered with a plastic cover. The temperature of the water bath was maintained at standard room temperature for the entire curing period of the specimen sample.

Figure 5.4 Water Bath Used for Undrained LBR Samples

Immersion curing of concrete samples is considered to be the most effective method for curing concrete (*7*). Accordingly, undrained LBR specimen samples were transferred into the water bath two days after being poured into LBR molds. The samples were cured in tap water continuously and were removed two days prior to LBR testing at 28 days.

6. MATERIALS

This section details information about the materials that were used in the preparation of mixes in the laboratory for this study. It was necessary for the design mixes prepared in the laboratory to adequately represent the samples obtained from the field. In order to ensure this, the materials used in creating the design mixes at the laboratory were procured from the same manufacturers who supplied the corresponding material to the contractors' concrete plant, from whom the approved design mixes were obtained. Furthermore, once the materials were procured, they were adequately tested to ensure that they conformed to the specifications cited for these materials by their manufacturers.

Table 6.1 provides a summary of the items acquired to carry out the study. The quantities shown are the amounts that the researcher deemed necessary to have in storage while the study was ongoing.

Table 6.1 Overall Quantities of Material Ordered

<table>
<tr><th colspan="2">Portland Cement (Type I)</th><th colspan="2">Fly Ash</th><th colspan="2">Slag</th></tr>
<tr><th>Manufacturer</th><th>Quantity (lb)</th><th>Manufacturer</th><th>Quantity (lb)</th><th>Manufacturer</th><th>Quantity (lb)</th></tr>
<tr><td>Company A</td><td>360</td><td rowspan="5">Company A</td><td rowspan="5">1000</td><td rowspan="2">Company A</td><td rowspan="2">1000</td></tr>
<tr><td>Company B</td><td>300</td></tr>
<tr><td>Company C</td><td>300</td><td rowspan="2">Company B</td><td rowspan="2">400</td></tr>
<tr><td>Company D</td><td>300</td></tr>
<tr><td>Company E</td><td>400</td><td>Company C</td><td>300</td></tr>
</table>

<table>
<tr><th colspan="2">Air Entrainer</th><th colspan="2">WR & Retardant</th></tr>
<tr><th>Manufacturer</th><th>Quantity (oz)</th><th>Manufacturer</th><th>Quantity (oz)</th></tr>
<tr><td>Arr-Maz Products (Euclid), Aren S</td><td>50</td><td rowspan="2">Arr-Maz Products , Redux DP</td><td rowspan="2">70</td></tr>
<tr><td>W.R. Grace, Darex AEA</td><td>50</td></tr>
<tr><td>Master Builders, MBAE-90</td><td>50</td><td>W.R. Grace, WRDA 64</td><td>70</td></tr>
</table>

In an effort to protect those manufacturers who have supplied cementitious materials (i.e., cement, fly ash, slag) to use in this research, the name of those manufacturers are not listed with any of the cementitious test results or quantities acquired.

6.1 Cement

The cement used was Type I Portland cement. It was procured from different manufacturers based on the information cited by various contractor mix designs provided for approval to FDOT district offices, whose mix designs were replicated for experimentation. The manufacturers include TARMAC (Uniland), TARMAC (Tampa), RINKER (Miami), and LAFARGE (Tampa). Chemical and physical analyses of cement were conducted by FDOT State Materials personnel (see Appendix B). The results can be seen in Tables 6.2 and 6.3. The cements procured met the specifications for Type I cement as given by C-114, C-109, C-151, C-187, C-204, and C-266.

Table 6.2 Chemical Composition of Cement Used

Chemical Composition	Portland Cement Type I			
	Company A (%)	Company B (%)	Company C (%)	Company D (%)
Loss of Ignition (LOI)	0.5	0.30	0.30	0.4
Insoluble Residue	0.12	0.10	0.11	0.13
Sulfur Trioxide (SO_3)	2.8	2.6	2.9	2.7
Magnesium Oxide (MgO)	0.9	1.5	0.8	1.1
Tricalcium Aluminate (Ca_3Al)	4.5	3.2	5.5	5.2
Total Alkali as (Na_2O)	0.29	0.51	0.29	0.19
Silicon Dioxide (SiO_2)	--	--	--	--
Aluminum Oxide (Al_2O_2	--	--	--	--
Ferric Oxide (Fe_2O_3)	--	--	--	--
Tricalcium Silicate (Ca_3Si_2)	--	--	--	--

The above table provides the results of chemical analysis on the Portland cement used for the mixtures. According to the analysis, all cement met FDOT specifications and passed the required chemical analysis tests in order to be considered for use in FDOT concrete mix.

6.2 Fly Ash

Strength of flowable fill can be improved by adding fly ash to the mixture. The fly ash acts to improve workability, and is a cementing agent that improves long-term strength. The silica glass in the fly ash reacts with the free lime liberated during hydration of Portland cement to form a more stable cementing compound (*7*).

Fly ash was procured in a manner similar to that of cement. Class F fly ash was acquired from different manufacturers, which included JTM and others. The testing performed on the fly ash conforms to the required specifications for fly ash as given by C-114 and C-311. The Class F fly ash used has a unique color, light gray, very close to that of silica fume. Appendix C provides more detailed information on the chemical composition testing on fly ash.

Table 6.3 Physical Characteristics of Cement

Company A						
Compressive Strength		Fineness (sq.m./kg)	Setting Time (Gilmore)		Soundness	Normal Consistency
3 Days	7 Days		Initial	Final	Autoclave	
Average (psi)	Average (psi)		Minutes	Minutes		
3860	5220	362	110	175	+0.02	-

Company B						
Compressive Strength		Fineness (sq.m./kg)	Setting Time (Gilmore)		Soundness	Normal Consistency
3 Days	7 Days		Initial	Final	Autoclave	
Average (Psi)	Average (Psi)		Minutes	Minutes		
4300	5390	371	101	167	+0.03	-

Company C						
Compressive Strength		Fineness (sq.m./kg)	Setting Time (Gilmore)		Soundness	Normal Consistency
3 Days	7 Days		Initial	Final	Autoclave	
Average (psi)	Average (psi)		Minutes	Minutes		
3680	5330	380	123	203	-0.02	-

Company D						
Compressive Strength		Fineness (sq.m./kg)	Setting Time (Gilmore)		Soundness	Normal Consistency
3 Days	7 Days		Initial	Final	Autoclave	
Average (psi)	Average (psi)		Minutes	Minutes		
4070	4720	375	118	197	+0.02	-

6.3 Slag

Ground blast furnace slag (ASTM C 989) was procured in a manner similar to the above. Chemical and physical analyses were carried out by FDOT State Materials personnel. Appendix D provides more detailed information on the chemical composition testing on ground blast furnace slag. The samples conform to the required specifications C-989, C-114, C-109, and C-430.

6.4 Aggregates

Procurement of aggregates was done in a manner similar to that of the cement. Table 6.4 provides a list for the locations where fine aggregates were obtained. Two types of fine aggregates were used for this study. These were silica sand and limestone screenings. Tests on these aggregates were performed accordingly as given by ASTM and FDOT specifications. The type of tests performed included the colorimetric and gradation tests. The colorimetric test was carried out to provide information on whether the aggregates contain impurities (*8*). The tests were conducted in accordance to AASHTO T21 and AASHTO T71. Impurities interfere with the process of hydration of cement; coatings would prevent the development of a good bond between aggregate and the hydrated cement paste as well as other individual particles which are weak.

Table 6.4 Fine Aggregates Location Sources

Fine Aggregate Type	Representative FDOT District	FDOT Approve Aggregate Source Pitt. No.	Locations
Silica sand	1	16-078	Sebring, FL
Silica sand	2	76-349	Melrose, FL
Silica sand	4&6	86-271	Dade County, FL
Limestone screening	4&6	87-090	Dade County, FL
Silica sand	5	11-057	Astatula, FL

The silica sand used in this study varied in color from light gray to sandy white. As specified by FDOT, the silica sands used were composed of naturally occurring hard, strong, durable, uncoated grains of quartz and graded from coarse to fine. This type of sand is the same used for concrete mixes.

The screenings used were composed of hard, durable particles that are naturally occurring and result from the crushing of Miami Oolite limestone. This type of limestone is a sedimentary rock formed by the consolidation of calcerous materials, which contain shell fragments.

6.4.1 Gradation

Gradation is perhaps the most important property of an aggregate. It affects almost all the important properties for a mix, including the relative aggregate proportions, as well as the cement and water requirements, workability, pumpability, economy, porosity, shrinkage, and durability. Therefore, gradation is a primary concern in concrete/flowable fill mix design. Aggregate gradation is the distribution of particle sizes expressed as a percent of the total weight. The gradation as a percent of the total volume is also important, but expressing gradation as a percent by weight is much easier and is a standard practice. Gradation analyses were performed on all fine aggregates used for all the mixtures created. The gradation was then compared using the ASTM and FDOT's upper and lower limit sieve analysis for fine aggregate as shown below in Table 6.5. ASTM and FDOT upper/lower limits shall be graded within the following limits.

Table 6.5 ASTM C33 and FDOT Fine Aggregate Gradation

Fine Aggregate Gradation		
Sieve (Specification E11)	Percent Passing	
	ASTM C33	FDOT
9.5 mm (3/8 in.)	100	100
4.75 mm (No. 4)	95 to 100	95 to 100
2.36 mm (No. 8)	80 to 100	85 to 100
1.18 mm (No. 16)	50 to 85	65 to 97
600 µm (No. 30)	25 to 60	25 to 70
300 µm (No. 50)	5 to 30	5 to 35
75 µm (No. 200)	0 to 10	4

Figure 6.1 illustrates the upper and lower limits of the ASTM C33 gradation for fine aggregates. According to Figure 6.1 none of the samples meet ASTM specifications (gradation must lay completely within the limits). The silica sand used for District 5 appears to be coarse, as does the limestone screenings used for District 4&6 non-excavatable mix. Figure 6.2 shows the gradation for fine aggregates in accordance with the FDOT fine aggregates specification. Unlike the ASTM C33 gradation boundaries, the FDOT gradation boundaries allow for District 1 and District 2 silica sand to fall within the required specification gradation limits. Table 6.5 gives fine aggregate gradation variation that starts from sieve no. 16 down to sieve no. 200 between ASTM C33 and Florida specification.

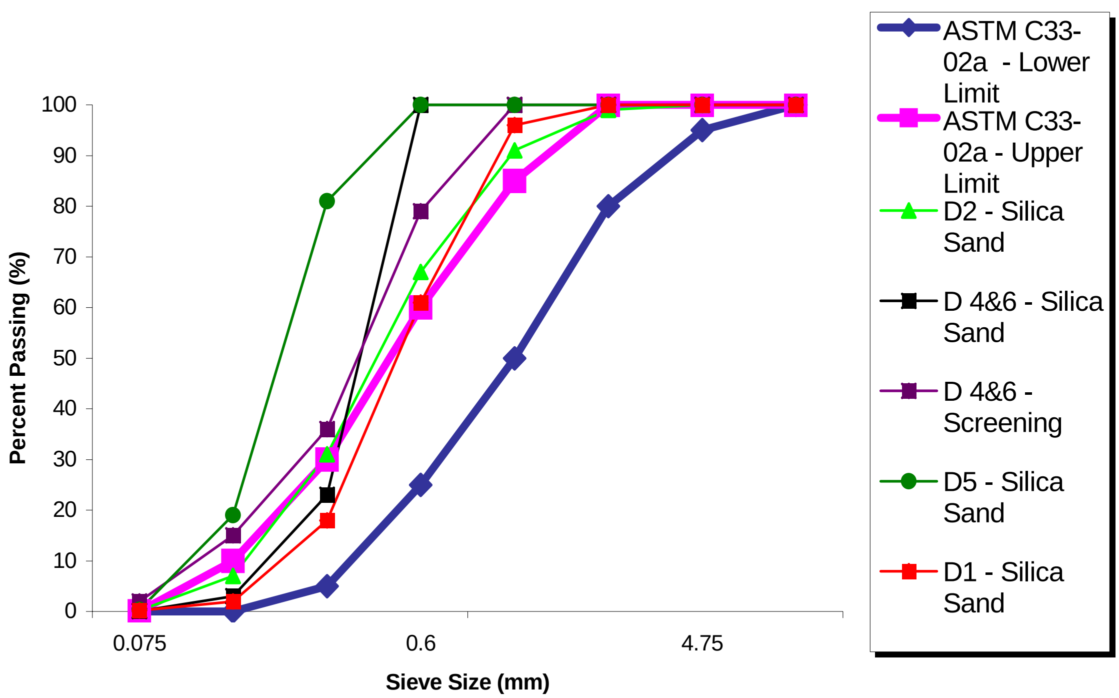

Figure 6.1 Gradation of Fine Aggregates – ASTM Specs

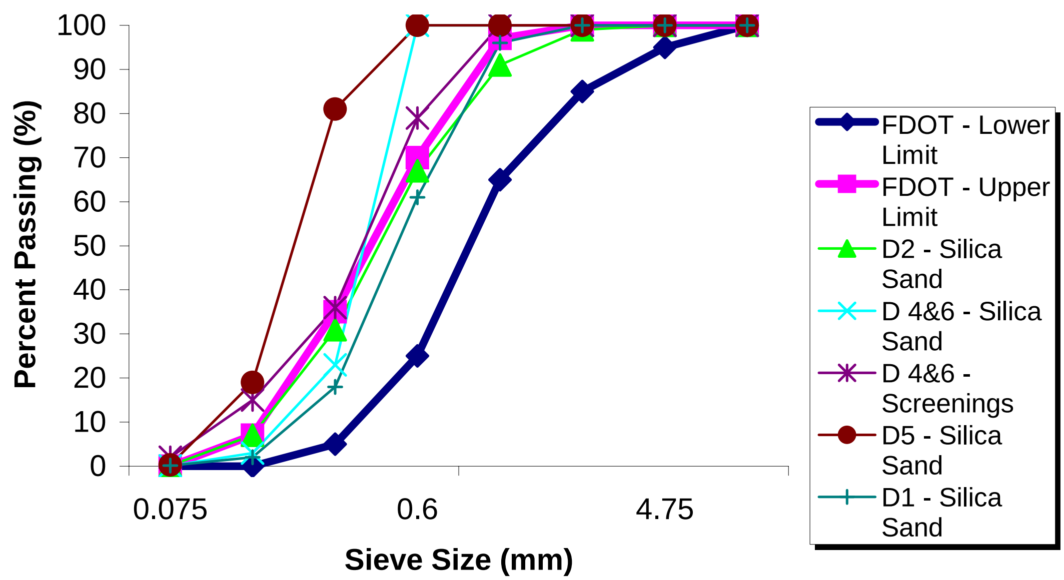

Figure 6.2 Gradation of Fine Aggregates – FDOT Specs

As shown, the limestone screenings from District 4&6 do not fall within the ASTM specified limits for fine aggregates, however it falls within the FDOT specified gradation limits.

6.4.2 Physical properties

The physical properties for the aggregates were provided by FDOT District 2 Materials Laboratory. The physical properties for these aggregates are summarized in Table 6.6.

Table 6.6 Physical Properties of Fine Aggregates (Silica Sand)

	District 1	District 2	District 4&6	District 5
Fineness Modulus	2.23	2.05	---	---
Dry Bulk Specific Gravity	---	2.62	2.63	2.64
Bulk Specific Gravity (SSD)	---	2.63	2.64	2.64
Apparent Specific Gravity	---	2.65	2.65	2.65
Absorption	---	0.44	---	---

--- No data available

6.4.3 Storage of fine aggregates

As fine aggregates were obtained from their aggregate source location, they were brought to the lab facility where mix was prepared and stored in an area designated for aggregate storage. The photograph shown in Figure 6.3 depicts the area where the fine aggregates were stored prior to being used in a mix.

Figure 6.3 Storage and Removal of Fine Aggregates

6.5 Admixtures

Admixtures used were obtained from the corresponding manufacturer as listed per design mix. The types of admixtures used were air entraining agents, high range water-reducer (HRWR) and retarder and accelerator. A list of the manufacturers from whom admixtures were obtained is given in Table 6.1 showing the overall quantities of ordered materials. All admixtures meet all the requirements of ASTM C494.

The accelerating admixture used was Accelguard 80 produced by the Euclid Chemical Company. This admixture is a non-chloride accelerating water reducing admixture used for improving properties of plastic and hardened concrete. It is designed to provide significant improvement in early stiffening and setting characteristics, improved workability, and decreased bleeding and segregation. This type of accelerating admixture is compatible with air entraining admixtures, HRWR admixtures (super plasticizers), and conventional water reducing admixtures.

7. LABORATORY DESIGN MIXES

7.1 Introduction

Design mixes of both excavatable and non-excavatable flowable fill were collected from various district field offices of the FDOT. The following sections discuss the design mixtures obtained and replicated.

7.2 Mixture Proportions of Design Mix

Tables 7.1 through 7.4 provide the constituents for the mixtures obtained from the field and their resulting proportions. The mix designs as shown in the tables, respectively, are excavatable non-accelerated, excavatable accelerated, non-excavatable non-accelerated, and non-excavatable accelerated. Mixes labeled as "accelerated" indicate that they contain accelerating admixtures. The proportion percentages were computed using the overall weights of the constituents.

The information shown in each mixture table was obtained in accordance with the selected mix design specification provided by the FDOT districts.

Table 7.1 Excavatable Non-accelerated Mix Design

		Field Mixture				Replicate Mixture			
		D1	D2	D4&6	D5	D1	D2	D4&6	D5
Constituent (lbs/yd^3)	Type I Cement	75	100	90	79	48.75	65	58.5	51.35
	Fly Ash	--	--	--	--	--	--	--	--
	Slag	150	--	--	--	97.5	--	--	--
	Fine Aggregate	2720	2163	2398	2385	1768	1405.95	1558.7	1550.25
	Air-Entrainer (oz)	10	3	15	4.1	6.5	1.95	9.75	2.67
	WR & Retardant (oz)	--	--	--	3.2	--	--	--	2.08
	Water	408	391.5	458	500	264.71	254.80	297.70	324.54
Proportions (% by weight)	Cement	2.24	3.77	3.05	2.67	2.24	3.77	3.05	2.67
	Fly Ash	--	--	--	--	--	--	--	--
	Slag	4.47	--	--	--	4.47	--	--	--
	Fine Aggregate	81.12	81.48	81.40	80.47	81.12	81.48	81.40	80.47
	Water	12.17	14.75	15.55	16.87	12.17	14.75	15.55	16.87
	w/c	5.44	3.92	5.09	6.32	5.44	3.92	5.09	6.32
	w/cm	1.81	3.92	5.09	6.32	1.81	3.92	5.09	6.32

Table 7.2 Excavatable Accelerated Mix Design

		Field Mixture				Replicate Mixture			
		D1	D2	D4&6	D5	D1	D2	D4&6	D5
Constituent (lbs/yd^3)	Type I Cement	75	100	90	79	48.75	65		51.35
	Fly Ash	--	--	--	--	--	--	58.5	--
	Slag	150	--	--	--	97.5	--	--	--
	Fine Aggregate	2720	2163	2398	2385	1768	1405.95	1558.7	1550.25
	Air-Entrainer (oz)	10	3	15	4.1	6.5	1.95	9.75	2.67
	WR & Retardant (oz)	--	--	--	3.20	--	--	--	2.08
	Accelerator Admixture (oz)	--	--	--	--	**7.80**	**10.4**	**9.36**	**8.216**
	Water	408	391.5	458	500	264.71	254.80	297.70	324.54
Proportions (% by weight)	Cement	2.24	3.77	3.05	2.67	2.24	3.77	3.05	2.67
	Fly Ash	--	--	--	--	--	--	--	--
	Slag	4.47	--	--	--	4.47	--	--	--
	Fine Aggregate	81.12	81.48	81.40	80.47	81.12	81.48	81.40	80.47
	Water	12.17	14.75	15.55	16.87	12.17	14.75	15.55	16.87
	w/c	5.44	3.92	5.09	6.32	5.44	3.92	5.09	6.32
	w/cm	1.81	3.92	5.09	6.32	1.81	3.92	5.09	6.32

Table 7.3 Non-excavatable Non-accelerated Mix Design

		Field Mixture				Replicate Mixture			
		D1	D2	D4&6	D5	D1	D2	D4&6	D5
Constituent (lbs/yd^3)	Type I Cement	150	125	150	150	97.50	81.25	97.50	97.5
	Fly Ash	--	--	--	595	--	--	--	386.75
	Slag	595	152	250	--	386.75	98.80	162.50	--
	Fine Aggregate	2170	2055	2475	2103	1410.50	1335.75	1608.75	1366.95
	Air-Entrainer (oz)	12	3	5	4.5	7.80	2	3.25	2.92
	WR & Retardant (oz)	50	--	--	6	32.50	--	--	3.9
	Water	408.2	391.5	500	484	265.31	254.48	325	314.76
Proportions (% by weight)	Cement	4.51	4.59	4.44	4.53	4.51	4.59	4.44	4.53
	Fly Ash	--	--	--	17.86	--	--	--	17.86
	Slag	17.90	5.58	7.41	--	17.90	5.58	7.41	--
	Fine Aggregate	65.30	75.45	73.33	63.11	65.30	75.45	73.33	63.11
	Water	12.28	14.38	14.81	14.53	12.28	14.38	14.81	14.53
	w/c	2.72	3.13	3.33	3.23	2.72	3.13	3.33	3.23
	w/cm	0.55	1.41	1.25	0.65	0.55	1.41	1.25	0.65

Table 7.4 Non-excavatable Accelerated Mix Design

		Field Mixture				Replicate Mixture			
		D1	D2	D4&6	D5	D1	D2	D4&6	D5
Constituent (lbs/yd^3)	Type I Cement	150	125	150	150	97.50	81.25	97.50	97.5
	Fly Ash	--	--	--	595	--	--	--	386.75
	Slag	595	152	250	--	386.75	98.80	162.50	--
	Fine Aggregate	2170	2055	2103	2103	1410.50	1335.75	1366.95	1366.95
	Air-Entrainer (oz)	12	3	5	4.5	7.80	2	3.25	2.92
	WR & Retardant (oz)	50	--	--	6	32.50	--	--	3.9
	Accelerating Admixture (oz)	--	--	--	--	**9.36**	**13.12**	**13.12**	**15.60**
	Water	408.2	391.5	500	484	265.31	254.48	325	314.76
Proportions (% by weight)	Cement	4.51	4.59	4.44	4.53	4.51	4.59	4.44	4.53
	Fly Ash	--	--	--	17.86	--	--	--	17.86
	Slag	17.90	5.58	7.41	--	17.90	5.58	7.41	--
	Fine Aggregate	65.30	75.45	73.33	63.11	65.30	75.45	73.33	63.11
	Water	12.28	14.38	14.81	14.53	12.28	14.38	14.81	14.53
	w/c	2.72	3.13	3.33	3.23	2.72	3.13	3.33	3.23
	w/cm	0.55	1.41	1.25	0.65	0.55	1.41	1.25	0.65

The dosage rates used for accelerating admixtures were measured using the manufacturer's recommended rate. It required the amount of accelerator used to be based on the amount of cement contained in the mix. For concrete temperatures of 32° F to 60° F, it recommends adding 16 ounces of accelerator for each 100 lb of cement. For instance, a mixture containing 82 lb of cement would require approximately 10.4 ounces of accelerator.

8. LABORATORY RESULTS AND DISCUSSIONS

8.1 Introduction

This chapter presents the laboratory results of 16 different flowable fill mixtures. The laboratory tests were conducted at the Florida Department of Transportation State Materials Office in Gainesville, Florida. The samples were prepared to study and evaluate the LBR, and Proctor penetrometer (Pogo Stick) over different curing periods.

The Proctor penetrometer (Pogo Stick) was used to determine the strength of the samples under different time-periods. In addition, samples were placed in the oven for both excavatable and non-excavatable accelerated conditions to determine the LBR values.

Drainage conditions (drained and undrained) and their impact on strengths gained over different time-periods for the two classes of flowable fill have also been discussed. The laboratory data were used to determine flowable fill curing duration and the effects on strength for drained and undrained samples. In addition, the effects of accelerated admixtures on strength were also determined. Field data were collected to observe the differences between the field and laboratory results. In Chapter 10, a comprehensive statistical analysis of all data (laboratory and field) is discussed.

8.2 Laboratory Results

8.2.1 Limerock Bearing Ratio (LBR)

Figures 8.1 to 8.4 graphically illustrate LBR results versus the curing duration of the different mixes at 6 hrs, 1 day, 2 days, 7 days, 14 days, 28 days, and 90 days. From the graphical charts it can be seen that no clear pattern exists among the individual mixes collected per district.

Statistical analyses of the LBR results are presented in Chapter 10. It can be seen in Figures 8.1 to 8.4 that the LBR values for non-excavatable mixtures are greater than those for the excavatable mixes. These results were expected since the non-excavatable mixes develop higher strengths than excavatable flowable fill mixes. It can also be seen that the drained and undrained LBR values differ. For example, the minimum drained LBR value for a 7-day test on non-excavatable mixture for District 2 (D2) shows as 200, while the minimum undrained LBR value is 150 (see Figures 8.3 and 8.4, respectively).

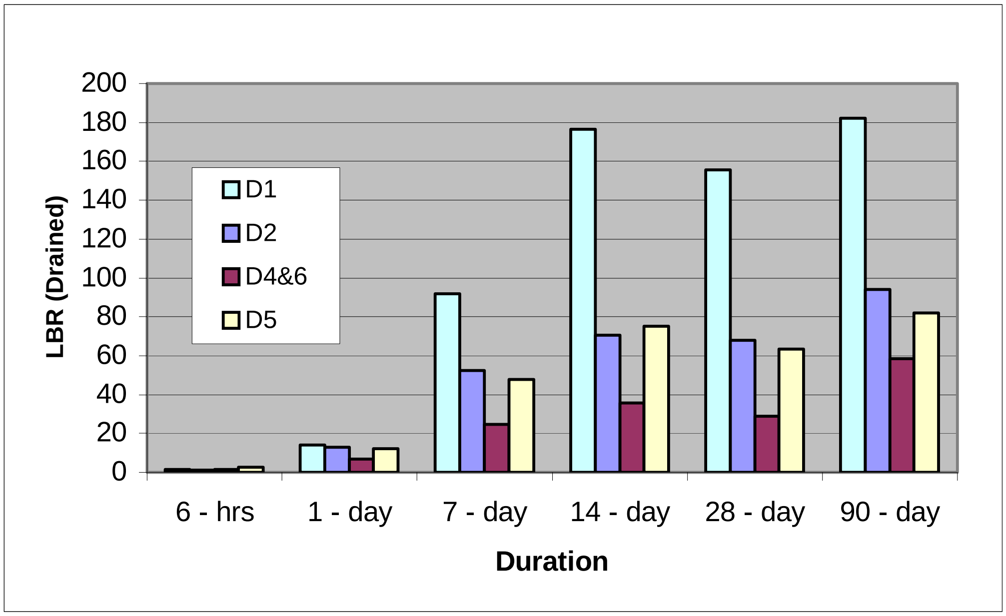

Figure 8.1 Drained Excavatable – LBR vs. Curing Duration

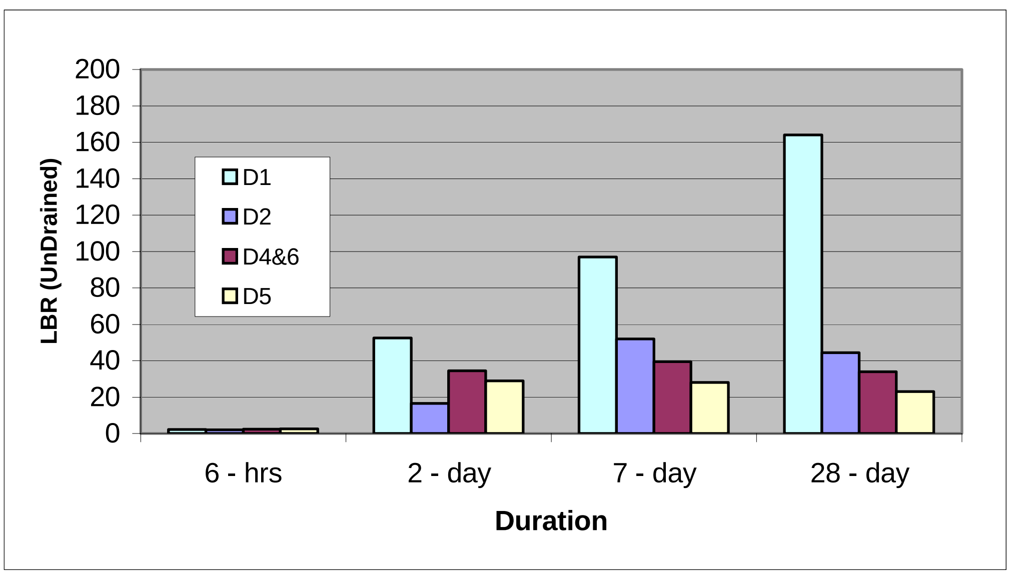

Figure 8.2 Undrained Excavatable – LBR vs. Curing Duration

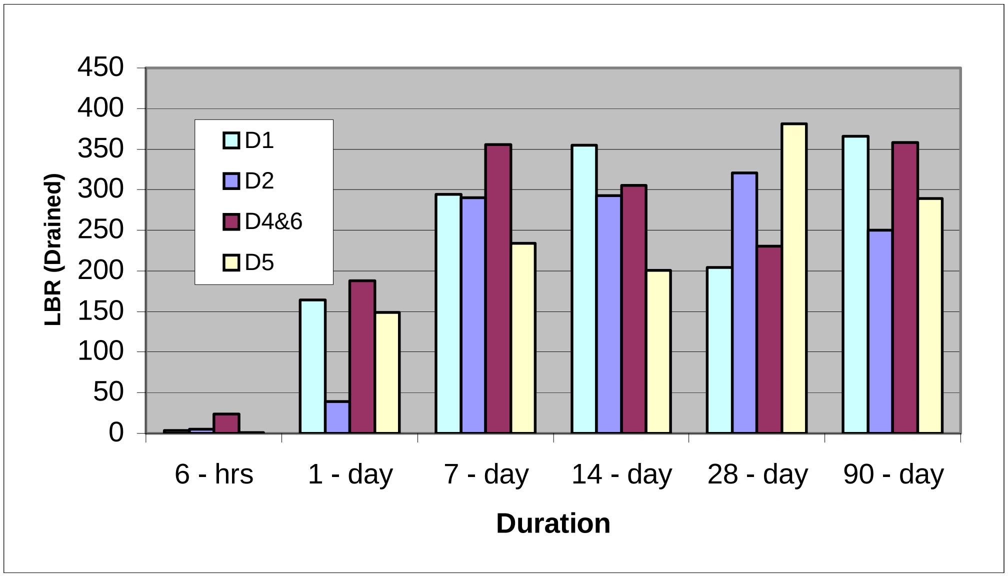

Figure 8.3 Drained Non-excavatable – LBR vs. Curing Duration

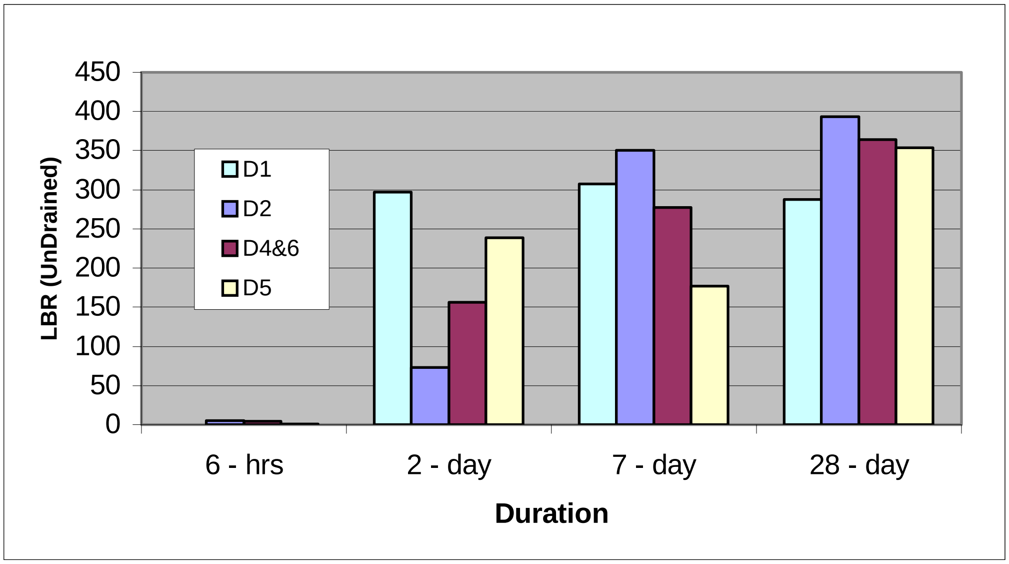

Figure 8.4 Undrained Non-excavatable – LBR vs. Curing Duration

8.2.2 Proctor penetrometer (Pogo Stick)

Figures 8.5 through 8.8 show the test results obtained for the mixtures tested using the Proctor penetrometer. The figures show stress values of all mix samples at different curing durations.

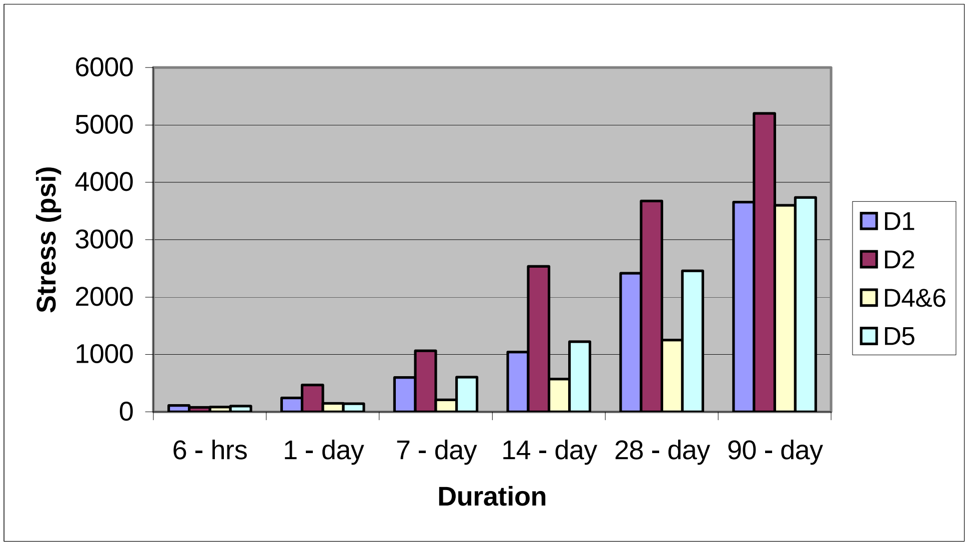

Figure 8.5 Results of Proctor Penetrometer Tests on Drained Excavatable Mixes

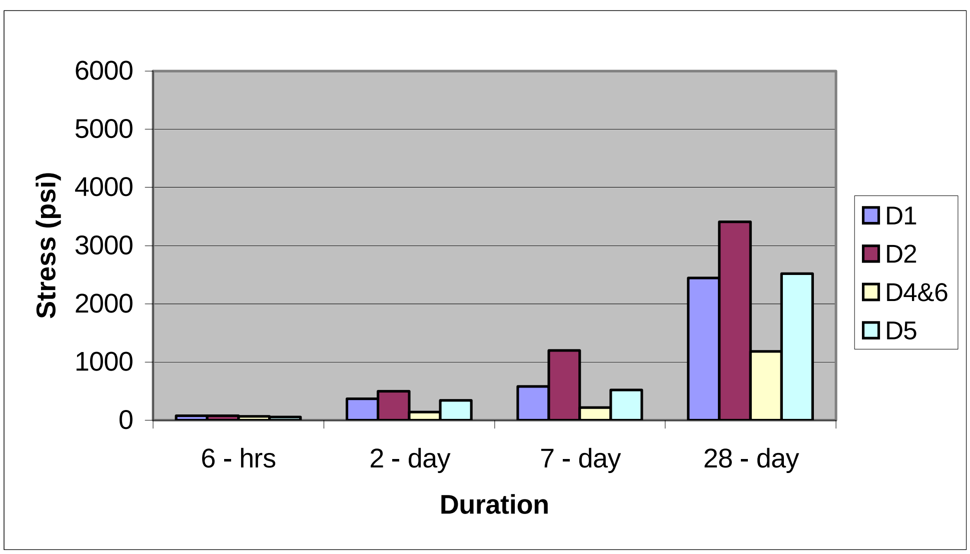

Figure 8.6 Results of Proctor Penetrometer Tests on Undrained Excavatable Mixes

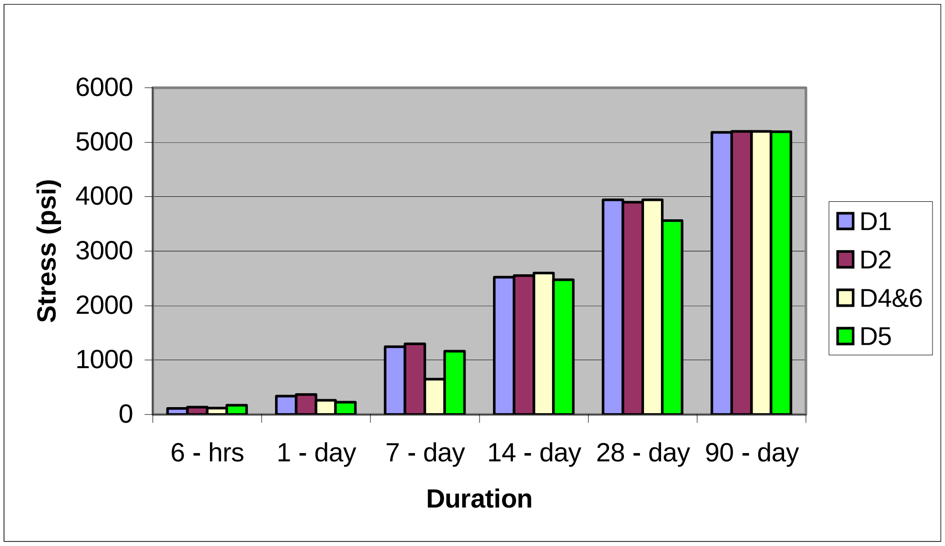

Figure 8.7 Results of Proctor Penetrometer Tests on Drained Non-excavatable Mixes

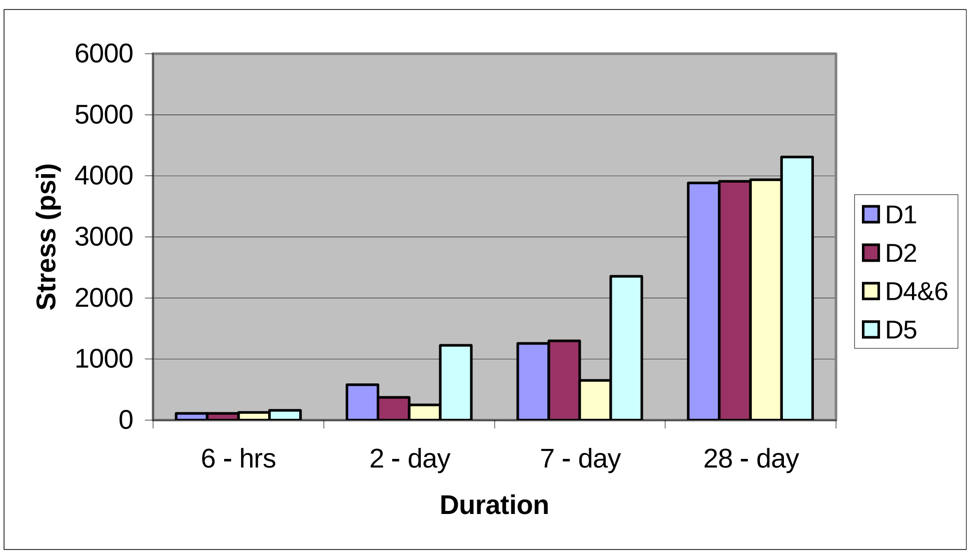

Figure 8.8 Results of Proctor Penetrometer Tests on Undrained Non-excavatable Mixes

In some cases, samples became too stiff to get a penetrometer reading. Between 28 and 90 days, compressive strength increased in all samples. As a result, it became difficult to obtain accurate reading from the Proctor penetrometer.

For those samples designated for testing at 6 hours, the following observations were noticed. At the beginning, since samples were soft, it was not possible to get any penetrometer readings. However, at a later time, the samples became stiff and penetrometer readings were obtained. This is due to the fact that flowable fill mixtures are often plastic several hours after mixing. Such observations were noticed only for 6-hour samples.

8.2.3 Strength gained between 28 and 90 days

Figures 8.9 and 8.10 illustrate the percent increase in strength between 28- and 90-day LBR results. The hydration of cement might continue for a long time beyond 28 days. A part of the fly ash and cementitious materials might be participating in the pozzolanic reaction depending on the nature of the fly ash (*7*). The 90-day strength was as high as 43% more than the 28-day strength. On average, there was a 5 to 15% increase in 90-day strength with respect to 28-day strength for excavatable mixes. The non-excavatable mixes appear to have a much smaller strength gain between 28 and 90 days.

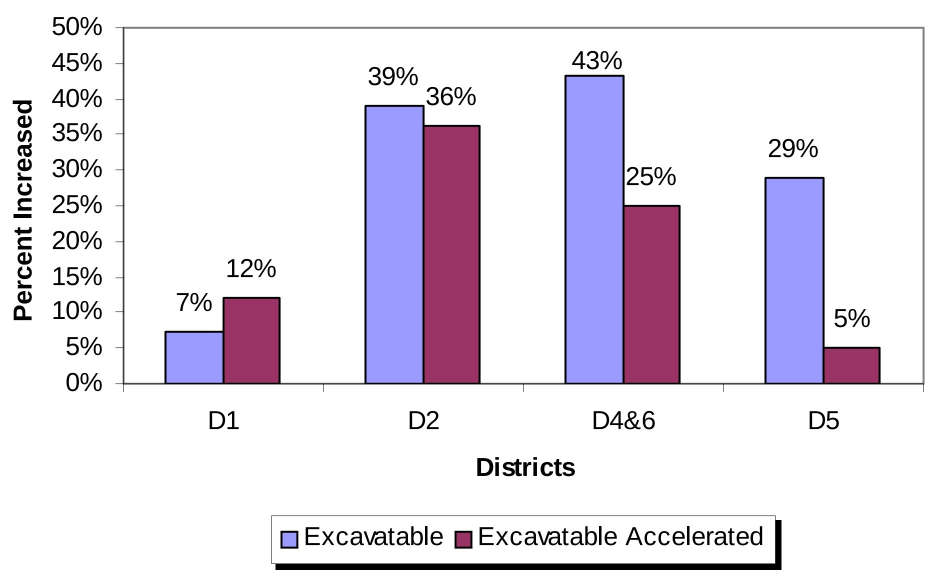

Figure 8.9 Increase in 90-day Strength as Compared to 28-day Strength – Excavatable Mixes

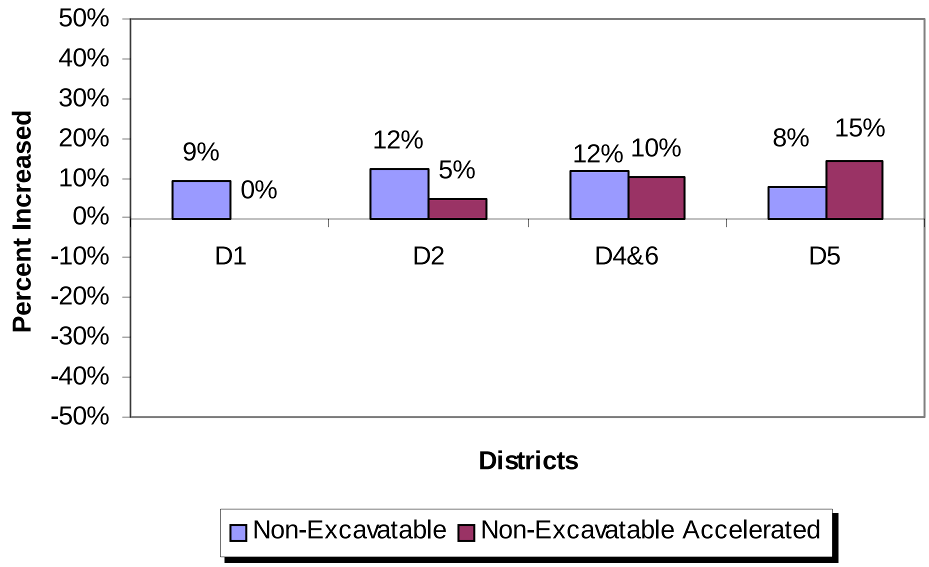

Figure 8.10 Increase in 90-day Strength as Compared to 28-day Strength
Non-excavatable Mixes

8.3 LBR Oven Sample Results

The results of the oven-dried LBR samples give us an exemplary observation of the role that temperature plays in the curing of flowable fill. As noted earlier, LBR samples were placed into an oven for curing for 2 days, 4 days, and 8 days. The oven was set at a temperature of 120° F for the duration of the curing. The average values from two samples per mix condition are presented in Tables 8.1 and 8.2. Appendix E contains the individual LBR values.

Table 8.1 LBR Values of Oven-dried Samples for Excavatable and
Excavatable Accelerated Flowable Fill Mixes

Excavatable			
Drained	2 Days	4 Days	8 Days
D1	89	102	160
D2	39	62	70
D4&6	24	54	58
D5	26	29	50
Undrained	2 Days	4 Days	8 Days
D1	61	114	65
D2	25	28	24
D4&6	14	18	26
D5	9	14	26

Excavatable Accelerated			
Drained	2 Days	4 Days	8 Days
D1	86	208	120
D2	17	37	51
D4&6	33	52	51
D5	31	36	60
Undrained	2 Days	4 Days	8 Days
D1	54	86	92
D2	20	21	31
D4&6	52	27	32
D5	13	11	33

Table 8.2 LBR Values of Oven-dried Samples for Non-excavatable and Non-excavatable Accelerated Flowable Fill Mixes

Non-Excavatable			
Drained	2 Days	4 Days	8 Days
D1	365	356	395
D2	406	341	390
D4&6	414	293	378
D5	399	391	370
Undrained	2 Days	4 Days	8 Days
D1	365	358	397
D2	93	165	171
D4&6	252	323	381
D5	142	217	352

Non-Excavatable Accelerated			
Drained	2 Days	4 Days	8 Days
D1	395	365	349
D2	128	278	207
D4&6	369	248	366
D5	391	397	347
Undrained	2 Days	4 Days	8 Days
D1	392	360	379
D2	80	186	238
D4&6	187	229	224
D5	87	196	48

Many of the 8-day LBR samples tested did not show higher LBR values. This is because of the hardness of the specimens that caused the LBR machine to terminate itself. Some of the specimen LBR plots show the LBR values going up and then coming down and then going up again. This peculiar behavior was observed for many of the samples containing fly ash, slag and high cement content. Many of the samples demonstrating the aforementioned behavior showed signs of fracture and cracking when the LBR test was performed.

To better understand the strength gain between the various intervals of testing, the percent increase was computed. As shown in Table 8.3, the largest average percent increase in strength occurred between two days of curing and four days of curing. This appears to be the case for all mixtures with the exception of two cases in which negative percent increases were attained.

8.4 Drainage Conditions

For much of the data gathered on the samples of drained versus undrained samples, it was observed in the lab that the drained samples gained strength at a much faster pace than the undrained samples. An explanation for this early strength gain is attributed to the reduction of water content through drainage. As water escapes the flowable fill, the water-cement ratio is reduced and a higher strength results for the same curing time.

Introduction of a plastic layer into the specimen mold provides for slow drainage in the undrained samples. Several mixtures included in this research study showed excessive amounts of bleeding which were often observed in field applications of flowable fill. In mixtures suffering from excessive bleeding such measures as using dense-graded aggregates, additional cement or fly ash can be used for controlling excessive bleeding. Some of the conditions in the field which may cause drainage depend on the nature of the surrounding soil. Soils that are granular with high permeability tend to speed up the bleeding in flowable fill, whereas soil types involving clay tend to lengthen bleeding due to low permeability. The undrained samples were used in this study to simulate lengthened drainage. From the data obtained, it was clear that drainage in flowable fill considerably influences the early strength of flowable fill.

Table 8.3 Percent Increase in LBR Values for Oven-dried Samples

Excavatable		
Percent Increased		
Drained	2 to 4	4 to 8
D1	13%	37%
D2	38%	11%
D4&6	56%	7%
D5	12%	42%
Average:	30%	24%
Undrained	2 to 4	4 to 8
D1	47%	-77%
D2	9%	-15%
D4&6	25%	29%
D5	36%	46%
Average:	29%	-4%

Excavatable Accelerated		
Percent Increased		
Drained	2 to 4	4 to 8
D1	59%	-74%
D2	54%	27%
D4&6	38%	-2%
D5	14%	41%
Average:	41%	-2%
Undrained	2 to 4	4 to 8
D1	38%	6%
D2	5%	31%
D4&6	-96%	16%
D5	-18%	67%
Average:	-18%	30%

Non-Excavatable		
Percent Increased		
Drained	2 to 4	4 to 8
D1	-3%	10%
D2	-19%	13%
D4&6	-41%	22%
D5	-2%	-6%
Average:	-16%	10%
Undrained	2 to 4	4 to 8
D1	-2%	10%
D2	43%	4%
D4&6	22%	15%
D5	35%	38%
Average:	25%	17%

Non-Excavatable Accelerated		
Percent Increased		
Drained	2 to 4	4 to 8
D1	-8%	-5%
D2	54%	-34%
D4&6	-49%	32%
D5	2%	-14%
Average:	0%	-5%
Undrained	2 to 4	4 to 8
D1	-9%	5%
D2	57%	22%
D4&6	19%	-2%
D5	55%	-312%
Average:	31%	-72%

8.5 Interpretation of Plastic Test Results

In reviewing the outcome of the plastic properties test, the results appear to match those found in approved flowable fill design mixtures. It was very important to obtain results that were similar to those of the mixes that were being replicated. Care was taken throughout the study, particularly at the time of mixing, to appropriately match the plastic test results provided for making duplicated mixtures. The plastic properties tests were performed at the end of every mix. The characteristics tested were unit weight, flowability, and air content. Table 8.4 illustrates the outcome of the plastic tests performed.

For a flowable fill to be self-leveling, it must have a spread of at least 9 inches (*4*). This type of spread is also known to provide suitable flow during placement of flowable fill in the field. LBR values in Table 8.1 show that almost all the excavatable mixes fall out of the category of having a 9-inch spread. On the other hand, the flow for the non-excavatable mixes exceeds the 9-inch requirement. To understand the behavior as to why one class of mixtures has high flow and the other class has less flow, it is critical to understand the behavior of different material ingredients in the flowable fill. Water, for example, is expected to be the ingredient responsible for flow. Looking at the water/cement (w/c) ratio in Table 8.4, however, it shows that most of the mixes with low-flow spread are those that contain a high w/c ratio. Though the excavatable and the non-excavatable mixes have substantially different w/c ratios, their water contents are fairly similar. The differences in flowability can be attributed to the different amounts of water reducing admixtures added.

Table 8.4 Plastic Properties Test Results

	District 1			
	Exc.	Exc. Acc.	Non-Exc.	Non-Exc. Acc.
Spread (in.)	6.00	4.38	10.00	11.00
Unit Weight (lb/ft^3)	113.60	111.60	132.40	130.20
Air (%)	13.00	16.00	4.50	5.40
w/c	1.81	1.81	0.55	0.55
	District 2			
	Exc.	Exc. Acc.	Non-Exc.	Non-Exc. Acc.
Spread (in.)	4.50	5.30	6.50	8.00
Unit Weight (lb/ft^3)	110.40	116.40	119.60	117.80
Air (%)	23.00	10.50	9.50	14.00
w/c	3.92	3.92	3.92	3.92
	District 4&6			
	Exc.	Exc. Acc.	Non-Exc.	Non-Exc. Acc.
Spread (in.)	8.20	7.50	10.75	7.63
Unit Weight (lb/ft^3)	119.79	120.00	125.80	129.40
Air (%)	7.90	14.50	19.00	3.90
w/c	5.09	5.09	1.25	1.25
	District 5			
	Exc.	Exc. Acc.	Non-Exc.	Non-Exc. Acc.
Spread (in.)	0.00	4.75	12.00	19.75
Unit Weight (lb/ft^3)	109.60	115.60	120.85	120.20
Air (%)	12.00	7.10	5.00	4.70
w/c	6.32	6.32	0.65	0.65

The FDOT specifications on unit weight target values on flowable fill are 90-110 (excavatable) and 90-110 (non-excavatable). Furthermore, the FDOT air content target values are 5-35 (excavatable) and 5-15 (non-excavatable). The plastic test results shown in Table 8.4 show District 2 and District 5 meeting FDOT specifications target air content, while District 4&6 air content values exceed the specifications. The unit weight for Districts 2 and 5 passes the FDOT target for excavatable flowable fill mix. However, it failed for all the remaining mixes in all districts.

8.6 Flowable Fill Setting Time

The setting time for flowable fill was measured using the Proctor penetrometer. During the first six hours of testing, many of the undrained samples exhibited bleed water on the surface. The height of the bleed water varied from 1 to 2.5 inches. This problem existed for the undrained samples only.

Studies on this test indicated that the penetration resistance at the hardening stage varied from 60-65 psi, depending on the weight of the person and the average contact area (*4*). This setting time for flowable fill mixture may be used as a reference for penetration resistance and to determine if the mixture has set. Using the Proctor penetrometer, the penetration resistance was obtained for drained and undrained samples. From Tables 8.5 and 8.6 below, it can be seen that penetration resistance for both the drained and undrained mixtures, at six hours, is well above the 60 to 65 psi range. Appendix F presents per sample Proctor penetrometer values.

Table 8.5 Proctor Penetrometer Data for District 1, Drained Samples

Drained	D1 (psi)			
Duration	Exc.	Exc. Acc.	Non. Exc.	Non. Exc. Acc.
6 - hrs	112.38	113.63	113.00	114.00
1 - day	242.75	158.67	342.80	315.91
7 - day	601.25	363.75	1,245.00	1,242.50
14 - day	1,041.38	1,138.75	2,522.50	2,532.50
28 - day	2,417.50	2,507.50	3,939.39	3,924.24
90 - day	3,659.09	3,863.64	5,185.00	5,195.00

Table 8.6 Proctor Penetrometer Data for District 1, Undrained Samples

Undrained	D1 (psi)			
Duration	Exc.	Exc. Acc.	Non. Exc.	Non. Exc. Acc.
6 - hrs	80.63	94.00	114.00	114.00
2 - day	367.50	252.25	580.00	604.38
7 - day	580.63	353.25	1,258.75	1,238.75
28 - day	2,442.50	2,467.50	3,886.36	3,928.03

8.7 Effects of Accelerated Admixtures on Flowable Fills

One of the objectives of the study was to evaluate the effect of accelerating admixture on flowable fill. The lab results obtained from the mixtures containing accelerator suggest that the accelerating admixtures did not perform to the level expected based on similar accelerated mixes. For the accelerator to work, a mix must have enough cement to allow the accelerator to fully react. For example, in the excavatable accelerated mix test performed for District 1 (Table 8.7), some of the mixtures had a percentage increase in strength while some showed a percentage reduction in strength (see Tables 8.7 through 8.10). The cause for this may be the extra cementitious material, such as slag contained in the cement. Slag appears to influence the varied accelerating behaviors of the mix designs. Other factors that may result in such behavior may include the w/c ratio, cement content, fly ash, or the type of fine aggregate used.

Table 8.7 LBR Data for District 1

Drained	D1			
Duration	Exc.	Exc. Acc.	Non. Exc.	Non. Exc. Acc.
6 - hrs	1.67	13.50	3.81	1.00
1 - day	14.00	15.50	164.00	33.50
7 - day	92.00	235.50	294.46	214.50
14 - day	176.50	231.50	354.92	218.00
28 - day	155.50	221.00	204.50	396.00
90 - day	182.00	256.50	365.50	380.50

Table 8.8 LBR Data for District 2

Drained	D2			
Duration	Exc.	Exc. Acc.	Non. Exc.	Non. Exc. Acc.
6 - hrs	1.13	1.00	5.00	22.50
1 - day	13.00	8.50	39.00	19.00
7 - day	52.50	26.50	290.50	104.00
14 - day	70.50	22.50	292.60	227.50
28 - day	68.00	58.50	320.81	230.96
90 - day	94.00	47.00	250.00	356.00

Table 8.9 LBR Data for District 4&6

Drained	D4&6			
Duration	Exc.	Exc. Acc.	Non. Exc.	Non. Exc. Acc.
6 - hrs	1.42	0.00	24.00	24.00
1 - day	7.00	10.00	188.00	39.00
7 - day	24.50	28.00	355.50	343.56
14 - day	35.50	37.50	305.00	357.60
28 - day	29.00	43.00	230.50	291.50
90 - day	58.50	61.00	357.96	337.50

Table 8.10 LBR Data for District 5

Drained	D5			
Duration	Exc.	Exc. Acc.	Non. Exc.	Non. Exc. Acc.
6 - hrs	2.75	2.00	1.00	1.00
1 - day	12.00	16.00	149.00	73.50
7 - day	48.00	30.50	234.00	211.00
14 - day	75.00	50.00	200.50	398.88
28 - day	63.50	28.00	381.50	399.65
90 - day	82.00	36.50	289.00	355.50

8.8 Effects of Fly Ash and Slag on Flowable Fill

Concrete mixes containing fly ash or slag will generally require less water than concrete mixes containing only cement (*7*). Like flowable fill, the mixes containing cementitious material show a lower water cement ratio than the latter. The mixtures containing fly ash exhibited higher strength, less bleeding, and segregation. Visual observation for bleeding and segregation were conducted in this study. Thorough observation made during mixing shows that mixes containing a high percentage of fine aggregates demonstrate bleeding at an early phase of mixing, and as the mixing was prolonged, the bleeding slowed. This phenomenon exists in excavatable mixes containing zero or little fly ash or slag. Excessive bleeding often indicates a bad mix. This type of mix should be avoided in the field due to the possibility of the mix not having good flow. In addition, such a mix may result in excessive initial subsidence of the surface after placement.

8.9 Field Experimental Results

8.9.1 Field sample data

Field data was collected from Lake Butler and Worthington Springs, Florida, on State Route 121. During the placement of a 36-inch diameter cross drain pipe, excavatable flowable fill was used to cover the trench dug diagonally across the road. The depth of the trench dug was approximately 6 to 9 feet and the width 3 to 4 feet. Table 8.11 presents the field cylinder sample data taken during the filling process. The cylinders were allowed to cure for 28 days before breaking.

Based on FDOT specifications, the maximum allowable 28-day compressive strength for excavatable flowable fill is 100 psi. It can be seen from Table 8.11 that the field compressive strength values are not within the FDOT specifications.

Table 8.12 presents the Proctor penetrometer test results. The Pogo Stick readings were taken from poured flowable fill within six hours of pouring at different locations in the field. The test values shown in Table 8.12 are higher than the FDOT specifications of 35 psi minimum penetration resistance, making them acceptable.

Table 8.11 Field Sample Compressive Strength

Sample	Worthington Springs SR-121 Area (in^2)	Failure Load (lb)	Compressive Strength (lb/in^2)	Lake Butler SR-121 Area (in^2)	Failure Load (lb)	Compressive Strength (lb/in^2)
1	12.57	17,910.00	1425.23	28.27	49,540.00	1752.12
2	12.57	14,710.00	1170.58	28.27	49,760.00	1759.90
3	12.57	17,170.00	1366.35	12.57	27,770.00	2209.87
4	12.57	15,340.00	1220.72	12.57	25,180.00	2003.76
5	12.57	15,050.00	1197.64	--	--	--
Average:		16,036.00	**1276.10**		38,062.50	**1931.41**

-- No data available

Table 8.12 Penetrometer Data for Field Samples (Worthington Springs Location)

Test Locations	Tip Area (in^2)	Penetrometer (Pogo Stick) Reading(s) (lb)				Average (lb)
Top of Pipe	0.5	70	73	85	84	78.00
Top of Pipe	0.5	86	76	72	69	75.75
Adjacent to Pipe	0.5	76	70	85	82	78.25
Test Locations	Tip Area (in^2)	Stress (lb/in^2)				Average (lb/in^2)
Top of Pipe	0.5	140	146	170	168	156.0
Top of Pipe	0.5	172	152	144	138	151.5
Adjacent to Pipe	0.5	152	140	170	164	156.5

Based on the results for field samples, one might conclude that FDOT specifications for flowable fill are not being followed properly by contractors and concrete producers for excavatable mixes. However, these results are based on samples from only one construction field project and may not accurately reflect the lack of conformance to the FDOT specifications for excavatable flowable fill on other such projects. But at the same time, it may also be argued that such a pattern of non-conformance may be found in other such projects involving flowable fill. It should be kept in mind that unlike concrete, flowable fill is not rigorously tested in the field, thereby rendering it vulnerable to violation of specifications due to lack of enforcement in the field. Another reason for this non-compliance may be attributed to contractors who do not properly check the product for different characteristics when it is received from the concrete plant.

A probable way for FDOT to assure field conformance for strength of flowable fill is to identify the variability among different samples taken randomly from different field sites in

Florida. This would allow help in verifying the state of conformance of different contractors to FDOT specifications. The variations observed in this process depict a lack of consistency between the flowable fill mixes, rendering the mixes to be of poor quality. In order to improve these quality characteristics of flowable fill, FDOT needs to apply different design techniques that will assist in the selection and evaluation of various quality characteristics of flowable fill. Furthermore, it should be ensured that there is a direct correlation between these quality characteristics and the performance criteria that they are intended to represent in order to ensure customer satisfaction.

The Proctor penetrometer helps in ascertaining the field conformance of FDOT specification on flowable fill. The Proctor penetrometer is used to measure penetration resistance of flowable fill. However, it is also a useful tool for strength measurement up to a certain point in curing time. The non-excavatable mixes cure faster than excavatable mixes. This is apparent from initial Proctor penetrometer testing of the mixes. For a non-excavatable mix, a 1/30-in^2 penetrometer needle for a 28-day test broke into two pieces due to the specimen stiffness. This only happened for non-excavatable mixes. As hydration proceeds and flowable fill gains stiffness, the penetrometer exhibits higher values. It was shown that data for 28 and 90 days of curing time present inaccurate results due to the inability of the penetrometer to penetrate through such strengthened flowable fill. This was the case for both excavatable and non-excavatable flowable fill. Moreover, it was harder to obtain reasonable results for non-excavatable mixtures. Hence, the penetrometer is a good test to use in the field where the strength needs to be measured in early setting times to determine if the flowable fill can support foot traffic and allow further loading. This would include placement of paving courses for an early opening of traffic, particularly on major arterials or where heavy volumes of traffic require use of the roadway during rush hour.

9. ACCELERATED STRENGTH TESTING

9.1 Introduction

The 28-day strength of excavatable flowable fill is to be restricted to 100 psi to allow for possible future excavation. To ensure that the strength of a particular mix of flowable fill does not exceed this value, the samples are required to be kept for 28 days for strength testing before this mix is used in the field. This can cause major delays in the construction work, and upset the economics of application of this material. This is viewed by many as a major drawback in the application of this material, particularly from the contractor's perspective. This disadvantage of flowable fill necessitated the development of accelerated strength testing to reduce the strength testing time. Accelerated strength testing speeds up the process of hydration of cement in flowable fill. The increase in temperature accelerates hydration of the cement. The ASTM C 684 Standard specifications discuss techniques to accelerate the development of strength for concrete. The techniques specified in ASTM are the Warm Water Method, Boiling Water Method, Autogenous Curing Method and High Temperature and Pressure Method. The Warm Water Method specifies curing the concrete specimens immediately after casting the samples, in water at 95 ^{o}F for 24 hours. The Boiling Water Method involves curing the concrete specimens one day after casting in boiling water for 3.5 hours. The Autogenous method involves storage of specimens in insulated curing containers in which the elevated curing temperature is obtained from heat of hydration of cement. The high temperature method involves simultaneous application of elevated temperature and pressure to the concrete using special containers. However, these techniques cannot be applied directly to flowable fill, as the quantity of cement is insignificant in relation to the total volume of the mix.

9.2 Mixes

The mixes considered for this evaluation include excavatable and excavatable accelerated samples. The mix samples used are LBR samples which were prepared in the same manner as previous samples.

9.3 Accelerated Curing

A drying oven was used to accelerate the curing of flowable fill samples. Both drained and undrained samples were used as part of the accelerated curing procedure. After each batch mix, oven samples were collected and assembled for placement into the oven. Samples were tested at curing intervals of 2 days, 4 days, and 8 days. The LBR samples were the only ones used for oven curing. The LBR samples were not de-molded prior to testing. All samples tested showed no sign of deterioration or disintegration from being placed in the oven.

9.4 Analysis

After the samples were tested and LBR results were collected, statistical analysis was performed in order to develop an accelerated strength. The accelerated strength would then be used to predict the 28-day strength using the standard curing 28-day LBR results and the accelerated curing oven-dried results.

9.4.1 Regression analysis

To estimate the potential later-age strength from a measured early-age accelerated strength, as stated in a previous section of this research, proper sample amounts were collected per mix. These mixtures included similar materials to those that are used in construction. Ordinary least squares regression analysis is used to obtain the equation of the line representing the relationship between standard cured and accelerated strengths (*9*, *10*). This relationship is applicable only to the specific materials and accelerated test procedure that were used. To account for the uncertainty in the resulting regression line, confidence bands for the line are established (*9*). Then, for a new accelerated strength, the confidence interval for the average later-age strength can be estimated. These procedures are based on the earlier work of Wills (*11*) and Carino (*12*).

In this study, it was assumed that the relationship between the standard or normal curing strength (Y) and the accelerated strength (X) can be represented by a straight line with the following equation:

$$Y = a - bX \tag{9.1}$$

However, for some flowable fill mixtures, the relationship between these two types of strength may not be linear. For these situations, the measured strength values should be transformed by taking their natural logarithms. The natural logarithms of the strengths would be used to obtain the average X and Y values to be used in later calculations. The last step would be to perform exponentiation to convert the computed confidence intervals to strength values.

Assume that n pairs of (X_i, Y_i) values are obtained from laboratory testing, where X_i and Y_i are the average strengths of accelerated and standard-cured specimens. The intercept, a, and slope, b, of the straight line are determined using the procedure of ordinary least squares (*9*):

$$b = \frac{S_{xy}}{S_{xx}} \tag{9.2}$$

$$a = \bar{Y} - b\bar{X} \tag{9.3}$$

where:

$$S_{xy} = \sum \left(X_i - \bar{X} \right)\left(Y_i - \bar{Y} \right) \tag{9.4}$$

$$S_{xx} = \sum \left(X_i - \bar{X} \right)^2 \tag{9.5}$$

Thus, S_{xy} is the sum of x deviations times y deviations and S_{xx} is the sum of x deviations squared.

$$\bar{X} = \sum \frac{X_i}{n} \tag{9.6}$$

$$\bar{Y} = \sum \frac{Y_i}{n} \tag{9.7}$$

The residual standard deviation, S_e, of the best-fit line is given by the following:

$$S_e = \sqrt{\frac{1}{n-2}\left(S_{yy} - \frac{S_{xy}^2}{S_{xx}}\right)} \tag{9.8}$$

where:

$$S_{yy} = \sum \left(Y_i - \bar{Y}\right)^2 \tag{9.9}$$

To illustrate the procedure, consider the 8 pairs of accelerated and standard-cured, 28-day strength samples which were oven-dried for two days and are given in the first two columns of Table 9.1. Each number is the average strength of two LBR specimen samples. The accelerated strength (X_i) is the value obtained from samples oven-dried for two days for excavatable mixes. Using the preceding equations, the following values are to be obtained:

$$\begin{aligned}
\bar{X} &= 35.50 \text{ LBR} \\
\bar{Y} &= 72.69 \text{ LBR} \\
S_{xx} &= 4983.50 \ (\text{LBR})^2 \\
S_{yy} &= 21970.97 \ (\text{LBR})^2 \\
S_{xy} &= 9737.75 \ (\text{LBR})^2
\end{aligned}$$

The slope of the line is b = 9737.75 /4983.50 = 1.95, and the intercept is 72.69 – 1.95 × 35.50 = 3.32 LBR. Therefore, the equation of the relationship between accelerated strength (X) and standard-cured strength (Y) is as follows:

$$Y = 3.32 + 1.95\, X \ (\text{LBR}) \tag{9.10}$$

Figure 9.1 shows the 8 data pairs and the calculated best-fit line. The regression graph presented in Figure 9.1 has been forced to zero (y-intercept is set to zero). The residual standard deviation of the line, S_e, is as follows:

$$S_e = \sqrt{\frac{1}{8-2}\left(21{,}970.97 - \frac{9737.75^2}{4983.50}\right)} = 22.149 \text{ LBR} \tag{9.11}$$

Table 9.1 Estimation of Confidence Interval for 28-day Strength – Excavatable Mixes

Limerock Bearing Ratio (LBR)					
Accelerated Strength, X_i	28-day Strength, Y_i	Estimated Strength, Y	W_i	Lower Confidence Limit	Upper Confidence Limit
9.00	23.00	20.91	27.52	-6.62	48.43
13.50	34.00	29.70	25.16	4.54	54.85
23.50	29.00	49.24	20.94	28.30	70.18
25.00	44.50	52.17	20.47	31.70	72.64
25.50	63.50	53.15	20.33	32.82	73.48
38.50	68.00	78.55	19.01	59.54	97.56
60.50	164.00	121.54	26.71	94.83	148.25
88.50	155.50	176.25	44.29	131.96	220.54
Confidence Interval for Estimated Strength at Accelerated Strength of 24.00 LBR					
24.00		50.22	20.78	29.44	70.99
23.16		48.58	21.05	27.52	
24.84		51.86	20.52		72.38

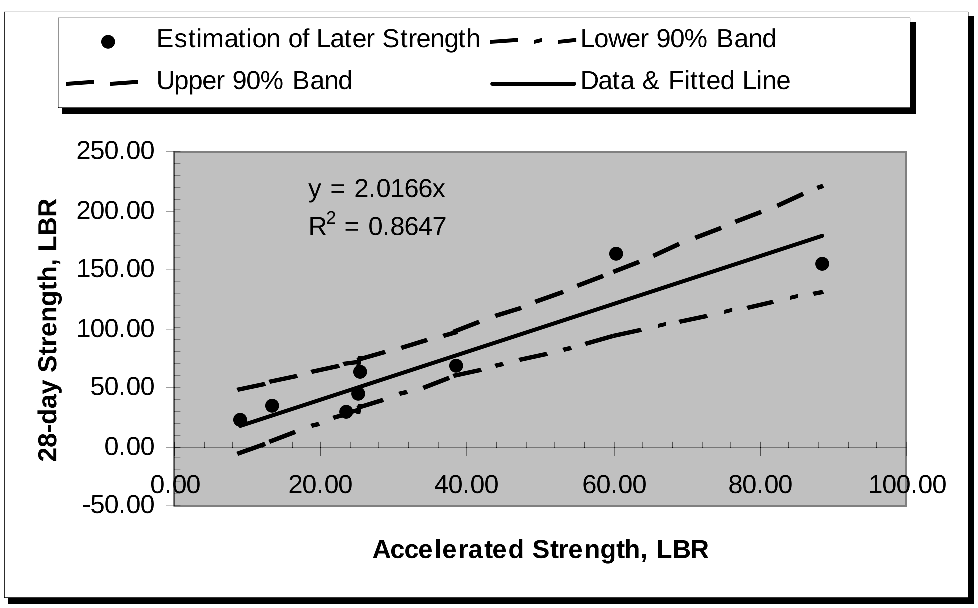

Figure 9.1 Confidence Bands for the Estimated 28-day Strength – Excavatable Mixes Oven Dried for Two Days

9.4.2 Confidence band for regression line

Because of the uncertainties in the estimates of the slope and the intercept of the line, there will be uncertainty when the line is used to estimate the average standard-cured strength from a measured accelerated strength. This uncertainty may be expressed by constructing the 90% confidence band for the line (*9*, *13*). This band is obtained by calculating Y for selected values of X_i using the equation of the line and plotting $Y_i \pm W_i$, versus X_i. The term W_i is the half-width of the confidence band at X_i and is given by the following equation:

$$W_i = S_e \sqrt{2F} \sqrt{\frac{1}{n} + \frac{\left(X_i - \bar{X}\right)^2}{S_{xx}}} \tag{9.12}$$

where:
- S_e = residual standard deviation for the best-fit line, (Equation 9.8)
- F = value from F-distribution table for 2 and n-2 degrees of freedom and significance level 0.10,
- n = number of data points used to establish regression line,
- X_i = selected value of accelerated strength, and
- $\bar{X}$ = grand average value of accelerated strength for all data used to establish the regression line.

The third column in Table 9.1 lists the estimated average 28-day strengths for the accelerated strengths in Column 1. The value of W_i at each value X_i is listed in the fourth column of Table 9.1. Finally, Columns 5 and 6 list the values of the lower and upper 90% confidence limits, which are shown in Figure 9.1. Note the width of the confidence band is narrowest when X_i equals $\bar{X}$, because the second term under the square root sign in Equation 9.12 equals zero.

9.5 Estimate of Later-age Strength

Suppose that the average accelerated strength of two LBR samples made in the lab from similar flowable fill is 24 LBR. From the regression equation, the estimated average 28-day, standard-cured strength is 50.2 LBR. If the accelerated strength was known without error, the 90% confidence interval for the average 28-day strength would be 29.44 to 70.99 LBR (see the bottom of Table 9.1). However, the accelerated strength has an uncertainty that is described by the within-batch standard deviation, which can be estimated from the differences between the accelerated strengths of pairs of LBR oven samples (*14*). Assume that the strengths measured on a flowable field mixture by the specific accelerated test method have a within-batch coefficient of variation (C.O.V) of 3.0%. Therefore, the standard deviation, *s*, at an average strength of 24.0 LBR is 0.72 LBR. The 90% confidence interval for the average accelerated strength of the two LBR samples is as follows:

$$24.0 \pm Z_{0.05} \frac{s}{\sqrt{2}} = 24.0 \pm 1.645 \times 0.72 \times 0.707$$

$$= 24.0 \pm 0.84 \text{ LBR} \tag{9.13}$$

where $Z_{0.05}$ is the value from the standard normal distribution corresponding to 5% of the area under the curve. Thus, the 90% confidence interval for the average accelerated strength is 23.16 to 24.84 LBR. Projecting the limits of this interval to the lower and upper confidence bands of the regression line results in 27.5 to 72.4 LBR for the approximate 90% confidence interval for the average standard-cured, 28-day strength. Each different measurement of accelerated strength produces a new confidence interval for the average 28-day strength.

9.6 Analysis on Other Samples

Regression analysis was also performed on the remaining excavatable oven-dried (i.e., 4-day, 8-day) samples. Figures 9.2 and 9.3 show the accelerated strength plotted against the 28-day strength (LBR) regression graphs along with partial regression analysis output. At 4 days of oven curing, the correlation between accelerated strength and 28-day strength is fairly good (Figure 9.2). The accelerated strength is approximately 85% (R-squared value, R^2) of the 28-day strength in LBR. The 8-day oven-curing plots show poor correlation between accelerated strength and 28-day strength. The coefficient of determination, R^2, at 54.5% was lower for the previous two oven-curing durations. In many cases, the 8-day oven-curing LBR samples showed a tremendous increase in the accelerated strength gained.

Figures 9.4 through 9.6 show the analysis of the accelerated strength plots against the 28-day strength of the excavatable accelerated samples for various oven-curing durations. Unlike the excavatable un-accelerated analysis plot which showed promising results, the excavatable accelerated regression analysis shows poor results in correlation. The coefficient of determination, respectively, for the 2-day, 4-day and 8-day oven-drying durations, was 62.9%, 0, and 0.05. It is clear that the accelerated strength in LBR of the 4-day and 8-day oven samples provide a modest correlation for predicting the 28-day strength. This was evident in their plot. The plots for the 4- and 8-day curing showed scattered data points with a decreasing slope.

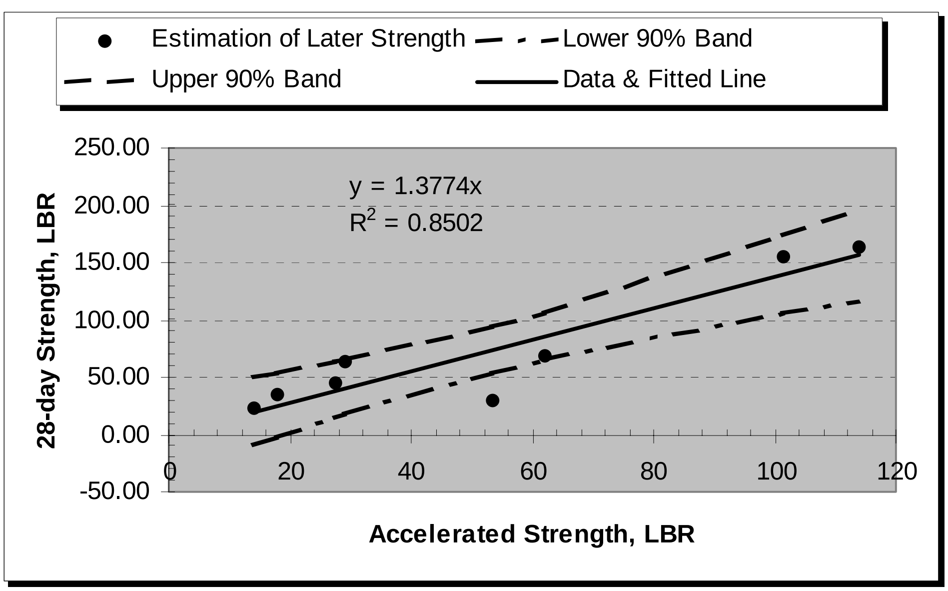

Figure 9.2 Confidence Bands for the Estimated 28-day Strength – Excavatable Mixes Oven Dried for Four Days

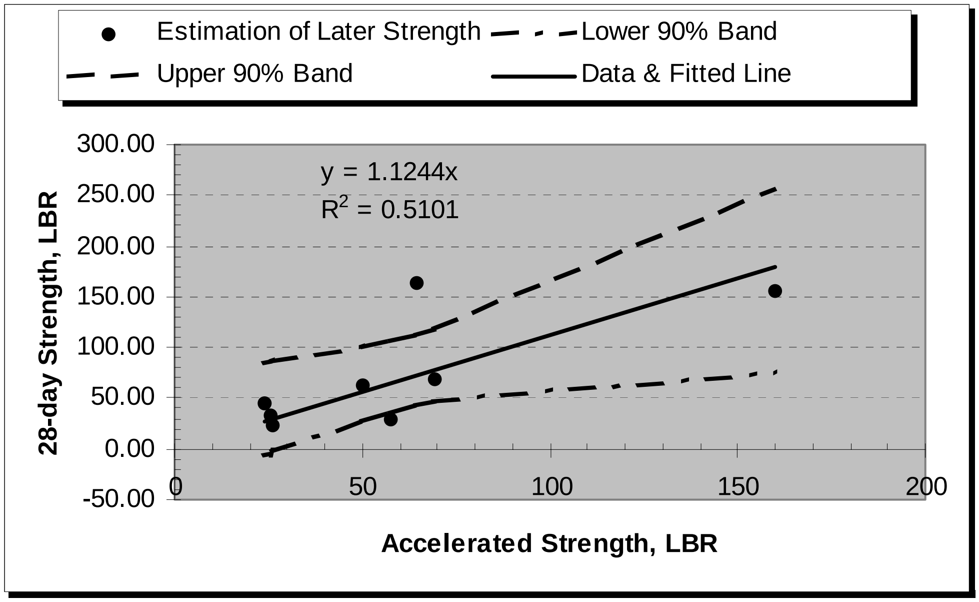

Figure 9.3 Confidence Bands for the Estimated 28-day Strength – Excavatable Mixes Oven Dried for Eight Days

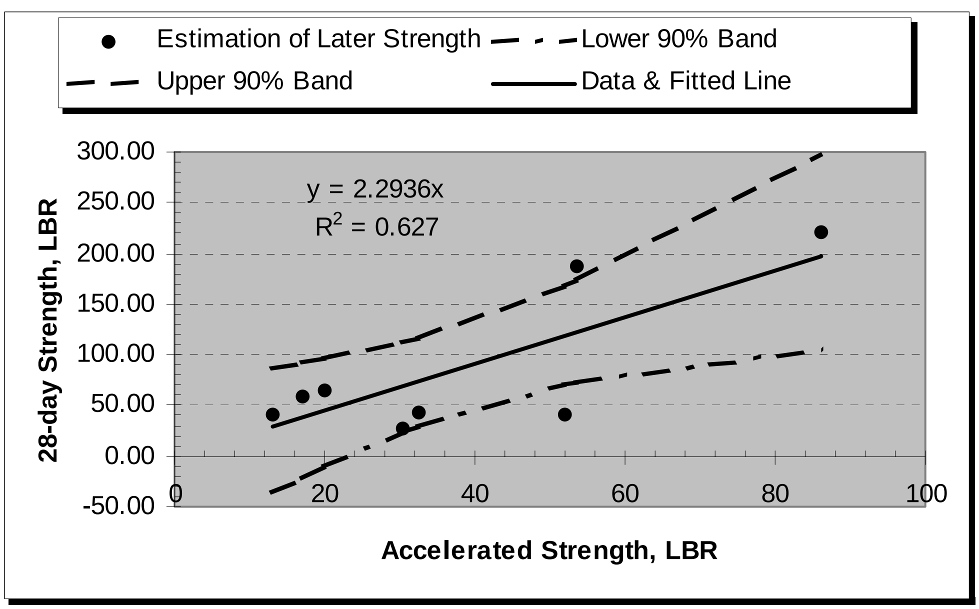

Figure 9.4 Confidence Bands for the Estimated 28-day Strength – Excavatable Accelerated Mixes Oven Dried for Two Days

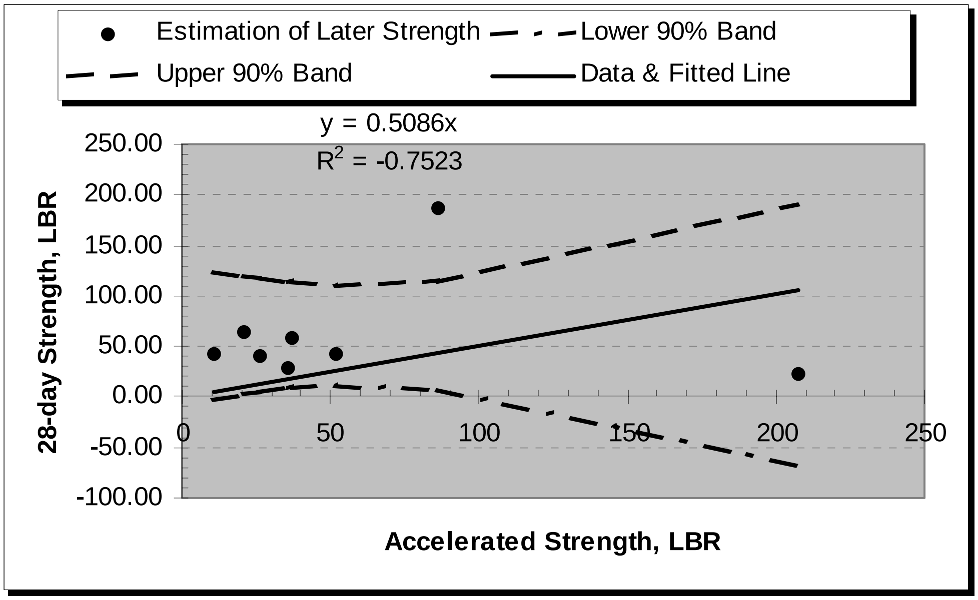

Figure 9.5 Confidence Bands for the Estimated 28-day Strength – Excavatable Accelerated Mixes Oven Dried for Four Days

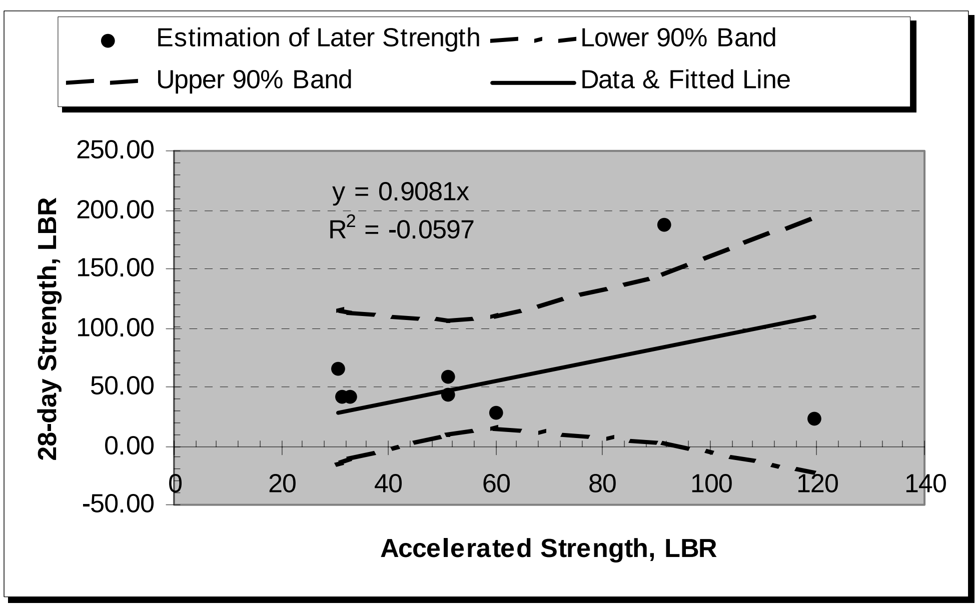

Figure 9.6 Confidence Bands for the Estimated 28-day Strength – Excavatable Accelerated Mixes Oven Dried for Eight Days

Continued curing in the oven showed no deterioration of samples. For most of the curing period, the integrity of the samples was not impacted and no damage caused to samples. Samples were strong enough to withstand stress during testing which is an indication that no damage existed internally. The 2-day and 4-day oven-curing durations gave the most encouraging results.

As the regression equation is used on a project, companion cylinders should be prepared along with cylinders for accelerated testing. The companion cylinders would be subjected to standard curing and tested for compressive strength at the designated age. The measured standard-cured strengths should be compared with the confidence intervals for the estimated strengths based on the companion accelerated strengths. If the measured strengths constantly fall outside the estimated confidence intervals, the reliability of the regression line should be questionable. The new companion results should be added to the data set from the laboratory correlation testing to calculate a new regression line and its corresponding statistics. This new line should be used for later estimates of potential later-age strength. The making of companion sets of accelerated and standard-cured cylinders should be continued until the measured strengths continue to fall within the corresponding calculated confidence intervals. Once the reliability of the procedure has been demonstrated, companion cylinders should be made at random intervals to reconfirm that the procedure continues to be reliable.

10. STATISTICAL ANALYSIS

10.1 Introduction

The data were statistically analyzed to determine if the contractor's field data and the laboratory readings complied with FDOT specifications for the pertinent mix design. This was performed for unit weight, air content, and compressive strength. Another reason for the analysis was to compare the contractor provided data with that of the laboratory measurements. More importantly, the analysis was done to establish relationships between the LBR and penetrometer readings to help ascertain the strength of the underlying mix in the field. Details of the analysis are presented in the following sections.

10.2 Unit Weight

The unit weights of samples produced and tested in the laboratory for various flowable fill mixes were measured using the procedure defined in ASTM D6023-02. These were included along with the contractor-provided data for the unit weights of similar design mixes as used by the contractors. The FDOT specifications for unit weights are also included in the table. The data were arranged separately for each design mix in Tables 10.1 through 10.4.

Table 10.1 Unit Weights for Excavatable Non-accelerated Design Mix

District	Unit Wt. (lb/ft^3) Laboratory	Unit Wt. (lb/ft^3) Contractor	Unit Wt. (lb/ft^3) Specified by FDOT
1	113.60	124.19	90-110
2	110.40	98.3	90-110
4&6	119.79	109	90-110
5	109.60	109.8	90-110

Table 10.2 Unit Weights for Excavatable Accelerated Design Mix

District	Unit Wt. (lb/ft^3) Laboratory	Unit Wt. (lb/ft^3) Contractor	Unit Wt. (lb/ft^3) Specified by FDOT
1	111.60	NA	90-110
2	116.40	NA	90-110
4&6	120.00	NA	90-110
5	115.60	NA	90-110

NA = Not available

Table 10.3 Unit Weights for Non-excavatable Non-accelerated Design Mix

District	Unit Wt. (lb/ft^3) Laboratory	Unit Wt. (lb/ft^3) Contractor	Unit Wt. (lb/ft^3) Specified by FDOT
1	132.40	123.07	100-125
2	119.60	100.9	100-125
4&6	125.80	125	100-125
5	120.85	123.44	100-125

Table 10.4 Unit Weights for Non-excavatable Accelerated Design Mix

District	Unit Wt. (lb/ft^3) Laboratory	Unit Wt. (lb/ft^3) Contractor	Unit Wt. (lb/ft^3) Specified by FDOT
1	130.20	NA	100-125
2	117.80	NA	100-125
4&6	129.40	NA	100-125
5	120.20	NA	100-125

The data depicts a high degree of variability among different mix designs. This is primarily due to the fact the districts are not targeting any specific value for the unit weight, but rather trying to fall somewhere within the FDOT specified range. The unit weight for a majority of the districts falls out of the FDOT specified range for both excavatable as well as non-excavatable design mixes.

10.3 Air Content

The data for the air content for various design mixes are shown in Tables 10.5 through 10.8.

Table 10.5 Air Content for Excavatable Non-accelerated Design Mix

District	Air Content (%) Laboratory	Air Content (%) Contractor	Air Content (%) Specified by FDOT
1	13.00	9	5-35
2	23.00	25	5-35
4&6	7.90	NA	5-35
5	12.00	NA	5-35

Table 10.6 Air Content for Excavatable Accelerated Design Mix

District	Air Content (%) Laboratory	Air Content (%) Contractor	Air Content (%) Specified by FDOT
1	16.00	NA	5-35
2	10.50	NA	5-35
4&6	14.50	NA	5-35
5	7.10	NA	5-35

Table 10.7 Air Content for Non-excavatable Non-accelerated Design Mix

District	Air Content (%) Laboratory	Air Content (%) Contractor	Air Content (%) Specified by FDOT
1	4.50	8.5	5 – 15
2	9.50	25	5 – 15
4&6	19.00	NA	5 – 15
5	5.00	NA	5 – 15

Table 10.8 Air Content for Non-excavatable Accelerated Design Mix

District	Air Content (%) Laboratory	Air Content (%) Contractor	Air Content (%) Specified by FDOT
1	5.40	NA	5 – 15
2	14.00	NA	5 – 15
4&6	3.90	NA	5 – 15
5	4.70	NA	5 – 15

It can be seen in Tables 10.5 through 10.8 that a high degree of variability exists among data for different mix designs. Again, this is primarily due to the fact that different districts are not targeting any specific value for the air content, but rather trying to fall somewhere within the FDOT specified range. However, it may be noted that air content for a majority of the districts falls within the FDOT specified range for both excavatable as well as non-excavatable design mixes.

10.4 Compressive Strength

The data for the compressive strength is given in Tables 10.9 through 10.12. Except for Districts 2 and 5, the compressive strength falls above the FDOT specified range for excavatable mixes. For the non-excavatable mixes, the compressive strength does comply with the FDOT range, but its value may be considered too high.

Table 10.9 Compressive Strength of Excavatable Non-accelerated Mix at 28 days

District	Compressive Strength (lb/in^2), Lab–Undrained	Compressive Strength (lb/in^2), Field	Desired Compressive Strength (lb/in^2)
1	273.04	NA	Less than 100 psi
2	40.89	NA	Less than 100 psi
4&6	NA	NA	Less than 100 psi
5	81.74	NA	Less than 100 psi

Table 10.10 Compressive Strength of Excavatable Accelerated Mix at 28 days

District	Compressive Strength (lb/in^2), Lab–Undrained	Compressive Strength (lb/in^2), Field	Desired Compressive Strength (lb/in^2)
1	394.14	NA	Less than 100 psi
2	36.98	1603.70	Less than 100 psi
4&6	NA	NA	Less than 100 psi
5	NA	NA	Less than 100 psi

Table 10.11 Compressive Strength of Non-excavatable Non-accelerated Mix at 28 days

District	Compressive Strength (lb/in^2), Lab–Undrained	Compressive Strength (lb/in^2), Field	Desired Compressive Strength (lb/in^2)
1	4608.34	NA	More than 125 psi
2	412.50	NA	More than 125 psi
4&6	869.80	NA	More than 125 psi
5	919.94	NA	More than 125 psi

Table 10.12 Compressive Strength of Non-excavatable Accelerated Mix at 28 days

District	Compressive Strength (lb/in^2), Lab–Undrained	Compressive Strength (lb/in^2), Field	Desired Compressive Strength (lb/in^2)
1	4309.77	NA	More than 125 psi
2	451.20	NA	More than 125 psi
4&6	887.10	NA	More than 125 psi
5	1059.60	NA	More than 125 psi

10.5 Relating LBR to Penetrometer Data

Most of the regression analysis performed with the original lab data for the LBR and penetrometer did not render a good value for the coefficient of determination. It was concluded that a major part of the variation in LBR readings was not catered to by the observed values of the penetrometer. Also, the residual graphs did not seem to be consistent with the underlying assumptions for estimating the regression parameters. Improvement was needed, therefore, in these two aspects of the analysis. While it might have helped to obtain more data and re-do the analysis to improve the residual graphs and the coefficient of determination, time constraints prohibited this. To achieve the objective, the data was transformed to get better results. The different transformations used included taking the natural logarithm, logarithm to the base 10, inverse and square root of the data. Different combinations were used, which included transforming the LBR readings exclusively, transforming the penetrometer readings exclusively, and then transforming both the LBR and penetrometer readings. The combination that gave the best results for the coefficient of determination was selected for the case in point and then other pertinent values were checked to ascertain the adequacy of the regression model. The mean squared error was also checked and compared with that of the original un-transformed case. Further improvement in the analysis was pursued through removal of unusual data. The unusual observation data were removed to further enhance the analysis and the coefficients of determination. These unusual observations are the outliers obtained from LBR and Proctor penetrometer test results. Due to the nature of the study, no clear reasons exist for explaining the existence of unusual observation in our study. A possible reason could be the use of various operators to perform the LBR and penetrometer testing for the study. As a result of not having a single exclusive operator performing the required testing for the samples, variability was thus introduced into the test results. A summary of the analysis for specific design mixes is provided below.

10.5.1 Excavatable accelerated mix

The results for the regression analysis carried out for this particular mix can be seen in Table 10.13. A variety of transformations were performed to cater for the non-linearity that may have been associated with the original data. The results depict that inverting the original values for the LBR and penetrometer readings gave the best value for the coefficient of determination (R^2) at 69.2%. But when the residual plots were observed, they were not very encouraging. Hence, the next best value for the coefficient of determination, 59.1%, obtained with the logarithmic transformation, was considered. While this transformation gave better results in terms of the coefficient of determination and improved the residual plots somewhat, most of the individual errors and the overall mean square error were not improved. In fact, they became worse. Detailed data for the residuals for excavatable accelerated mix are presented in Table 10.14.

A graphical representation, in a comparative context, for the errors corresponding to the original data as well as various transformations is shown in Figure 10.1. The data is plotted against the run order. Keeping this error analysis in view, the transformation could not be adopted due to a high level of error. The unusual observations were then removed from the original data. For doing this, the unusual observations suggested by MINITAB (a widely used statistical analysis software), as well as those that were thought to be recorded in unusual conditions were taken into account. The unusual observations that were identified and removed

Table 10.13 Regression Analysis Results for Excavatable Accelerated Mix

Type of Transformation	Equation	S	R-Sq	F(R)	P(R)	T(C)	P(C)	T(PEN)	P(PEN)
No Transformation*	LBR = 27.2 + 0.0281 PEN	63.55	22.2%	10.86	0.002	2.11	0.042	3.29	0.002
Log(LBR) Log(PEN)	Log(LBR) = - 1.11 + 0.931 Log(PEN)	0.4399	59.1%	54.85	0.000	-3.26	0.002	7.41	0.000
Sq(LBR) Sq(PEN)	Sq(LBR) = 2.27 + 0.149 Sq(PEN)	3.275	38.5%	23.77	0.000	2.40	0.021	4.88	0.000
Inv(LBR) Inv(PEN)	Inv(LBR) = - 0.0941 + 60.5 Inv(PEN)	0.1853	69.2%	85.52	0.000	-2.30	0.027	9.25	0.000
Original with Unusual Observa-tions Removed	LBR = - 0.51 + 0.0594 PEN	27.86	79.8%	122.2	0.000	-0.08	0.934	11.06	0.000

* No Transformation: The row presents the analysis results for original untransformed data.

Note: S: Standard deviation of the overall observations
F(R): F-statistic for regression
P(R): P-value for the F-statistic for regression
T(C): t-statistic for intercept in regression equation
P(C): P-value for the t-statistic for intercept in regression equation
T(PEN): t-statistic for slope in regression equation
P(PEN): P-value for the t-statistic for slope in regression equation

Table 10.14 Residuals Data for Excavatable Accelerated Mix

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
13.50	113.63	16.89	7.09	1.38	11.21	7.26
1.00	102.63	29.08	4.82	13.28	1.01	4.58
1.00	86.50	28.63	3.96	12.35	0.65	3.62
1.72	69.00	27.41	2.29	10.57	0.45	1.85
15.50	158.66	16.16	6.70	1.69	12.01	6.56
8.50	301.50	27.18	7.39	15.10	0.88	8.89
10.00	152.67	21.49	1.56	6.90	6.69	-
16.00	158.16	15.65	7.28	1.17	12.53	7.11
235.50	363.75	198.06	216.56	209.34	221.66	-
26.50	551.88	16.23	1.41	6.83	38.01	5.76
28.00	227.75	5.61	15.75	7.56	22.17	14.9
30.50	365.51	6.98	11.48	4.27	16.51	9.30
231.50	1138.75	172.25	176.69	178.39	255.89	-
22.50	943.75	31.26	23.50	24.46	55.83	33.03
37.50	611.88	6.92	6.77	1.97	170.83	1.67
50.00	631.25	5.03	18.36	13.78	538.23	13.02
221	2507.50	123.22	106.68	126.07	235.28	72.61
58.50	2227.50	31.39	43.87	28.23	73.42	-
43.00	1246.50	19.28	16.62	13.82	64.92	30.50
28.00	1218.75	33.50	30.38	27.93	50.47	43.85
256.50	3863.65	120.50	85.49	123.16	269.23	27.59
47.00	4566.25	108.71	152.80	105.67	59.36	-
61.00	3829.55	73.98	108.58	71.38	73.77	-
36.50	2545.00	62.32	79.40	59.52	50.70	-
8.83	94.00	21.01	3.46	4.95	7.01	3.76
1.00	64.63	28.01	2.786	11.02	0.18	2.32
1.00	71.63	28.21	3.16	11.46	0.33	2.74

Table 10.14 – continued

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
1.00	72.63	28.24	3.22	11.52	0.35	2.80
36.00	252.25	1.70	22.53	14.48	29.18	21.53
20.00	266.25	14.69	5.84	2.11	12.49	4.69
13.50	150.34	17.93	5.18	3.28	10.25	5.08
51.00	247.25	16.84	37.78	29.71	44.35	36.8
141.50	353.25	104.35	123.07	115.76	128.56	-
23.50	315.38	12.57	6.92	0.68	13.27	5.28
23.00	234.00	10.78	10.44	2.28	16.92	9.61
20.00	345.07	16.91	1.97	5.40	7.69	0.01
187.50	2467.50	90.85	74.88	93.73	201.86	41.49
65.00	2570.00	34.53	51.97	31.74	79.16	87.09
41.00	1243.75	21.20	18.49	15.73	62.97	32.34
41.50	1220.00	20.03	16.93	14.48	63.97	30.43

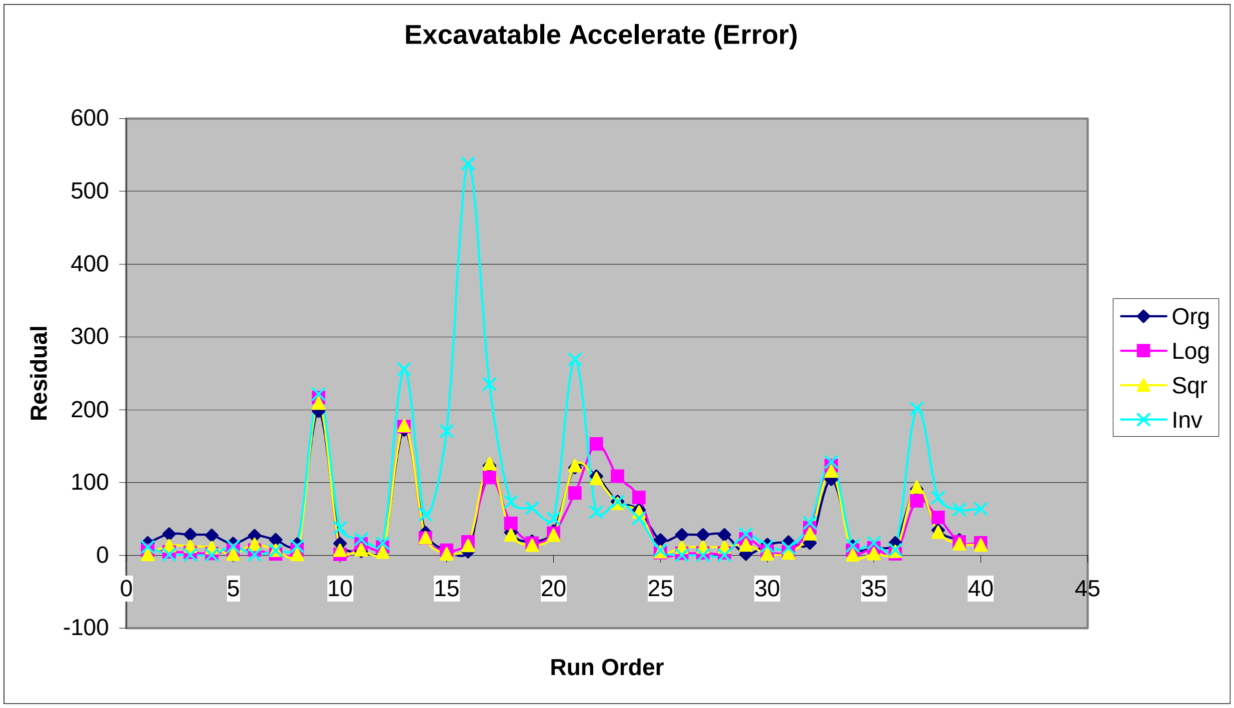

Figure 10.1 Comparative Error Plots for Different Transformations vs. Run Order for Excavatable Accelerated Mix

for the purpose of analysis can be found in Table 10.15. After removing these observations and rerunning the analysis, better values of coefficient of determinations, as well as better mean squared errors with acceptable residual plots, were obtained. A summary of the mean square errors, as well as the coefficient of determination for the original data and the transformations, is given in Table 10.16. The regression plots for the original data, one including unusual observations and one with them removed, are shown in Figures 10.2 and 10.3, respectively. It can be seen that the coefficient of determination has improved to 79.8%. At the 95% confidence interval, total observations being 33, the reference *t* statistic value is 2.042. The comparison with the *t* value for the slope, 11.06, indicates that the value lies far into the critical region. It is therefore safe to conclude that the values for the LBR are strongly linked to the values obtained

Table 10.15 Unusual Observations – Excavatable Accelerated Mix

Mix Type	District	Curing Time	LBR	PEN
Drained	1	7 days	235.50	363.75
Drained	1	14 days	231.50	1138.75
Drained	2	28 days	58.50	2227.5
Drained	2	90 days	47.00	4566.25
Drained	4&6	90 days	61.00	3829.54
Drained	5	90 days	36.50	2545.0
Undrained	1	7 days	141.50	353.25

Table 10.16 Summary of Mean Squared Error and Coefficient of Determination for Excavatable Accelerated Mix

	Original	Log Transformation	Sqrt Transformation	Inv Transformation	Original with Unusual Observations Removed
Mean Square Error	61.94	65.04	62.25	129.04	27.42
R^2	22.2%	59.1%	38.5%	69.2%	79.8%

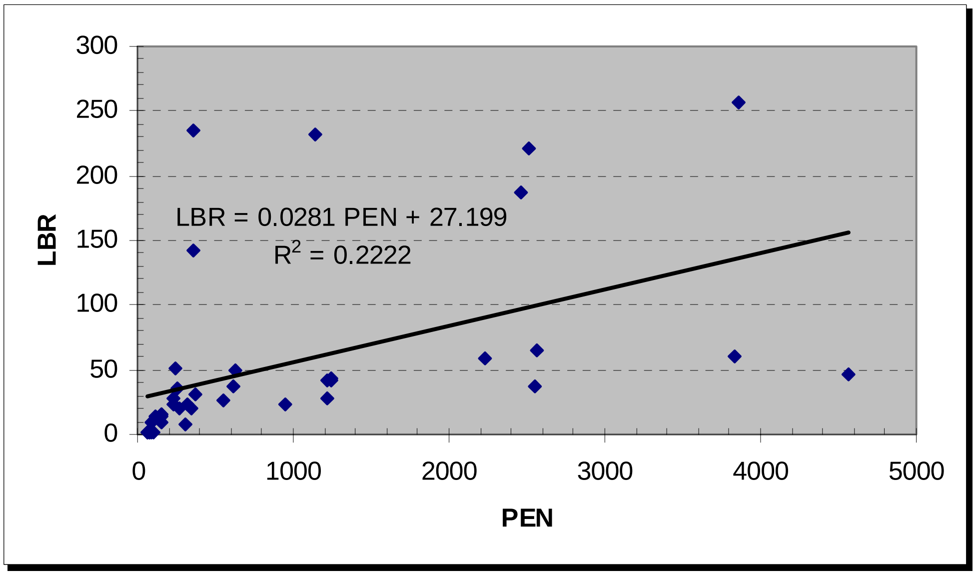

Figure 10.2 Regression Plot Including Unusual Observations for Excavatable Accelerated Mix

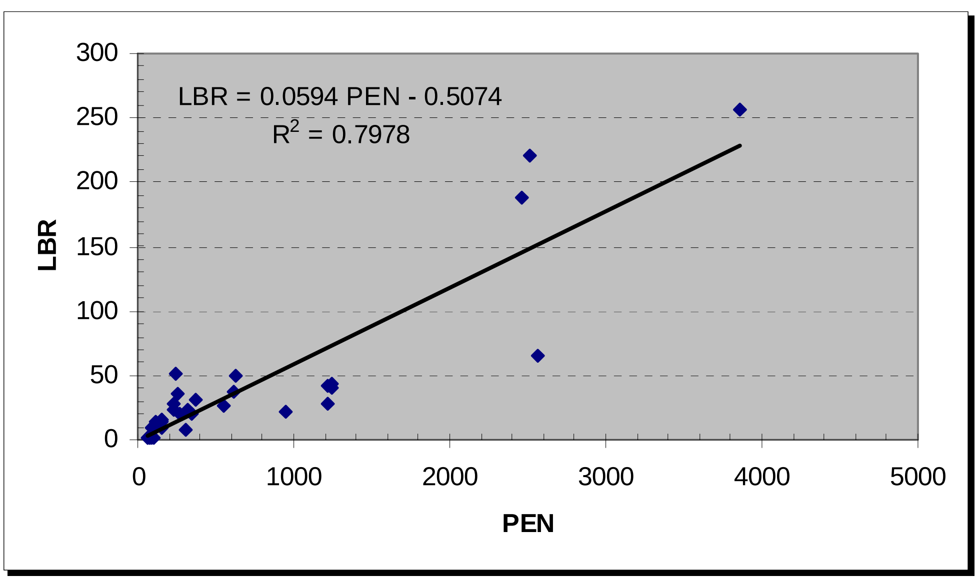

Figure 10.3 Regression Plot After Removing Unusual Observations for Excavatable Accelerated Mix

from the penetrometer and that their relationship is somewhat linear. The residual plots for this analysis can be seen in Figures 10.3 through 10.6. The plots comply with the underlying assumptions for the regression analysis.

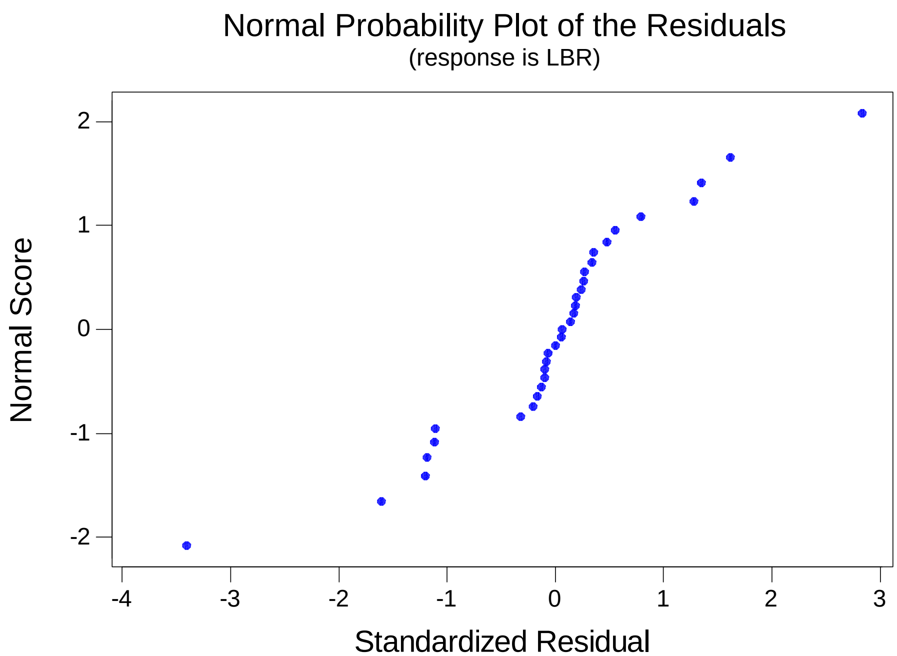

Figure 10.4 Normal Probability Plot for Excavatable Accelerated Mix

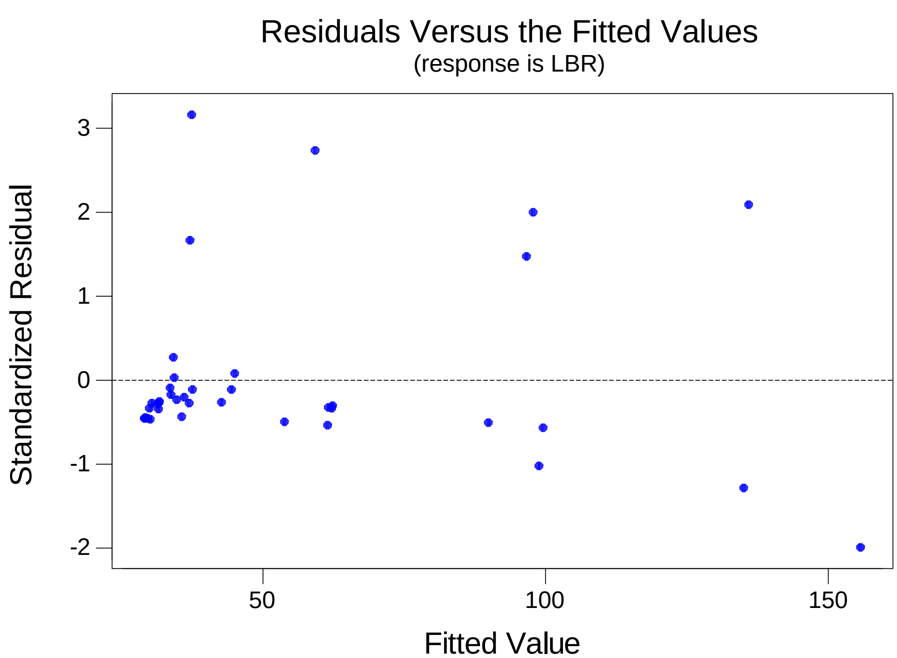

Figure 10.5 Residuals vs. Fitted Values Plot for Excavatable Accelerated Mix

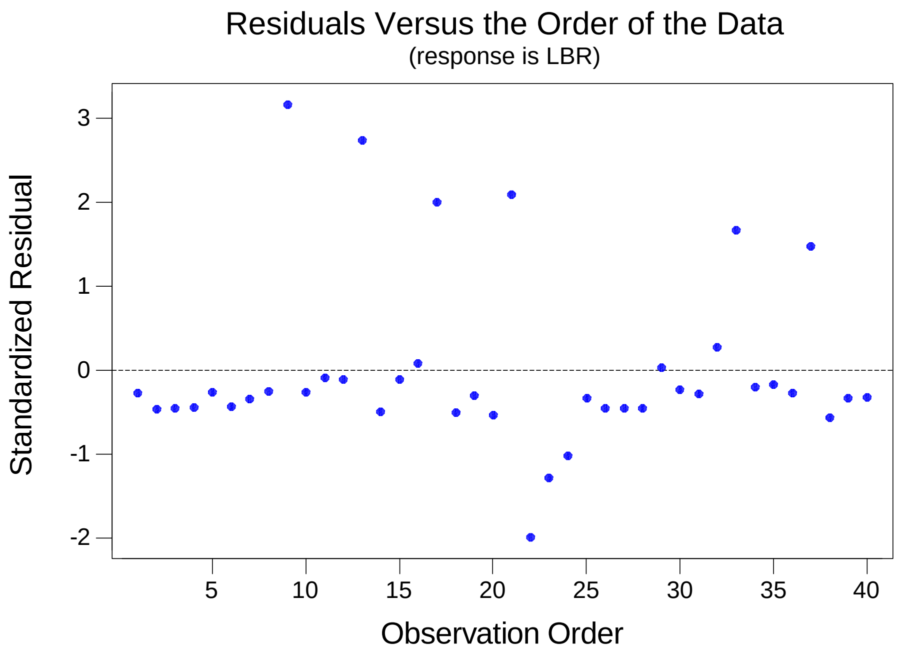

Figure 10.6 Residuals vs. Order of the Data Plot for Excavatable Accelerated Mix

10.5.2 Excavatable non-accelerated mix

The results for the regression analysis carried out for this particular mix can be seen in Table 10.17. Transformations were performed in a manner similar to the ones discussed for the earlier mix. Taking the logarithm to the base 10 for the original values for the LBR and penetrometer readings gave the best value for the coefficient of determination at 69.9%. The residual plots for this case also looked somewhat better than the other alternatives. However, the individual errors and the mean squared error were worse than the original case. Refer to Table 10.18 and Figure 10.7 to see the error trends. Keeping this error analysis in view, the logarithmic transformation was rejected. The unusual observations from the original data were removed to improve the results by following the same guidelines as for the previous case. Refer to Table 10.19 for these unusual observations. After removing these observations and rerunning the analysis, a better coefficient of determination, 72.9%, as well as better mean squared errors with acceptable residual plots, were obtained. The summary of observations in this regard can be seen in Table 10.20. Figures 10.8 and 10.9 show regression plots for original data with unusual observations included and with them removed, respectively. The *t* statistic value, 2.042, when compared with the *t* value for the slope, 8.99, proved the significance of regression at 95% confidence. This was also confirmed through the corresponding *F*-statistic, 4.17, when compared to *F*-value for regression, 80.81. The corresponding *P*-values for both the statistics were also very low. The residual plots for this analysis can be seen in Figures 10.10 through 10.12. These plots do validate, while not perfectly, the underlying assumptions for regression analysis.

Table 10.17 Regression Analysis Results for Excavatable Non-accelerated Mix

Type of Transformation	Equation	S	R-Sq	F(R)	P(R)	T(C)	P(C)	T(PEN)	P(PEN)
No Transformation	LBR = 23.8 + 0.0207 PEN	41.08	32.7%	18.47	0.00	2.69	0.011	4.30	0.000
Log(LBR) Log(PEN)	Log(LBR) = - 1.13 + 0.908 Log(PEN)	0.36	69.9%	88.37	0.00	-4.15	0.000	9.40	0.000
Sq(LBR) Sq(PEN)	Sq(LBR) = 2.09 + 0.134 Sq(PEN)	2.49	51.5%	40.30	0.00	2.79	0.008	6.35	0.000
Inv(LBR) Inv(PEN)	Inv(LBR) = - 0.0271 + 42.8 Inv(PEN)	0.13	69.8%	87.76	0.00	-0.96	0.34	9.37	0.000
Original with Unusual Observa- tions Removed	LBR = 6.10 + 0.0437 PEN	25.29	72.9%	80.81	0.00	1.02	0.31	8.99	0.000

Note: S: Standard deviation of the overall observations
F(R): F-statistic for regression
P(R): P-value for the F-statistic for regression
T(C): t-statistic for intercept in regression equation
P(C): P-value for the t-statistic for intercept in regression equation
T(PEN): t-statistic for slope in regression equation
P(PEN): P-value for the t-statistic for slope in regression equation

Table 10.18 Residuals Data for Excavatable Non-accelerated Mix

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
1.66	112.38	24.42	3.68	10.64	1.16	9.34
1.12	78.13	24.26	2.72	9.58	0.79	8.39
1.00	82.50	24.47	3.04	9.92	1.03	8.71
2.79	103.63	23.12	2.18	9.13	0.19	7.84
14.00	242.75	14.78	3.22	3.45	7.29	2.71
13.00	471.88	20.52	6.71	12.03	2.74	13.73
7.00	148.16	19.83	0.11	6.83	3.17	5.58
12.00	140.66	14.67	5.43	1.52	8.38	0.25
92.00	601.25	55.80	67.43	63.07	69.27	59.61
52.50	1062.50	6.76	11.29	10.72	23.83	0.05
24.50	1210.00	24.28	21.85	21.15	97.45	34.49
48.00	606.50	11.69	23.24	18.91	24.95	15.38
176.50	1041.38	131.20	136.04	135.29	104.55	-
70.50	2537.50	5.72	20.32	7.82	167.58	46.52
35.50	571.88	0.09	12.02	7.44	14.53	4.39
75.00	1220.00	26.01	28.29	29.08	51.58	15.56
155.50	2422.50	81.65	68.42	79.89	260.76	43.49
68.00	3671.25	31.65	59.02	36.48	132.51	-
29.00	1251.25	20.63	18.79	17.73	113.85	31.80
63.50	2455.00	11.01	24.64	12.87	166.59	49.92
182.00	3659.00	82.59	55.35	77.79	246.93	15.94
94.00	5200.00	37.25	80.26	44.50	146.91	-
58.50	3598.40	39.65	66.23	44.33	124.28	-
82.00	3738.65	19.05	47.15	24.00	145.69	-
2.22	80.63	23.20	1.73	8.60	0.24	7.39
2.04	79.13	23.36	1.85	8.71	0.09	7.52
2.00	68.63	23.18	1.42	8.22	0.32	7.10

Table 10.18 – continued

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
2.41	58.00	22.55	0.52	7.24	1.00	6.22
52.50	367.50	21.13	36.78	30.70	41.28	30.33
16.50	496.88	17.54	4.15	9.29	0.47	11.32
34.50	140.33	7.82	27.94	20.97	30.89	22.26
29.00	338.87	1.77	14.40	8.22	18.90	8.08
97.00	580.63	61.22	73.19	68.68	75.49	-
52.00	1197.50	3.47	6.08	6.66	64.27	6.45
39.50	217.25	11.23	29.75	22.97	33.60	23.89
28.00	521.25	6.54	6.42	1.45	9.78	0.89
164.00	2442.50	89.74	76.25	87.92	268.16	51.12
44.50	3409.09	49.73	74.26	54.02	112.99	-
34.00	1182.50	14.21	11.40	10.93	77.11	23.79
23.00	2515.00	52.75	67.09	54.79	122.00	-

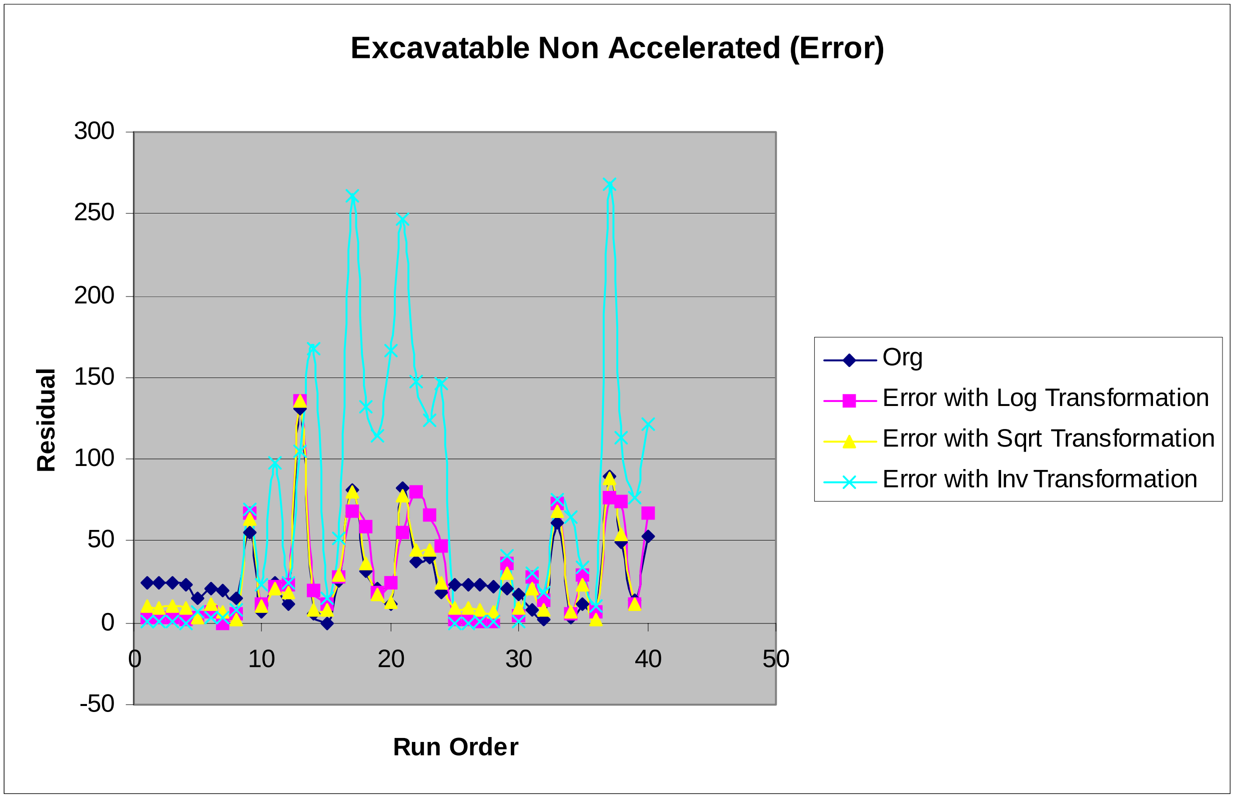

Figure 10.7 Comparative Error Plots for Different Transformations vs. Run Order for Excavatable Non-accelerated Mix

Table 10.19 Unusual Observations – Excavatable Non-accelerated Mix

Mix Type	District	Curing Time	LBR	PEN
Drained	1	14 days	176.5	1041.37
Drained	2	28 days	68.00	3671.25
Drained	2	90 days	94.00	5200.00
Drained	4&6	90 days	58.50	3598.40
Drained	5	90 days	82.00	3738.65
Undrained	1	7 days	97.00	580.62
Undrained	2	28 days	44.50	3409.09
Undrained	5	28 days	23.00	2515.00

Table 10.20 Summary of Mean Squared Error and Coefficient of Determination for Excavatable Non-accelerated Mix

	Original	Log Transformation	Sqrt Transformation	Inv Transformation	Original with Unusual Observations Removed
Mean Square Error	40.04	43.46	40.12	102.78	24.48
R^2	32.7%	69.9%	51.5%	69.8%	72.9%

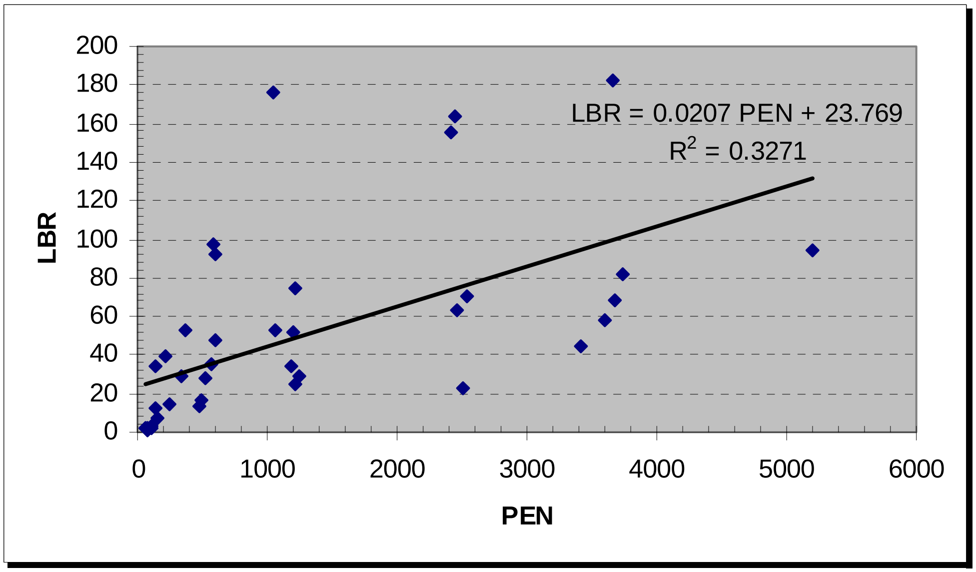

Figure 10.8 Regression Plot Including Unusual Observations for Excavatable Non-accelerated Mix

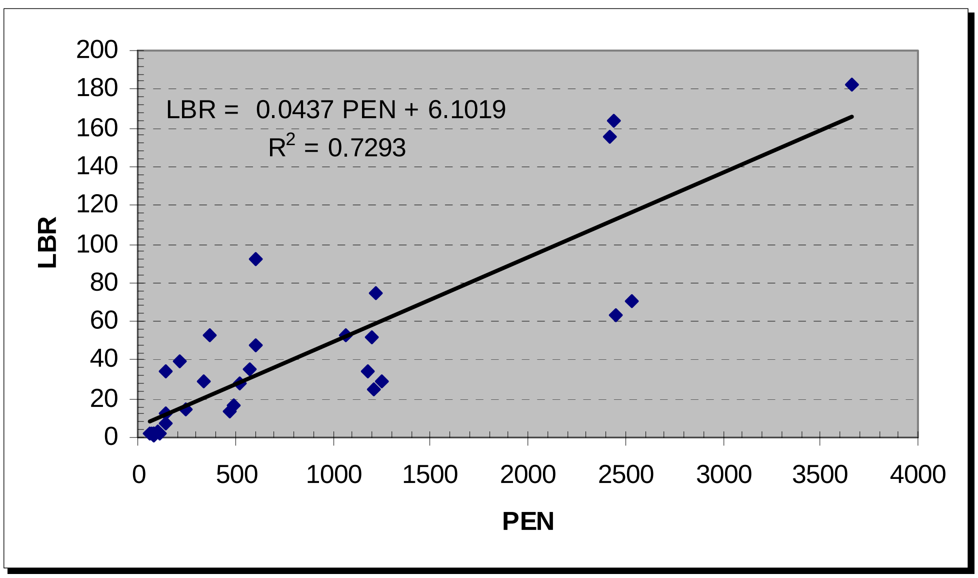

Figure 10.9 Regression Plot After Removing Unusual Observations for Excavatable Non-accelerated Mix

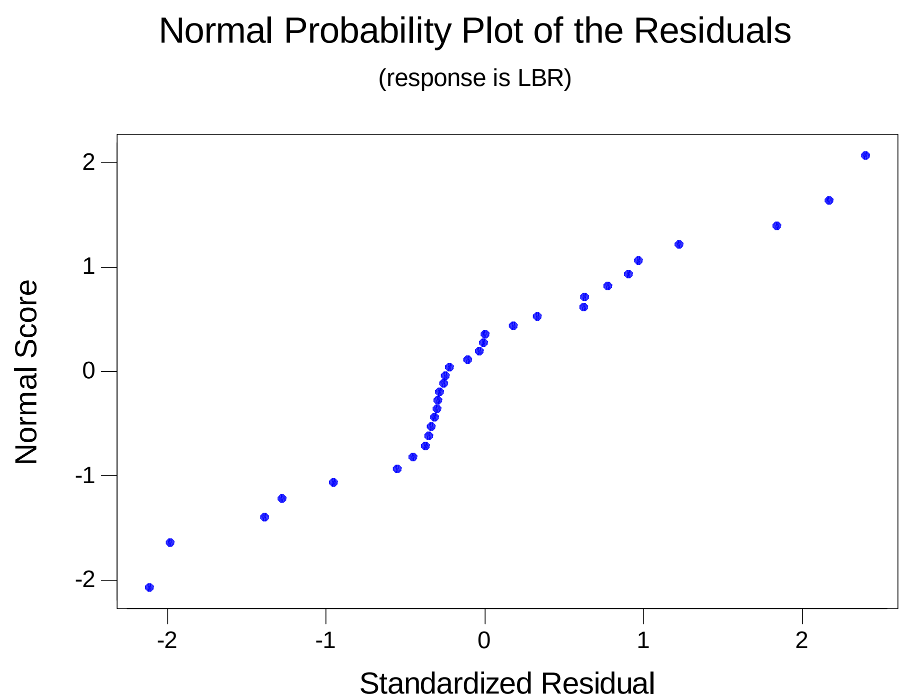

Figure 10.10 Normal Probability Plot for Excavatable Non-accelerated Mix

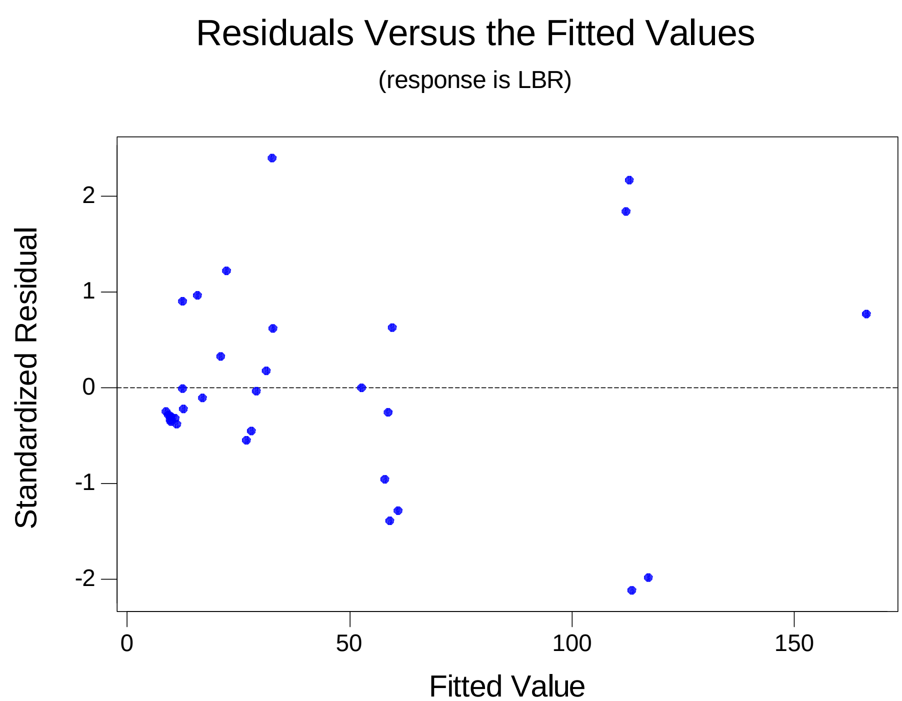

Figure 10.11 Residuals vs. Fitted Values Plot for Excavatable Non-accelerated Mix

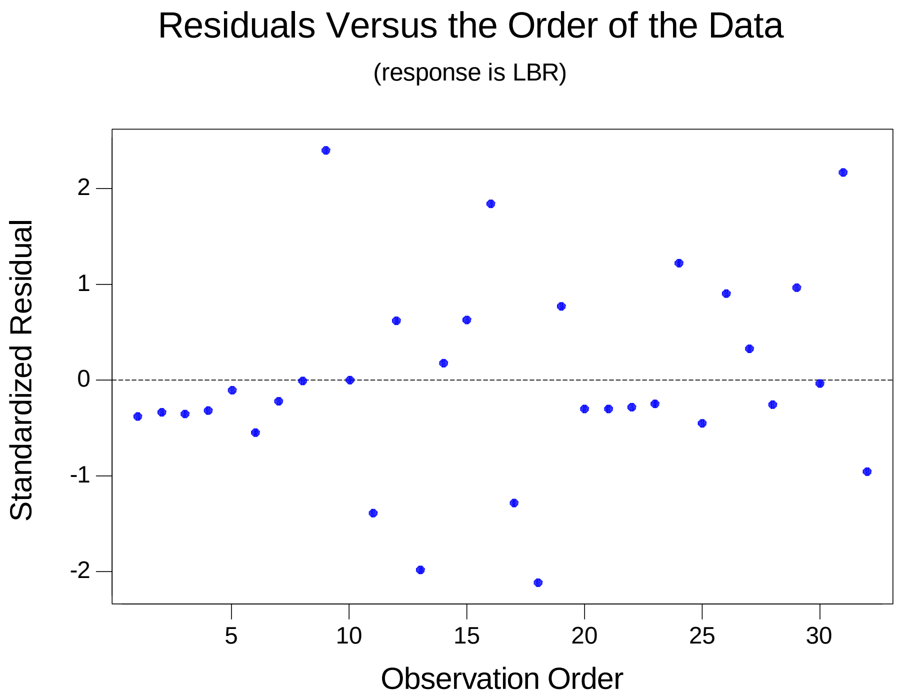

Figure 10.12 Residuals vs. Order of the Data Plot for Excavatable Non-accelerated Mix

10.5.3 Non-excavatable accelerated mix

The results for the regression analysis carried out for this particular mix can be seen in Table 10.21. Transformations were performed as discussed earlier. The square root transformation gave the best value for the coefficient of determination at 64.9%. The residual plots for this case looked almost the same as for the data without transformation. Hence, the small advantage that is achieved from the improvement in coefficient of determination value is not considered large enough to warrant switching to transformed responses. Also, the error terms for the squared case, as well as for other transformations, looked worse than the original case. Refer to Table 10.22 and Figure 10.13 for error trends. To further improve on the results, unusual observations were removed. See Table 10.23 for the observations removed. Table 10.24 gives a summary of the mean squared errors, as well as the coefficient of determination for the original data and the transformations. Improved coefficient of determination came to 84.5%, as can be seen in the regression plot shown with unusual observations included in Figure 10.14 and with them removed in Figure 10.15. The *F* (179.39) and *t* (13.39) statistics for regression and slope, respectively, validated the significance of regression at 95% confidence interval, with very low P-values for the respective statistic. The plots for residuals also looked good as can be seen in Figures 10.16 through 10.18.

Table 10.21 Regression Analysis Results for Non-excavatable Accelerated Mix

Type of Transformation	Equation	S	R-Sq	F(R)	P(R)	T(C)	P(C)	T(PEN)	P(PEN)
No Transformation	LBR = 75.7 + 0.0601 PEN	87.97	61.5%	60.64	0.000	3.80	0.001	7.79	0.000
Log(LBR) Log(PEN)	Log(LBR) = - 0.876 + 0.964 Log(PEN)	0.5005	60.0%	57.06	0.000	-2.29	0.027	7.55	0.000
Sq(LBR) Sq(PEN)	Sq(LBR) = 3.80 + 0.227 Sq(PEN)	3.841	64.9%	70.25	0.000	3.27	0.002	8.38	0.000
Inv(LBR) Inv(PEN)	Inv(LBR) = - 0.0317 + 37.7 Inv(PEN)	0.1919	28.7%	14.47	0.001	-0.79	0.436	3.80	0.001
Original with Unusual Observations Removed	LBR = 44.9 + 0.0688 PEN	56.23	84.5%	179.39	0.000	3.31	0.002	13.39	0.000

Note: S: Standard deviation of the overall observations
F(R): F-statistic for regression
P(R): P-value for the F-statistic for regression
T(C): t-statistic for intercept in regression equation
P(C): P-value for the t-statistic for intercept in regression equation
T(PEN): t-statistic for slope in regression equation
P(PEN): P-value for the t-statistic for slope in regression equation

Table 10.22 Residuals Data for Non-excavatable Accelerated Mix

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
0.00	114.00	82.58	12.75	38.76	3.34	52.72
22.50	109.63	59.82	10.21	15.68	19.29	29.91
11.00	120.5.00	71.97	2.45	28.61	7.44	42.16
1.00	116.75	81.74	12.05	38.12	2.43	51.90
33.50	315.90	61.22	0.56	27.88	22.09	33.13
19.00	331.13	76.63	16.64	43.90	6.83	48.66
117.00	173.33	30.84	97.89	70.89	111.62	60.19
73.50	378.04	24.95	33.00	6.03	58.81	2.60
214.50	1242.50	64.07	87.06	75.28	983.73	84.09
104.00	1132.50	39.81	12.54	26.80	521.00	18.83
275.62	258.00	184.38	247.60	220.16	266.89	-
211.00	1295.00	57.42	78.38	67.81	611.00	76.97
218.00	2532.50	9.97	35.10	13.61	277.52	1.21
227.50	2522.50	0.12	24.61	3.41	287.38	8.97
357.50	2600.00	125.47	97.90	121.26	415.63	133.64
399.00	2427.50	177.33	156.00	174.62	461.11	-
396.35	3924.24	84.71	10.33	71.88	441.59	81.33
230.95	3939.39	81.59	156.48	94.49	276.19	85.11
291.50	3939.39	21.04	95.93	33.94	336.74	24.56
399.50	3844.70	92.64	21.05	80.23	445.16	89.95
380.12	5195.00	7.90	125.69	26.01	421.10	22.37
356.04	5200.00	32.29	150.25	50.42	397.02	46.80
337.50	5200.00	50.83	168.79	68.96	378.48	65.33
355.75	5120.00	27.77	143.01	45.61	396.90	41.58
0.00	114.00	82.58	12.75	38.76	3.34	52.72
18.50	100.88	63.29	9.16	18.49	15.57	33.31

Table 10.22 – continued

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
1.00	106.00	81.10	10.89	36.68	2.08	51.16
43.00	120.63	39.98	29.52	3.37	39.44	10.17
182.50	604.38	70.43	118.86	94.51	149.92	96.02
48.50	319.13	46.41	14.10	13.21	36.93	18.34
89.00	173.33	2.84	69.89	42.89	83.62	-
58.50	612.63	54.06	5.97	30.19	25.05	28.54
321.50	1238.75	171.30	194.41	182.56	1154.83	-
175.00	1232.50	25.17	48.55	36.53	1084.09	45.28
275.62	260.00	184.26	247.38	219.95	266.80	-
168.50	1248.75	17.70	40.44	28.81	835.16	37.66
376.50	3928.03	64.63	9.86	51.77	421.74	61.22
101.50	3939.39	211.04	285.93	223.94	146.74	-
291.50	3939.39	21.04	95.93	33.94	336.74	24.56
287.50	3916.67	23.68	97.80	36.46	332.95	26.99

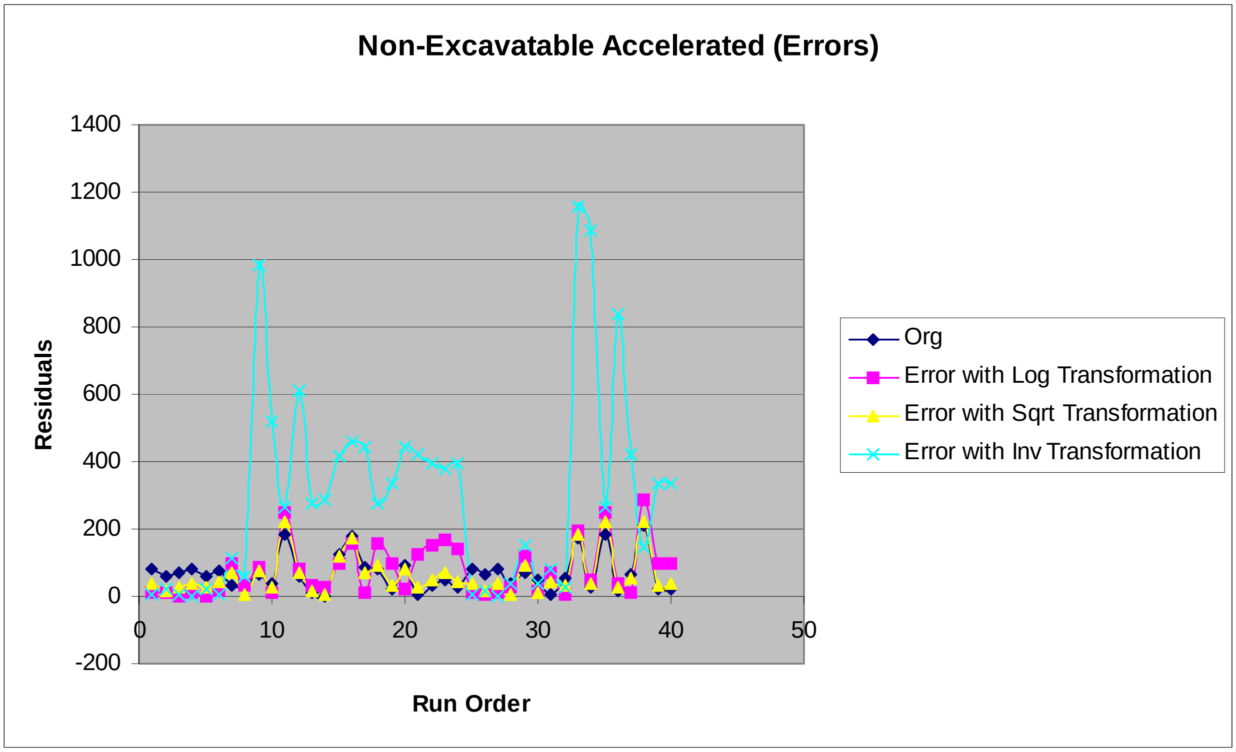

Figure 10.13 Comparative Error Plots for Different Transformations vs. Run Order for Non-excavatable Accelerated Mix

Table 10.23 Unusual Observations – Non-excavatable Accelerated Mix

Mix Type	District	Curing Time	LBR	PEN
Drained	4&6	7 days	275.62	258.00
Drained	5	14 days	399.00	2427.50
Undrained	1	7 days	321.50	1238.75
Undrained	4&6	7 days	275.62	260.00
Undrained	2	28 days	101.50	3939.39

Table 10.24 Summary of Mean Squared Error and Coefficient of Determination for Non-excavatable Accelerated Mix

	Original	Log Transformation	Sqrt Transformation	Inv Transformation	Original with Unusual Observa-tions Removed
Mean Square Error	85.74	108.16	86.98	424.22	55.12
R^2	61.5%	60%	64.9%	28.7%	84.5%

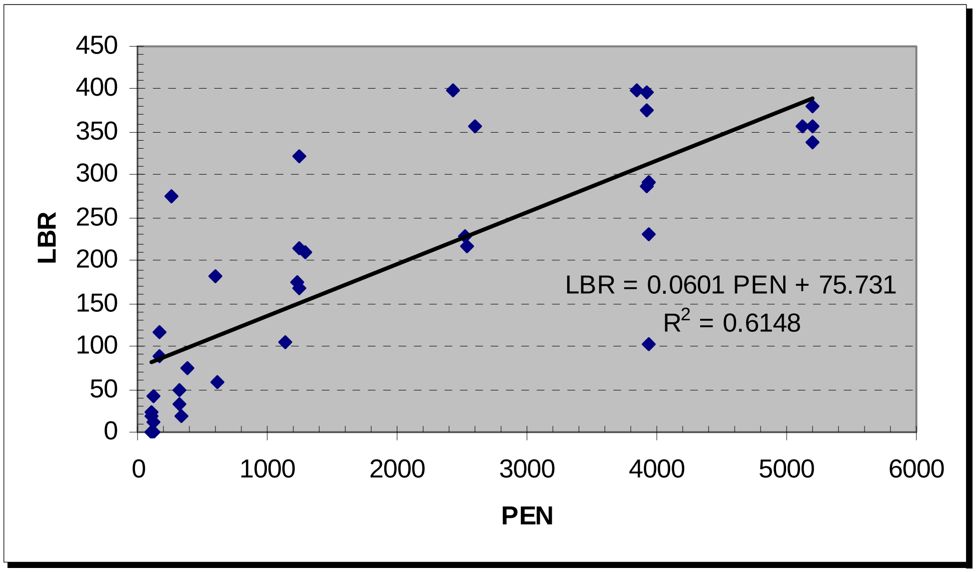

Figure 10.14 Regression Plot Including Unusual Observations for Non-excavatable Accelerated Mix

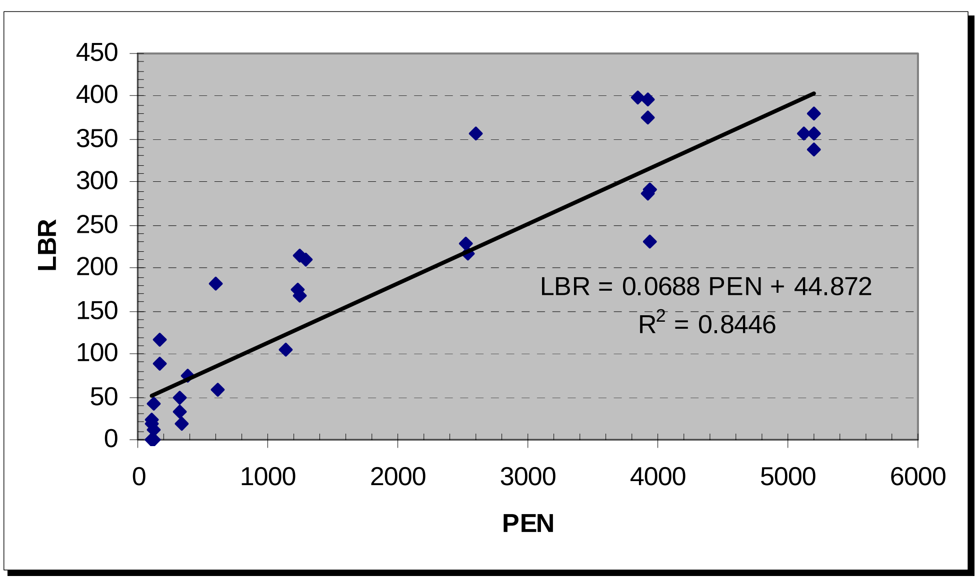

Figure 10.15 Regression Plot After Removing Unusual Observations for Non-excavatable Accelerated Mix

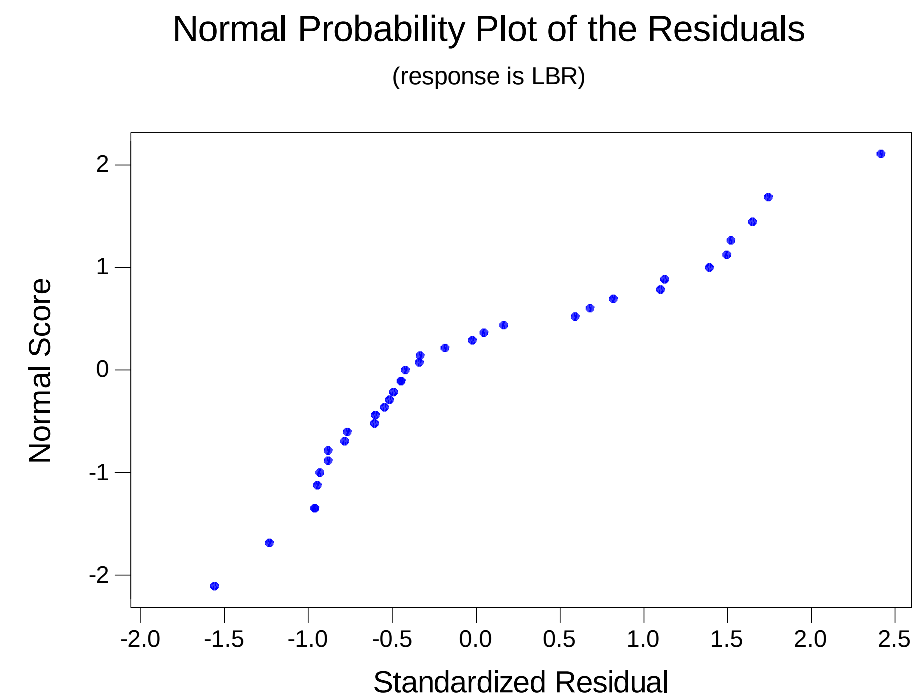

Figure 10.16 Normal Probability Plot for Non-excavatable Accelerated Mix

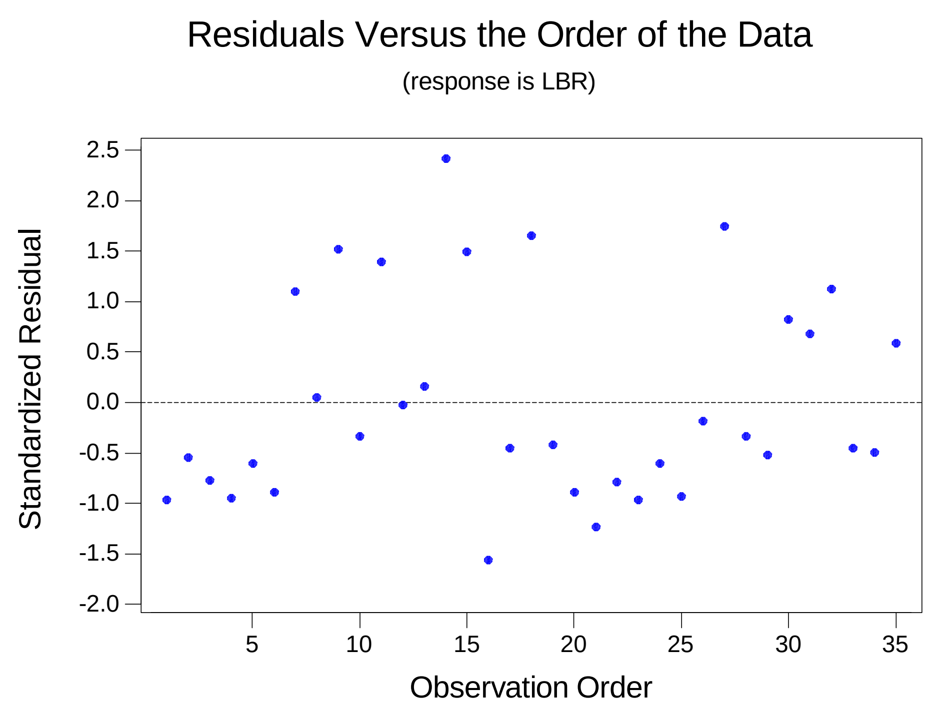

Figure 10.17 Residuals vs. Order of the Data Plot for Non-excavatable Accelerated Mix

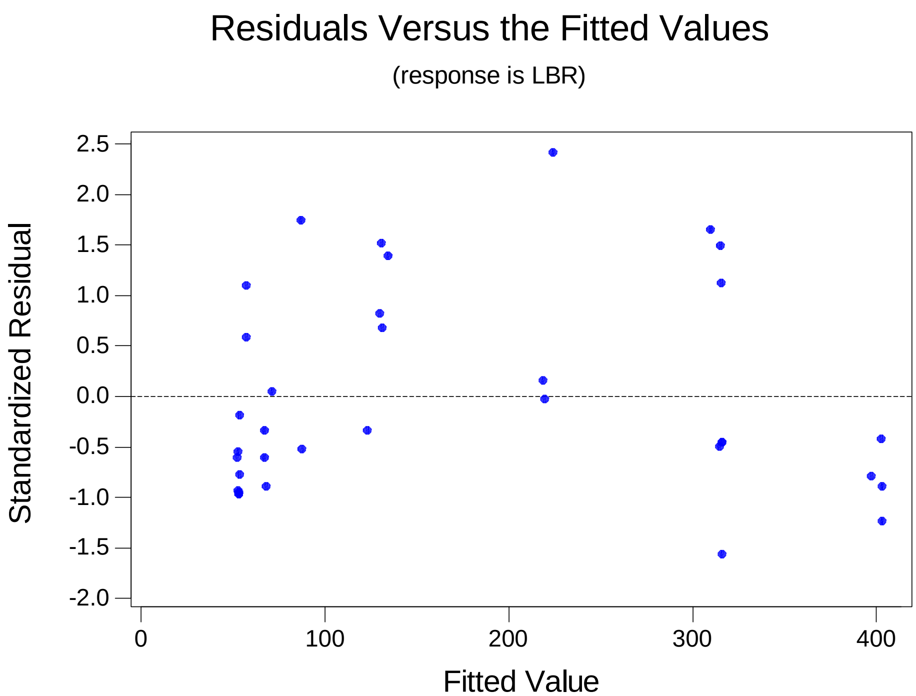

Figure 10.18 Residuals vs. Fitted Values Plot for Non-excavatable Accelerated Mix

10.5.4 Non-excavatable non-accelerated mix

The results of the regression analysis carried out for this particular mix can be seen in Table 10.25, and the error terms in Table 10.26 and Figure 10.19. Transformations were performed as discussed earlier. Square root and logarithmic transformations gave better results. But on examining the residual plots, it was observed that the plots obtained with the original data, as shown in Figures 10.20 through 10.24, validated the adequacy of the model better than the plots obtained with transformations. Furthermore, the error terms for the original case depicted less error than that of the transformations (Table 10.26 and Figure 10.19). Hence, it was decided to go with the results obtained from original data, with the value of coefficient of determination at 44.2%. However, unusual observations were removed to improve the coefficient of determination that came to 61.9% after improvement. Figures 10.20 and 10.21 provide regression plots for the unusual observations included and with them removed, respectively. See Table 10.27 for the unusual observations removed. As in the previous cases, the *F* (50.37) and *t* (7.10) statistics for regression and slope, respectively, validated the significance of regression at 95% confidence interval, with very low P-values for the respective statistic. Table 10.28 contains the summary of the mean squared errors, as well as the coefficient of determination for the original data and the transformations.

Table 10.25 Regression Analysis Results for Non-excavatable Non-accelerated Mix

Type of Transformation	Equation	S	R-Sq	F(R)	P(R)	T (C)	P(C)	T(PEN)	P(PEN)
No Transformation	LBR = 118 + 0.0490 PEN	100.2	44.2%	30.15	0.000	5.06	0.000	5.49	0.000
Log(LBR) Log(PEN)	Log(LBR) = - 1.30 + 1.10 Log(PEN)	0.5562	58.9%	54.39	0.000	-2.85	0.007	7.37	0.000
Sq(LBR) Sq(PEN)	Sq(LBR) = 5.09 + 0.212 Sq(PEN)	4.350	54.3%	45.16	0.000	3.68	0.001	6.72	0.000
Inv(LBR) Inv(PEN)	Inv(LBR) = - 0.0700 + 96.2 Inv(PEN)	0.4491	29.3%	15.78	0.001	-0.76	0.452	3.97	0.000
Original with Unusual Observa-tions Removed	LBR = 72.2 + 0.0593 PEN	87.62	61.9%	50.37	0.000	3.01	0.005	7.10	0.000

Note: S: Standard deviation of the overall observations
F(R): F-statistic for regression
P(R): P-value for the F-statistic for regression
T(C): t-statistic for intercept in regression equation
P(C): P-value for the t-statistic for intercept in regression equation
T(PEN): t-statistic for slope in regression equation
P(PEN): P-value for the t-statistic for slope in regression equation

Table 10.26 Residuals Data for Non-excavatable Non-accelerated Mix

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
3.81	113.00	119.85	5.43	50.09	2.53	75.09
5.00	136.50	119.82	6.39	52.24	3.42	75.30
24.00	121.88	100.10	13.94	31.19	22.61	55.43
1.00	170.16	125.47	13.52	60.68	1.01	81.29
164.00	342.80	29.06	132.56	82.74	159.25	-
39.00	371.88	97.35	4.62	45.21	33.70	55.26
188.00	260.00	57.12	164.82	115.63	184.66	-
149.00	225.75	19.80	129.16	80.54	146.19	63.40
294.50	1245.00	115.34	164.27	136.52	157.51	148.43
290.50	1300.00	108.65	153.91	128.39	40.50	141.16
355.50	650.00	205.50	291.87	245.37	342.67	-
234.00	1165.00	58.76	112.96	82.09	154.63	92.67
355.00	2522.50	113.23	71.45	107.37	386.34	133.13
292.50	2550.00	49.38	5.48	43.04	323.45	69.00
305.00	2600.00	59.43	11.77	52.25	335.30	78.54
200.50	2477.50	39.06	77.53	44.14	232.55	18.69
204.50	3939.39	106.71	258.94	133.87	226.42	101.42
321.00	3900.00	11.71	137.35	14.91	343.02	17.41
230.50	3939.39	80.71	232.94	107.87	252.42	75.42
381.50	3558.75	88.93	32.88	66.96	404.75	98.15
365.50	5185.00	6.77	261.83	48.78	384.91	14.32
250.00	5200.00	123.05	379.36	165.18	269.41	130.71
416.50	5200.00	43.49	212.86	1.31	435.91	35.78
289.02	5195.00	83.74	339.76	125.87	308.43	91.39
0.35	114.00	123.36	8.98	53.69	0.93	-
5.30	111.00	118.27	3.76	48.31	4.04	73.48

Table 10.26 – continued

LBR	PEN	Original Error	Error with Log Transformation	Error with Sqrt Transformation	Error with Inv Transformation	Original Error Unusual Observations Removed
4.50	127.88	119.89	6.13	51.54	3.03	75.29
0.60	157.50	125.24	12.73	59.44	1.24	80.93
297.00	580.00	150.44	240.88	193.08	286.57	-
73.00	371.88	63.35	38.62	11.21	67.70	21.26
156.50	251.00	26.06	134.26	85.14	153.32	-
239.00	1223.75	60.88	111.23	82.62	122.72	94.19
307.50	1258.75	127.67	175.70	148.47	151.25	160.61
350.50	1300.00	168.65	213.91	188.39	100.50	-
277.00	650.00	127.08	213.37	166.87	264.17	-
176.50	2355.00	57.06	86.40	59.95	210.74	35.42
287.30	3886.36	21.31	169.36	47.77	309.37	15.47
393.00	3912.88	83.08	67.04	56.27	414.97	88.64
213.40	3939.40	97.81	250.04	124.97	235.32	92.52
354.00	4308.00	24.71	157.56	7.11	374.96	26.20

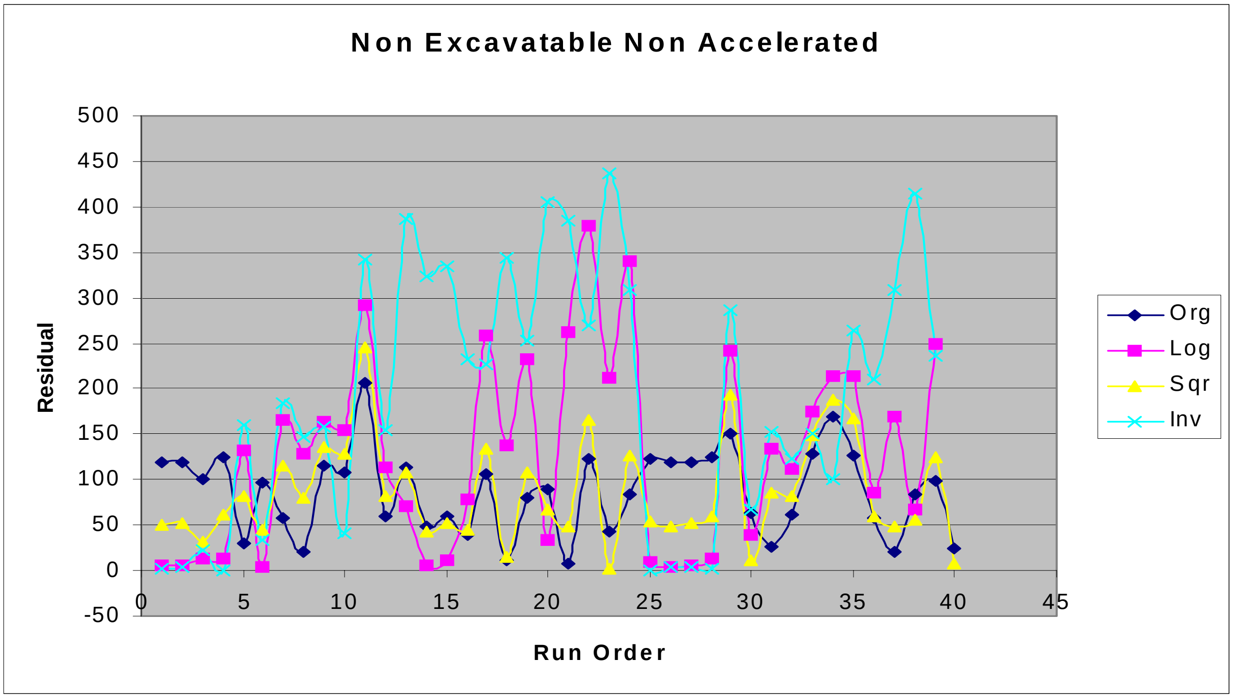

Figure 10.19 Comparative Error Plots for Different Transformations vs. Run Order for Non-excavatable Non-accelerated Mix

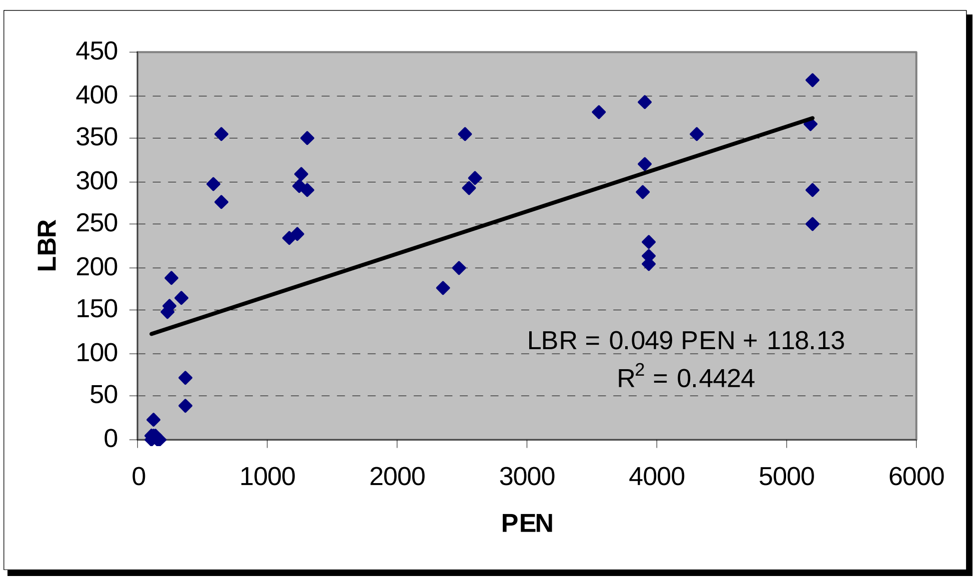

Figure 10.20 Regression Plot Including Unusual Observations for Non-excavatable Non-accelerated Mix

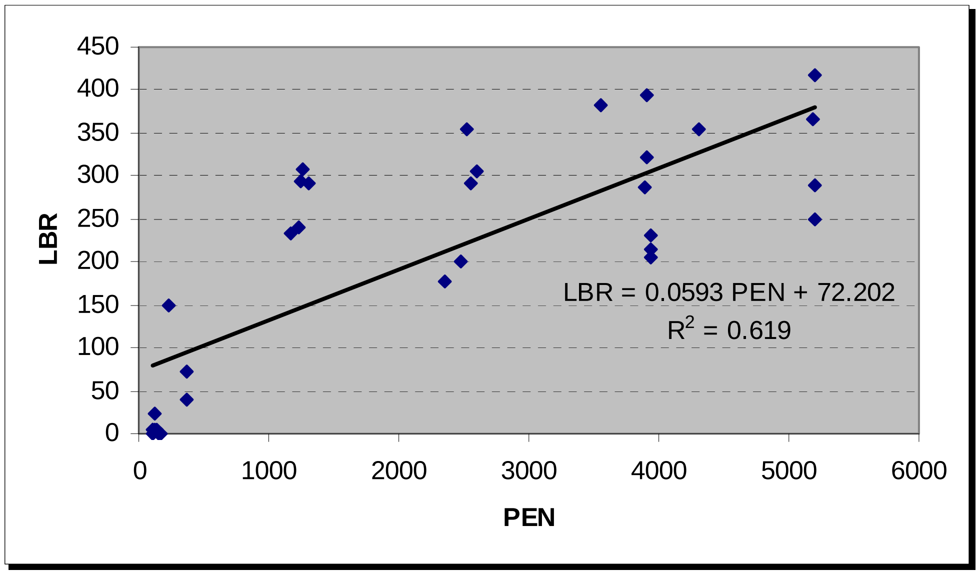

Figure 10.21 Regression Plot After Removing Unusual Observations for Non-excavatable Non-accelerated Mix

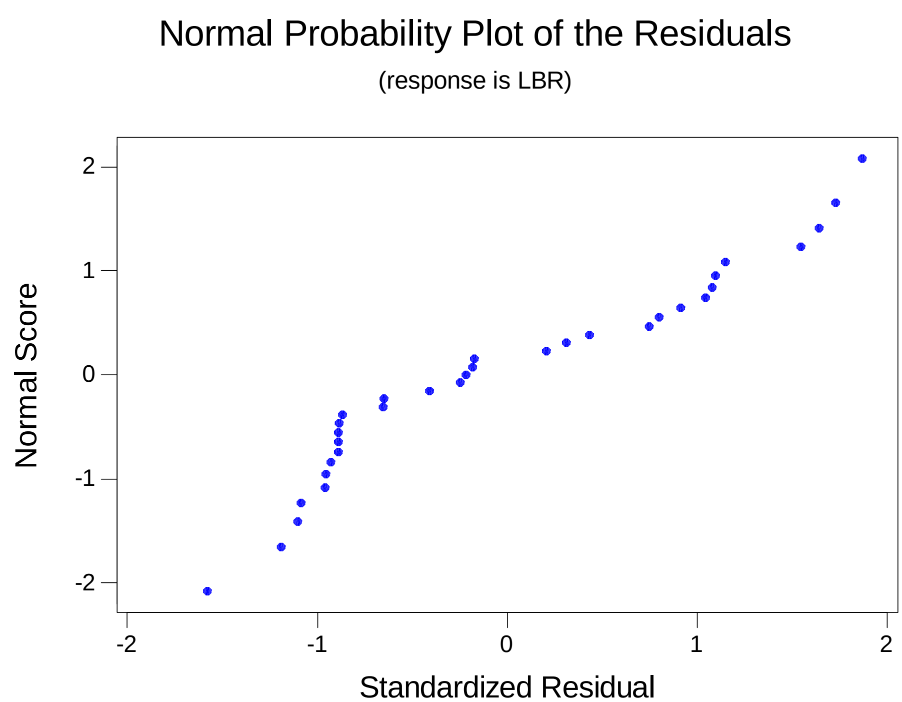

Figure 10.22 Normal Probability Plot for Non-excavatable Non-accelerated Mix

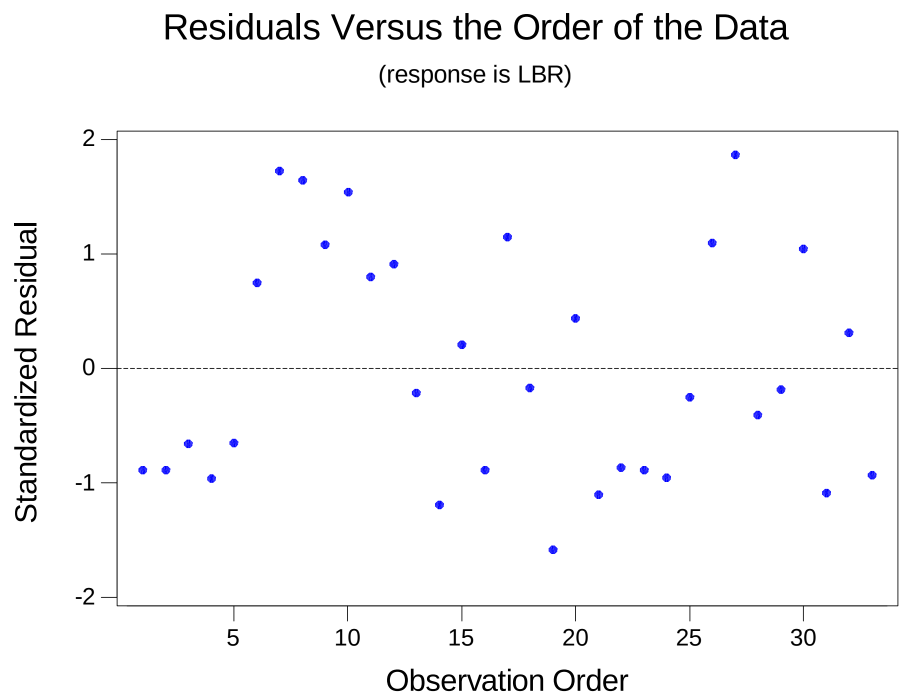

Figure 10.23 Residuals vs. Order of the Data Plot for Non-excavatable Non-accelerated Mix

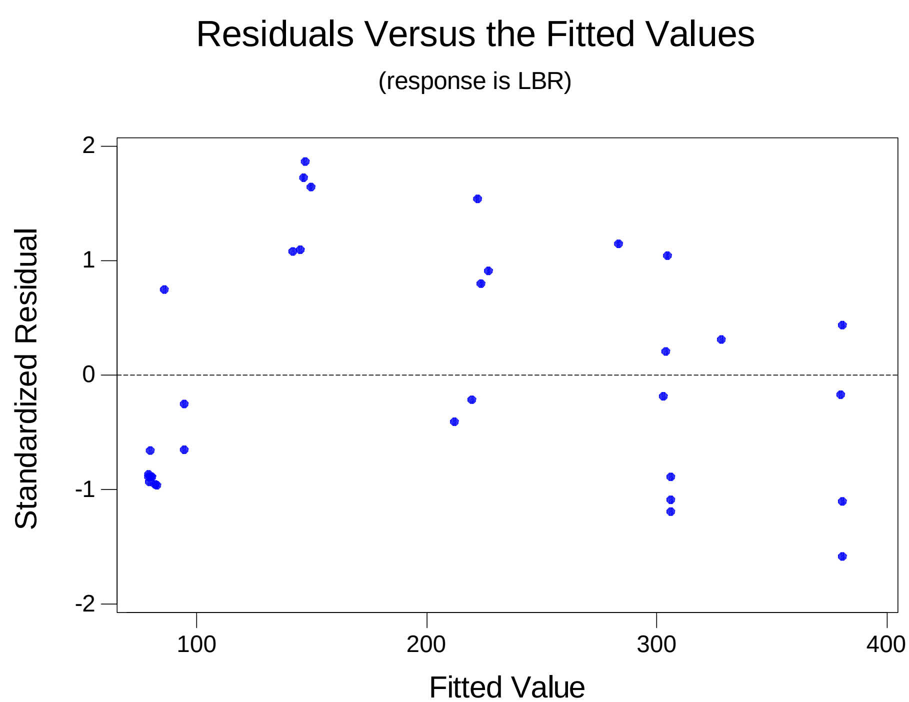

Figure 10.24 Residuals vs. Fitted Values Plot for Non-excavatable Non-accelerated Mix

Table 10.27 Unusual Observations – Non-excavatable Non-accelerated Mix

Mix Type	District	Curing Time	LBR	PEN
Drained	1	1 days	164.00	342.80
Drained	4&6	1 days	188.00	260.00
Drained	4&6	7 days	355.50	650.00
Undrained	1	2 days	297.00	580.00
Undrained	4&6	7 days	156.50	251.00
Undrained	2	7 days	350.50	1300.00
Undrained	4&6	7 days	277.00	650.00

Table 10.28 Summary of Mean Squared Error and Coefficient of Determination for Non-excavatable Non-accelerated Mix

	Original	Log Transformation	Sqrt Transformation	Inv Transformation	Original with Unusual Observations Removed
Mean Square Error	97.67	164.06	101.43	240.28	85.11
R^2	44.2%	58.9%	54.3%	29.3%	61.9%

10.6 Relating LBR to Penetrometer Data (6 hrs, 1 day and 2 days)

The previous section (section 10.5) provided the statistical analysis relating LBR to penetrometer data combining all data. In this section, similar statistical analysis was performed using the data for curing durations of 6 hours, 1 day, and 2 days. These sets of data were selected due to the understanding that the field specialist would benefit greatly from early curing duration for correlating LBR and hand-held proctor penetrometer test results. Table 10.29 provides a list of data used for early curing duration analysis.

The initial analysis performed was for 6 hours. The results for that analysis provided a very weak correlation. For example, the R^2 values obtained for 6-hour duration data for all mixes (excavatable, non-excavatable, excavatable accelerated, and non-excavatable accelerated) were, respectively, 0.019, 0.417, 0.091, and 0.106. Seeing that the correlation output was discouraging and weak, a variety of transformations were used (similar to those used in the previous section) to account for the non-linearity that may have been associated with the original data. The regression results for the transformation again did not show encouraging correlation.

A second analysis of the data included the 1-day and 2–day data. As seen in Table 10.29, this addition greatly increased the size of data sets. The regression results for the complete sets of data (shown in Table 10.29) yielded positive correlation results. These correlation results were positive only with the removal of the unusual observations. While positive correlation results were obtained, most of the individual errors and the overall mean square errors were not positive.

The LBR values obtained for the early curing duration of 6 hours, as shown in Table 10.29, appear to be low. For example, there is a higher frequency of LBR values equal to 1.0 than any other higher LBR value. In fact, the highest LBR value recorded higher than 1.0 was 86.00. At six hours of curing the LBR samples rendered little resistance to compression. It also shows that 6 hours of curing is insufficient time for the flowable fill to cure and be paved over for traffic.

The FDOT specifications on flowable fill state that flowable fill should be left undisturbed until the material obtains sufficient strength. It defines sufficient strength to be equivalent to a reading of 35-psi penetration resistance as measured with a hand-held penetrometer, in accordance with ASTM C 403. While the FDOT specifications do not specify a time at which to test the material to verify that a 35-psi strength has been established, in this study we were able to obtain penetration resistances higher than 35-psi at six hours of curing. This inference shows a need for FDOT to re-write or re-clarify their specifications on flowable fill.

For field applications, the equations developed in this report can be used as a guide for developing a mixture to ensure future excavation of flowable fill or to ensure that a minimum strength is obtained to meet a design specification. It should be noted that the derived equations do have limitations. Due to the nature of the study, the research team can only ensure the validity of the equations with the materials used in this study. It is strongly recommended that individuals interested in predicting flowable fill strength perform a series of mixtures using local materials to generate a database that can serve as a tool and as a source for predictive models.

Table 10.29 List of Data Used in Analysis

Mix Type	District	Curing Time	Excavatable		Excavatable Accelerated		Non-excavatable		Non-excavatable Accelerated	
			LBR	PEN	LBR	PEN	LBR	PEN	LBR	PEN
Undrained	1	6 hrs	2.00	80.63	9.00	94.00	1.00	114.00	1.00	114.00
Undrained	2	6 hrs	2.00	79.13	1.00	64.53	5.00	111.00	19.00	100.88
Undrained	4&6	6 hrs	2.00	68.63	1.00	71.63	5.00	127.88	1.00	106.00
Undrained	5	6 hrs	1.00	58.00	1.00	72.63	1.00	157.50	**86.00**	**120.63**
Drained	1	6 hrs	2.00	112.38	14.00	113.63	4.00	113.00	1.00	114.00
Drained	2	6 hrs	1.00	78.13	1.00	102.63	5.00	136.50	23.00	109.63
Drained	4&6	6 hrs	2.00	82.50	1.00	86.50	24.00	121.88	11.00	120.50
Drained	5	6 hrs	1.00	103.63	5.00	69.00	1.00	170.17	1.00	116.75
Undrained	1	2 days	**52.00**	**367.50**	**36.00**	**252.25**	**297.00**	**580.00**	**183.00**	**604.38**
Undrained	2	2 days	**17.00**	**496.88**	**20.00**	**266.25**	73.00	371.88	49.00	319.13
Undrained	4&6	2 days	**35.00**	**140.33**	14.00	150.33	156.50	251.00	**189.00**	**173.33**
Undrained	5	2 days	**29.00**	**338.64**	**51.00**	**247.25**	**239.00**	**1223.75**	117.00	612.50
Drained	1	1 day	14.00	242.75	16.00	158.67	164.00	342.80	34.00	315.91
Drained	2	1 day	**13.00**	**471.88**	9.00	64.53	39.00	371.88	**19.00**	**331.13**
Drained	4&6	1 day	7.00	148.16	10.00	152.67	188.00	260.00	**117.00**	**173.33**
Drained	5	1 day	12.00	140.67	16.00	158.17	149.00	225.75	74.00	378.03

Shaded cell denotes unusual observations

11. CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The objective of this study was to evaluate the performance of flowable fill in pavement sections using accelerated and non-accelerated mixtures. Evaluation included determination of strength, set time, and flow properties applicable to conditions in Florida.

The literature review provided in-depth information on flowable fill technology, type, specifications, mix designs, tests methods, current studies, and use of flowable fill in the state of Florida. From responses to two sets of questionnaires sent to Florida counties, municipalities and FDOT maintenance districts, it was found that more than 1000 yd^3 of flowable fill were used around culverts, backfill, manholes, bridge abutments, support walls, sub base, and pipe pluggings. In Florida, it was found that some users follow FDOT specifications and some are using a mix that provides 800 – 1000 psi strength. For short-term testing, the penetrometer test is the one most widely used. Some users suggested that admixtures be used to reduce shrinkage, control bleed and promote setting. A majority of districts used flowable fill to backfill trenches in pavement. Most users bring the flowable fill to the top of subgrade and top of base. Trench widths varied from 2-ft to 20-ft. Flowable fill was used in both longitudinal and transverse openings in the pavement and the majority of users were satisfied with the performance of flowable fill.

Before conducting the laboratory work, trial testing was planned and wooden molds for forming $16'' \times 8'' \times 10''$ specimens were constructed. Steel molds for LBR samples were obtained. A trial mix was prepared and samples were taken to be tested by pocket penetrometer, Proctor penetrometer, and LBR to measure sample strengths. To obtain current approved flowable fill mix design on FDOT projects, FDOT approved material suppliers were contacted who donated materials that met each design mix criteria for flowable fill mixes.

Pre-planning included identifying a process for preparing both drained and undrained samples; proper test equipment, such as the Proctor penetrometer; and a designated location for storing both oven and normal cured samples. Four mixes were formulated for each district for a total of sixteen mixes. In each mix, 52 samples (20 wooden and 32 LBR molds) were prepared. Tests were conducted on set-time, flow, strength and other flowable fill properties, such as unit-weight and air content.

Material suppliers donated sand, cement, fly ash, slags, and admixtures. Accordingly, materials were matched with the mix used in each district. Tests were performed to determine the chemical composition of materials, physical properties, and gradation.

Laboratory results indicated that most of the excavatable mixes exceeded the maximum allowable compressive strength recommended by FDOT strength specifications (100 psi) at 6 hours to 90 days, and the LBR values for excavatable mixes varied from 1.67 to 182. For the same duration and for excavatable mixes, penetrometer readings varied from 112 psi to 3659 psi. The compressive strengths of the excavatable mixes at 28 days varied from 81.74 psi to 273.04

psi. For field samples, strengths after 28 days varied from 1170.58 psi to 2209.87 psi. On the other hand, the non-excavatable mixes met or exceeded the minimum FDOT specifications strength of 125 psi.

After 6 hours, the laboratory result of penetration resistance for both excavatable and non-excavatable mixes was 65 psi or greater. The recommended penetration resistance value obtained from the literature search is 65 psi. The flow of both excavatable and non-excavatable mixes varied from 4.38 inches to 19.75 inches. The recommended flow value in the literature is 9 inches. The coefficient of determination (R^2 = 0.8647, R^2 = 0.627) on excavatable and excavatable accelerated mixes resulted from two days of oven curing with 90% confidence (refer to Figures 9.1 and 9.4). The accelerated strengths of the 2-day oven-cured samples provided better correlation values to predict the 28-day strength using the standard curing LBR results and the accelerated oven-dried curing results.

With the study objective in mind, the following conclusions are derived. The analysis for the unit weights of the mixes depicts substantial variability among different mix designs, as well as different districts, within the same mix design with a majority of the readings not complying with FDOT specifications. This may be attributed to the fact that different districts are targeting no specific value for the unit weight, but rather are attempting to fall somewhere within the FDOT specified range. The findings that most of the mixes did not meet density requirement may mean that density requirement was not strictly enforced. The density could be easily reduced to within specifications by increasing the air contents accordingly. Similar conclusions are drawn for the air content of different mixes. However, it may be noted that the air content for a majority of the districts falls within the FDOT specified range for both excavatable and non-excavatable design mixes. The compressive strength exceeds the FDOT specified range for excavatable mixes, except for Districts 2 and 5. For the non-excavatable mixes, the compressive strength complies with the FDOT specifications, and its value may be considered too high.

Various transformations were performed and the models checked for adequacy to establish a relationship between LBR readings and penetrometer readings. After removing the unusual observations, pertinent regression equations relating LBR to the penetrometer data were obtained. The unusual observations were removed because they did not fit the trend line. The regression analysis showed poor and good correlation. Poor correlation was observed for LBR and penetrometer readings containing unusual observations, while good correlation was observed with removal of unusual observations. It is emphasized that the results presented in this report are based on laboratory and field tests and for the specific materials evaluated.

Other findings of the research follow. It was found that accelerating admixtures can be used to help reduce the curing time of flowable fill to a definite point. It was shown in mixtures containing accelerator that cement content impacts the curing of a specimen due to the heat produced from the hydration process. Accelerating mixes containing low cement content did not appear to reduce the curing time of a mix.

In the research, undrained samples were designed to simulate conditions in Florida where contractors experience high water table elevation during placement of flowable fill, and based on the results obtained, it was found that curing times are affected when dire drainage conditions around flowable fill are experienced.

When trenches are backfilled under a roadway, a question had arisen concerning how close the flowable fill could be brought to the bottom of the asphalt without a detrimental affect on the roadway itself. The concern is with the flowable fill not having the same bearing as the compacted stabilized soil subgrade involved. According to FDOT specifications, stabilized subgrades are required to have a bearing value of 40 LBR. Laboratory results for the performance of the mixes in the lab show flowable fill mixes containing LBR values that are well above FDOT specification requirements. In fact, because the strength obtained for both excavatable and non-excavatable mixes exceeds the specification requirements; there is no limit to the elevation for which one can bring the flowable fill to the bottom of the asphalt, although such a decision should be left to the discretion of the project engineer responsible.

According to the responses received from the research questionnaires, most respondents indicated that flowable fill trenches are normally cut at a width of 2 to 20 ft. The respondents did not indicate any problems occurring with slippage between the asphalt and the flowable fill that could be associated with trench width.

Control over the compressive strength in the field is important because CLSM backfill must gain sufficient strength to support working loads, yet the ultimate strength must allow re-excavation of the material, if necessary. From the specimens acquired for this study, it has been found that the long-term strength for flowable fill goes beyond what is defined and established as the strength to reach. It was shown that excavatable flowable fill continues to gain long-term strength beyond the normal 28-day curing period.

Finally, the current means of determining acceptance of flowable fill after placement in the field was found to be the use of the Proctor penetrometer.

11.2 Recommendations

The following recommendations are made for future flowable fill research:

1. It would be helpful for more data on unit weight, air content, and compressive strength to be collected for all design mixes.

2. The Department of Civil and Coastal Engineering at the University of Florida owns an Advanced Digital Triaxial System (TRI – SCAN 50). This equipment can be used to break flowable fill cylinders in order to measure strength. Having sufficient data points would allow pertinent tests to ascertain whether the lab readings for different measures of flowable fill are close to the field readings for similar design mixes. This would also improve the accuracy of the analysis. It is advised that this data be collected in a controlled environment for the purpose of consistency. Furthermore, the equations relating the LBR readings with those obtained from the penetrometer should be validated by employing field data that indicates the strength of the underlying mix.

3. FDOT specifications should begin requiring contractors to furnish the FDOT with sufficient fresh flowable fill samples to be tested to verify specification compliance.

4. Future research should include the examination of existing concrete and soil testing procedures and their applicability to flowable fill.

5. Create mix designs using various materials that are commonly used in Florida, such as crushed limerock, silica sand, etc. Such trial mix designs should be tested to determine strengths for possible model development to predict strengths of excavatable and non-excavatable flowable fill mixes (not using an oven).

6. A maturity meter should be used to provide strength data in the field. The maturity meter system consists of sacrificial sensors placed in the flowable fill to measure flowable fill strength.

7. Finally, splitting tests should be used for indicating excavatability. The tensile strength of flowable fill should be investigated using current concrete and cement testing standards (i.e., briquets, ASTM C 190).

In closing, the authors of this report hope the information within provides in-depth guidance and further knowledge of the use of flowable fill. In implementing this study, the most significant constraints were time and manpower. This study will have proven most worthwhile if the findings and recommendations are pursued through further investigation. Further investigation into the uses of flowable fill will have a significant impact on the construction industry.

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