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Final Report

USE OF WASTE FOUNDRY SAND IN
HIGHWAY CONSTRUCTION

Sayeed Javed

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

JHRP-94/23
Final Report

**USE OF WASTE FOUNDRY SAND IN
HIGHWAY CONSTRUCTION**

Sayeed Javed

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FINAL REPORT

**USE OF WASTE FOUNDRY SAND IN
HIGHWAY CONSTRUCTION**

by

Sayeed Javed
Graduate Research Assistant

Joint Highway Research Project

Project No: C-36-50N
File No: 6-19-14

Prepared as Part of an Investigation
conducted by the
Joint Highway Research Project
Engineering Experiment Station
Purdue University

Funded By
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The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of or policies of the Indiana Cast Metals Association. This report does not constitute a standard, specifications, or regulations.

School of Civil Engineering
Purdue University
West Lafayette, Indiana 47907

May 1994

Final Report

USE OF WASTE FOUNDRY SAND IN
HIGHWAY CONSTRUCTION

To: Vincent Drnevich, Director
Joint Highway Research Project

May 02, 1994
Project No: C-36-50N
File No: 6-19-14

From: C.W. "Bill" Lovell
Professor of Civil Engineering
Purdue University
West Lafayette, IN 47907

Attached is the Final Report titled "Use of Waste Foundry Sand in Highway Construction." The report was prepared by Mr. Sayeed Javed, Graduate Research Assistant, under my direction.

A total of ten waste foundry sands were tested extensively to provide information on the properties of Indiana waste foundry sands. The results of detailed evaluations show that waste foundry sands can be used in embankments, subgrades, asphalt concrete and controlled low strength materials.

Leaching characteristics of the various waste foundry sands under laboratory leaching procedures and under actual field conditions have been reviewed. Chemical analysis of the leachates showed that waste foundry sand is nonhazardous and its effect on the quality of groundwater is low.

The report is submitted for review, comment and acceptance in fulfillment of the referenced study.

Respectfully submitted

C. W. Lovell
Research Engineer

cc:

A.G. Alschaeffl
L. Bandy
P.L. Bourdeau
M.D. Bowman
M.J. Cassidy
L.M. Chang
M. Cohen
E. Cox

S. Diamond
V.P. Drenvich
A.A. Fendrick
J.D. Fricker
K.R. Hoover
R.B. Jacko
C.V. Kahl
R.H. Lee

C.W. Lovell
D.W. Lucas
B.Mason
B.G. McCullouch
B.K. Partridge
F.P' Pool
J.A. Ramirez
G.F. Scholer

K.C. Sinha
D.L. Tolbert
L. Tucker
R. VanCleave
T.D. White
R.K. Whitford
J.R. Wright

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
AFS	American Foundrymen's Society
AASHTO	American Association of State Highway & Transportation Officials
ASTM	American Society for Testing and Materials
CALTRANS	California Department of Transportation
CBR	California Bearing Ratio
CLSM	Controlled Low Strength Material
EPA	Environmental Protection Agency
EPTC	Environmental Procedure Toxicity Characteristics
FM	Fineness Modulus
IAC	Indiana Administrative Code
INCMA	Indiana Cast Metals Association
IDOH	Indiana Department of Highways
INDOT	Indiana Department of Transportation
IDEM	Indiana Department of Environmental Management
LOI	Loss on Ignition
NPDWS	National Primary Drinking Water Standard
PCC	Portland Cement Concrete
RCRA	Resource Conservation and Recovery Act
TCLP	Toxicity Characteristic Leaching Procedure
WFS	Waste Foundry Sand
VMA	Voids in Mineral Aggregate

IMPLEMENTATION REPORT

The aim of this research was to investigate different uses of WFS in highway construction. Based on laboratory evaluation, these materials have proven technically feasible to be used in embankments, subgrade, surface layer in asphalt concrete and CLSM.

The exact benefit in utilizing these materials will depend on the various costs involved including: cost of WFS; cost of transportation; additional costs due to clay layer in the case of embankments or due to processing of WFS in asphalt concrete; and the cost of conventional aggregates. In Indiana, most of the foundries are currently willing to provide WFSs without cost. Transportation costs in Indiana vary from \$5 to \$10/ton for a distance of 100 miles. It is thus critical that the costs associated with WFS including hauling costs and additional costs due to environmental concerns be less than those of using a conventional construction material. The exact economic benefits can be determined on a case-by-case basis.

The following suggestions are made as possible ways the results of this report might be implemented.

A field study is recommended, which should include the construction of a test embankment and a test section of subgrade, with adequate monitoring devices, to measure the long term mechanical and environmental performance and development of correlations between the laboratory and field parameters.

For the case of embankment and subgrade, every attempt shall be made possible to place these materials above the water table and out of contact with ground water. The

green WFSs are suggested to be compacted using pneumatic tired rollers. Vibratory compaction using smooth wheel rollers is suggested for chemically bonded and shell molded WFSs. It is proposed that the strength and compressibility parameters determined as part of this research be used for design and evaluation of embankments containing WFS, until such time as field results are available. For subgrade, CBR and resilient modulus values discussed in this report can be used.

The WFS embankment should be encapsulated using a compacted clay base, sidewalls and top cover having permeability less than 10^{-7} cm/sec. The clay base should be at least three feet thick to prevent any ground water contamination and help in attenuation mechanisms. However, the requirement of a clay base should be dealt on a case-by-case basis. For very low permeability green WFS; Type IV WFS; or the site already containing sufficient thick natural low permeability layers, this clay base requirement may be omitted or the thickness may be reduced. The top cover and sidewalls should be at least two feet thick to greatly reduce any infiltration and be properly compacted. The requirement of a clay base should also be considered for subgrade incorporating WFSs.

Creep tests is recommended in the laboratory to study the rutting tendencies of mixes of asphalt concrete incorporating WFS. Different replacement levels of WFS in the asphalt concrete mix would be tried. However, a maximum replacement level of 25% WFS with respect to the total weight of aggregates, should be used. Those bituminous mixes surviving the laboratory testing should be further tested in the accelerated pavement facility at the INDOT Division of Research. Finally, several strips should be placed in the field for long term behavior of asphalt pavements with WFSs.

It is recommended that INDOT use Mix No. 3 developed as part of this research to evaluate the use of WFS in CLSM mixes. Indiana Department of Transportation should use these materials in appropriate situations, on a trial basis, to evaluate their field suitability and the applicability of the laboratory results. Probably, small amounts should be used at first, and it should be recognized that the mix designs given in the report are intended only as a guide and will probably have to be modified to suit the requirements of the specific use and materials available.

More detailed recommendations and specifications for the above proposed uses of WFS, are given in Appendix D. It is recommended that the ideas in those sections be followed initially and modified as needed for individual projects.

CHAPTER 1

INTRODUCTION

Waste Foundry Sand (WFS) is a byproduct of the casting industry which results from the molding and core making processes. The mold forms the outside of the castings while the core forms the internal shape. Generally for each ton of good castings shipped, the typical foundry generates something like a ton of WFS (Kennedy and Linne, 1987). According to the 1992 survey of Indiana Cast Metals Association (INCMA), the annual generation of WFS in Indiana is about 450,000 tons (INCMA, 1992). The bulk of this WFS is non-hazardous and is currently deposited in solid waste landfills. The scarcity of landfill spaces and increase in tipping fees have stimulated the pursuit of non-landfill disposal or beneficial reuse.

In view of the benefits to be gained from the utilization of WFS as a construction material, research on this material is desired. Unfortunately, an extensive review of the literature reveals that the amount of laboratory and field data on the properties and performance of this material for highway purposes are very limited. In order to develop constructive uses of foundry sand, a substantial database on their properties is needed. The purpose of this research was to investigate the uses of WFS in highway construction. Among the different uses of WFS in highway construction, WFS as geotechnical fill material in embankment and subgrade, fine aggregate supplement in

asphalt concrete and fine aggregate in Controlled Low Strength Material (CLSM) were evaluated. The objectives set forth for this study have been achieved by synthesizing available information obtained from a comprehensive literature review and conducting different types of laboratory tests including geotechnical properties tests, asphalt concrete tests and CLSM tests.

The discussion in the following chapters is limited to foundry wastes which are produced in the molding and coremaking, and does not include melting waste, slag or waste generated by other foundry processes.

Chapter 2 synthesizes the information on WFS, their generation processes, their types and disposal options for WFS. Known physical/mechanical and chemical/environmental properties of these WFS from different resources are also included in this chapter.

Chapter 3 describes the testing program and laboratory test results for the characterization tests performed on ten different samples of WFS. Chapters 4, 5 and 6 deal with the geotechnical properties, asphalt concrete properties and controlled low strength material properties associated with WFS. Leachate results on different WFS are discussed in Chapter 7. Chapter 8 summarizes the main conclusions of the experimental study and provides recommendations for different uses. Future research needs associated with WFS are also included in this chapter. Standards and specifications for major recommended uses are appended.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Waste Foundry Sand (WFS) is generated by industries that use sands, binders and additives to form molds, and cores for castings. The mold forms the outside of the castings; the core forms the internal shape. When the part to be made has deep recesses or hollow portions, sand cores must be provided in the mold.

From the earliest days of founding, sand has been used for producing molds into which metal is to be poured. The reasons for the use of sand are (Parkes et al., 1970):

- a) it is readily available in the quantities required;
- b) because of its availability in the right form, it is cheap;
- c) it is sufficiently highly refractory (fusion point, depending upon purity is 1550-1650°C);
- d) it is readily bonded by clays or other inorganic and organic materials.

The material to be used to form molds and cores in a foundry must have several characteristics. First, it must be cohesive so that the individual grains stick together while the pattern is being removed, otherwise the mold will break apart. Second, it must be porous enough so that gases and water can escape when metal is poured into the mold

(Cannon, 1986). To a certain degree, the properties of cohesion and porosity work at cross purposes. Adding binder will improve the cohesiveness of the sand grains, but will tend to reduce porosity. Molding sand must also be refractory to withstand the molten metal's high temperature.

Binder is any material which is used to hold sand grains together. Binders which are commonly used are bentonite, resins, cement, sodium silicate and oils. Bentonite is typically used in a green sand system whereas resins are used in the chemically bonded process and the shell molding process, as will be discussed later.

Additives are those materials which are added to the bonded sands to improve properties, either during the molding process or during the casting process or both. The primary purpose of combustible additives is to alleviate "burn-on" or fusing of sand to the casting surface. The most widely used combustible additives for green sand molding operations are seacoal, cellulose (wood flour, oat, hulls, cob flour), cereal binder and seacoal substitutes. Seacoal is typically used in sand systems for gray iron, ductile iron and malleable iron castings. Seacoal is a highly volatile bituminous coal, ground to various degrees of fineness by pulverizing mills (Soderlund, 1983).

Other additives which are used are iron oxide and water. Water is added to give flowability to the sand mixture and to activate clay binder. Iron oxide is added to reduce tendency to pinholing and metal penetration. Iron oxide is added in small quantities to some steel foundry molding sand mixes in order to increase the strength of the sand and prevent erosion. Higher additions, of the order of 3-5%, of iron oxide are used in core sands to inhibit pinholing defects, particularly in ferrous foundries, and also to improve strength (Beale, 1970).

2.2 Types of Waste Foundry Sand

There are three types of WFS based on molding processes. The molding processes which involve sand are:

1. Green sand molding
2. Chemically bonded process
3. Shell molding process

In Indiana, the most commonly used process is green sand molding. Green sand indicates that the metal is poured into the molds when the sand is damp, as it is when the mold is made (Wendt, 1942). Green sand is composed of four major materials. Sand comprises 85 to 95% of the green sand mixture. Most often the sand is inert silica, but olivine and zircon sand are also used. Approximately, 4 to 10% of the mixture is made of some form of clay, such as western or southern bentonite and fireclay. The clay acts as a binder for the green sand and provides strength and plasticity. Combustible additives like seacoal, cereal, fuel oil, and wood flour typically make up from 2 to 10% of the green sand mixture. The final additive of green sand is water which is usually added in small percentages (2 to 5% by weight) (Kunes, 1987).

Chemically bonded sands are those that use furan, phenolic urethane and acid-cured nobake systems, as well as alkyd and phenolic urethane cold box processes (Hayes, 1993). Cold box processes involve the gassing of core sand mixtures to achieve almost instantaneous curing, resulting in high handling strength and precise dimension.

Shell molding uses a mixture of sand and thermosetting resin (usually phenol-formaldehyde) to form the mold. When it touches a heated pattern, the sand-resin

mixture forms a thin shell due to the polymerization of the resin which binds the sand particles. The thin shell is used as a mold, backed up by loose sand (Cannon, 1986).

2.3 State of Foundry Industry in Indiana

According to the 1992 Harris Manufacturers Directory, there are about 154 foundries in Indiana (Harris, 1992). However, there are about 38 INCMA foundry members, and hence, all the possible information regarding the annual production tonnage of WFS and the annual production tonnage of different metals cast in Indiana is very restricted. The list of 1992 foundry members of INCMA and their location are appended in Appendix A. Table 2.1 summarizes important information about the 30 foundry members of INCMA.

Table 2.1 Statistical Information Survey Results (From INCMA, 1992)

Type of Metal Cast	Tons Per Year
Gray Iron	642,139
Ductile Iron	63,905
Steel	47,978
Aluminum	4,608
Copper	3,230
Brass/Bronzes	2.5
Nickel Base	50
Stainless Steel	165
Mn Steel	280
Type of Molding Sand	Tons Disposed
Green Sand	247,651
Chemically-Bonded	176,610
Shell Mold	21,783

2.4 Waste Sand Generation

Although there may be differences in certain operations, the basic foundry process varies only slightly from one foundry to another. All foundry operations produce castings by pouring molten metal into molds, often consisting of molding sand and core sand. Once the casting has hardened, it is separated from the molding and core materials in the shakeout process. Castings are cleaned, inspected, and then shipped for delivery. Figure 2.1 is a schematic of a typical foundry process, showing both finished product and the types of air emissions and wastes generated.

In Indiana, the most commonly used process is green sand as discussed earlier. Figure 2.2 shows a schematic of a typical green sand system. The wastes common to this sand system can be grouped into two general categories: waste sands and emission control residuals. Waste sands generally consist of three individual waste types:

1. Waste return sand
2. Mold and core lumps
3. Waste green sand

Waste return sand is generated in several areas; at shakeouts; as floor sweeping in finishing areas; and as losses from the sand conveying system. This sand has gone through the pouring process and has been subjected to pouring temperatures. Large amounts of sand are also generated from sand screenings. The mold and core lumps generated can be a significant quantity depending on the amount of core used in the molding process. Waste green or system sand in foundries with high core usage represents the larger quantity of waste sand generated.

Figure 2.1 Iron and steel foundry process flow and emission sources (USEPA, 1980)

Figure 2.2 Schematic of typical green sand molding system (Kunes, 1983)

The second category of wastes, emission control residuals, vary greatly in chemical and physical characteristics. The primary emission control residuals from the green sand molding system consists of dusts generated off of mold making, pouring, shakeout, return sand lines and those generated from sand and bentonite storage and sand mixing processes. In many foundries all these processes may be handled by the same dust collection system or may be collected by multiple dust collection units.

2.5 Waste Use and Disposal Options

The available options for WFS fall into the following categories:

- Reusing
- Reclamation of waste materials
- Constructive uses of non hazardous wastes
- Treatment of hazardous wastes and disposal

2.5.1 Reusing

Most foundries reuse some portion of their foundry sand. However, some new sand and binder is typically added to the used sand to maintain the molding properties of the sand and enhance casting quality. Although some sand is lost to spills and shakeout, an additional amount of sand must often be removed so the system can accommodate the portion of new sand and binder that must be added.

2.5.2 Reclamation

Sand reclamation is defined as the physical, chemical or thermal treatment of a

refractory aggregate to allow reuse without significantly changing its original properties (Hayes, 1993). Two types of reclamation system are mostly used. Mechanical reclamation works well with organic/resin bonded sands. Thermal reclamation, on the other hand, is usually used if mechanical recovery cannot do the job. It is important to remember that inorganic binders do not burn.

Mechanical reclamation includes lump reduction, magnetic materials separation and mechanical scrubbing before sand cooling and dedusting (Hayes, 1993). Lump breaking is achieved by mulling and scrubbing until the sand can pass through primary and final screens. Coarse screens are used to remove large chunks of metal and core butts. The larger metal pieces collected in the screens are usually remelted in the furnace. Increasingly finer screens remove additional metal particles and help to dedust the sand before it is molded. Some foundries remelt these smaller particles, other foundries sell this portion to metal reclaimers (Ostrom, 1989).

Thermal reclamation regenerates molding sand by stripping the used sand of its binder in a rotary kiln or fluidized bed application and restoring the sand to a virgin condition. Thermal treatment does not remove inorganics i.e. clay and sodium silicate, but may prepare them for easier attrition. Organic binders are incinerated in the thermal process, metals captured by the baghouse may be reclaimed, and the treated sand substituted for new sand.

2.5.3 Constructive uses

Two types of constructive uses for WFS are reported in the literature:

A) Aggregate uses

B) Chemical uses

Aggregate uses include application of WFS in geotechnical fill, Portland cement concrete, asphalt concrete, and snow and ice abrasives. Chemical uses include application of WFS in cement, smelting, and vitrification of hazardous wastes and rock wool. The author synthesized the information reported in the literatures for constructive uses (Javed, 1991) and (Javed and Lovell, 1992)

2.5.4 Treatment and disposal

For the portion of the waste stream that cannot be recycled, or reused, chemical stabilization has been demonstrated to be an effective technology for reducing the degree of hazard associated with these wastes (Ostrom, 1989).

Generally, WFS from ferrous foundries are found to be non hazardous (Ham et al., 1990). Foundries casting copper-based alloys (brass or bronze foundries), in particular, generate hazardous waste sand contaminated with cadmium, lead, copper, nickel and zinc, often in total and extractable concentrations. Thus the treatment will be applied to foundries generating hazardous wastes.

Most chemical stabilization used for treating hazardous waste employs cement or pozzolanic materials as stabilizing agents. Some related technologies, encapsulation and thermoplastic binding are not as widely used on hazardous waste foundry sand (Ostrom, 1989).

Chemical stabilization, often referred to as solidification or fixation, encompasses treatment processes that chemically reduce the mobility of metal constituents in a waste,

thereby minimizing the tendency for metals to leach from the treated sand. This technology is applicable to wastes containing heavy metals with a high level of suspended solids, low total organic content and low oil and grease content. Stabilizing agents, generally lime or cement-based, form a lattice structure and/or chemical bonds that bind the metal constituents to the solid matrix. This process reduces the leachability of the metals when the treated sand comes in contact with water or a mildly acidic solution, such as that likely to be found in a land disposal facility. The stabilization process may also employ additives, such as soluble silicates, that accelerate the curing rates or enhance the stabilizing properties of the treated sand. In most stabilization applications, the process consists of first mixing the waste, stabilizing agent and additives, and then curing the mixture for 7 to 28 days (Ostrom, 1989).

The cement-based stabilization process combines Portland cement and water to form calcium hydroxide and a calcium silicate hydrate called tobermorite gel, the main cementing component of concrete. The high pH of the cement mixture helps to keep metals in the form of insoluble hydroxides and carbonate salts. The lime based process uses pozzolan, a finely divided, noncrystalline silica, such as fly ash or cement kiln dust. When combined with lime and water, the pozzolan becomes cementitious and incorporates the waste into the stabilized structure (Ostrom, 1989).

Generators of hazardous WFS are required to meet a certain treatment standard before disposing of the waste to land disposal. The treatment standard for hazardous WFS is usually based on sand reclamation and metal recovery used in conjunction with chemical stabilization applied to the unrecoverable waste fraction (Ostrom, 1989). The treated sand meeting the treatment standard is still considered hazardous and must be

disposed of in a hazardous waste land disposal facility unless the treatment process allows foundries to render the WFS to be nonhazardous or below the regulatory limits. Then it can be disposed of safely or used for construction purposes.

2.6 Physical/Mechanical Properties

This section has been subdivided in five subsections, namely, physical characteristics, geotechnical fill properties, asphalt concrete properties, Portland cement concrete properties and controlled low strength material properties. Among the physical characteristics, physical appearance, specific gravity, loss on ignition and gradation are reported in the literature. Among the geotechnical properties, only moisture-unit weight relationships and permeability on WFS, using the green sand process, have so far been reported. Data on asphaltic concrete properties include results on percentage voids, voids in mineral aggregate, stability, flow and unit weight of asphaltic mixtures of control and mixtures fabricated with 10% iron WFS. In addition, moisture conditioning of asphaltic mixtures fabricated with the same 10% iron WFS is also reported. Data on Portland cement concrete have so far been reported by two sources (AFS, 1992 and McIntyre et al., 1991). However no published data on use of WFS in controlled low strength material are so far reported.

2.6.1 Physical Characteristics

2.6.1.1 Gradation

The grain size distribution is normally expressed as relative percentages of the total weight. For materials that have variable specific gravities dependent on particle

sizes, the standard "percent finer by weight" plots may result in misleading interpretation of the material's gradation (Gallaway and Hargett, 1969). In such cases, it would be physically more meaningful to plot particle sizes as a function of solid volume rather than weight, because volume is generally the parameter of interest (Horvath, 1983). In other words, a grain size distribution based on "percent finer by solid volume" would provide a more realistic indication of the gradation (Huang, 1990).

The grain size distribution of WFS is quite uniform, with a majority of the sizes falling within a narrow range between the No. 50 and No. 100 sieves. Most of the WFS materials reported are found to be medium to fine sand. Figure 2.3 shows distributions of the ten samples of ferrous WFS and their comparison with gradation of typical construction aggregates (AFS, 1992). WFS have been found to be too fine to satisfy the specifications for general fine aggregate.

2.6.1.2 Specific Gravity

Specific gravity is the ratio of the mass of a given volume of aggregate to the mass of an equal volume of water. The specific gravity of WFS depends on chemical composition of the sand as well as the internal porosity of the constituent particles. Sands with high metal contents will have higher specific gravities. The bulk specific gravities reported in the literature on four green sand samples ranged from 1.985 to 2.45 (AFS, 1991 and McIntyre et al., 1991). The bulk specific gravity of a chemically bonded WFS was found to be 2.60 (McIntyre et al., 1991). These specific gravities were carried out according to ASTM C 128 which involves removing air bubbles by agitating, rolling, and inverting the pycnometer.

Figure 2.3 Gradations of typical construction aggregates and WFS (AFS, 1992)

2.6.1.3 Moisture Content

Moisture content is one of the most significant index properties used in establishing a correlation between soil behavior and an index property. It is also used in almost every equation expressing the phase relationships of air, water and solids in a given volume of material.

In most of the cases WFSs have been reported to be almost dry. However variation from one foundry to another, and the manner in which the WFSs are stored, may result in inconsistency in the moisture contents. The moisture contents for the green sand samples, chemically bonded samples and shell molded samples were reported to be in the range of 0.08% to 4.59%, 0.11% to 3.48% and 0.16 to 0.18%, respectively (AFS, 1991).

2.6.1.4 Loss on Ignition

Loss on ignition (LOI), determines the amount of unburned carbon. As mentioned in the previous sections, some carbonaceous and organic matters are used as additives to the foundry sand. Differences in the proportions of these additives and different pouring temperatures result in different values of LOI. Also the LOI values are affected by the manner in which the WFS materials are stored on the foundry property before they are taken to landfills.

The LOI values for WFS using the green sand process, the chemically bonded process and the shell molding process were reported to be in the range of 0.45% to 9.47%, 0.37% to 3.51% and 0.41% to 1.83%, respectively. The LOI values for virgin sand has been reported to be in the range of 0.07% to 0.29% (AFS, 1991, McIntyre et

al., 1991).

2.6.1.5 Shape and Texture

In a foundry process, a significant number of agglomerates result due to non-homogeneous mixing of sand with binders and additives which surround the individual sand grains (McIntyre et al., 1991). Thus the shape and texture of the WFSs are functions of their formation and the appearance of virgin sand. It has been reported by AFS research that most of the WFSs tested contained subangular to rounded grains and a few had rounded grains (AFS, 1991).

In asphalt concrete, angular aggregates result in aggregate interlock that increases the stability of asphalt concrete mixtures. Conversely, the use of well-rounded gravel in either dense or open-graded asphalt mixtures gives reduced stability. Also, in general, the rougher the surface texture, the higher the stability and durability of the asphalt concrete mixture, because rougher texture offers better adhesion to hold the aggregate in place (Barksdale, 1991).

On the other hand, greater angularity and roughness is generally considered a disadvantage in Portland cement concrete because the water demand to maintain a workable mix increases. Consequently, more cement is needed to maintain the same water/cement ratio and overall strength.

2.6.1.6 Deleterious materials

Presence of certain substances in an aggregate are harmful to the desired properties of aggregate-binder systems. These substances occasionally found in aggregate

include: (1) structurally soft and/or weak particles, (2) clay and other types of surface coatings, (3) organic materials (4) aggregate particles such as chert which exhibit disruptive expansion, and (5) aggregate particles which react chemically (Barksdale, 1991).

In asphalt concrete, the plasticity index (PI) is used to identify and measure the quantity of deleterious materials. ASTM D 1073 limits the PI to a value of four or less. So far no information on PI for WFS has been reported.

Organic material affects the cement hydration process and therefore the strength and durability of concrete (Barksdale, 1991). Loss on ignition (LOI) determines the amount of organic material. Reported data on LOI for WFS are contained in the LOI section.

Another indicator for deleterious materials is the excess of particles smaller than No. 200 sieve. An excess of particles smaller than 200 mesh can interfere with the bonding of aggregates by stripping the binder from the surface of the grains and degrading the durability of the hardened concrete. Clays and other fines can increase the water demand which increase the amount of cement needed to maintain strength. The standard ASTM C33 allows for 5% by weight of minus 200 mesh material. Approximately half of the 27 WFS tested in the AFS research failed this requirement (AFS, 1991).

2.6.1.7 Clay Lumps and Friable Particles

Clay lumps are lumps of clay and silt which remain cohesive during processing. Friable particles are characterized by a poor bond between the grains, hence they break

down easily into many smaller pieces. These lumps and friable particles in the finished hot mix asphalt mixture can break down from freezing and thawing or wetting and drying and cause stripping, ravelling, or otherwise affect the durability of the asphalt mixture.

General purpose fine aggregate may contain up to 3% clay lumps and friable particles. The plus 12 mesh coarse material measured in the AFS testing is an indication of the amount of clay lumps and agglomerated material present. In the AFS research, sixteen of twenty seven contained less than 3% clay lumps and/or friable particles. The values ranged from less than 1% to over 32% (AFS, 1991).

2.6.1.8 Durability/Soundness

Durability is intended to be a measure of the material's resistance to all types of weathering action. The soundness test, ASTM C 88 is an empirical screening test that is intended to provide an indication of durability. The physical damage produced during the test includes crumbling, flaking, splitting, cracking, and granular disintegration of the aggregate particles (Mantuani , 1978).

It has been suggested that the sulfate test might be used to accept aggregates but not to reject them (Woolf, 1956), the assumption being that aggregates that withstand the test are good while those that break down may or may not be bad. Unfortunately, the test is not reliable even to that extent. Vollick and Skillman report that durable concrete was produced with aggregates having as much as 32 percent loss in the sodium sulfate solution (Vollick and Skillman, 1952). A low loss in sulfate soundness test is usually, but not always, evidence of good durability, while a high loss places the material in a questionable category until performance data become available (Yoder et al., 1975).

The soundness losses on two WFS from the green sand process have been reported to be 5% and 15% (AFS, 1991).

2.6.1.9 Absorption

Absorption values are used to calculate the change in the weight of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition, when it is deemed that the aggregate has been in contact with water long enough to satisfy most of the absorption potential. If a construction aggregate is highly absorptive, the binder requirement and/or mixing water requirement for designed mixing characteristics is increased.

Because of the surface area per unit volume of material, for similar minerals, absorption is generally higher for fine aggregates than for coarse aggregates. Crushed angular particles generally have higher absorptions than smooth rounded particles because the surface area is higher (Mullen, 1978). Absorption by various types of aggregate ranges from virtually zero to over 30% of the dry aggregate weight. The percentage absorption values on two green WFS samples have been reported to be 2.7 and 1.5.

2.6.2 Geotechnical Properties

The author is unaware of any published field data on geotechnical properties on WFS. However from unpublished sources, it was reported that around 10,000 cubic yards of WFS was incorporated into a roadway embankment in Waupaca county, Wisconsin. The maximum thickness of WFS in the embankment was about 15 ft. After the WFS was placed and compacted, a 2-ft thick layer of compacted clay was used to

cover the WFS embankment. A layer of top soil was placed on the side slopes. The embankment was then fertilized and seeded according to Wisconsin Department of Transportation (WDOT) specifications. No engineering properties for this WFS are available. It was reported that WFSs readily compacted and supported the hauling equipment (WDOT, 1990).

Laboratory data on a few geotechnical properties have been developed by AFS research which are included in the discussion below.

2.6.2.1 Permeability

The parameter that defines the rate at which a fluid or gas passes through a material is the coefficient of permeability. The value of the coefficient of permeability, often referred to as permeability, gives the superficial or discharge velocity per unit of gradient, as if the flow occurred through the total volume of the medium, not the void area only. Permeability is the most variable engineering properties of soils, with an extremely large range (i.e., from 10 cm/sec for gravel to 10^{-9} cm/sec for colloidal clay). It depends on the characteristics of both the permeant and the soil. The void ratio, composition, fabric, and degree of saturation are the major characteristics which govern the permeability of soils (Lambe and Whitman, 1969).

Table 2.2 lists the coefficient of permeability for various types of soils (Hough, 1969). Table 2.3 gives a classification of soil on the basis of permeability (Terzaghi and Peck, 1967).

Table 2.2 Typical Values of Coefficients of Permeability (Hough, 1969)

	Particle size range, (mm)		"Effective" size		Coefficient of permeability, k
	D_{max}	D_{min}	$D_{20}(\text{in.})$	$D_{10}(\text{mm})$	
Clean, fine to coarse GRAVEL	80	10	1/2	--	10
Fine, uniform GRAVEL	0	1.5	1/8	--	5
Very coarse, clean, uniform SAND	3	0.8	1/16	--	3
Uniform, coarse SAND	2	0.5	---	0.6	0.4
Uniform, medium SAND	0.5	0.25	---	0.3	0.1
Clean, well-graded SAND & GRAVEL	10	0.05	---	0.1	0.01
Uniform, fine SAND	0.25	0.05	---	0.06	40×10^{-4}
Well-graded, silty SAND & GRAVEL	5	0.01	---	0.02	4×10^{-4}
Silty SAND	2	0.005	---	0.01	10^{-4}
Uniform SILT	0.05	0.005	---	0.006	0.5×10^{-4}
Sandy CLAY	1.0	0.001	---	0.002	0.05×10^{-4}
Silty CLAY	0.05	0.001	---	0.0015	0.01×10^{-4}
CLAY (30 to 50% clay sizes)	0.05	0.0005	---	0.0008	0.001×10^{-4}
Colloidal CLAY ($-2\mu\text{m} \geq 50\%$)	0.01	10A	---	40A	10^{-9}

Table 2.3 Classification of Soils According to Their Coefficients of Permeability (Terzaghi and Peck, 1967)

Degree of Permeability	Value of k (cm/sec)
High	Over 10^{-1}
Medium	10^{-1} to 10^{-3}
Low	10^{-3} to 10^{-5}
Very low	10^{-5} to 10^{-7}
Practically impermeable	less than 10^{-7}

Permeability values on three WFS from green sand processes have been reported to be in the range of 1×10^{-3} cm/sec to 1.3×10^{-6} cm/sec. The range of permeability on WFS seems to be large and it primarily depends on the amount and type of binders and additives used and the pouring temperatures through which these sands have undergone. High pouring temperatures destroy the activity of some bentonite.

2.6.2.2 Compaction Characteristics

Compaction produces densification of soils by the application of mechanical energy. Investigation and experience have shown that physical properties of a soil mass are greatly affected by increases in unit weight or degree of density brought about by compaction. There are several advantages which occur through compaction: (a) soil strength increases and slope stability can be improved, (b) detrimental settlements can be reduced, (c) bearing capacity of structural fills or pavement subgrades can be improved, and (d) undesirable volume changes can be controlled (Holtz and Kovacs,

1981).

The compaction characteristics of soils are commonly discussed in terms of their moisture-unit weight relations. If completely dry soil is placed in a mold in layers and each layer compacted under the weight of a falling hammer, a particular unit weight is obtained. In general, if a small percentage of water is added and the test repeated, a higher unit weight is obtained because the water lubricates the soil grains, permitting greater compaction. By repeating the test on samples with increasing percentage of water, a curve is developed relating dry unit weight to moisture content, and a peak value is found beyond which the addition of moisture causes a decrease in unit weight as shown in Figure 2.4 (Krebs and Walker, 1971).

The results of the moisture-unit weight relation tests (ASTM D 698) on three WFS samples from the green sand process are shown in Figure 2.5 (AFS, 1991). The results indicate that these materials are about equally compactible over a wide range of water content.

Moisture-unit weight relations of uniform cohesionless soils are somewhat different in shape (as noted above). Uniformly graded sands consisting of a narrow range of particle sizes, give a flatter compaction curve from which the optimum condition is not easy to define. A "double peak" is often obtained from uniformly graded sands such as shown by Curve 4 in Figure 2.6 (Head, 1980). At intermediate water content, some menisci begin to form in the partially saturated soil. These menisci formed by capillary stresses cause an apparent cohesion between particles (Mitchell, 1976), thus increasing the shear strength which, in turn, resists rearrangement of the sand grains. Upon the addition of more water, the negative pore water pressure and the antilubricant effect

Figure 2.4 Typical moisture-unit weight curve (Krebs and Walker, 1971)

Figure 2.5 Moisture-unit weight relations of three WFS from green sand process (AFS, 1992)

Figure 2.6 Compaction curves for some typical soils (Head, 1980)

come in balance. At water contents larger than those at which significant negative pore water pressure exists, the water produces a lubrication effect on the soil particles and causes an increase in density. The limit of lubrication of the particles is reached when the voids become filled with water (Lee and Suedkamp, 1972).

2.6.2.3 California Bearing Ratio

The California Bearing Ratio (CBR) Test, (ASTM D 1883), is used to evaluate and classify the support, expressed as a CBR value, of laboratory-compacted soil, soil-aggregate combinations, and aggregate base. The test indicates resistance of the material to a punching shear failure (Barksdale, 1990). The CBR test is normally performed on remolded (compacted) specimens, although it may be performed on undisturbed soils or on soil in situ. In the laboratory the test is normally conducted in accordance with ASTM D 1883. In the field the CBR test is performed to obtain a measure of the natural subgrade resistance by jacking the plunger against the reaction of a truck. Field CBR tests occasionally are used for evaluation and design when (1) the degree of saturation of the material to be evaluated is 80% or greater, (2) the material is coarse grained and cohesionless, or (3) the material has not been modified by construction activities during the two years preceeding the test. The test is performed in accordance with ASTM D 4429 (Barksdale, 1991).

The CBR value is calculated by dividing the force on the piston at 0.10 or 0.20 in. penetration by a standard reference load of 1,000 or 1,500 lb at penetrations of 0.1 or 0.2 in., respectively. A CBR value of 100 is used as the standard reference, as it indicates excellent material with resistance and support properties similar to those of

crushed rock.

Factors contributing to developing high CBR values are: (1) a large maximum size, (2) a proper gradation defined by good representation of various grain size fractions, (3) a greater amount of crushed material and improved geometric properties (shape/angularity/surface texture), and (4) a reduced plasticity index. For a given granular material, the CBR value can be significantly increased by increasing the compacted density (Barksdale, 1991).

High quality, dense graded crushed stone commonly has CBR values in excess of 100. Well graded gravels typically have CBR values ranging from 30 to 80. Less well graded gravel typically develop lower CBR values ranging from about 20 to 60. The CBRs for natural sand generally vary from 10 to 30.

2.6.2.4 Shear Strength

Many geotechnical problems such as bearing capacity, lateral earth pressures, and slope stability are related to the shear strength of a soil. Shear strength is the measure of the rupture strength ordinarily applied in geotechnical problems and is represented by the strength mobilized during the displacements of adjacent elements along a planar or curved surface (Hunt, 1986). Components of shear strength can be the angle of shearing resistance ϕ or cohesion c or both.

The strength parameter of granular soil is ϕ , the angle of shearing resistance. This angle is affected by gradation, grain shape and roughness of grain surface, coarseness of grains, and state of compaction (Leonards, 1962). The angle of shearing resistance is only moderately influenced by the rate of shear strain (Casagrande and Shannon, 1948);

it is hardly influenced by previous stress history (Bishop and Eldin, 1953); and the effect of confining pressure can be neglected within the pressure range of practical interest (Bishop and Eldin, 1953).

A greater angle of shearing resistance can be obtained in well-graded materials than in uniformly graded materials because higher density can be achieved in the well-graded materials. Angular particles can be fitted together in a very dense condition which results in a high degree of interlocking, whereas rounded or spherical particles cannot be so fitted. Particle size affects the shearing resistance by influencing the amount of shearing displacement required to overcome interlocking and to bring the grains to a free sliding position (Hough, 1969). For a coarse material the amount of movement required for this purpose is, of course, greater than for a finer material.

Table 2.4 shows typical values of the angle of shearing resistance for sands. As discussed above, ϕ increases with the degree of compaction, angularity of grains and grain size. Also, it is larger for well-graded soils than for uniformly graded granular soils.

The author is unaware of any published information on shearing properties of WFS. From one unpublished source, the angle of shearing resistance for different WFS specimens has been reported to be about 34 degrees, which is comparable to reported values for conventional sands.

Table 2.4 Summary of Shearing Resistance Data from Different Sources

Classification	State of Compaction	Values of ϕ Degrees	References
Uniform fine to medium sand	Medium dense	30 to 34	Hough, 1957
	Dense	32 to 36	
Well graded sand	Medium dense	34 to 40	Hough, 1957
	Dense	38 to 46	
Uniform medium sand	Very loose	28-30	Leonards, 1962
	Moderately dense	32-34	
	Very dense	35-38	
Well graded medium sand	Very loose	32-34	Leonards, 1962
	Moderately dense	36-40	
	Very dense	44-46	

2.6.2.5 Compressibility

A change in the stress system on a soil mass will result in a change in volume of the mass. The compressibility of a fill or embankment determines the magnitude of the vertical deformation at the surface of the fill or embankment. The deformation of the granular soils is caused by two mechanisms; distortion and crushing of individual particles, and relative motion between particles as the result of sliding or rolling (Lambe and Whitman, 1969). For granular materials, this deformation is a result of relative movement and rearrangement of the individual particles, when loading is low to moderate. At higher loading, particles begin to crush and fracture.

For granular materials, settlement occurs instantaneously upon the application of load. In saturated fine-grained cohesive soils, because the interstices between the particles are small, a longer time is required for settlement. When present in the pore spaces, micas, clays, and other fine grained materials appear to act like a dry lubricant and increase sand compressibility (Allen and Chilingarian, 1975). Shultze and Moussa also report an increased compressibility of sand when cohesive soil had been mixed with it (Shultze and Moussa, 1961).

The degree to which a granular soil can undergo deformation is dependent upon (a) original void ratio, (b) shape of the grains, (c) roundness of grains, (d) composition of the sand and (g) size grading. At least for temperatures up to 140°F and up to overburden loads of about 3000 psi, compressibility does not seem to be dependent to any large degree upon temperature or pore fluid type (Allen and Chilingarian, 1975).

In general, a uniformly graded soil compresses more than a well-graded soil; and an angular sand is more compressible than a rounded sand. Roberts and DeSouza observed that, at moderately low pressures, angular sands crushed and compressed more than rounded sands; but at very high pressures, the compression behaviour of angular and rounded soil is very similar (Roberts and DeSouza, 1958). Lee and Farhoomand tested different granular soils and found that coarse soils compressed more and showed more particle crushing than fine soil (Lee and Farhoomand, 1967). The author is unaware of any reported information on the compressibility of WFS.

2.6.2.6 Resilient Characteristics

The response of subgrade material under dynamic loading that simulates traffic

is different from that under static loads. Therefore it should be tested under dynamic stresses of a magnitude expected in a pavement structure in order to characterize the material for the evaluation of pavement response under traffic. This has been recognized by researchers since 1958 (Seed and Chan, 1958).

The resilient modulus (M_r) is a dynamic test response defined as the ratio of repeated axial deviator stress (σ_d) to the recoverable or resilient axial strain (ϵ_r) or

$$M_r = \frac{\sigma_d}{\epsilon_r} \quad (2.1)$$

Many studies (Grainger and Lister, 1962; and Seed et al., 1962) showed that the measured loading pulse is approximately sinusoidal, and that its magnitude decreases with depth while the duration increases with depth. It was shown by Barksdale (1971) that the magnitude and duration of the loading pulse are a function of the vehicle speed.

The most important factors influencing the resilient behavior of granular materials are the state of stress, degree of saturation, initial density and gradation. Other factors, such as stress duration, stress frequency, sequence of load, and number of stress repetitions necessary to reach an equilibrium-resilient strain have in general little effect on the M_r response. These have been covered adequately in the literature (Monismith et al., 1967; Monismith et al. 1971; Chou, 1977; Smith and Nair, 1973; Hicks and Monismith, 1971; Tanimoto and Nishi, 1970; Allen and Thompson, 1974, Kalcheff and Hicks, 1973).

Hicks and Monismith (1971), Kalcheff and Hicks (1973), Monismith et al. (1967), Allen and Thompson (1974), Brown and Pell (1967) and Khedr (1985) have reported a significant increase in resilient modulus for untreated granular base course materials

with an increase in confining stress. Smaller increases in resilient modulus are associated with an increase in repeated deviator stress at a constant confining stress. These effects of confining stress and deviator stress upon resilient modulus have been approximated by

$$M_r = k_1 \theta^{k_2} \quad (2.2)$$

where θ is the first stress invariant ($\sigma_1 + \sigma_2 + \sigma_3$), and k_1 and k_2 are constants obtained from regression analysis of the test results and depend on the type of material and physical properties of the specimen during the test.

The above model known as the k - θ model has been extensively used because of its simplicity. However it has some deficiencies. First, equation 2.2 is dimensionally unsatisfactory. Second, there is evidence that the relationship between M_r and θ varies with the magnitude of the repeated deviator stress. Repeated load triaxial testing of a crushed granite by Brown (1974), indicated that the relationship cannot be represented by a single straight line. Furthermore, Cole et al. (1981) and Johnson et al. (1986) showed that the relationship is dependent on stress ratio, and proposed an equation similar to the k - θ model, involving the second invariant of stress (J_2) and the octahedral stress ratio (τ_{oct}):

$$M_r = k_1 \left(\frac{J_2}{\tau_{oct}} \right)^{k_2} \quad (2.3)$$

where $J_2 = \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1$, $\tau_{oct} = (\sqrt{2}/3)\sigma_d$, and k_1 and k_2 are constants.

Furthermore, k - θ implies that for a constant confining pressure, the resilient modulus should increase with an increase in repeated deviator stress. However, Khedr

(1985) found that for deviator stress less than 10 psi, the modulus decreased with increased deviator stress. Uzan (1985) also noticed the reversed trends of resilient modulus of a dense graded aggregate. Uzan suggested that the repeated deviator stress σ_d be included in the model:

$$M_r = k_1 \theta^{k_2} \sigma_d^{k_3} \quad (2.4)$$

where k_1 , k_2 , and k_3 are constants.

Equations 2.2, 2.3, and 2.4 clearly underline the influence of repeated deviator stress on the resilient modulus of granular materials; however, they are dimensionally unsatisfactory and have not been generally accepted for material characterization. On the other hand, the k - θ model remains popular because of its simplicity and containing only one variable.

Nataatmadja and Parkin (1989) proposed the following model which is dimensionally satisfactory and incorporates deviator stress.

$$\frac{M_r \sigma_d}{\theta} = A + B \sigma_d \quad (2.5)$$

A plot of $(M_r \sigma_d)/\theta$ versus σ_d allows A and B to be determined as the intercept value and the slope of the straight line respectively.

The degree of saturation of most untreated granular base course material has generally been found to affect its resilient characteristics. Repeated load triaxial tests conducted by Haynes and Yoder (1963) on gravels and crushed stone, indicated that there was a critical degree of saturation near 80-85 percent, above which granular materials became unstable and deteriorated rapidly under repeated loading.

Smith and Nair (1973) found that for well graded gravels, k_1 was reduced and k_2 unchanged with increasing saturation. Rada and Witczak (1981) showed marked reduction in the magnitude of k_1 with increasing degree of saturation for 159 separate test results on a variety of aggregates. The influence of the degree of saturation on k_2 showed no distinctive pattern and was rather unaffected. Lee (1993) concluded that the change of compaction water content had no effect on the resilient characteristics of dune sands compacted with same compactive effort. Parameters k_1 and k_2 were found to be unaffected by the change of water content for both impact and vibratory compactive methods.

Several studies have been conducted by previous researchers into the effect of density on the M_r response of granular materials (Monismith et al., 1967; Monismith et al. 1971; and Chou, Y.T., 1977). These studies have indicated that, although increase in density results in an increase in modulus, the effect is relatively small compared with changes caused by stress level and moisture. Hicks and Monismith (1971) showed that the coefficient k_1 increases with increasing density while k_2 remains relatively constant or decreases slightly. Rada and Witczak (1981) observed that k_1 increased gradually with increasing compaction energy, and that k_2 showed no distinctive pattern and remained essentially constant.

Previous research investigations of the effect of aggregate gradation have indicated no general trend regarding the influence of fines (percentage passing No. 200 sieve) on the M_r response (Monismith et al. 1967; Monismith et al. 1971; Chou, 1977; Rada and Witczak, 1981). Knutson and Thompson (1977) found that the resilient moduli of No. 4 and No. 5 ballast gradation aggregates (American Railway Engineering Association)

are usually slightly lower than that of a well graded aggregate.

Hicks and Monismith (1971) showed that the constant k_1 of partially crushed aggregate generally increased as fines content increased. The same trends were observed for the partially saturated and saturated test series.

Cohesive soils typically display a decrease in moduli with increasing deviator stress (Terrel and Award, 1972). The response of fine grained soils is mostly related to the water content, dry density, index properties (Soderman et al., 1968; Thomson and Robnett, 1979; Bandyopadhyay and Frantzen, 1983; Thorton and Elliot, 1986). For a given soil sample, i.e., constant soil parameters, M_r still varies with the applied stress level (σ_d and σ_3) as shown in Figure 2.7. Due to the stress dependency of M_r , it is difficult to arrive at a single design value of M_r . Resilient modulus for fine grained soils are generally expressed in the following form:

$$M_r = A \sigma_d^B \quad (2.6)$$

Both the A and B parameters are determined experimentally. The A parameter gives a measure of stiffness of the soil sample. The value of the B parameter is usually negative, suggesting an inverse relationship between M_r and the applied stress (σ_d). Terrel and Award (1972) suggested that the resilient modulus-deviator stress relationship (M_r - σ_d) shown in Figure 2.7 can be defined in terms of a "breakpoint" modulus; that is, a deviator stress at which a significant change in the slope occurs. A breakpoint resilient modulus M_{ri} , corresponding to the modulus at a deviator stress of 6 psi was used by Thompson and Robnett (1979) to characterize the resilient response of a wide range of Illinois subgrade soils.

Figure 2.7 Typical variation of M_r with σ_d and σ_3 for cohesive soils

In addition to the factors described above, several other factors such as: the number of stress applications (Seed et al. 1962; 1967; Monismith et al., 1967), thixotropy (Mitchell, 1960; Seed and Chan, 1957), matrix suction (Fredlund et al. 1975) and fabric (Bohra, 1993) influence the M_r values. A discussion of these factors is given by Lee et al. (1993).

2.6.2.7 Frost Susceptibility

If a material is capable of drawing water up from the water table by capillary action to the depth at which the temperature is below freezing, the material is susceptible to frost action. Soil susceptibility to frost heave and ice lensing depends on its gradation. In uniform soils ice lenses do not develop unless the grains are smaller than 0.01 mm; fairly uniform soils must contain at least 10% of grains smaller than 0.02 mm (Terzaghi and Peck, 1967). Waste foundry sands have been mostly reported to be poorly graded and having less than 10% by weight passing the 0.02 mm mesh.

2.6.2.8 Liquefaction

The loss of strength with remolding accounts for the phenomenon of liquefaction in quick clays and very loose sands. Field experience has demonstrated that there are a number of conditions under which a soil becomes susceptible to cyclic liquefaction. From the aspects of gradation, fine sands and silty sands are most susceptible, especially when they are poorly graded, as shown in Figure 2.8. Permeability is relatively slow, and to be susceptible, the stratum must be below the groundwater level and saturated, or nearly so, without the capacity to drain freely. Boundary drainage conditions and soil

stratification, therefore become important (Hunt, 1986).

Kezdi has reported that liquefaction susceptible soils have their effective diameter smaller than 0.1 mm, their uniformity coefficient smaller than 5 and their natural porosity is at least 44% (Kezdi, 1974). Castro (1969) concluded that of the three sands tested, the one with the subrounded to subangular grains was more susceptible to liquefaction than the sands with angular grains. Kishida (1969) reported that most of the liquefaction of sands occurred under these conditions, for sand in which $D_{50} < 2$ mm. and $C_u < 10$. The effective overburden pressure was less than 2.0 kg/cm^2 , $D_r < 75\%$ and no fine-grained soil strata layer above the saturated sands. D'Appolonia suggested that liquefaction might occur where relative density values were as high as 50% during ground accelerations in the order of $0.1g$, but for sands with relative density in the range of 75% or greater, liquefaction was unlikely (D'Appolonia, 1970). Other influencing factors are the effective overburden pressure and the duration, amplitude, and period of the induced ground motion.

Proper compaction and control of ground water and surface water will be essential to provide a stable WFS embankment and to minimize environmental effects.

Figure 2.8 Effect of grain size distribution on cyclic liquefaction susceptibility (Finn, 1972)

2.6.2.8 Erosion

The slopes of highway and railroad embankments and earth cuts are subject to erosion by the runoff from precipitation and/or melting snow. The susceptibility to erosion increases as the slope of the surface increases and also varies with the type of soil in the slope. Fine granular soils and silts without clay binder are least resistant to erosion.

The oldest method to resist erosion consists of mixing of granular soils with clay which provides a binder, improves strength and compactibility. Erosion of WFS from the green sand process should not be a problem because WFS from the green sand process contains clay binder. Moreover, environmental considerations will require that WFS from any process be properly compacted and capped with clay layer and vegetation. This will result in a non erodible embankment and minimal environmental effects.

2.6.3 Asphalt Concrete Properties

Asphalt concrete properties have been reported in AFS research (AFS, 1991). The various properties were developed on a control mixture and a mixture fabricated with 10% iron WFS. The gradation of the control and mixture containing 10% iron WFS are shown in Figure 2.9. The optimum asphalt content for the control mixture and for the WFS mixture were found to be 4.7% and 4.5% respectively. The values of various properties are shown in Table 2.5.

Figure 2.9 Gradation of WFS and control mixture (AFS, 1991)

Table 2.5 Properties of Asphalt Concrete with WFS Compared to Control (AFS, 1991)

Properties	Foundry Sand (4.5% Asphalt)	Control (4.7% Asphalt)	Criteria
Voids, %	4.0	4.0	3.0-5.0
VMA, %	11.5	13.8	13.0, min.
Stability, lb	2250	2300	1800, min.
Flow, 0.01 in.	6	9	8-14
Unit weight, pcf	149.5	150.8	n/a

A certain percentage of air voids is always desirable to ensure that there will be space remaining for expansion of the bitumen if further densification is expected under traffic or expansion of the asphalt that would occur on a hot summer day (Goetz and Wood, 1960). However, if the air void contents are high, there is a possibility that water can enter the mix, penetrate the thin asphalt films within the aggregate and asphalt mass, and lower the resistance of the mix to the action of water. Thus the void content at optimum asphalt content is recommended by most agencies to lie between 3 and 5 percent.

Voids in the Mineral Aggregate, VMA, is the total volume of voids within the mass of the compacted aggregate. The VMA significantly affects the performance of a mixture because if the VMA is too small, the mix may suffer durability problems, and if the VMA is too large, the mix may show stability problems and be uneconomical to produce. The VMA has two components: the volume of the voids that is filled with asphalt and the volume of voids remaining after compaction. The volume of asphalt

cement is critical for durability of the mixture. This asphalt cement volume along with the aggregate gradation determines the thickness of the asphalt film around each aggregate particle. Without adequate film thickness, the asphalt cement can be oxidized faster, the films are more easily penetrated by water, and the tensile strength of the mixture is adversely affected (Roberts et al., 1991). The VMA for any given mix must be sufficiently high to ensure that there is room for the asphalt cement plus the required air voids. The decrease of VMA in the AFS research was attributed to fineness of the minus 200 mesh content. Hydrometer analysis revealed that approximately 50% of the minus 200 mesh material was finer than the 400 mesh sieve (AFS, 1991).

Marshall stability is defined as the maximum load carried by a compacted specimen tested at 140°F at a loading rate of 2 in./min. This stability is generally a measure of the mass viscosity of the aggregate-asphalt cement mixture and is affected significantly by the angle of shearing resistance of the aggregate and the viscosity of the asphalt cement at 140°F. The primary use of Marshall stability is in evaluating the change in stability with increasing asphalt content to aid in selection of the optimum asphalt content (Roberts et al., 1991).

The flow is equal to the vertical deformation of the sample (measured from start of loading to the point at which stability begins to decrease) in hundredths of an inch. High flow values generally indicate a plastic mix that will experience permanent deformation under traffic, whereas low flow values may indicate a mix with higher than normal voids and insufficient asphalt for durability. Such a mix may experience premature cracking due to mixture brittleness during the life of the pavement (Roberts et al. 1991).

The WFS mixture was also subjected to moisture conditioning according to ASTM D 4867. Ratios of wet tensile strength to dry tensile strength with and without an anti-stripping agent were measured. The values are shown in Table 2.6. The high sensitivity to moisture was attributed to the low VMA values.

Table 2.6 Comparison of Wet and Dry Tensile Strengths of Asphalt Concretes (AFS, 1991)

	Wet (Without	Wet (With	Ratio (Without	Ratio (With
	Anti-stripping	Anti-stripping	Anti-stripping	Anti-stripping
Dry	Agent)	Agent)	Agent) %	Agent) %
97.4	29.1	36.5		
83.8	33.7	40.6		
79.9	33.7	39.5		
avg = 87.0	avg = 32.2	avg = 38.9	36.9	44.7

3.6.5 Portland Cement Concrete Properties

Portland Cement Concrete (PCC) consists of Portland cement, water and aggregates of various sizes. In a cubic yard, there is typically 1800 to 1900 pounds of coarse aggregate and 1200 to 1400 pounds of fine aggregate. The important parameters for PCC have been reported by two sources (AFS, 1991 and McIntyre et al., 1991).

In the AFS research, three different WFS samples were tested: code name 4WE101, a shell molding WFS from a gray iron foundry; 7BE105, a green WFS from a gray iron foundry; and 8GU108, a green WFS from a steel foundry. A blending of 33% substitution for the fine aggregate in a batch of normal weight concrete was carried

out. The compositions of the batches and their properties are provided in Table 2.7. Each of the concrete batches were tested for compressive strength at 1, 3, 7 and 28 days. The results are shown in Figure 2.10.

In the later research of AFS, a blending of 45% shell WFS was carried out (AFS, 1992). Besides compressive strength, additional testing were also conducted to compare concrete performance and durability to industry recognized standards. The results are shown in Table 2.8.

The data reported by McIntyre et al., contained results on WFS mixtures prepared in concrete cylinders (6 in. $\times$ 12 in.) and in concrete blocks (8 in. $\times$ 8 in. $\times$ 16 in.). The concrete cylinder tests incorporated WFS from all three foundry processes while the concrete block tests included WFS from only the green sand process. The mix designs for the concrete cylinders were determined using the American Concrete Institute (ACI) absolute volume method. A water to cement ratio of 0.50 was used. The mix substitutions for the fine aggregate with WFS were determined using sieve analysis, specific gravity and bulk density data. The mix designs for the concrete blocks were determined using the fineness modulus (FM) method which is a function of the sieve analysis data. A total of three substitutions of the fine aggregate, including 15% (which met the FM standard), 30% (slightly above the FM standard), and 45% (well above the FM standard), were produced.

Table 2.7 Concrete Mix Designs for One Cubic Yard and Their Properties (AFS, 1991)

Mix	Cement	Standard	Foundry	Coarse	Water
Identifier	lb	Sand, lb	Sand, lb	Aggregate, lb	lb
Control	519	1494	0	1777	253
4WE101	520	998	489	1780	265
7BE105	505	970	477	1730	303
8GU108	492	945	425	1685	315

		Total sand	Slump	Air	Unit Weight,
Mix Identifier	W:C Ratio	Vol. %	in.	Content, %	pcf
Control	0.489	46.0	3.7	2.2	148.4
4WE101	0.511	45.9	3.6	1.4	149.6
7BE105	0.600	46.1	3.3	1.3	146.8
8GU108	0.640	46.2	3.2	2.6	144.8

Figure 2.10 Compressive strength of WFSs and control mixture (AFS, 1971)

Table 2.8 Optimized Concrete Mix for Shell WFS (AFS, 1992)

	7 day	28 day	28 day	Modulus of
	Compressive	Compressive	Flexural	Elasticity,
	Strength, psi	Strength, psi	Strength, psi	psi $\times 10^{-6}$
Control	4140	5080	740	4.4
45% WFS	4090	5200	675	4.3
100% WFs	1600	3000	-	-
Typical range	-	-	530 to 710	-

	Average	Average	Average	Average
	Poisson's	Shrinkage, 28	Expansion 28	Autoclave
	Ratio	days, %	days, %	Expansion, %
Control	0.23	0.007	0.022	0.05
45% WFS	0.23	0.012	0.025	-
100% WFs	-	-	-	0.11
Typical range	-	0.02 to 0.03	-	0.8 max.

The compressive strength obtained on the concrete cylinder control mixes and from mixes containing WFS are shown in Table 2.9. Compression results for the concrete block tests are shown in Table 2.10.

In the concrete block tests, the fineness modulus standard was met only for the 15% mix in each case. For this case, the following general trends were observed.

- (1) Strength increased with curing time, but not as quickly as in the control
- (2) Strength decreased as the quantity of WFS in the mix increased from 15% of the fine aggregate to 45% of the fine aggregate.
- (3) The strengths were in general lower than the control values.

2.6.6 Controlled Low Strength Material

Controlled Low Strength Material (CLSM) is defined as a cementitious material that is in a flowable state at placement and has a specified compressive strength of 1200 psi or less at 28 days (ACI Committee 229). If future excavatability (for instance, water or gas utility lines) is important, the strength of the material must be closely controlled. Fifty to one hundred psi is considered acceptable compressive strength, so that normal construction equipment and handwork can readily excavate CLSM. At compressive strength exceeding 150 psi, the material starts to take on more concrete like properties, and excavation becomes extremely difficult (Amon, 1990).

Table 2.9 Concrete Cylinder Compression Test Data, Slump, Air, % WFS Addition, and Unit Weight (McIntyre et al., 1991)

Sample	Compressive		Slump (in.)	Air (Vol., %)	% WFS	Unit
	Strength (psi)				Addition	Weight
	7 days	28 days			(Wt., %)	(pcf)
Green WFS	1379	1530	8	6	13	137
Control	1285	1509	7	6	-	129
Green WFS	2199	2400	1.5	2	15	144
Control	1480	1981	5	6	-	150
Shell	1580	2234	3.5	5	11.4	150
Chem. Bonded	1309	1591	3.5	5.5	20	154
Chem. Bonded	1327	1697	3.5	7.25	19.6	154
Control	1544	2204	1.5	6	-	144

Table 2.10 Concrete Block Compression Test Data (McIntyre et al., 1991)

Foundry	Fine Aggregate Substitution, %	Compressive strength (psi)		
		7 days	14 days	28 days
Green WFS	15	1051	1193	1888
	30	930	1096	1278
	45	486	494	635
Green WFS	15	1458	1499	1773
	30	1374	1525	1643
	45	1438	1668	1539
Green WFS	15	1433	1803	1641
	30	1697	1559	1832
	45	1138	1000	1331
Control	-	-	1850	2000

Controlled low strength material should not be classified as a type of low strength concrete nor soil cement. The CLSM is a mix of materials similar to that of soil (Nantung, 1993). The low range of strength, i.e. 50 to 100 psi, is similar to that of many undisturbed or recompacted soils. The permeability of a CLSM mixture containing fly ash, cement and water has been reported to be approximately 5×10^{-6} cm/sec, which places it among typical silty soil materials (Fuston, et al. 1984). However the resilient characteristics for CLSM closely resembles granular materials (Nantung, 1993). The reported data on properties of CLSM are very limited and more research is required before concluding that this material has soil like properties.

Controlled low strength material should be highly flowable to allow ease of construction and does not require consolidation. It should easily flow into inaccessible spots, flowing under and around pipe to provide perfect bedding (Kepler, 1986). This requires that the consistency of CLSM should be like that of slurry or lean grout, yet several hours after placement, the material should harden enough to support traffic loads without settling. Time is minimized because compaction is not necessary when placing (Nantung, 1993). However, setting time may not be so critical as compared to cost. In some cases, users may be willing to accept the construction delay in order to lower the cost.

Controlled low strength material is an inexpensive material used as a low cost alternative to structural backfill in utility cuts and culvert placement. Class F fly ash and sand are selected for their ability to flow, rather than for their contribution to strength properties. This implies that ingredients not suitable for regular concrete may perform quite well in CLSM. In other words, CLSM can successfully use waste products from

many mineral processing operations with a reduction in cost for the CLSM and a contribution in eliminating what would have been a disposable by-product.

The various applications of CLSM have been reported by Naik and Larsen. Naik reported applications in abandoned steam service tunnels, sidewalks, steam utility facilities and sewers (Naik et al., 1990). In these particular applications, CLSM contained cement, fly ash and water, and no sand was included. Larsen has reported use of CLSM to protect groundwater from contamination; to protect riverbanks, culverts, drainage ditches, seawalls, and bridges from the damaging effects of moving water; and to correct damage done to structures by moving water (Larsen, 1990).

2.7 Chemical/Environmental Properties

This section describes the chemical composition and associated Portland cement properties, pH and environmental concerns related with WFS.

2.7.1 Chemical Composition and Associated Portland Cement Properties

The chemical composition on a green WFS from gray iron foundry has been reported in AFS research on the basis of chemical oxide analysis using x-ray fluorescence (Table 2.11). The main constituents were found to be silica (SiO_2), alumina (Al_2O_3) and ferric oxide (Fe_2O_3).

Portland cement is the pulverized form of clinker, the product of the kiln. Clinker is composed of calcium silicates, calcium aluminates and calcium aluminoferrites inter-ground with calcium sulfate (gypsum). Raw materials for the manufacture of Portland cement must contain appropriate proportions of calcium oxide, silica, alumina and iron

Table 2.11 Chemical Oxide Analysis of a WFS (AFS, 1991)

Analyte	%
SiO ₂	87.91
Al ₂ O ₃	4.70
Fe ₂ O ₃	0.94
CaO	0.14
MgO	0.30
SO ₃	0.09
Na ₂ O	0.19
K ₂ O	0.25
TiO ₂	0.15
P ₂ O ₅	0.00
Mn ₂ O ₃	0.02
SrO	0.03
LOI	5.15
Total	99.87

oxide. Much of these raw materials are contained in shale and limestone. All of the selected raw materials are crushed, milled, proportioned and then sent through the kiln at temperatures of 2700°F where they undergo chemical transformation to grayish black pellets called clinker.

The chemical composition contained in Table 2.11 was found to be very suitable for the manufacture of Portland cement. Four mixes were proportioned with limestone, clay, iron ore and magnesium carbonate and three of the mixes with an increment of WFS: 4.45%, 8.90% and 13.36%. Briquetted samples of each mix were subjected to heat cycle and atmosphere that simulated a kiln at a temperature of 1500°C. Even with the highest increment of WFS, the oxide and free lime analysis of the resulting clinkers showed no significant trend (Table 2.12).

Each of the clinkers were ground with gypsum to produce cement. Each cement was tested for compressive strength and time of set and compared to the control mix. All of the cements set within twenty minutes of each other. This indicated that the WFS had no effect on the time of set. Compressive strength development over 28 days indicated that use of the WFS contributed a small beneficial effect in strength development over the control mix as strength increased with increasing increments of WFS (Figure 2.11).

Table 2.12 Chemical Oxide and Free Lime Analysis of Clinkers (AFS, 1991)

Analyte	0% WFS	13.36 WFS
SiO ₂	21.43	21.72
Al ₂ O ₃	5.26	4.63
Fe ₂ O ₃	3.81	3.80
CaO	65.30	65.53
MgO	1.56	1.68
SO ₃	0.33	0.22
Na ₂ O	0.13	0.17
K ₂ O	0.37	0.29
TiO ₂	0.36	0.28
P ₂ O ₅	0.03	0.03
Mn ₂ O ₃	0.05	0.06
SrO	0.03	0.03
LOI	0.35	0.76
Total	99.01	99.17
Free lime	0.20	0.26

Compressive Strengths of Cements

Figure 2.11 Compressive strength of cements (AFS, 1991)

2.7.2 pH

Besides other indicators such as resistivity, soluble chloride and soluble sulfide, pH is one of the indicators for determining corrosivity of fill material (Ke, 1990). In order to be corrosive, pH should lie below 5.5 (CALTRANS, 1978 and CALTRANS, 1986). Also, pH is one of the parameters in the Indiana Department of Environmental Management system of ranking waste (Table 2.15).

The pH range of WFS from the green sand process, the chemically bonded process and the shell molding process has been reported to be in the range of 6.4 to 9.6, 6.8 to 10.3 and 7.7 to 8.6, respectively. The pH range for virgin sand has been reported to be in the range of 6.8 to 8.0.

2.7.3 Environmental Concerns

The primary environmental concern about the use and disposal of WFS is the potential for certain constituents to leach into the soil and groundwater at concentrations determined to be potentially hazardous to human health and to the environment.

The degree of environmental impact is determined by the amount of these elements leached from a WFS deposit. Small amounts of heavy metals released to the environment may constitute a hazard both to health and environment. A high content of salts may adversely affect the quality of ground water, although it does not constitute any danger to human health.

The other environmental effects of the disposal or utilization of WFS could be spreading of dust and the appearance of WFS deposits as an aesthetically undesirable feature of the landscape. For example, a high content of minus 200 mesh material may

be viewed as a dust hazard. The spreading of dust and unpleasant appearance can be controlled by rapid covering of exposed surfaces, and by appropriate handling during construction, e.g., sprinkling.

2.7.3.1 Waste Classification

Under RCRA regulations, a waste may be classified as hazardous in three ways: 1) it is a listed waste, 2) it is a mixture containing listed waste, or 3) it has any of four specific characteristics defined in the RCRA for hazardous wastes. An unlisted waste is classified as hazardous if it exhibits one of the four properties: 1) ignitability, 2) corrosivity, 3) reactivity, and 4) extraction procedure toxicity (Federal Register, 1980). Ignitable wastes can create fires under certain conditions. Reactive wastes are unstable under normal conditions. They can create explosions, toxic fumes, gases or vapors when mixed with water. Corrosive wastes include those that are acidic and those that are capable of corroding metal. Toxic wastes are harmful or fatal when ingested or absorbed or may leach from the waste and pollute groundwater (Parker and Corbitt, 1993).

Areas in the foundry which deserves special attention to determine whether or not the wastes being generated are hazardous include (From Kunes et al., 1982):

- machining, plating, and painting operations which are likely to generate wastes included on the RCRA lists of hazardous wastes;
- inadvertent mixing of *listed* hazardous wastes with other foundry process solid wastes, thus increasing the amount of hazardous wastes generated by virtue of the "mixture rule;"
- use of melt materials containing significant amounts of certain heavy metals

such as lead, cadmium and chromium which may lead to wastes which are classified as hazardous due to EP toxicity;

- some coremaking processes which use strongly acidic or basic substances and which may generate ignitable and reactive slag;
- nonferrous alloy castings which contain lead, such as certain brasses and bronzes, and which generate wastes that may be hazardous due to EP toxicity, especially for lead.

It is unlikely that WFS would be ignitable or reactive. Therefore only the categories of corrosivity and toxicity will be reviewed.

2.7.3.1.1 Characteristics of Corrosivity

According to EPA's regulations, a solid waste exhibits the characteristics of corrosivity if it has either of the following properties (USEPA, 1990):

- 1) it is aqueous and has a pH less than or equal to 2 or greater than or equal to 12.5;
- 2) it is a liquid and corrodes steel at a rate greater than 0.25 in. per year at a temperature of 55°C.

2.7.3.1.2 Leaching properties of WFS

The extent to which a waste is hazardous to the environment is dependent upon the amount of contaminants that will be released from a deposit. In general, the leachate properties are governed by the physical-chemical characteristics of the WFS and the soil-water matrix through which the leachate flows. Water contact may originate from direct interaction between the waste and surface or groundwater bodies, but

landfills/embankments are now designed to minimize this occurrence. On-site precipitation remains the major source of water for leachate formation, where downward movement of percolate arising from precipitation provides the necessary water-waste contact for leaching to occur (Ham et al., 1981). In order to estimate the leachate quantity at any point, one must know the laboratory leachate properties and the specific attenuation mechanisms.

2.7.3.1.2.1 Leaching tests

There are numerous leaching tests which have been applied to a variety of waste materials, including foundry wastes for determining the leaching characteristics. A review and assessment of both published and unpublished tests by Löwenback (1978) indicates the wide variety of tests and some of the problems and advantages associated with them. A few of the leaching tests which are commonly applied to foundry wastes are described below.

2.7.3.1.2.1.1 Extraction Procedure Toxicity Characteristics (EPTC)

The EP toxicity test was developed to provide a method for classifying wastes as hazardous or nonhazardous under standard conditions, rather than for predicting the amount of contamination that could occur from the waste. Three major postulates of EP toxicity are chosen: 1) groundwater as the exposure pathway, 2) landfill as the particular disposal environmental model, and 3) multiples of drinking water standards as thresholds indicative of unacceptable levels of contamination (Daniels, 1981).

In the EPTC test, a representative sample of a solid waste is extracted with

deionized water maintained at a pH of 5 using acetic acid (EPA, 1985). The extract derived from the EPTC test is then analyzed for eight elements to determine if the waste is classified as hazardous or nonhazardous. The maximum contaminant levels specified for characterizing hazardous waste are such that they are one hundred times the National Primary Water Standards (EPA, 1975). The test also considers six herbicides and pesticides which are not found in the WFS. Table 2.13 lists the maximum acceptable extract concentrations for a nonhazardous waste, along with the Primary Drinking Water Standards.

Table 2.13 EPA Criteria Pollutants - Primary Metals (EPA, 1975)

Parameters	Primary drinking water standard ^a (mg/liter)	EP toxicity maximum acceptable amount (mg/liter)
Arsenic	0.05	< 5
Barium	1.00	< 100
Cadmium	0.01	< 1
Chromium	0.05	< 5
Lead	0.05	< 5
Mercury	0.002	< 0.2
Selenium	0.01	< 1
Silver	0.05	< 5

^a EPA Interim Primary Drinking Water Standards (EPA, 1975)

2.7.3.1.2.1.2 Toxicity Characteristics Leaching Procedure (TCLP)

Toxicity Characteristics Leaching Procedure (TCLP) is a relatively new test and was presented to the public in April 1985 (EPA, 1985). The TCLP is designed to determine the mobility of both organic and inorganic analytes present in liquid, solid, and multiphasic wastes. Differences between the EPTC and the TCLP can be grouped into three classes as described below (From Huang, 1990).

Changes in Equipment The filter in the EPTC is a 0.45 micron nitrocellulose membrane while the TCLP specifies a 0.7 micron glass fiber filter containing no binders. The TCLP also introduces the zero headspace extractor which is designed to run the leach testing of a waste without losing the volatile components during the extraction.

Leach Medium The TCLP requires a determination of the appropriate extraction fluid be carried out before running the TCLP. Once the extraction fluid has been selected, the extraction fluid is added to the waste at one time. Thus the constant pH monitoring of the slurry, as required by the EPTC, is not necessary.

Regulated Analytes As previously noted, the EPTC classifies wastes on the concentrations of eight metals and six herbicides and pesticides found in the EPTC leachate. Besides the eight metals, the TCLP also includes organic compounds in the classification. The list of TCLP regulated organic compounds and their current regulatory levels is given in Table 2.14.

2.7.3.1.2.1.3 AFS test

Both the EPTC and TCLP test methods call for an acidic leaching solution with a pH of 5. This best represents a "worst case" type of environment where foundry waste

Table 2.14 Maximum Concentration of Contaminants for the Toxicity Characteristics
(From Federal Register, 1992)

Contaminant	Regulatory level (mg/L)
Arsenic	5.0
Barium	100.0
Benzene	0.5
Cadmium	1.0
Carbon tetrachloride	0.5
Chlordane	0.03
Chlorobenzene	100.0
Chloroform	6.0
Chromium	5.0
o-Cresol	⁴ 200.0
m-Cresol	⁴ 200.0
p-Cresol	⁴ 200.0
Cresol	⁴ 200.0
2,4-D	10.0
1,4-Dichlorobenzene	7.5
1,2-Dichloroethane	0.5
1,1-Dichloroethylene	0.7
2,4-Dinitrotoluene	³ 0.13
Endrin	0.02
Heptachlor (and its epoxide)	0.008
Hexachlorobenzene	³ 0.13
Hexachlorobutadiene	0.5
Hexachloroethane	3.0
Lead	5.0
Lindane	0.4
Mercury	0.2
Methoxychlor	10.0
Methyl ethyl ketone	200.0
Nitrobenzene	2.0
Pentachlorophenol	100.0
Pyridine	³ 5.0
Selenium	1.0
Silver	5.0
Tetrachloroethylene	0.7
Toxaphene	0.5
Trichloroethylene	0.5
2,4,5-Trichlorophenol	400.0
2,4,6-Trichlorophenol	2.0

Table 2.14, Continued

Contaminant	Regulatory level (mg/L)
2,4,5-TP (Silvex)	1.0
Vinyl Chloride	0.2

³ Quantitation limit is greater than the calculated regulatory level. The quantitation limit therefore becomes the regulatory level

⁴ If o-, m-, and p-Cresol concentrations cannot be differentiated, the total cresol concentration is used. The regulatory level of total cresol is 200 mg/l. Tests do not represent conditions present in most parts of a landfill used solely for foundry wastes.

is disposed of along with municipal wastes in unmanaged open dump conditions. A low pH leaching condition is likely to be present at a site such as this. Under low pH conditions, heavy metals such as lead, cadmium, and chromium are more soluble and will leach out more readily than under neutral or alkaline conditions (Nichols and Kunes, 1979).

The AFS test was developed to simulate conditions in a monofill, common for foundry waste disposal, by using deionized water as leaching medium. It also simulates a new leaching medium coming into contact with a given sample of foundry waste in a landfill by using three elutions over a total of six days of contact (Ham et al., 1990).

2.7.3.1.2.1.4 Indiana leach test

The Indiana leaching method test is conducted as specified for EP toxicity testing, except with no addition of acetic acid. The pH of the extract is determined at the end of the 24-hour extraction period (Huang, 1990).

2.7.3.1.2.2 Attenuation mechanisms

Several chemical mechanisms in soil and groundwater act to attenuate or reduce the mobility and concentrations of contaminants in groundwater. These mechanisms can be grouped into two categories:

- precipitation and adsorption in soil and rock
- dispersion and dilution in groundwater and surface water

Both reactions are affected by the pH of the soil and groundwater systems, the ionic strength and composition of the leachate and receiving water, the character of the

soil and rock matrices, and other factors described below.

2.7.3.1.2.2.1 Precipitation and adsorption

Precipitation occurs when the concentrations of chemicals in the interstitial waters exceed equilibrium values. When the water reaches the soil, changes in environmental conditions, such as pH or temperature, or changes in speciation of the element, may drastically lower the equilibrium concentrations, producing an oversaturated solution. Precipitation will begin, converting the element to a solid form much less likely to migrate with the groundwater (Devinny, 1990). Historical research data compiled by EPRI indicates that precipitation is a primary attenuation mechanism for iron, aluminum and manganese because these elements form a variety of low-solubility compounds which limit their concentrations in groundwater. Other compiled data suggest that the formation of iron-containing solids may be a significant attenuation mechanism for both cationic (e.g. chromium, nickel and zinc) and anionic (arsenic, chromium, molybdenum, selenium and vanadium) constituents in diverse hydrochemical environments. Under reducing conditions, the precipitation of metal sulfides (of lead and zinc, for example) may be an important means of attenuation. The precipitation of solid solutions (bi-metal hydroxides and carbonates) is also expected to be an important mechanism (EPRI, 1984).

Adsorption is the process by which molecules of dissolved chemicals in a fluid attach to solid surfaces. Several different mechanisms commonly cause molecules to leave solution and stick to the surfaces of soil particles. These are chemical bond formation, ion exchange, hydrophobic bonding, Van der Waals forces or sometimes two or more of these mechanisms working at the same time. For trace metals, ion exchange is the

dominant form of adsorption. Bailey et al. (1986) showed that the adsorption of trace metals is reduced by the presence of some organic solvents. Hexane, benzene, and phenol all diminished adsorption of cadmium, copper, nickel, and zinc. Presumably, the organic species were competing for adsorption sites with the metals.

The cationic elements are adsorbed in some cases by a combination of precipitation and adsorption. The adsorption of most cationic elements increases as pH increases; therefore, the cations are significantly more mobile under acidic conditions (EPRI, 1984). The EPRI researchers found that at soil pH values greater than 6, cadmium concentrations are maintained at low levels by a combination of precipitation and adsorption (EPRI, 1988)

2.7.3.1.2.2.2 Dilution and dispersion

Dilution and dispersion within the environment reduce leachate concentrations over a successively greater volume of soil, rock or water with time. In ground-water systems, dispersion results from mixing and spreading caused in part by molecular diffusion and in part by variations in groundwater velocity (mechanical mixing) caused by local and large-scale heterogeneities within the porous media comprising the aquifer. Molecular diffusion is a transport process in which chemical species in solution move proportionately in response to concentration gradients rather than a hydraulic gradient. Diffusion is usually considered a minor dispersive mechanism in ground-water systems. Dispersion occurs both in the direction of flow (longitudinally) and laterally perpendicular to the flow direction. Longitudinal dispersion usually exceeds lateral dispersion.

2.7.3.2 Laboratory and experimental observations

Extensive work on the chemical/environmental properties of ferrous foundry wastes has been carried out in Wisconsin. Laboratory study was conducted at the University of Wisconsin, Madison. Waste foundry sand was collected from three ferrous foundries and also natural soils were tested for comparison purposes. The results of that study indicated that none of the foundry sands tested would be classified as hazardous by the Resource Conservation and Recovery Act (RCRA) definition of 100 times the primary drinking water standard in the Toxicity Characteristic Leaching Procedure (TCLP) test. The parameter of highest concern for sands from all three foundries in that study was iron. The concentration of iron did not meet the drinking water standard in the TCLP leachates of the foundry sands from the three foundries, and it was significantly higher than in leachates from the Wisconsin soils tested.

Leaching characteristics of the foundry wastes under actual field conditions was measured through the use of lysimeters to collect portions of the leachate under test piles, and groundwater monitoring wells.

Two field leaching sites were selected. Test fill cells of 5, 10 and 15 feet heights were constructed. Each site had two fills of these heights, one of foundry sand and one of native soil. Manganese, arsenic and total dissolved solids (TDS) were found at significantly higher concentrations than the drinking water standard levels, both in the foundry sand test piles and in the natural soil test piles at both sites. Since they were found in both types of materials, the source of these parameters may not be from waste foundry sand alone. A source common to both piles such as rainfall or lysimeter

construction materials and practices could be responsible for the high concentration of arsenic, manganese and TDS found in the lysimeter leachate. There was no evidence that the waste foundry sand tested would pose a threat to groundwater when compared to natural soils.

In an another study Ham (1989) discussed the laboratory and field data about the organics in foundry wastes. The laboratory leach tests showed that none of the ferrous foundry wastes tested, either as composite or individual components would be classified as hazardous wastes by EPA's proposed toxicity characteristic because of organics contamination. The compounds leached in the laboratory at the highest concentrations were benzoic acid, naphthalene, methylnaphthalene, phenol, metylenebisphenol, diethylphenol, and 3-methylbutanoic acid. All were present at over 300 mg/l in one or more of the samples.

2.7.3.3 Indiana State Regulations

The Office of Solid and Hazardous Waste Management of the Indiana Department of Environmental Management (IDEM) adopted final solid waste management regulations in August 1988 which became effective in February 1989. These regulations classify foundry wastes on the basis of results from the EP toxicity test and a modified EP toxicity water leaching procedure (Indiana leach test) as shown in Table 2.15 (Indiana Legislative Council, 1992). The Indiana leaching method test is conducted as specified for EP toxicity testing, except with no addition of acetic acid. Wastes which leach parameters in concentration at or below the concentration shown are classified as wastes suitable for disposal in Types I, II, III, or IV sites. Wastes that are documented to pass

the Type IV criteria have minimal requirements for disposal and are not subject to the provisions of the regulations. The regulations also provide for beneficial use of foundry sand meeting the Type III category, if the use is "legitimate", including the use as a pavement base. Other uses may be approved if they determined to be legitimate uses that do not pose a threat to public health or the environment (Indiana Legislative Council, 1992).

For sites Type I, II, and III, additional siting restrictions apply. These facilities must also have a soil barrier between the solid waste and any aquifer. The thickness of the soil barrier depends on the waste type and permeability, the physical and chemical properties of the soil, the nature of groundwater resources in the area and the use of alternative liner technology (Indiana Legislative Council, 1992). Facilities accepting waste Type I, II or III require formal detailed permit applications, with Type III being somewhat less restrictive. For example, Type III sites only require additional cover and do not require groundwater monitoring (Indiana Legislative Council, 1992).

Table 2.15 IDEM Foundry Waste Classification Guidelines (Indiana Legislative Council, 1992)

(1) For Parameters Using the EP Toxicity Test:

Parameter	Concentrations (Milligrams per liter)			
	Type IV	Type III	Type II	Type I
Arsenic	≤ 0.05	≤ 0.50	≤ 1.25	< 5.00
Barium	≤ 1.00	≤ 10.00	≤ 25.00	< 100.00
Cadmium	≤ 0.01	≤ 0.10	≤ 0.25	1.00
Chromium	≤ 0.05	≤ 0.50	≤ 1.25	< 5.0
Lead	≤ 0.05	≤ 0.50	≤ 1.25	< 5.0
Mercury	≤ 0.002	≤ 0.02	≤ 0.05	< 0.20
Selenium	≤ 0.01	≤ 0.10	≤ 0.25	< 1.0
Silver	≤ 0.05	≤ 0.50	≤ 1.25	< 5.0

(2) For Parameters Using the Leaching Method Test:

Parameter	Concentrations (Milligrams per liter)			
Barium	≤ 1.00	≤ 10.00	≤ 25.00	*
Boron	≤ 2.00	≤ 20.00	≤ 50.00	*
Chlorides	≤ 250.00	≤ 2.50	≤ 6.25	*
Copper	≤ 0.25	≤ 2.50	≤ 6.25	*
Cyanide, Total	≤ 0.20	≤ 2.00	≤ 5.00	*
Fluoride	≤ 1.40	≤ 14.00	≤ 35.00	*
Iron	≤ 1.50	≤ 15.00	*	*
Manganese	≤ 0.05	≤ 0.50	*	*
Nickel	≤ 0.20	≤ 2.00	≤ 5.00	*
Phenols	≤ 0.30	≤ 3.00	≤ 7.50	*
Sodium	≤ 250.00	≤ 2.50	≤ 6.25	*
Sulfate	≤ 250.00	≤ 2.50	≤ 6.25	*
Sulfide, Total	$\leq 1.00^{**}$	≤ 5.00	≤ 12.50	*
Total Dissolved Solids	≤ 500.00	≤ 5.00	≤ 12.50	*
Zinc	≤ 2.50	≤ 25	≤ 62.50	*

Parameter	Acceptable Range (Standard Units)			
pH	6-9	5-10	4-11	*

* Testing is not required

** If detection limit problems exist, please consult the office of solid and hazardous waste for guidance.

CHAPTER 3

CHARACTERIZATION TESTS

A large number of physical tests were performed on ten WFS samples to evaluate if they can meet the basic requirements for different beneficial uses. Seven were from green sand processes, code name G1 through G7; two were from chemically bonded processes, code name C1 and C2; and another one from shell molding process, code name S1. In addition, data on raw sand for G1, designated as R1 are also included for comparison purposes. In the following sections, the testing procedures and results of the physical properties will be presented and discussed.

3.1 Gradation and Plasticity

Gradation was performed by first soaking the oven dried samples for at least 5 hours and then determining the material finer than No. 200 sieve in accordance with ASTM C 117 (Method A). Any core and lumps present were either broken or removed prior to soaking. Dry sieving of the retained oven dried portion on the No. 200 sieve was then carried out in accordance with ASTM C 136. The determination of finer portion on G3 and G5 were performed by means of hydrometer analysis.

The results of the gradation analyses obtained on each of foundry sand received at different times are presented graphically in Figures 3.1 through 3.11. These Figures

Figure 3.1 Grain size analysis of G1

Figure 3.2 Grain size analysis of G2

Figure 3.3 Grain size analysis of G3

Figure 3.4 Grain size analysis of G4

Figure 3.5 Grain size analysis of G5

Figure 3.6 Grain size analysis of G6

Figure 3.7 Grain size analysis of G7

Figure 3.8 Grain size analysis of C1

Figure 3.9 Grain size analysis of C2

Figure 3.10 Grain size analysis of S1

Figure 3.11 Grain size analysis of R1

show that about 70-100% of the foundry sands was retained on No. 50 and No. 100 sieves. As can be seen, the majority of green WFS are poorly graded containing 5 to 12% fines. It is author's belief that these fines were either due to the binders and additives or the dusts generated off of mold making, pouring, shakeout, return sand lines and sand mixing processes. The coefficient of uniformity C_u for WFS ranges from 1.6 to 5. Table 3.1 summarizes the C_u and the coefficient of curvature (C_c) for all the foundry sands studied, along with the classification based on the Unified Soil Classification System (USCS).

Atterberg limits including liquid and plastic limits were performed in accordance with ASTM D 4318 on the green WFS samples. Only three samples showed plastic behavior. Table 3.2 summarizes the results of Atterberg limits for the three samples.

The gradation curves for each of the foundry sands sampled at different times provide an indication of the potential variability. It can be seen from the Figures that gradation of foundry sands do not change much with time. It is believed that a foundry would use the same amount of binders and additives. Therefore, the only variation should be due to the lack of control in the amounts of dust generation.

3.2 Specific Gravity

The specific gravity of the foundry sands were determined in accordance with ASTM D 854. In this method the entrapped air was removed by boiling of the contents in the pycnometer. Results of specific gravity on foundry sands received at different times are shown in Table 3.3. The variation in the specific gravity values within a foundry were again due to the lack of control in the amounts of dust generation.

Table 3.1 Unified Soil Classification of Foundry Sands

Sample #	C_u^a		C_c^b		USCS ^c Classification	
	First	Second	First	Second	First	Second
G1	1.6	3.9	0.9	1.6	SP-SM	SP-SM
G2	2.2	2.1	1.0	0.9	SP	SP
G3	- ^d	- ^d	- ^d	- ^d	SM	SM
G4	3.8	- ^e	1.1	- ^e	SP-SM	- ^e
G5	- ^d	3.0	- ^d	1.54	SC	SP-SM
G6	2.2	2.7	2.8	2.2	SP-SM	SP-SM
G7	5.0	2.9	1.3	1.1	SP-SM	SC
C1	1.7	- ^e	0.8	- ^e	SP	- ^e
C2	2.1	1.9	0.9	0.9	SP	SP
S1	2.0	- ^e	1.0	- ^e	SP	- ^e
R1	1.8	- ^e	0.9	- ^e	SP	- ^e

^a Coefficient of uniformity = D_{60}/D_{10}

^b Coefficient of curvature = $D_{30}^2/(D_{60} \times D_{10})$

^c Unified Soil Classification System

^d Not required

^e Sample not available

Table 3.2 Results of Atterberg Limits

Sample #	Liquid limit		Plasticity index	
	First sample	Second sample	First sample	Second sample
G3	44.3	35.2	11.8	8.0
G5	29.1	NP ^a	8.3	NP ^a
G7	NP ^a	29.7	NP ^a	10.9

^a Non Plastic

Table 3.3 Specific Gravity of the Foundry Sand Samples

Sample #	First sample	Second sample
G1	2.55	2.53
G2	2.48	2.58
G3	2.35	2.52
G4	2.46	-
G5	2.39	2.56
G6	2.44	2.51
G7	2.50	2.48
C1	2.64	-
C2	2.61	2.62
S1	2.64	-
R1	2.65	-

Generally the specific gravity of green WFSs were found to be lower than those of chemically bonded and shell molded WFSs. This may be due to the presence of additives like seacoal in the green WFS. Seacoal contains carbon which is known to be porous, which might have resulted in lower specific gravity for the green WFS.

3.3 Moisture Contents

The moisture contents of various foundry sands were determined in accordance with ASTM D 2216. The results of moisture contents on foundry sands, received at different times are summarized in Table 3.4. Not much variation was found in the samples of WFS within a foundry. In general, foundry sands were found to be quite dry.

3.4 Loss on Ignition

Loss on ignition (LOI) was determined by calculating the weight loss on heating the foundry sands from 110°C to 550°C, and is expressed as a percentage of the oven-dry weight. A muffle furnace capable of generating a maximum temperature of 1100°C was used in the test.

The resulting LOI values determined on samples received at different times are presented in Table 3.6. As can be seen, LOI values were relatively higher for green WFS. This was probably due to the presence of additives like seacoal in the green WFS.

3.5 Shape and Texture

The particle shape and texture were performed by conducting a microscopic examination. Microscopic examination was performed by the use of black and white

Table 3.4 Percentage Moisture Contents of Foundry Sands

Sample #	First sample	Second sample
G1	0.3	1.4
G2	0.3	0.1
G3	10.1	7.5
G4	0.7	-
G5	1.4	1.2
G6	2.0	1.8
G7	1.0	4.4
C1	0.1	-
C2	0.3	0.2
S1	0.1	-
R1	0	-

Table 3.5 Percentage Loss on Ignition of Foundry Sands

Sample #	First sample	Second sample
G1	3.16	5.11
G2	2.11	2.64
G3	12.06	10.07
G4	3.75	-
G5	5.32	2.82
G6	5.43	4.61
G7	6.31	7.66
C1	1.61	-
C2	1.01	0.61
S1	0.35	-
R1	0.12	-

photomicrographs taken from a Polaroid camera attached with a microscope. Figure 3.12 shows the magnification of 1 mm. division. All the micrographs were taken at this magnification which was equal to 33. Figures 3.13 through 3.23 are photomicrographs of all the foundry sands studied. These Figures suggest that in general foundry sands were subangular to rounded. Moreover, green WFS seems to be relatively rough as compared to other foundry sands.

In addition to the microscopic examination, a flow test was also performed in accordance with the National Aggregate Association Uncompacted Voids Test to determine the uncompacted void content which correlates with the particle shape and texture of fine aggregate (Meininger, 1989). The following exceptions were used: apparent specific gravity values according to ASTM D 854 were used to calculate the void content, and the right cylinder to be filled with fine aggregate was 3 inches in diameter and 3.5 inches high. The results are summarized in Table 3.6.

The test was performed to compare the shape and texture of WFSs among themselves and with the conventional asphalt concrete aggregates. The comparison of uncompacted void content of WFSs with the conventional aggregates is given by Javed et al. (1994). Any effect of using the apparent specific gravity and 24.74 in³ volume is therefore ignored because all the aggregates were tested under the same conditions. Moreover, the results reported herein, should not be compared with any other result using the standard procedure.

An increase in void content indicates greater angularity or rougher texture or both. Lower void contents are associated with more rounded, smooth surfaced fine aggregate. The uncompacted void content for a virgin foundry sand was found to be

43.7%. This suggests that WFS were a little rougher. This roughness may be due to agglomeration of sand with binder and additives.

3.6 Clay Lumps and Friable Particles

According to ASTM C 142, the test should be performed on at least 25 gm of sample, retained on the No. 12 sieve, after thorough washing. Since most of the WFS samples were finer than the No. 12 sieve, a lot of sample was required to meet this requirement. Moreover, this retained portion may not be a true representation for ASTM C 142 testing. An alternate procedure using an AFS method was used where + No. 12 sieve coarse material is an indication of clay lumps and agglomerated material present (AFS, 1991). The results are summarized in Table 3.6. Two types of lumps were encountered. Lumps associated with molding sand were mostly found to be easily disintegrated with water. However, the one which are associated with cores (core lumps) were found to be hard and could not be easily broken. These kind of lumps need to be crushed for beneficial reuse. The first kind of lumps was found to inhibit mixing of hot asphalt cement with individual grains, and needs either to be washed, screened off or crushed for use in asphalt concrete.

Figure 3.12 Micrograph of 1 mm division

Figure 3.13 Micrograph of G1

Figure 3.14 Micrograph of G2

Figure 3.15 Micrograph of G3

Figure 3.16 Micrograph of G4

Figure 3.17 Micrograph of G5

Figure 3.18 Micrograph of G6

Figure 3.19 Micrograph of G7

Figure 3.20 Micrograph of C1

Figure 3.21 Micrograph of C2

Figure 3.22 Micrograph of S1

Figure 3.23 Micrograph of R1

3.7 Soundness

This test was carried out in accordance with ASTM C 88. Test results for soundness of aggregate by sodium sulfate are summarized in Table 3.6. According to Indiana specifications for fine aggregate, weighted percent loss should not exceed 10% after being subjected to five cycles of sodium sulfate test (Standard Specifications, 1988). Six of the ten samples failed this requirement. The probable explanation of the failure of WFS would be the agglomeration due to binders. Due to the presence of binders, particles stick together and when exposed to the aggressive environment of the saturated solution of sodium sulfate the binders wash out and the particles became separated. A strong possibility exists that the particles themselves did not break under the severe exposure condition of the chemicals, but they merely became separated and passed through the mesh opening of the test sieve. This fact becomes more evident, if we compare the soundness value of R1 with G1, which suggests that foundry sand itself is relatively sound but the binders and other additives lead it to a higher percentage loss.

3.8 Absorption

The absorption test was carried out in accordance with ASTM C 128 with the following exceptions: (1) the metal mold in the form of a frustum of a cone had a height of 67 mm, and (2) the metal tamper weighed 230 gm and had a circular tamping face 34 mm in diameter.

A height of 67 mm of the metal mold as compared to the standard 75 ± 3 mm. would result in lesser amount of aggregates and the aggregates would therefore be in a relatively compacted state than as specified by standard ASTM C 128. However, the

pressure applied by the tamper was less than as specified by the standard due to lesser weight of tamper (230 g as opposed to 340 ± 15 g). Also the large diameter of tamping face (34 mm as opposed to 25 ± 3 mm) resulted in less kneading action and therefore in less densification as opposed to the standard diameter. Therefore, the combined effects are self compensating and any minor error due to the above exceptions used are ignored.

The absorption values for the foundry sands are presented in Table 3.6. The saturated surface dry absorption in WFS ranges from 0.3 to 5.1. The high absorption values in green WFS are probably due to the presence of carbon which is known to be highly porous. Another possible explanation of higher absorption values than the virgin sand is due to the relatively rougher surface texture formed due to the presence of binders and additives, which resulted in retention of a significant amount of moisture.

Table 3.6 Uncompacted Void Content, Clay Lumps and Friable Particles, Soundness and Absorption Values for the Foundry Sands Tested

Sample #	Uncompacted Voids, %	Clay Lumps & Friable Particles, %	Soundness %	Absorption %
G1	48.6	1.35	9	1.2
G2	45.1	1.72	6	1.0
G3	58.3	44.33	25	5.1
G4	47.8	2.59	45	1.6
G5	49.9	0.62	9	3.5
G6	51.3	2.26	17	2.0
G7	51.1	23.22	47	2.3
C1	45.23	100.00	12	0.3
C2	47.0	0.00	21	0.3
S1	47.2	10.64	10	0.3
R1	43.7	0.00	4	0.2

CHAPTER 4

GEOTECHNICAL PROPERTIES

This Chapter includes testing procedures, equipment, and discussion of results on selected WFSs. The WFSs selected for geotechnical properties included two from the green sand process, code name G1¹ and G3²; one from the chemically bonded process, code name C2²; and another one from the shell molding process, S1¹. In addition, data on raw sand for G1, designated as R1¹ are also included. Superscript 1 and 2 denotes the first or second sample used for detailed testing. Characterization test results on the first or second sample are already given in Chapter 3. The geotechnical properties described here are permeability, maximum and minimum index unit weights, moisture-unit weight relationships, California Bearing Ratio (CBR), shear strength, compressibility and resilient characteristics.

4.1 Permeability

Permeability was measured using a flexible wall permeameter by the falling head method. A comprehensive review of the flexible wall permeameter has been given by Daniel (1985). The major advantages of the flexible wall permeameter are in minimizing sidewall leakage, permitting high hydraulic gradients, permitting convenient back pressuring of the soil and enabling one to verify saturation. However, there is a need to

apply significant confining pressures at high hydraulic gradients in order to maintain contact between the membrane and the soil. This may result in closing cracks that may be present in the specimen.

For the green WFSs, samples were first compacted at standard Proctor energy near the optimum in a 2.8 inch diameter mold. The ends of the compacted samples were then trimmed and samples of approximately twice the diameter were placed in the permeameter. The details of this hammer and compaction mold are described by Lee, (1993). The samples were subjected to a small vacuum at the base. Saturation was accomplished by first inundating the sample and then applying back pressures in 5 psi increments. Each increment was maintained until it was noted that the level of water in the burette was no longer changing. The amount of water taken by the sample and the time required to reach equilibrium became less and less at each successive back pressure increment. When less than 0.1 cc change was observed to reach equilibrium for a final 5 psi increment, saturation was considered very close to 100%. After saturation, head a pressure head was applied to measure the permeability.

For C2, S1 and R1, two sets of moist samples at two relative densities were prepared in the permeameter using a split mold. The samples were then saturated by adopting the same procedures as described above except that the samples became saturated at a very low back pressures. No pressure head was employed. For all the above cases, the effective confining stress was 5 psi, following instructions in the manual for the instrument (Geotest Instrument Corporation, 1991).

Table 4.1 gives the results of falling head permeability tests. Generally, the coefficients of permeability of green WFS fall in a very low permeability range, while

Table 4.1 Coefficients of Permeability of Foundry Sands

Sample #	Energy	Percent fines ^a	k (cm/sec)
G1	99.1 MDD ^b	5.27	2.76×10^{-5}
G3	99.4 MDD	35.18	2.56×10^{-6}
C2	31.7 Dr ^c	0.27	4.49×10^{-3}
C2	89.6 Dr		5.86×10^{-4}
S1	20.9 Dr	0.72	8.49×10^{-4}
S1	83.3 Dr		2.66×10^{-4}
R1	18.0 Dr	0.03	6.20×10^{-4}
R1	83.9 Dr		2.71×10^{-4}
Very fine sands ^d			5×10^{-2} to 5×10^{-4}
Sands ^e			10^{-3} to 10^{-4}
Uniform fine sand ^f			4×10^{-3}

^a Percent finer than the No. 200 sieve (0.075 mm)

^b MDD = Maximum Dry Density

^c Dr = Relative Density

^d From Whitlow, 1983

^e From Verruijt, 1970

^f From Hough, 1969

others fall in a low permeability range.

It can also be noted from the Table that the percentage of fines had a predominant effect on the permeability of WFS. Generally the low permeability of green WFS was due to the presence of both clay binder and seacoal additives. These clay binders and seacoal additives resulted in the generation of many fines and thus contributed a significant reduction in permeability.

4.2 Maximum and Minimum Index Unit Weights

The maximum index unit weight of selected WFSs was determined in a 4 in. diameter mold by using a vibratory table and a 2 psi surcharge. The test was performed in accordance with ASTM D 4253 using the dry method in a standard Proctor mold. No effect is expected as long as the energy applied per unit volume remains the same by using 4 in. mold or by using the specified mold according to ASTM D 4253. To determine the optimum amplitude of vibration for the particular mold and vibrating table, the method given in Appendix of ASTM D 4253 was followed. The optimum amplitude of vibration was found at dial setting of 8 having the double amplitude of vertical vibration equal to 0.0068 in. at 60 Hz. The calibration of double amplitude of vertical vibration and dial setting for the particular vibrating table is given by Lee (1993).

The minimum index unit weight was determined by three different methods in accordance with ASTM D 4254. The following exceptions were involved. The mold used for Methods A and B was a standard Proctor mold of 4 in. diameter, and the graduated cylinder for Method C had a volume of 1000 ml. Smaller volume mold and graduated cylinder would result in relatively higher unit weight than would be calculated using the

specified mold/cylinder according to ASTM D 4254. A smaller volume mold/cylinder would result in relatively non uniform settling of soil particles because of relatively more disturbance due to compactness of mold/cylinder as compared to a bigger volume mold/cylinder. In order to see any size effect, minimum index unit weight by methods A and B was also performed for R1 in a 6 in. diameter mold having a height of 7 in. Minimum index unit weight was found out to be 92.4 pcf using a 6 in. diameter mold as opposed to 92.7 pcf using a 4 in. diameter mold. Therefore, for all practical purpose, any effect on minimum index unit weight values by using smaller volume mold/cylinder is ignored.

The maximum and minimum index unit weights of selected samples along with the corresponding maximum and minimum void ratios are summarized in Table 4.2. In all the above cases for minimum index unit weights, Method B yielded the minimum values and these are reported.

The samples of green WFS showed lesser values than the other sands tested. The other sands were cohesionless and were fairly clean. Hence the effect of vibration was pronounced in these cases where vibration temporarily reduced the internal friction between the particles and enabled them to reorient in a more dense arrangement.

Table 4.2 Maximum and Minimum Void Ratios and Unit Weights of Selected Samples According to ASTM D 4253 and ASTM D 4254

Sample #	Void ratio		Unit weight (pcf)	
	Minimum	Maximum	Maximum	Minimum
G1	0.540	0.830	103.4	86.8
G3	0.899	1.289	83.1	68.7
C2	0.465	0.731	111.4	93.9
S1	0.573	0.852	105.3	89.1
R1	0.558	0.783	106.6	92.7
Uniform sand ($C_u=2.3$) ^a	0.54	0.94	107	85
Silty sand ($C_u=31$) ^a	0.83	1.36	97	75
Uniform subangular sand ($G_s=2.67$) ^b	0.45	0.85	115	90

^a From Hilf, 1976

^b From Sowers, 1979

4.3 Moisture-Unit Weight Relations

The moisture-unit weight relationships were carried out on G1, G3, C2 and R1 in accordance with ASTM D 698. The resulting moisture-unit weight relationships are presented in Fig 4.1 through 4.4. Samples of C2 and R1, being uniformly graded cohesionless soils, gave a flatter compaction curve, as opposed to clayey soils and well-graded sandy or silty soils, which show a clearly defined compaction curve peak. As discussed earlier, water does not have a pronounced influence on the unit weight of cohesionless soils. Johnson and Sallberg (1962) showed that some sands display straight-line impact compaction curves throughout the range from the dry to saturated condition. The low unit weights obtained at intermediate water contents for C2 and R1 were due to capillary forces resisting rearrangements of the sand grains.

The compaction curve for green WFS samples showed a relatively defined peak. It was found that a slight addition of bentonite and other additives to sand improved the grading and permitted the development of greater unit weight for the same compactive effort. The effect of moisture was considerable. So long as the amount of bentonite and additives added were small and was no greater than was needed to partially fill the voids of the sand, the maximum unit weight increased, and the optimum moisture content decreased, as compared to cohesionless soils described above. This fact was observed for G1. A larger amount of fine particles reversed this trend, i.e., the maximum unit weight decreased and the optimum moisture content increased. This was observed for G3 where greater surface area of fine particles and relatively high loss on ignition resulted in a greater water requirement.

Figure 4.1 Moisture-unit weight-CBR relationship of G1

Figure 4.2 Moisture-unit weight-CBR relationship of G3

Figure 4.3 Moisture-unit weight-CBR relationship of C2

Figure 4.4 Moisture-unit weight-CBR relationship of R1

4.4 California Bearing Ratio (CBR)

The values of CBR on the selected foundry sands were determined in accordance with ASTM D 1883. At least three specimens were compacted in a 6 inch mold with a spacer according to ASTM D 698, covering the moisture range wet and dry of optimum. The CBR of each specimen was obtained for the dry and the soaked condition. The correction of load-penetration curves were carried out following the correction procedure of ASTM D 1883.

Results of the test on selected specimens are summarized in Table 4.3. In general the 0.1-in. CBR value was less than the 0.2-in value. A similar behavior was also reported by Huang, 1990 and Franco and Lee, 1987. Figures 4.1 through 4.4 show the moisture-unit weight-CBR relations of foundry sands. In the case of green WFS samples, the sharp decrease in as compacted CBR which occurred with increasing moisture content is thought to be due to fines acting as a binding agent at low moisture contents and as a lubricant at high moisture contents. The as compacted CBR of C2 and R1 did not vary significantly with increase in moisture content. The soaked CBR for all the cases was generally found to vary in accordance with an increase or decrease in unit weight.

Basic criteria for the design of flexible pavement layers and the supporting subgrade are based on the CBR values. An approximate correlation between CBR values, various soil classes and the rating of soils for subgrade, subbase or base light-traffic pavements is given in Figure 4.5. It is seen that CBR values less than 5 represent a poor subgrade for light-traffic pavements, values less than 20 are unacceptable for light-traffic subbases, and values less than 80 are unacceptable for base courses.

Table 4.3 CBR Test Results on Selected Specimens

Sample #	Water Content %	CBR As Compacted		Water Content %	CBR Soaked	
		0.1 in.	0.2 in.		0.1 in.	0.2 in.
G1	6.53	22.03	23.44	6.94	4.33	4.84
	9.62	20.33	23.11	9.87	11.33	14.29
	12.13	12.10	16.93	11.68	14.33	18.00
	15.37	1.83	2.67	13.17	14.33	13.98
G3	13.60	30.90	30.51	14.4	12.07	11.60
	15.58	29.67	27.11	18.59	18.83	19.60
	18.47	21.93	24.33	20.91	9.43	11.78
	24.51	1.83	2.33	23.75	1.83	2.55
				27.00	0.9	1.09
C2	9.33	17.33	*	10.66	3.33	4.15
	11.53	16.27	*	12.10	4.86	11.98
	14.51	17.77	14.20	13.86	9.56	12.49
	16.02	13.00	16.11	14.60	5.67	7.55
R1	11.55	15.00	*	11.76	12.67	13.91
	13.64	14.17	*	13.88	15.67	13.17
	15.40	15.80	*	19.80	11.67	10.24
	17.33	18.33	*			
	18.81	17.67	*			

* Peak resistance occurred before 5.08 mm. penetration

Figure 4.5 Approximate correlation of soil ratings for use in design of light traffic pavements (Asphalt Institute, 1970)

Samples G1 and G3 showed small swelling which became zero at wet of optimum, thus it would be advantageous to compact on the wet side. However, due to possible liquefaction concerns, it would be advisable to compact on the dry side of the optimum. Also, it can be seen from Figures 4.1 through 4.4 that in general, the peak of as-compacted and soaked CBR occurred at dry or near optimum.

For cohesionless soils like WFSs from the chemically bonded process, vibratory compaction using smooth rollers is suggested. Although, for these soils, water content does not have pronounced influence in increasing unit weight, an air-dried condition may not be recommended for field construction. The part played by the water would be to reduce capillary tension between the particles and to allow them to move readily into denser arrangements. Maximum effectiveness would be obtained at a water content just below the optimum required and more than the value at which capillary tension develops. The layer to be compacted should be given the first one or two coverages with a low water content because the capillary tension in the loose cohesionless soil would prevent the equipment from sinking into the surface. Water should then be added gradually in the course of subsequent passes to eliminate the capillary effects after the partially compacted layer is strong enough to support the roller without the temporary cohesion of capillarity (Rodriguez et al., 1988).

For sands from the green WFS process, pneumatic-tired rollers are suggested. Pneumatic-tired rollers are known to be used for sandy soils and clays with low to medium plasticity; such soils have no hard lumps to be broken and consequently do not require such concentrated pressures as those produced by sheepfoot rollers. These rollers

produce some kneading action which causes large angular deformations and more efficient densification. The kneading is caused by the tire tread and the tire flexing (Rodriguez et al., 1980). They are more efficient than smooth-wheeled rollers when there is a greater fines content in a frictional soil because their efforts can be transmitted to greater depths. They can usually compact in less time and at lower cost than a sheepfoot roller. In geographic areas where rainfall may occur frequently, construction of earth embankments is expedited by the use of rubber-tired rollers which seal the compacted surface and retard infiltration (Hilf, 1976).

4.5 Shear Strength

The shear strength parameters were determined by performing multistage direct shear tests on dry samples at various densities. The normal stress used in the test ranged from 5 to 19 psi. Figures 4.6 through 4.10 present the results of these tests on the tested sands at various relative densities. The measured angles of shearing resistance along with the strength intercepts are summarized in Table 4.4. The values of ϕ in this Table represent peak strength for dense samples and ultimate strength for loose samples. These values compared very well with the reported values for conventional materials. It should be pointed out that because of the possibility of progressive failure in backfill or embankment, the average strength on the failure surface is not the peak strength, but between the peak and residual. Burmister suggested that only 50 to 70 percent of the increase of the value of ϕ over its value at a very loose state be used, depending on the amount of restraint against progressive failure (Burmister, 1948). Moreover, it is known that the strength angle from a triaxial test is somewhat smaller than that from a plane

Figure 4.6 Results of direct shear test on G1

Figure 4.7 Results of direct shear test on G3

Figure 4.8 Results of direct shear test on C2

Figure 4.9 Results of direct shear test on S1

Figure 4.10 Results of direct shear test on R1

Table 4.4 Results of Direct Shear Tests

Sample #	Dr	Loose		Dr	Dense	
		c (psi)	ϕ (deg)		c (psi)	ϕ (deg)
G1	29	0.60	32.4	90	1.44	36.6
G3	34	0.75	34.2	98	1.82	40.9
C2	22	0.06	30.4	94	1.04	34.9
S1	31	0.06	30.8	94	0.69	36.5
R1	32	0.03	30.4	88	0.17	33.8
Uniform	Moderately			Very		
medium sand ^a	dense		32-34	dense		35-38
Sand ^b	Loose		29-30	Dense		36-41

^a From Terzaghi and Peck, 1948

^b From Peck, Hanson and Thornburn, 1974

strain test. Marachi, Chan, Seed, and Duncan (1969) found that for very dense sand, ϕ was 7° greater for plane strain shear than for triaxial shear. This reduced to about 3° for loose sand specimens and indicated that at $D_r=0$ there would be no difference in ϕ . Although embankment loading is a plane strain case, embankment loading involves rotation of principal stresses, which is not reproduced in direct shear tests. Therefore, it is proposed to reduce the peak ϕ value on the order of 75 to 90%, depending upon the initial density.

Besides the effect of unit weight and normal stresses, particle shape and texture were also found to influence the ϕ value. The combined effect of particle shape and texture is described in section 3.5. As mentioned before, increase in void content indicates greater angularity or rougher texture or both. It can be seen that WFS values were relatively higher, especially the WFS from green sand process. This roughness might be due to the agglomeration of sand with binder and additives which resulted in increased strength parameters.

4.6 Compressibility

One dimensional compressibility tests were performed in a dense condition. The consolidometer had a diameter of 2.5 in. and the specimens were 1 in. high. Initially, dry materials were placed in the consolidometer and compressed until they yielded 95% of maximum dry density determined by either the impact compaction (ASTM D 698) or by vibratory compaction (ASTM D 4253). Two samples of each foundry sand were tested, one in a dry condition and the other one in a saturated condition. The saturated compressibility on C2, S1 and R1 was performed by first soaking the samples for 24

hours at a seating pressure of 0.7 psi and then applying the loads. Saturation on green WFS samples was performed by first applying a seating load and then inundating the sample. Seating loads were gradually increased according to the change in dial gage. Back pressure was then applied in 5 psi increments. Not less than a half hour was allowed for each back pressure increment. The maximum back pressure used was 50 psi. At this maximum back pressure, an interval of 24 hours was given for equilibration of pressure within the specimen, before compressibility testing was performed. A B parameter check to ensure 100% saturation could not be accomplished due to the relatively open fabric of these materials which allowed any excess pore pressure to dissipate very rapidly.

Immediate measurements of deformation were made at 1 or 2 minutes depending upon the soil after the application of each load. For saturated compressibility of green WFS samples, readings were continued until the dissipation of excess pore pressures as measured by a calibrated transducer. The development of excess pore pressures was found to be very insignificant. The calibration of the transducer and data for saturated compressibility of G1 and G3 are appended (Appendix B). All specimens were also maintained under maximum stress until no further deformation was observed.

Swelling was measured in accordance with ASTM D 4546 Method A, by soaking the samples for 24 hours at a seating pressure of 0.7 psi. No swelling was observed for C2, S1 and R1. The percentage swelling and swelling pressure of G1 and G3 are shown in Table 4.5.

Table 4.5 Percentage Swelling and Swelling Pressures of WFS

Sample No.	Swelling, %	Swelling pressure, psi
G1	0.15	1.43
G3	0.82	4.50

The stress-strain relationships for WFS and a virgin sand from one-dimensional compression tests are presented graphically in Figures 4.11 and 4.12. It can be seen that WFSs, especially the sands from the green sand process, are more compressible than the virgin sand.

It is generally known that soils with bulky, or rounded particles are less compressible than those with flat particles. The WFSs are surrounded with binders and additives. These binders and additives are far from bulky and perhaps more platy and hence contribute to increased compressibility as compared to virgin sand.

When vertical loads of large lateral extent are applied to the foundry sand layers, the compression behaviour becomes one-dimensional and the parameter used in estimating settlement is the secant constrained modulus. The secant constrained modulus is the rate of change of vertical stress with respect to the vertical strain under conditions of zero lateral strain, and can be expressed as

$$D = \frac{\Delta \sigma_v}{\Delta \epsilon_v} = \frac{\sigma_{v2} - \sigma_{v1}}{\epsilon_{v2} - \epsilon_{v1}} \quad (4.1)$$

where D = secant constrained modulus,

ϵ_{v1} = vertical strain at a stress level of σ_{v1} , and

ϵ_{v2} = vertical strain at a stress level of σ_{v2} .

Figure 4.13 shows the secant constrained modulus from zero stress to various stress levels. It is found that the moduli of WFSs are smaller than the virgin sand. The possible cause of this could be the self compressibility of binders and additives which act like a dry lubricant and have relatively high compressibility as compared to virgin sands.

Figure 4.11 Stress-strain relations for dry foundry sands

Figure 4.12 Stress-strain relations for saturated foundry sands

Figure 4.13 Relationship between constrained modulus and vertical stress

4.7 Resilient Modulus

Determination of resilient modulus in the laboratory requires application of different combinations of axial dynamic loading and confining pressure. Reliable measurements of the applied loads and resulting deformation require that the test be performed with an automated setup and preferably with a data acquisition system. A computer controlled closed-loop servo-hydraulic MTS-810 system was used to perform the resilient modulus tests. Waveforms were monitored on an oscilloscope to make adjustments between the applied and actual loadings. Two load transducers of different capacity were used for different sizes of specimen. For specimens of 2.8 inch diameter, a load transducer of 220 lb capacity was used with a 200 lb range cartridge, since the maximum load applied during the test was about 125 lb. Another transducer of 5.5 kip capacity with a 550 lb range cartridge was used for the 4 inch diameter specimens which were subjected to maximum loading of about 250 lb during the tests. A DC type displacement gage (with maximum displacement of 4 mm) was employed for the measurement of elastic and permanent deformations. The displacement gage was mounted between the load cell and sample, outside the triaxial cell. Applied confining pressure was regulated by Bellform pressure regulator. The complete test sequence was controlled by software. A Haversine waveform of a load duration of 0.1 second and a cycle duration of 1.0 second was used to apply the axial load simulating traffic loading. Detailed information about the setup, control units, software, and gages can be found in Lee et al. (1993).

A cylindrical area correction was used, keeping in view the difficulty of measuring the volume change during the resilient modulus tests on the partially saturated

soils. Moreover, the measured axial strains at the end of the resilient modulus tests were usually less than 1 percent, therefore, no volume changes of the specimens during M_r tests was assumed. The cross sectional area of the specimens was corrected as follows:

$$A_{corr} = \frac{A_i}{1 - \frac{d_{perm}}{L_i}} \quad (4.2)$$

where A_{corr} and A_i are the corrected and initial cross-sectional area of specimen, respectively; d_{perm} is the permanent displacement; L_i is initial specimen length at the start of the test. Repeated deviator stress was calculated by dividing the obtained difference between maximum and minimum load with corrected cross-sectional area of specimen. Resilient modulus, is, then, obtained as follows:

$$M_r = \frac{\sigma_d}{\epsilon_r} \quad (4.3)$$

where σ_d is the repeated deviator stress and ϵ_r is the resilient strain.

The testing procedures in this research confirmed with AASHTO Designation T 274-82, "Standard Method of Test for Resilient Modulus of Subgrade Soils." The resilient modulus tests were conducted on G1, G3, S1 and R1 at different moisture contents and initial unit weights. The samples G1 and G3 were prepared in a 2.8 in. diameter mold using impact compaction. Due to shortage of G1 and G3 samples, a 2.8 in. mold was chosen. Other reasons were the ease and speed of preparation, and the uniformity obtained. Vibratory compaction was used for samples S1 and R1 and prepared in a 4 in. diameter split mold. In order to determine the influence of method of compaction on cohesionless sands, M_r tests were also performed on R1 using impact

compaction in a 4 in. diameter split mold. For both impact and vibratory compaction on S1 and R1, the rubber membrane which is typically used for the preparation of granular specimens, was not used. In order to reduce the attraction force between soil and mold, the mold was covered with a plastic wrap which was later removed after the mold was split. All the samples were prepared for a length-to-diameter ratio of about 2.

Samples G1, S1 and R1 were tested as granular soils. Sample G3 had about 36% fines and was therefore cohesive as per AASHTO classification (AASHTO M 145). The test for granular soil consists of 6 conditioning stages and 27 testing stages, which have combinations of different magnitudes of confining stress (σ_3) and deviator stress (σ_d). The cohesive sequence of testing consists of three levels of confining pressure (0, 3 and 6 psi) and five levels of deviator stress (1, 2, 4, 8 and 10 psi). During the resilient modulus test, it was observed that, for all the tests performed on G1 and S1, the extensometer showed a marked increase in deformation and exceeded its limit (4 mm) at confining stress of 1 psi and repeated deviator stress of 10 psi. Under these stress conditions, the sample failed by a very small bulging. The test was therefore terminated at repeated deviator stress of 7.5 psi. All the samples of R1 having lesser shear resistance as described in Section 4.5 failed at a confining stress of 1 psi and repeated deviator stress of 7.5 psi. The G3 samples did not fail under any stress conditions. However when tested wet of optimum, the sample exceeded the limit of the extensometer during the conditioning stage because of the large compressibility of these soils. The G3 samples were therefore not tested wet of optimum.

As discussed in section 2.6.2.6, previous studies have indicated that the resilient modulus can be conveniently expressed in terms of bulk stress

$$M_r = A\theta^B \quad (4.4)$$

Another model which incorporates both deviator stress and bulk stress as proposed by Nataatmadja and Parkin (1989) was also used to analyse the results

$$\frac{M_r \sigma_d}{\theta} = C + D\sigma_d \quad (4.5)$$

Results of resilient modulus tests reduced by the above equations for R1 and S1 are presented in Table 4.6. Detailed output of the resilient modulus test results can be found in Appendix D.

It may be noted that the model proposed by Nataatmadja and Parkin (1987) does not necessarily result in an increase in correlation coefficient for all the cases. Moreover, it involves two variables. Therefore, only the $k-\theta$ model is used in the further discussion because of its simplicity and its more popular use.

The values reported in Table 4.6 are modified in Table 4.8 by considering some of the data points as outliers. These outliers were typically found to be at low stress levels. Table 4.7 shows the outliers considered for R1, S1 and G1. It may be observed from Table 4 that the compaction water content and initial dry unit weight by the same method of compaction showed no particular trend for the A and B parameters for these uniformly graded cohesionless sands. A similar kind of result has been reported by Lee (1993). An average value of constants A and B is determined (shown in Table 4.9) because of their non dependency on moisture content and initial unit weight by the same compaction method.

Table 4.6 Regression Coefficients for R1 and S1

Test ID	W/C %	γ_d pcf	A	B	R^2	C	D	R^2	Note
R11V	4.49	103.8	16344.8	0.27	0.70	3104.4	657.1	0.68	Vib.
R12V	7.93	105.2	8844.2	0.36	0.87	1799.8	580.7	0.77	Vib.
R17V	10.36	105.4	7494.8	0.44	0.81	1512.1	774.6	0.85	Vib.
R13V	12.03	103.9	12647.5	0.29	0.66	2448.7	548.4	0.73	Vib.
R14V	16.27	106.5	8096.3	0.41	0.84	2061.4	558.5	0.81	Vib.
R11I	8.50	102.5	6409.0	0.44	0.84	1532.5	534.5	0.89	Impact
R13I	12.88	102.3	12701.8	0.31	0.73	2683.5	575.8	0.73	Impact
R15I	15.18	103.7	8935.7	0.38	0.81	1952.5	577.2	0.83	Impact
R14I	17.10	104.9	7351.7	0.43	0.94	1851.1	608.4	0.81	Impact
S11	8.61	103.0	3875.9	0.62	0.76	1982.0	584.6	0.92	Vib.
S12	10.36	103.7	3718.1	0.56	0.94	1192.0	548.2	0.90	Vib.
S15	11.44	102.8	2873.5	0.67	0.87	1278.1	588.8	0.95	Vib.
S13	14.88	103.8	7570.0	0.42	0.73	2278.3	529.8	0.78	Vib.
S14	16.79	104.8	5537.0	0.52	0.77	2116.2	570.7	0.90	Vib.

Table 4.7 Information About Outliers Considered

Test ID	$\sigma_3 = 1$ psi	$\sigma_3 = 5$ psi	$\sigma_3 = 10$ psi	$\sigma_3 = 15$ psi	$\sigma_3 = 20$ psi
R11V	$\sigma_d = 1,2$ psi	$\sigma_d = 1$ psi			
R12V	$\sigma_d = 1$ psi				
R13V	$\sigma_d = 1$ psi	$\sigma_d = 1$ psi			
R13I	$\sigma_d = 1,2$ psi	$\sigma_d = 1$ psi		$\sigma_d = 1$ psi	
R15I	$\sigma_d = 1$ psi	$\sigma_d = 1$ psi			
S13	$\sigma_d = 1,2$ psi				
S14	$\sigma_d = 1$ psi				
G11					$\sigma_d = 5$ psi
G12			$\sigma_d = 1$ psi	$\sigma_d = 1$ psi	$\sigma_d = 1,2$ psi
G13		$\sigma_d = 1$ psi	$\sigma_d = 1$ psi	$\sigma_d = 1$ psi	$\sigma_d = 1,2$ psi
G15		$\sigma_d = 1$ psi	$\sigma_d = 1,2$ psi	$\sigma_d = 1,2$ psi	$\sigma_d = 1,2$ psi
G17		$\sigma_d = 1$ psi			

Table 4.8 Modified Resilient Modulus Test Results for R1 and S1

Test ID	W/C %	γ_d pcf	A	B	R ²	Note
R11V	4.49	103.8	9481.3	0.413	0.86	Vibratory
R12V	7.93	105.2	7506.7	0.405	0.89	Vibratory
R17V	10.36	105.4	7494.8	0.435	0.81	Vibratory
R13V	12.03	103.9	8479.8	0.395	0.85	Vibratory
R14V	16.27	106.5	8096.3	0.405	0.84	Vibratory
			8212.2	0.411		Average
R11I	8.50	102.5	6409.0	0.435	0.83	
R13I	12.88	102.3	7862.9	0.433	0.86	Impact
R15I	15.18	103.7	6801.3	0.446	0.86	Impact
R14I	17.10	104.9	7351.7	0.434	0.94	Impact
			7106.2	0.437		Average
S11	8.61	103.0	3875.9	0.624	0.76	Vibratory
S12	10.36	103.7	3718.1	0.562	0.94	Vibratory
S15	11.44	102.8	2873.5	0.670	0.87	Vibratory
S13	14.88	103.8	4718.0	0.549	0.78	Vibratory
S14	16.79	104.8	4260.2	0.586	0.83	Vibratory
			3889.1	0.598		Average

In order to determine the influence of compaction method on M_r , the M_r values at different bulk stresses are shown in Table 4.9 using the average values reported in Table 4.8. Rada and Witczak (1981) have reported that most highway design structures result in bulk stress values near $\theta = 10$ psi (for subbase) and $\theta = 20-40$ psi for bases. For subgrade, the θ values between 5 to 10 psi are of particular interest. It can be observed from Table 4.9 that vibratory compaction resulted in a small increase in M_r values. Lee (1993) has also reported an increase in modulus values using vibratory compaction on dune sands. It may be noted that the increase in unit weight values by vibratory compaction over impact compaction was very small for R1 ($\Delta\gamma = 1-2$ pcf) whereas it was very prominent for the dune sand reported by Lee (1993) ($\Delta\gamma = 5-6$ pcf). It is the author's belief that as long as the vibratory compaction does not result in a significant increase in unit weight of cohesionless sands, M_r values are little affected by the method of compaction.

Finally Table 4.9 also shows that the resilient modulus values for the subgrade conditions were fairly high for the virgin foundry sands as compared to the waste shell molded sand. However, the waste shell molded sand had higher resilient modulus values than values reported for dune sand by Lee (1993) and Rada & Witczak (1981). The dune sand is typically used as subgrade in northern parts of Indiana and the sand reported by Rada & Witczak was used as sand aggregate subbase blend in Maryland study (Rada & Witczak, 1981).

Table 4.9 Resilient Modulus Values at Different Bulk Stresses

Reference	$\theta = 5$ psi	$\theta = 10$ psi	$\theta = 50$ psi	Note
R1	15912	21157	40996	Vibratory
R1	14358	19437	39272	Impact
S1	10182	15412	40349	Vibratory
Dune Sand, Lee (1993)	8145	12302	32053	Vibratory
Dune Sand, Lee (1993)	5855	8843	23040	Impact
Silty Sand Rada & Witzak (1981)	4394	6753	18318	

The models presented in equations 4.4 and 4.5 did not fit well for green WFSs. However, in general, an inverse relationship between the resilient modulus values and deviator stress was found to be effective. The following equation was used for green WFSs:

$$M_r = E \sigma_d^F \quad (4.6)$$

In the case of G1, some of the data points were considered as outliers to better fit the above model (Table 4.7). No outliers were considered for G3. The reduced results of G1 and G3 are contained in Table 4.10 and 4.11. Table 4.10 also contains the reduced results of G3 subjected to granular sequence of testing for comparison purposes. This sample of G3 was prepared near optimum.

A break-point resilient modulus was considered at $\sigma_3 = 3$ psi and $\sigma_d = 6$ psi to characterize a wide range of Indiana cohesive subgrade soils (Lee et al., 1993). In this study confining stresses of 3 psi and 1 psi were considered as representative for subgrade conditions for cohesive and granular sequence of testing. Table 4.12 shows the effect of water content, initial dry unit weight, percentage compaction and CBR on the resilient modulus values at different values of repeated deviator stress.

Table 4.10 Constants E and F Parameters for G1

Test ID	W/C %	γ_d pcf	$\sigma_3 = 20$ psi			$\sigma_3 = 20$ psi		
			E	F	R ²	E	F	R ²
G11	6.93	105.0	41690	-0.05	0.66	42267	-0.11	0.99
G17	7.54	106.7	40910	-0.04	0.68	39491	-0.06	0.87
G12	9.41	108.3	45045	-0.04	0.99	60916	-0.20	0.96
G15	11.39	109.1	89699	-0.19	0.98	78180	-0.19	0.95
G13	13.44	99.0	47936	-0.05	0.74	59194	-0.17	0.96
G33	20.76	98.1	41397	-0.28	0.96	42403	-0.32	0.99

Test ID	$\sigma_3 = 10$ psi			$\sigma_3 = 5$ psi			$\sigma_3 = 1$ psi		
	E	F	R ²	E	F	R ²	E	F	R ²
G11	42560	-0.20	0.92	29923	-0.19	0.80	21199	-0.70	0.85
G17	45612	-0.20	0.73	32160	-0.17	0.85	34765	-0.55	0.89
G12	66304	-0.31	0.84	53596	-0.32	0.85	47897	-0.51	0.80
G15	84410	-0.28	0.99	63364	-0.28	0.99	45702	-0.40	0.98
G13	56587	-0.23	0.87	59481	-0.36	0.86	39219	-0.47	1.00
G33	40161	-0.36	0.78	51856	-0.60	0.93	46089	-0.77	0.97

Table 4.11 Constants E and F for G3

Test ID	Water Content %	Unit Weight pcf	$\sigma_1 = 6 \text{ psi}$			$\sigma_1 = 3 \text{ psi}$			$\sigma_1 = 0 \text{ psi}$		
			E	F	R^2	E	F	R^2	E	F	R^2
G3A4	13.72	93.1	48540	-0.37	0.93	47552	-0.40	0.80	48121	-0.53	0.93
G3A1	15.63	95.0	36465	-0.28	0.81	36459	-0.31	0.72	24751	-0.48	0.87
G3A2	17.63	96.8	45268	-0.41	0.99	29350	-0.24	0.81	31738	-0.39	0.98
G3A3	20.14	98.4	39753	-0.44	0.93	34534	-0.41	0.98	25731	-0.53	0.99

Table 4.12 Effect of Water Content, Dry Unit Weight, Percentage Compaction and CBR on the M_r Response for Green WFSs

Test ID	Water Content %	Dry Density pcf	Compaction %	CBR %	Resilient Modulus (psi)			σ_3 psi
					$\sigma_d = 3$ psi	$\sigma_d = 4$ psi	$\sigma_d = 9$ psi	
G3A4	13.72	93.1	94.6	30.7	30642	27311	19746	3
G3A1	15.63	95.0	96.5	27.5	25936	23723	18450	3
G3A2	17.63	96.8	98.4	25.3	22548	21043	17322	3
G3A3	20.14	98.4	100.0	18.2	21297	18765	13133	3
G33	20.76	98.1	99.7	16.0	19779	15849	8488	1
G11	6.93	105.0	96.2	23.4	9825	8033	4554	1
G17	7.54	106.7	97.7	23.1	18999	16218	10383	1
G12	9.41	108.3	99.2	23.1	27291	23553	15550	1
G15	11.39	109.1	99.9	18.8	29128	25888	18565	1
G13	13.44	108.1	99.0	10.6	23325	20357	13872	1

It is clearly evident from Table 4.12 that increase in water content had a significant effect in the case of G3. In the case of G1, dry unit weight and corresponding percentage compaction were influential for the resilient modulus values. As can be seen from Table 4.12, a general correlation between M_r and CBR does exist for G3. One of most-widely used correlations between M_r and CBR for fine grained soils is given as follows (Huekelom and Foster, 1960)

$$M_r = 1500 CBR \quad (4.7)$$

Because the M_r values from the resilient tests are stress dependent, there cannot be a unique relationship. An attempt has been made to analyse the results by using the relation

$$M_r(\sigma_d) = F(CBR) \quad (4.8)$$

where F is the adjustment factor necessary for equivalence (comparable to the 1500 value as described in Equation 4.7. The average F values for $\sigma_d = 3$ psi and $\sigma_d = 9$ psi were found to be equal to 1000 and 679. By using a linear relation between CBR and σ_d , the following general relation that relates M_r to σ_d and CBR is proposed for green WFSs having about 36% fines. The equation is valid within -7% points of moisture content and optimum moisture content

$$M_r = (1161 - 54\sigma_d) CBR \quad (4.9)$$

where σ_d is in psi and CBR in percent.

It was observed that the resilient modulus for G3 at $\sigma_3 = 3$ psi and $\sigma_d = 6$ psi in the cohesive sequence of testing was comparable to modulus values at σ_3

= 1 psi and $\sigma_d = 4$ psi) in the granular sequence of testing. Therefore, for G1, a representative M_r was chosen at $\sigma_3 = 1$ psi and $\sigma_d = 4$ psi. The following equation is proposed relating M_r to percentage compaction for G1. The equation is valid for percentage compaction (% COMP) within 96% to 100%.

$$M_r = -449833 + 4763\%COMP \quad (4.10)$$

Table 4.12 also shows that G33 had lower modulus values than G15 considering that both were prepared near optimum by the same method of compaction and subjected to the same sequence of testing. This suggests that increasing fines in green WFS would result in lower modulus values near optimum. However, on the dry side of optimum, modulus values increase with increasing amount of fines. Therefore, in general, for the case of green WFS, it would be advantageous to compact them on the dry side of optimum (preferably within -3 percentage points of moisture content to optimum moisture content).

Lee (1993) reported M_r on a wide variety of cohesive soils typically used as subgrade in Indiana. Most of the soils had M_r values between 4000 and 18000 psi. Finally, from Table 4.12, it is observed that the laboratory compacted green WFS had comparable or higher values.

CHAPTER 5

ASPHALT CONCRETE PROPERTIES

This chapter presents the suitability of using WFS as a fine aggregate supplement in asphalt concrete. Based on the characterization tests (see Chapter 3), G1 was selected to compare physical and mechanical properties of a control asphalt mixture with a mixture containing different proportions of G1. The physical and mechanical tests included in this category were bulk specific gravity and theoretical maximum specific gravity as physical tests and Marshall stability and flow as mechanical tests. In addition moisture susceptibility using indirect tensile strength is also discussed.

5.1 Introduction

The gradation of a control mix (aggregates with no WFS) and samples prepared by blending 15%, 20% and 30% of WFS with respect to the control are shown in Figure 5.1. The upper and lower limits of #12 mix according to Indiana specifications (Indiana, 1988) are also included in the Figure 5.1. Instead of scalping the fines from the normal fine aggregate, blending was carried out as a partial replacement, keeping in view that a scalping procedure would be expensive and non-productive.

The control mix contained limestone aggregates down to the No. 16 sieve. The remainder consisted of natural sands. These aggregates were combined with asphalt in

Figure 5.1 Gradation of the control, specimens blended with foundry sand and boundary limits of #12 mix

accordance with procedures outlined by the Marshall Method of Mixture Design (Asphalt Institute, 1984), using 75 blows per side of each specimen. Bulk specific gravity, theoretical maximum specific gravity and Marshall stability and flow on the compacted mixtures were carried out in accordance with ASTM D 2726, D 2041 and D 1559, respectively (ASTM, 1991). Results of this work produced mixtures with the properties shown in Figure 5.2. The design criteria according to the Asphalt Institute are shown in Table 5.1.

Figure 5.2 indicates that control specimens without foundry sand prepared at 5.75% asphalt were at or near optimum. Waste foundry sand was then blended in different proportions at 5.75% asphalt and the above properties were then again determined. Figure 5.3 depicts these properties when WFSs were blended at 15%, 20% and 30% of the total aggregates. The determination of the various properties and their discussion follows.

5.2 Bulk Specific Gravity

The bulk specific gravity of the compacted specimens was determined in accordance with ASTM D 2726. The bulk specific gravity of the compacted mixture (G_{mb}) is calculated as

$$G_{mb} = \frac{W_D}{W_{SSD} - W_S}$$

where,

W_D = Dry weight, gm;

W_{SSD} = Saturated surface dry weight, gm; and

Table 5.1 Asphalt Institute Criteria

Parameters	Acceptance Range
Marshall Stability, lb.	1500 minimum
Flow (0.01 in.)	8-16
Air Voids, %	3-5
VMA, % for 3/8 in. max. size	14 minimum

Figure 5.2 Physical and mechanical properties of the conventional aggregates at varying asphalt content

Figure 5.3 Physical and mechanical properties using different percentages of foundry sand at 5.75% asphalt content

W_s = Saturated surface dry weight submerged in water, gm.

The results of the bulk specific gravity and unit weight along with other properties for the control mixture and mixtures proportioned with different amounts of WFS are summarized in Table 5.2 and Table 5.3.

As can be seen from Figure 5.2, unit weight increased initially as the asphalt content increased because the hot asphalt cement lubricated the particles allowing the compactive effort to force them close together. The unit weight reached a peak and then began to decrease because the additional asphalt cement produced thicker films around the individual aggregates, thereby pushing the aggregate particles further apart and resulting in lower unit weight.

Figure 5.3 shows that increasing the amount of WFS in the control mix resulted in a decrease of the unit weight. This was expected because increasing amounts of WFS were replacing the heavier conventional materials. The bulk specific gravity of G1 was 2.50 while that of the control mix was 2.66.

5.3 Theoretical Maximum Specific Gravity

Theoretical maximum specific gravity was carried out in accordance with ASTM D 2041. The test was carried out in a 8 in. diameter steel container which was 6.5 in. high. This container had a lid at top and an "O" ring to seal the container. The maximum theoretical specific gravity of the mixture (G_{mm}) was calculated as follows

$$G_{mm} = \frac{W_{mm}}{V_{mm}}$$

Table 5.2 Physical Properties of Control Mixture at Different Asphalt Contents

Sample #	AF	BF	CF	DF	EF
Asphalt, %	5.25	5.50	5.75	6.00	6.25
G _{mb}	2.373	2.386	2.394	2.391	2.381
Unit Weight, pcf	148.075	148.886	149.386	149.198	148.574
Air Voids, %	5.743	4.924	4.134	3.620	3.394
VMA, %	15.473	15.234	15.175	15.506	16.083

Table 5.3 Physical Properties of Asphalt Mixtures Using Different Percentages of WFS at 5.75% Asphalt Content

Sample #	CF15	CF20	CF30
WFS, %	15	20	30
G _{mb}	2.356	2.335	2.271
Unit Weight, pcf	147.014	145.704	141.710
Air Voids, %	4.654	5.048	7.228
VMA, %	16.048	16.670	18.739

where,

W_{mm} = weight of the separated sample in air;

V_{mm} = volume of the voidless mixture (equal W_{mm} + weight of container and water at 25°C less weight of container, sample and water at 25°C)

Theoretical maximum specific gravity was used to determine the percentage air voids in the specimen. The following relationship was used to determine the percentage air voids (V_a)

$$V_a = \left(1 - \frac{G_{mb}}{G_{mm}}\right) 100$$

Voids in the mineral aggregate (VMA) was determined using the following relationship

$$VMA = \left(1 - \frac{G_{mb}(1 - P_b)}{G_{sb}}\right) 100$$

where,

G_{mb} = Bulk specific gravity of compacted mixture;

P_b = Asphalt content; and

G_{sb} = Bulk specific gravity of aggregate.

Percentage air voids and VMA of the control and mixtures proportioned with different amount of WFS are shown in Figure 5.2 and 5.3. Figure 5.2 shows that the percentage air voids decreased with increasing asphalt content. This reduction was due to filling of aggregate voids with the addition of asphalt. However asphalt content decreased air-void volume to some minimum value which was approached asymptotically.

With still greater addition of asphalt material, the particles of aggregate were only pushed apart and very little change occurred in air-void volume. Percent VMA decreased with increasing asphalt content, reached a minimum and then increased. The VMA has two components: the volume of voids that is filled with asphalt and the volume of voids remaining after compaction. The initial decrease of VMA was due to decrease in air-void volume. However, at higher asphalt contents, the volume of asphalt increased but the decrease in air-void volume was not significant, which led to overall increase in VMA.

Percentage air voids and VMA were found to increase with increased blending of foundry sand (Figure 5.3). This was due to a deviation from dense gradation. The volume of asphalt was the same for different replacement levels. However, it was the percentage air voids that was increasing the VMA. A certain percentage of air voids is always desirable to ensure that there will be space remaining for expansion of the bitumen if further densification is expected under traffic or expansion to the asphalt that would occur on a hot summer day (Goetz and Wood, 1960). However, if the air void contents are high, there is a possibility that water can get into the mix, penetrate the thin asphalt films within the aggregate and asphalt mass, and lower the stability.

5.4 Marshall Stability and Flow

Marshall stability is defined as the maximum load carried by a compacted specimen tested at 140°F at a loading rate of 2 in./min. The flow is measured at the same time as the Marshall stability. The flow is equal to the vertical deformation of the sample (measured from start of loading to the point at which stability begins to decrease) in hundredths of an inch.

The Marshall stability and flow tests were carried out in accordance with ASTM D 1559. Figure 5.2 shows that the stability value increased with increasing asphalt content up to a maximum after which the stability decreased. This stability is generally a measure of the mass viscosity of the aggregate-asphalt cement mixture and is affected significantly by the angle of internal friction of the aggregate and the viscosity of the asphalt cement at 140°F (Roberts et al., 1991). Stability values obtained by blending 15% WFS were found to be essentially the same as these of the control mix (Figure 5.3). However by blending more WFS, stability was found to decrease as compared to the control because angular limestone aggregates were being replaced by relatively rounded aggregates of WFS.

Flow was found to increase with increasing asphalt content (Figure 5.2). High flow values generally indicate a plastic mix that will experience permanent deformation under traffic, whereas low flow values may indicate a mix with higher than normal voids and insufficient asphalt for durability. Such a mix may experience premature cracking due to mixture brittleness during the life of the pavement (Roberts et al., 1991). It was found that flow values decreased with increased amount of WFS (Figure 5.3). The low flow values were associated with increasing air voids.

5.5 Moisture Susceptibility

Control and mixtures containing 15% WFS and 30% WFS were evaluated to determine their indirect tensile strength under normal conditions and soaked conditions to determine the potential of moisture susceptibility. Six specimens at 5.75% asphalt content using 75 blows at each side were prepared for each type of mixture. Each set of

six specimens were then sorted into two groups so that both the groups yield similar average bulk specific gravity. The first group of three samples was then tested after an air bath of five hours at 25°C temperature. The second group of another three samples was tested after first immersing the samples in water at 60°C for 24 hours and then later submerging them at 25°C for 2 hours. The results are shown in Table 5.4.

The indirect tensile strength also decreased with increased blending of WFS. Both the control sample and sample containing 15% WFS showed increase in strength after immersion in water (Table 5.4). This might have occurred due to asphalt hardening. However, the sample containing 30% of WFS showed decrease in strength after immersion. This was due to significant increase in percentage air voids. High air voids resulted in stripping caused by the introduction of water between the asphalt and the aggregate particles.

5.6 Economic Implications

The cost for conventional fine aggregate is approximately \$7.50 a ton. The INDOT No. 12 mix consists about 96-100% of fine aggregate. Thus by blending 15% WFS with the conventional aggregate, the cost for fine aggregate would be reduced to \$6.50 a ton.

However, WFS usually contains lumps and friable particles which require some processing prior to use in asphalt concrete. This may require an activity by the foundry industry costing from \$3 to \$10 a ton. For foundries whose disposal costs are more than \$20 a ton, this use of WFSs in asphalt concrete remains an economic option.

Table 5.4 Results of Indirect Tension Before and After Immersion

Before Immersion

Sample No.	CF0	CF15	CF30
Foundry sand, %	0	15	30
Bulk Specific Gravity	2.393	2.341	2.281
Tensile strength, psi	206.76	194.67	118.19

After immersion

Sample No.	CF0	CF15	CF30
Foundry sand, %	0	15	30
Bulk Specific Gravity	2.395	2.345	2.280
Tensile strength, psi	218.38	210.72	99.07

The contractor could save \$1 a ton by the using of WFS. The foundries could save at least \$10 a ton in disposal cost. The actual costs of the aggregates will depend on the hauling distances for either natural or WFS.

CHAPTER 6

CONTROLLED LOW STRENGTH MATERIAL PROPERTIES

A waste foundry sand G1 was selected for evaluating its use in Controlled Low Strength Material (CLSM). It was believed that CLSM could use WFS because CLSM does not require the strength of concrete. The mix designs were developed to satisfy three criteria: compressive strength, spread, and set time. The mixes involved total replacement of conventional aggregates with WFS. No additives or admixtures were added to the mix.

6.1 Materials

The materials used in this study were Type I cement, class F fly ash and WFS. The Type I cement was locally available. Table 6.1 (from Nantung, 1993) shows the analyses of the Type I cement provided by the cement manufacturer.

Stout Station fly ash (Indianapolis) is available commercially and marketed as ASTM C-618 class F fly ash. The color of this fly ash was very typical of class F fly ash, which is olive gray. The fly ash was the result of burning a mixture of several Illinois Basin or Eastern coals. Table 6.2 (from Nantung, 1993) shows the chemical analyses of Stout fly ash. Table 6.3 (from Nantung, 1993) shows the physical analyses

Table 6.1 Analyses of Type I Cement: (a) Total Analysis, (b) Potential Compound Composition, (c) Physical Tests, (d) Setting Time, and (f) Compressive Strength (From Nantung, 1993)

(a)

% CaO	64.87
% SiO ₂	20.82
% Al ₂ O ₃	5.29
% Fe ₂ O ₃	2.12
% Na ₂ O	0.12
% K ₂ O	0.58
% SO ₃	3.04
% MgO	2.84
T.A. as Na ₂ O	1.04
Ignition Loss	1.10
Insoluble residue	0.33
F CaO	0.43

(b)

C ₃ S	58.60
C ₂ S	15.35
C ₃ A	10.44
C ₄ AF	6.43
CaSO ₄	5.17

(c)

Normal Consistency %	25.50
Expansion %	-0.22
Air Entrained	11.40

(d)

Gilmore:	
Initial. Hr:Min	1:30
Final. Hr:Min	2:40
Vicat. Min	100/200

(e)

Sieve #325. % passing	89.0
Wagner. cm ² /g	2120
Blaine. cm ² /g	3970

(f)

1-day. psi	2100
3-day. psi	3850
7-day. psi	4850
28-day. psi	6350

Table 6.2 Chemical Analyses of Stout Fly Ash: (a) Total Analysis, Ignited Weight Basis, (b) Parameters Derived From Total Analysis, and (c) Other Tests (From Nantung, 1993)

(a)

% CaO	1.72
% SiO ₂	42.9
% Al ₂ O ₃	26.1
% Fe ₂ O ₃	21.1
% Na ₂ O	0.27
% K ₂ O	2.60
% SO ₃	1.00
% MgO	5.23
% P ₂ O ₅	0.66
% TiO ₂	0.66

(b)

Total % of SiO ₂ + Al ₂ O ₃ - Fe ₂ O ₃	90.10
Total alkalies, as equivalent % Na ₂ O	1.96

(c)

Loss on ignition, ignited weight basis	1.40
% carbon by LECO analysis, ignited weight basis	1.10
The following are determined on oven dry basis:	
% Total SO ₃	1.00
% Soluble SO ₃	0.42
% of the total SO ₃ that is soluble	42 %
% Total alkalies, as equivalent % Na ₂ O	0.05
% Soluble Na ₂ O	0.02
% Soluble K ₂ O	1.95
Soluble alkalies, as equivalent % Na ₂ O	0.06
% of the alkalies that are soluble	3 %

Table 6.3 Physical Analyses of Stout Fly Ash: (a) Particle Size Parameters, (b) Surface Area, and (c) Specific Gravity Measurements (From Nantung, 1993)

(a)

% CaO	1.72
% SiO ₂	42.9
% Al ₂ O ₃	26.1
% Fe ₂ O ₃	21.1
% Na ₂ O	0.27
% K ₂ O	2.60
% SO ₃	1.00
% MgO	5.23
% P ₂ O ₅	0.66
% TiO ₂	0.66

(b)

Total % of SiO ₂ + Al ₂ O ₃ - Fe ₂ O ₃	90.10
Total alkalis, as equivalent % Na ₂ O	1.98

(c)

Loss on ignition, ignited weight basis	1.40
% carbon by LECO analysis, ignited weight basis	1.10
The following are determined on oven dry basis:	
% Total SO ₃	1.00
% Soluble SO ₃	0.42
% of the total SO ₃ that is soluble	42 %
% Total alkalis, as equivalent % Na ₂ O	0.05
% Soluble Na ₂ O	0.02
% Soluble K ₂ O	1.95
Soluble alkalis, as equivalent % Na ₂ O	0.06
% of the alkalis that are soluble	3 %

of Stout fly ash. The sand used was G1 and its physical properties are described in Chapter 3.

6.2 Mixing Procedure

The mixing was done in a 4 cubic foot, electric powered mortar mixer. First WFS, fly ash and water were mixed dry for 2 to 3 minutes and then water was added and mixed for another 3 to 4 minutes. At that time mixing was stopped and testing began. First the spread was measured as proposed by ACI Committee 229, then nine 3 in. $\times$ 6 in. cylinders for compressive strength were made. Next the unit weight of the mix was determined. Finally, the remaining mix was poured into the mold for penetration resistance.

6.3 Testing Procedure

The CLSM mixes were tested for flow, according to the procedure suggested by ACI Committee 229. The flow test was performed by placing an open-ended 3 in. diameter by 6 in. high plastic cylinder on a smooth transparent plastic plate and filling it with CLSM mix. The use of the plastic plate was to minimize friction between the CLSM and the flat surface. The cylinder was then slowly lifted, letting the CLSM spread laterally on the flat surface. After the CLSM stopped flowing (in 10 to 15 seconds), the diameter of the CLSM mass was measured in three directions and the average diameter was calculated. To have acceptable flow, the measured spread of the CLSM should be at least eight inches (ACI Committee 229).

The 3 in. $\times$ 6 in. cylinders used for compressive strength testing were made in

accordance with ASTM C-192, with the following exceptions: the mortar was not consolidated by either rodding or vibration, and the cylinders were allowed to remain covered in the laboratory for 72 hours before stripping. The compressive strength determination of the CLSM was done in accordance with ASTM C-39 and the rate of CLSM loading was 35 psi/sec. Each mix was tested at 3 days, 7 days and 28 days. The cylinders for 7 days and 28 days strength determination were placed in the fog room until the day of the test.

The unit weights were determined in accordance with ASTM C-138, with the following exceptions: the container was 1/10th cubic foot in volume, and the CLSM was not consolidated by rodding or vibration.

The set time was defined by determining the hardening stage as proposed by Nantung (1993). The hardening stage was determined when the bleeding after penetration resistance had subsided, and the slope of penetration resistance versus time suddenly became larger after a certain penetration number was exceeded. The hardening stage was based on: (i) CLSM mixes had a higher penetration resistance because of a disappearance of the lubrication effect (no more excess water surrounded the particles) and the initiation of inter particle forces; (ii) the cement particles are already hydrated entering an acceleration period indicated by a suddenly higher strength gain (Nantung, 1993).

Penetration resistance was measured according to ASTM C-403. The container for the penetration resistance test was a (6 in. $\times$ 11 in. $\times$ 6 in.) steel container. The container was sealed using grease so that water or even slurry could not escape from the sides. The clear distance between the two tests was at least 1.5 in. to avoid interferences from other penetration holes.

6.4 Discussion

Five different types of mixes were prepared with the objective of proposing a most economical mix and satisfying the requirements of flowability, compressive strength and set time. The total weight of each component material was recorded for each mix. The final mix proportions per cubic yard were calculated using the actual material weights and checked against the unit weights of the mixes. Final mix proportions along with the spread, unit weight and compressive strength data are given in Table 6.4. This Table also includes data, using conventional materials, from two sources. The data for Mix ES-1 is taken from Nantung (1993) while the data for Mix 1A is taken from Amon (1990). These data are included for comparison purposes.

It can be noted that CLSM mixes using WFS incorporated more water than conventional sands. This was due to higher absorption values of WFS than conventional sands. This higher water incorporation resulted in more cement demand to maintain the same type of strength as can be achieved using conventional materials.

Figure 6.1 shows the compressive strength of different mixes. Mix 4, after 28 days in the fog room did not gain any strength and is therefore not included. Figure 6.1 shows that the rate of strength gain for WFS mixes was slower than that of conventional materials. This slow rate of strength gain was more prominent at later stages (7 days to 28 days). For easy removal with a small backhoe, the compressive strength should preferably be in the 50-100 psi range. Moreover, the long term strength development of CLSM is a major concern, if later removeability is taken into consideration. Thus a slower rate of strength gain in the later stages is an advantage.

The strength was found to be primarily a function of the cement content. The

Table 6.4 Spread, Unit Weight and Compressive Strength for Different Mixes

Mix No.	1	2	3	4	5	1A ¹	ES-1 ²
Cement (pcy)	131	124	99	55	76	80	63
Fly ash (pcy)	436	414	158	183	139	420	321
Water (pcy)	698	745	741	738	765	561	494
WFS or Sand (pcy)	1922	1822	2134	2128	2126	2535	2774
Spread (in.)	7.5	9.0	8.2	8.1	8.2	-	5-6
Unit weight (pcf)	118	115	116	115	115	-	134
Compressive strength (psi)							
3 - Day	43	41	36	8.5	24	-	20
7 - Day	67	54	44	9	31	45	30
28 - Day	103	80	70	8	55	120	80

¹ From Amon (1990)² From Nantung (1993)

Figure 6.1 Compressive strength of different mixes

water to cement ratio did not influence the rate of strength gain. Unlike concrete, the mechanism of strength development in CLSM based on water to cement ratio is not applicable because of high water and low cement contents (Nantung, 1993).

Kepler (1986) reports that if fly ash is added, the strength goes up, partially due to some pozzolanic effect, but principally because the fly ash-water paste increases the viscosity of the carrier suspension, providing a more uniform consistency. The effect of fly ash in terms of strength was not found to be significant in this study. However, Stout fly ash is relatively larger in size and hence was not very reactive. It is believed that this Stout fly ash would affect the longer time strength. It was shown by Nantung (1993) that smaller diameter fly ashes are ready to react just a few hours after the cement was placed in contact with water. Smaller fly ash particle sizes provide larger surface area for precipitation of cement hydration products, hence higher strength is expected. Thus mixes with Schafer fly ash (mean diameter of 3 μm) resulted in higher strength as compared to mixes of Stout fly ash (mean diameter of 17 μm) (Nantung, 1993).

It was found that a spread less than 8 inches resulted in forming layers while the mixes were being poured. Thus a spread of at least 8 inches is desired from a flowability point of view. The role of fly ash in increasing the flow seems to agree with the explanation of Helmuth (1987). According to Helmuth (1987), the combination of finer particles and repulsion forces causes an increase in workability. The positively charged cement particles can be completely enclosed and neutralized by the negatively charged fly ash particles. Since the rest of the contents of fly ash are negatively charged, the repulsion plays a major role in increasing the workability.

In CLSM, the water content is high but the cement content is low. The higher

water content gives higher mobility and a thicker water film to all the particles. Hence, the interparticle distances are increased and the particle attraction forces (van der Waals forces) are decreased. The high fly ash content in CLSM can cover the positively charged cement particles completely. Therefore, the effectiveness of the repulsion forces in overcoming the attractive van der Waals forces determines the flowability (Nantung, 1993).

Because fly ash and WFS from green sand process both contain carbon, it was found that in order to maximize the use of WFS, a lesser amount of fly ash is advisable. Otherwise, the porous carbon particles require too much water, which consequently requires more cement.

To be economically feasible, CLSM should set up between 4 and 24 hours. If it sets up too quickly, it would set up in the mixing/transportation devices. If it sets up too slowly, it would slow construction too much (Kepler, 1986). The results of penetration resistance against time are shown in Figures 6.2 through Figure 6.7. For the first mix, the set time was determined based on a penetration number i.e. (penetration resistance of 400 psi). Thus the set time for this mix was at hour 16. However, it is author's belief that this mixture had a set time at 3 to 4 hours based on Nantung's definition of hardening stage. For the latter mixes, the set time was determined by determining the hardening stage as proposed by Nantung (1993). Hardening stage was indicated by a penetration resistance number of 40 psi and a sudden increase in the slope of the curve of the penetration resistance. These indications guaranteed that the mix already had a load carrying capacity and had passed the accelerated period in cement hydration. Therefore proper cement hydration had already occurred.

Figure 6.2 Penetration resistance of Mix 1 versus time

Figure 6.3 Penetration resistance of Mix 2 versus time

Figure 6.4 Penetration resistance of Mix 3 versus time

Figure 6.5 Penetration resistance of Mix 4 versus time

Figure 6.6 Penetration resistance of Mix 5 versus time

The penetration resistance number of 40 psi is based on values of unconfined compression strength in soil using the penetrometer. A value between 25 to 55 psi is classified as a stiff soil and a value higher than 55 psi is classified as a hard soil. Thus an intermediate value of 40 psi is chosen as a minimum penetration number.

The set time of Mix 2 was at 6 to 7 hours and of Mix 3 was at 5 to 6 hours. Mix 4 did not set at all. Mix 5 set at between 7 and 8 hours. Generally, set time was essentially dependent on water to cement ratio (i.e. lesser the water to cement ratio, earlier the hardening stage). Comparing mixes 3, 4 and 5, this conclusion seems true. However, comparing mixes 2 and 3, this conclusion does not hold. For this case, it was the increase in unit weight of mix 3 which caused it to be more resistant than Mix 2. Thus for mixes having identical unit weight, the hardening stage is dependent on water to cement ratio.

6.5 Economics

The bulk of volume of CLSM is provided by sand and water. Fly ash and cement do not contribute significantly to volume. Therefore, even for the most uneconomical mix in this study (Mix 1), it is cheaper as compared to existing mix design for conventional materials. A sample calculation is provided below.

Cost of Type I cement	= \$5.50/bag
1 bag of cement	= 94 lb
Cost of sand (conventional)	= \$6/ton
Cost of fly ash ¹	= 0
Cost of waste foundry sand ¹	= 0

¹ These are waste products and hence assumed to be supplied free of charge

Existing mix design for conventional mix

Cement : Fly Ash : Sand : Water

For one cubic yard; 60 lb : 330 lb : 2860 lb : 510 lb

Cost for cement = \$3.50

Cost for sand = \$8.60

Total cost = \$12.10

Mix 1 using WFS

Cement : Fly Ash : Sand : Water

For one cubic yard; 131 lb : 436 lb : 1922 lb : 689 lb

Total cost = cost of cement = \$7.70.

Mix 3 using WFS

Cement : Fly Ash : Sand : Water

For one cubic yard; 99 lb : 158 lb : 2134 lb : 741 lb

Total cost = cost of cement = \$5.80

6.6 Long Term Backfill Properties

If CLSM using WFS is used as a backfill, the following long-term properties should be considered

- Durability
- Ability to withstand erosion or abrasion corrosion potential
- Corrosion potential

Twenty-eight days unconfined compression strengths of 50 to 150 psi are normally specified for CLSM mixes. As low strength mixes are not durable under freeze-thaw conditions, sand or natural soil should be used for the upper 2 to 3 feet of the backfill.

Controlled low strength material mixes may deteriorate when exposed to erosive or abrasive forces. Soil cover or pavement should be applied over trench backfill and protective facing must be used against retaining backfill. For retaining wall backfill, drainage should also be provided as would be placed for a soil backfill. Drains may be placed between the CLSM and natural soil, and/or between the backfill and the retaining wall (GAI Consultants, 1992).

Research for corrosion potential is desired for CLSM mixes using WFS. Electrical resistivity measurements may be used as an indication of corrosion potential. As a rule, the higher the resistivity, the less corrosive the material.

CHAPTER 7

ENVIRONMENTAL CONCERNS

The environmental concerns center around leaching heavy metals from embankments constructed of WFS. The Office of Solid and Hazardous Waste Management of the Indiana Department of Environmental Management (IDEM) classifies foundry wastes on the basis of results from the EP toxicity test and a modified EP toxicity water leaching procedure (Indiana leach test) as shown in Table 1.13. Results of the leachate analysis of WFS are presented in Table 7.1 along with the National Primary Drinking Water Standard (NPDWS) and with the maximum contaminant levels specified by EPA.

The results from seven WFSs show that all of these wastes are well below the RCRA limits and are therefore non hazardous. It should be noted that four of the foundries (G3, G4, G7 and C1) used TCLP results. It is believed that the TCLP test is more aggressive and if the waste streams can pass TCLP, they can also pass EP toxicity. Table 7.2 shows comparison of EP toxicity and TCLP on two WFSs which support the above statement.

When compared with the NPDWS, few of the parameters exceeded the recommended value. Except for lead and selenium in G3, lead in G4 and barium in G7, which exceeded the NPDWS, it is unknown whether concentrations of other parameters

Table 7.1 Results of the Toxicity Test on WFS Samples

Parameters	Concentration (mg/l)									
	G1	G2	G3 ^a	G4 ^a	G6	G7 ^a	Cl ^a	RCRA limits	NPDWS limits	
Arsenic	<0.003	<0.01	0.001	<0.2 [?]	0.02	<0.2 [?]	<0.2 [?]	5.0	0.05	
Barium	<0.05	<0.5	0.4	0.2	0.50	1.1	0.2	100.0	1.0	
Cadmium	<0.0003	<0.01	0.01	<0.1 [?]	0.004	<0.1 [?]	<0.1 [?]	1.0	0.01	
Chromium	<0.01	<0.05	<0.02	<0.1 [?]	0.02	<0.1 [?]	<0.1 [?]	5.0	0.05	
Lead	0.004	<0.01	0.09	0.2	0.02	<0.1 [?]	<0.05	5.0	0.05	
Mercury	<0.0002	<0.001	<0.002	<0.05 [?]	0.002	<0.05 [?]	<0.1 [?]	0.2	0.002	
Selenium	<0.003	<0.005	0.03	<0.2 [?]	0.01	<0.2 [?]	<0.2 [?]	1.0	0.01	
Silver	<0.01	<0.05	0.03	<0.1 [?]	0.003	<0.1 [?]	<0.1 [?]	5.0	0.05	

^a TCLP test used[?] Not detected at the detection limit

Table 7.2 Comparison of EP Toxicity and TCLP Test Results

Parameters	G1		G2	
	EPTC	TCLP	EPTC	TCLP
Arsenic	<0.003	<0.003	<0.01	<0.1
Barium	<0.05	0.39	<0.5	0.58
Cadmium	<0.0003	<0.005	<0.01	<0.03
Chromium	<0.01	<0.01	<0.05	0.04
Lead	0.0004	<0.1	<0.01	<0.1
Mercury	<0.0002	<0.0002	<0.001	<0.005
Selenium	<0.003	<0.003	<0.005	<0.1
Silver	<0.01	<0.01	<0.05	<0.03

in G4, G7 and C1, exceeded the drinking water standards, since the detection limits were higher than the standards. However, these parameters exceeded NPDWS by very low margins. The parameter of highest concern was lead which in G4 exceeded the NPDWS by 0.15 mg/l.

Most of the foundries using green sand process in Indiana cast iron products. As already mentioned in section 2.5.4 and 2.7.3.2, green WFS from ferrous foundries are believed to be non hazardous. The data from the above foundries also confirm that these WFS are non hazardous according to the RCRA definition of 100 times the NPDWS in the TCLP or EP toxicity test.

The results of the additional parameters using the Indiana leaching method are summarized in Table 7.3. In this Table the concentrations of the regulated analytes are compared with the Type III and Type IV limits specified in the Indiana Administrative Code (Indiana legislative council, 1992).

The values show that G1, G2 and G6 samples meet the Type IV criteria. However in G6, some of the analytes are not reported. In G3, with the exception of fluoride and pH, all the other parameters meet the Type IV criteria. However, fluoride values in G3 are far less than specified for Type III limits.

As an embankment material, WFS will be placed in a moistened, highly compacted state. Moreover, a top and sides clay cover would be specified to limit water infiltration into the WFS embankment. A waste foundry sand embankment will be a kind of foundry sand monofill and the acidic conditions used in the laboratory tests are not likely to exist in a foundry monofill. Moreover, the laboratory tests do not account for attenuation mechanisms, such as precipitation, adsorption, dilution and dispersion. Thus

Table 7.3 Results of the Indiana Leaching Method Test on WFS Samples

Parameters	Concentrations (mg/l)					
	G1	G2	G3	G6	Type III	Type IV
Barium	0.15	<0.5	<0.4		10.0	1.0
Boron	0.4	<0.1	0.146		20.0	2.0
Chlorides	7.4	4.0	<100.0	<2.0	2.5	250.0
Copper	0.06	0.12	<0.04	<0.005	2.5	0.25
Cyanide, total	<0.01	0.006	<0.06	0.005	2.0	0.2
Fluoride	<0.2	0.34	1.59	<0.1	14.0	1.4
Iron	0.3	0.24	<0.08	1.06	15.0	1.5
Manganese	<0.005	<0.05	<0.04	0.012	0.5	0.05
Nickel	<0.04	<0.1	<0.01	<0.03	2.0	0.2
Phenols	0.18	0.19	<0.25	0.04	3.0	0.3
Sodium	17.0	10.0	35.98	25.43	2.5	250.0
Sulfate	10.0	8.0	85.03	47.1	2.5	250.0
Sulfide, total	<1.00	<0.2	<0.5	<0.1	5.0	1.0
TDS ^a	190.0	56.0	208.46	236.0	5.0	500.0
Zinc	60.0	<0.05	<0.04	0.06	25.0	2.5
pH	9.8	7.8	9.09	8.3	5-10	6-9

^a Total Dissolved Solids

^b Concentrations represent the composite of waste streams and not the sand itself

at the site, actual leached quantities are expected to be even lower than the laboratory determined values because of cover material, attenuation mechanisms, low hydraulic conductivity of the green WFS itself and proper drainage.

CHAPTER 8

CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH NEEDS

8.1 Conclusions

This study based on a comprehensive literature search, and testing and evaluation of test results, assesses the feasibility of using WFS in embankments, as an aggregate supplement in asphalt concrete and as an aggregate in CLSM. Ten WFSs were extensively studied in the laboratory so as to provide a data base on the properties of WFSs available in Indiana. In addition, the study briefly analyses the environmental impacts of the different applications of WFS. An extensive review of the literature has been presented on the current status of knowledge of WFS. Also previous laboratory and field experiences with WFS have been reviewed and documented. Based on the results of detailed laboratory evaluation and the literature review, the following conclusions are drawn.

8.1.1 Literature review

- Waste foundry sand is generated by industries that use sands, binders and additives to form molds and cores for castings. The mold forms the outside of the castings while the core forms the internal shape.
- Binder is any material which is used to hold sand grains together. Additives are

those materials which are added to the bonded sands to improve properties, either during the molding process or during the casting process or both.

- There are three types of WFSs based on the molding process. In Indiana, the most commonly used molding process is the green sand process where the metal is poured into the molds when the sand is damp, as it is when the mold is made. Other processes are the chemically bonded process and the shell molding process.
- The various options available to reduce the WFS disposal problem include: reusing some portion of foundry sand, reclamation of waste materials, constructive uses of non-hazardous wastes and treatment of hazardous wastes and disposal.
- Generally WFS from ferrous foundries are found to be non-hazardous and can be used beneficially.
- Generators of hazardous WFS are required to meet a treatment standard before disposing of the waste to land disposal. Chemical stabilization technology has been found to be the most effective technology for reducing the degree of hazard associated with these wastes. This technology employs cement or pozzolanic materials as stabilizing agents.
- Based on the chemistry of WFS and bench scale testing, WFS can be used as a raw material for manufacture of Portland cement.
- Physical properties of the WFS surveyed did not conform to ASTM specifications for fine aggregate in Portland cement concrete. However possibility exists for blending of WFS with standard aggregates.
- The primary environmental concern about the use and disposal of WFS is the

potential for certain constituents to leach into the soil and groundwater at concentrations determined to be potentially hazardous to human health and the environment.

- Generally WFS are alkaline and non corrosive based on reported pH values.
- The AFS test simulates conditions likely to develop in a foundry monofill, while the EP toxicity and TCLP test methods represent a type of environment where foundry wastes are disposed along with municipal wastes.
- There are several chemical mechanisms in soil and groundwater such as precipitation, adsorption, dispersion, dilution, etc., which act to attenuate or reduce the mobility and concentration of contaminants in groundwater.

8.1.2 Characterization tests

- Generally, green WFSs were found to be uniformly graded with 5 to 12% fines whereas chemically bonded and shell molded WFS were found to be clean and uniformly graded.
- Most of the WFSs were found to be quite dry.
- Loss on Ignition values were found to be relatively high for green WFS. This was due to the presence of additives like seacoal in the green WFS.
- In general, foundry sands were found to be subangular to rounded.
- Green WFS were relatively rough as compared to other sands tested.
- For beneficiation purposes where WFSs are to be mixed dry with cementing agents like asphalt cement, clay lumps and friable particles associated with the molding sand need to be washed, or screened off or crushed.

- Core lumps are required to be crushed for beneficial reuse.
- Waste foundry sand exhibited high soundness losses. A possibility exists that the particles themselves did not break but that the binders and other additives became separated under severe exposure conditions of the chemicals and passed through the mesh opening of the test sieves.
- High carbon content and relatively rough surface texture in the green WFS resulted in high absorption values.
- Variation within a foundry sample is principally attributed to the lack of control in the dust generation.

8.1.3 Geotechnical properties

- Because most of the WFSs are quite dry, they can be used in as-received conditions.
- The permeability of green WFS was found to be low as compared to the chemically bonded or shell molding sand. The low permeability of green WFS was due to the presence of both clay binder and seacoal additives which resulted in the generation of many fines and thus contributed a significant reduction in permeability. The permeability of chemically bonded and shell molded sand was comparable to uniform fine sand.
- The laboratory compaction showed vibratory compaction to be more effective for chemically bonded and shell molded sand. Green WFS compacted more effectively by impact compaction.
- The as compacted CBR for green WFS decreased significantly with increasing

moisture content. However, little variation with moisture content, in the as compacted CBR values was found for cohesionless soils, like C2 and R1.

- The soaked CBR values for all the cases were found to vary in accordance with the dry unit weight.
- The CBR values suggest that these sands can be used for subgrade materials. However, their use as subbase and base is unacceptable.
- Waste foundry sand from the green sand process showed higher shear strength as compared to chemically bonded and shell molded WFS. This may be due to their better grading and relatively rougher surface texture.
- In general, WFSs were found to be more compressible than the natural sand. Green WFSs were found to be more compressible than the chemically bonded and shell molded WFSs. This was due to a greater fines content in the green WFS.
- Resilient moduli of uniformly graded cohesionless sands like R1 and S1 were found to be independent of the increase in compaction water content and initial dry unit weight obtained by the same method of compaction.
- Vibratory compaction resulted in increase in resilient modulus for cohesionless sands.
- For green WFSs, as long as the fines are low (about 6% passing # 200 sieve), M_r is affected by the initial dry unit weight obtained by the same method of compaction. When the fines are more (about 36% passing # 200 sieve), M_r tends to decrease with increasing amount of water content.
- In general, WFSs have M_r values comparable or higher than most soils used as subgrade in Indiana.

- From the aspect of gradation, WFSs have negligible to low frost susceptibility but they are susceptible to liquefy, if not properly placed under controlled conditions.
- Chemically bonded and shell molded sands are not very resistant to erosion because of lack of cohesion. On the other hand WFS from green sand process are more resistant to erosion because of the presence of bentonite.

8.1.4 Asphalt concrete properties

- When as much as 15% of WFS is blended with conventional aggregates, the performance of the asphalt concrete mixture is not very different from that using conventional materials. However, using more than 15% of WFS in the conventional aggregates resulted in low flow values and high air voids, which may lead to mixture brittleness and consequently premature cracking.
- Because the WFSs of different Indiana foundries are similar in gradation (Figure 3.2), the above conclusion may be generally applicable.
- Lumps in the WFS may be a problem, requiring some cleaning/washing prior to use.
- Even with the cleaning and cleaning and handling requirements, WFS may be viable for limited blending with conventional aggregates in asphaltic mixtures.

8.1.5 Controlled low strength material properties

- Wet unit weight affects the pressures applied by the CLSM on pipes or retaining walls. Thus mixes using WFS are better than conventional mixes in this connection.

- The rate of strength gain for mixes using WFS is lower than for mixes using conventional materials. This fact is an advantage for long term strength development of CLSM, if later removeability is taken into consideration.
- The strength was primarily dependent on the cement content. Higher cement content resulted in higher strength.
- In general, the hardening stage of the CLSM mixes were dependent on water-to-cement ratio. The hardening stage was reached earlier for mixes having lower water-to-cement ratio. But for mixes having unlike unit weights, the hardening stage was reached earlier for mixes having higher unit weights.
- Based on critical review of the mixes prepared in this study, Mix 3 is best.
- Controlled low strength materials using WFS are economical as compared to conventional mixes and their use should be encouraged.

8.1.6 Environmental concerns

- Indiana Department of Environmental Management classifies foundry wastes on the basis of EP toxicity and Indiana leach tests.
- None of the seven WFS reported in Chapter 7 would be classified as hazardous by the RCRA definition of 100 times NPDWS in the EP toxicity or TCLP test.
- The parameter of highest concern was found to be lead in one of the foundry which exceeded NPDWS by 0.15 mg/l.
- The results from the four foundries show that generally these WFSs meet the Type IV criteria.
- In practical use, actual leached quantities are expected to be even lower than the

laboratory determined values because of cover material, attenuation mechanisms, low hydraulic conductivity and proper drainage.

8.2 Recommendations

- For embankment and subgrade projects that involve large-volume utilization, it is important to have sufficient supplies of the material from a single source to complete the project. Any changes in the source or type of WFS are strongly discouraged because they could result in significant variation from the properties desired.
- It is critical that the costs associated with WFS including hauling costs and additional costs due to clay cover be less than those of using a conventional construction material.
- Based on the Marshall stability and flow and moisture susceptibility results, it is recommended that WFS can be used as a partial replacement for conventional aggregates in asphaltic surface mixes.
- A replacement level of 15% is recommended using the Asphalt Institute criteria. The best use of WFS in asphalt concrete is possible when higher percentage air voids are desired, such as in Indiana Specifications which allow 4 to 8% air voids. In these cases up to a 25% replacement level can be allowed.
- A separate bin is recommended for WFSs so that they can be blended with conventional aggregates.
- Core lumps need to be crushed whereas lumps associated with molding sand need

asphalt pavements using WFSs.

- A laboratory study using WFS in a manner such that the WFS replaces an equal volume of the mineral aggregate, thereby retaining the same gradation. Such a study will help in understanding the influence of basic properties such as absorption, particle shape and texture, on the asphaltic mixes.
- Freezing-thawing durability is one of an important property for CLSM mixes without cover. Freeze-thaw studies for the regular CLSM are available using Nantung's procedure, which will serve as the basis to pursue this research further.
- Research for corrosion potential is desired for CLSM mixes using WFS. Electrical resistivity measurements may be used as an indication of corrosion potential.

to be washed or screened off or crushed before their use in manufacturing asphalt concrete.

- It is important that the hauling and processing costs for WFS do not offset the other economic advantages.
- Based on compressive strength, unit weight, setting time and economics of CLSM mixes with WFS, it is recommended that WFS can be used as regular fine aggregate in CLSM mixes.
- A LOI value of 3-4% for WFS should be considered as an upper limit until data for CLSM using WFS, having higher LOI values, become available.

8.3 Future Research Needs

- A field study which should include the construction of a test embankment and a test section of subgrade, with adequate monitoring devices, to measure the geotechnical properties and the leachates from fill is recommended. The study will be very helpful in determining the long-term performance and development of correlations between the laboratory and field parameters.
- The effect of freeze thaw on M_r for WFSs should be conducted.
- Creep tests should be conducted in the lab for rutting tendencies on different bituminous mixes incorporating WFSs.
- Those bituminous mixes surviving the laboratory testing should be further tested in the accelerated pavement facility at the INDOT Division of Research.
- Finally several strips should be placed in the field for long term behavior of

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Appendix A
1992 INCMA Foundry Members

INDIANA CAST METALS ASSOCIATION

1992 MEMBERSHIP

FOUNDRY MEMBERS

A B C Rail Corporation, Anderson, Indiana
 Accurate Castings, Inc., LaPorte, Indiana
 American Steel Foundries, East Chicago, Indiana
 Atlas Foundry Company, Inc., Marion, Indiana
 Auburn Foundry, Inc., Auburn, Indiana
 Bahr Brothers Mfg., Marion, Indiana
 Beckett Bronze Company, Muncie, Indiana
 Bremen Castings, Inc., Bremen, Indiana
 Charles O. Hiler & Son, Inc., LaPorte, Indiana
 Crosbie Foundry Company, Inc., Elkhart, Indiana
 Dalton Foundries, Inc., Warsaw, Indiana
 Decatur Casting Division, Decatur, Indiana
 Dillon Pattern & Foundry, Inc., Anderson, Indiana
 Dodge/Reliance RMG Foundry, Mishawaka, Indiana
 Electric Steel Castings Company, Indianapolis, Indiana
 Elkhart Foundry & Machine Company, Elkhart, Indiana
 Essex Castings, Inc., Columbus, Indiana
 Ford Meter Box Company, Inc., Wabash, Indiana
 Gardand Foundry Company, Inc., Terre Haute, Indiana
 Grede New Castle, New Castle, Indiana
 Harrison Steel Castings Company, Attica, Indiana
 Indiana Copper Corporation, Ft. Wayne, Indiana
 Interstate Castings, Inc., Indianapolis, Indiana
 Kingsbury Casting Division, LaPorte, Indiana
 Kunkle Foundry Company, Andrews, Indiana
 Maco Corporation, Huntington, Indiana
 Mahoney Foundries, Inc., Kendallville, Indiana
 Navistar International Transportation Corp., Indianapolis, Indiana
 Newnam Manufacturing, Inc., Kendallville, Indiana
 Noblesville Castings, Inc., Noblesville, Indiana
 North Manchester Foundry Company, North Manchester, Indiana
 Plymouth Foundry, Inc., Plymouth, Indiana
 Richmond Casting Company, Inc., Richmond, Indiana
 Rochester Metal Products Corp., Rochester, Indiana
 Shenango Industries, Inc., Terre Haute, Indiana
 Sterling Castings Corp., Bluffton, Indiana
 Teledyne Casting Service, LaPorte, Indiana
 Zimmer - USA, Inc., Warsaw, Indiana

Appendix B
Calibration of Transducer and Compressibility Data for G1 and G3

CALIBRATION OF PORE PRESSURE TRANSDUCER

Voltage Pressure
mV Kg/cm²

1.59	0.0
8.73	0.5
15.93	1.0
23.23	1.5
30.60	2.0
37.77	2.5
45.10	3.0
59.49	4.0
73.97	5.0
88.46	6.0
73.88	5.0
59.42	4.0
45.01	3.0
37.71	2.5
30.39	2.0
23.28	1.5
15.98	1.0
8.79	0.5
1.58	0.0

Regression Output:

Constant	-0.106
Std Err of Y Est	0.004
R Squared	1.000
No. of Observations	19
Degrees of Freedom	17
X Coefficient(s)	0.069
Std Err of Coef.	0.000

CALIBRATION OF PORE PRESSURE TRANSDUCER

SATURATED COMPRESSIBILITY DATA FOR G1

Applied Stress Kg/cm ²	Elapsed Time min.	Dial Reading 10 ⁻⁴ in	Voltage mV	Pore Pressure Kg/cm ²
0.079	0	3969	52.85	3.5459
	0.25	3950	52.85	3.5459
	0.5	3949	52.85	3.5459
	1	3949	52.85	3.5459
0.158	0	3949	52.84	3.5452
	0.25	3921	52.89	3.5486
	0.5	3920	52.89	3.5486
	1	3918	52.87	3.5472
	2	3917	52.87	3.5472
	4	3916	52.86	3.5466
0.316	0	3916	52.84	3.5452
	0.25	3883	53.01	3.5569
	0.5	3880	52.94	3.5521
	1	3875	52.90	3.5493
	2	3871	52.85	3.5459
	4	3869	52.82	3.5438
0.632	0	3869	52.82	3.5438
	0.25	3824	53.24	3.5728
	0.5	3818	-	-
	1	3810	52.96	3.5535
	2	3805	52.85	3.5459
	4	3801	52.81	3.5431

SATURATED COMPRESSIBILITY DATA FOR G1

Applied Stress Kg/cm ²	Elapsed Time min.	Dial Reading 10 ⁻⁴ in	Voltage mV	Pore Pressure Kg/cm ²
1.263	0	3801	52.87	3.5472
	0.25	3724	53.38	3.5825
	0.5	3720	52.97	3.5542
	1	3714	52.89	3.5486
	2	3709	52.83	3.5445
	4	3705	52.81	3.5431
2.526	0	3705	52.81	3.5431
	0.25	3623	53.46	3.5880
	0.5	3618	52.94	3.5521
	1	3612	52.87	3.5472
	2	3608	52.82	3.5438
	4	3604	52.79	3.5417
5.052	0	3604	52.79	3.5417
	0.25	3511	53.58	3.5963
	0.5	3508	52.99	3.5555
	1	3505	52.87	3.5472
	2	3501	52.80	3.5424
	4	3499	52.68	3.5341
10.104	0	3499	52.68	3.5341
	0.25	3421	53.54	3.5935
	0.5	3419	52.92	3.5507
	1	3417	52.82	3.5438
	2	3415	52.72	3.5369
	4	3413	52.66	3.5327
	780	3400	49.70	3.3282
	1270	3400	49.68	3.3268

SATURATED COMPRESSIBILITY DATA FOR G3

Applied Stress Kg/cm ²	Elapsed Time min.	Dial Reading 10 ⁻⁴ in	Voltage mV	Pore Pressure Kg/cm ²
0.079	0	3925	52.89	3.5486
	0.25	3898	52.89	3.5486
	0.5	3898	52.89	3.5486
	1	3898	52.89	3.5486
0.158	0	3898	52.89	3.5486
	0.25	3870	52.89	3.5486
	0.5	3867	52.89	3.5486
	1	3864	52.87	3.5472
	2	3863	52.87	3.5472
0.316	0	3863	52.87	3.5472
	0.25	3824	52.89	3.5486
	0.5	3819	52.89	3.5486
	1	3813	52.89	3.5486
	2	3808	52.88	3.5479
	4	3804	52.88	3.5479
	8	3800	52.87	3.5472
0.632	0	3800	52.87	3.5472
	0.25	3736	53.01	3.5569
	0.5	3729	52.97	3.5542
	1	3720	52.93	3.5514
	2	3713	52.90	3.5493
	4	3707	52.88	3.5479
	8	3702	52.87	3.5472

SATURATED COMPRESSIBILITY DATA FOR G3

Applied Stress Kg/cm ²	Elapsed Time min.	Dial Reading 10 ⁻⁴ in	Voltage mV	Pore Pressure Kg/cm ²
1.263	0	3702	52.87	3.5472
	0.25	3527	53.38	3.5825
	0.5	3516	53.20	3.5701
	1	3504	53.05	3.5597
	2	3498	52.90	3.5493
	4	3491	52.87	3.5472
2.526	0	3491	52.87	3.5472
	0.25	3286	53.80	3.6115
	0.5	3275	53.44	3.5866
	1	3260	52.15	3.4975
	2	3250	52.90	3.5493
	4	3242	52.84	3.5452
5.052	0	3242	52.84	3.5452
	0.25	3016	53.98	3.6239
	0.5	3004	53.58	3.5963
	1	2989	53.13	3.5652
	2	2972	52.88	3.5479
	4	2965	52.84	3.5452
10.104	0	2965	52.84	3.5452
	0.25	2690	54.36	3.6502
	0.5	2680	53.48	3.5894
	1	2666	53.06	3.5604
	2	2655	52.90	3.5493
	4	2645	52.84	3.5452
	1200	2613	52.80	3.5424
	1320	2613	52.80	3.5424

Appendix C
Resilient Modulus Test Results

Test/File Name : TESTR11V

Start Date : 02-08-1994

Start Time : 12:25:21

End Date : 02-08-1994

End Time : 14:16:39

Soil Sample : R1

Sample Number : 1

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.53e+000	1.4234e-004	8.103e+000	3.1850e+004
5.00	5.00	200	4.64e+000	1.4234e-004	8.103e+000	3.2614e+004
10.00	5.00	100	9.55e+000	2.8481e-004	8.100e+000	3.3518e+004
10.00	5.00	200	9.70e+000	2.9433e-004	8.099e+000	3.2953e+004
10.00	10.00	100	1.08e+001	2.4689e-004	8.098e+000	4.3875e+004
10.00	10.00	200	1.16e+001	2.7537e-004	8.098e+000	4.2186e+004
15.00	10.00	100	1.48e+001	3.5146e-004	8.095e+000	4.1984e+004
15.00	10.00	200	1.47e+001	3.5146e-004	8.095e+000	4.1921e+004
15.00	15.00	100	1.49e+001	2.9450e-004	8.094e+000	5.0473e+004
15.00	15.00	200	1.47e+001	3.0400e-004	8.094e+000	4.8465e+004
20.00	15.00	100	2.03e+001	3.9902e-004	8.094e+000	5.0963e+004
20.00	15.00	200	2.01e+001	3.9902e-004	8.094e+000	5.0252e+004
1.00	20.00	100	9.15e-001	1.9003e-005	8.093e+000	4.8173e+004
1.00	20.00	200	9.15e-001	1.9003e-005	8.093e+000	4.8173e+004
2.00	20.00	100	1.92e+000	3.8005e-005	8.093e+000	5.0467e+004
2.00	20.00	200	1.94e+000	3.8005e-005	8.093e+000	5.1040e+004
5.00	20.00	100	4.77e+000	7.6011e-005	8.093e+000	6.2796e+004
5.00	20.00	200	4.73e+000	8.5512e-005	8.093e+000	5.5309e+004
10.00	20.00	100	9.68e+000	1.7102e-004	8.093e+000	5.6583e+004
10.00	20.00	200	9.76e+000	1.7102e-004	8.093e+000	5.7093e+004
15.00	20.00	100	1.50e+001	2.6604e-004	8.093e+000	5.6446e+004
15.00	20.00	200	1.50e+001	2.6604e-004	8.093e+000	5.6364e+004
20.00	20.00	100	1.99e+001	3.5156e-004	8.093e+000	5.6664e+004
20.00	20.00	200	2.01e+001	3.5156e-004	8.093e+000	5.7222e+004
1.00	15.00	100	1.09e+000	3.8003e-005	8.094e+000	2.8676e+004
1.00	15.00	200	1.07e+000	1.9001e-005	8.094e+000	5.6205e+004
2.00	15.00	100	2.03e+000	3.8003e-005	8.094e+000	5.3338e+004
2.00	15.00	200	1.98e+000	3.8003e-005	8.094e+000	5.2191e+004
5.00	15.00	100	4.77e+000	8.5507e-005	8.094e+000	5.5822e+004
5.00	15.00	200	4.79e+000	8.5507e-005	8.094e+000	5.6077e+004
10.00	15.00	100	9.68e+000	1.9951e-004	8.094e+000	4.8504e+004
10.00	15.00	200	9.68e+000	1.9951e-004	8.094e+000	4.8504e+004
15.00	15.00	100	1.50e+001	3.1352e-004	8.094e+000	4.7759e+004
15.00	15.00	200	1.50e+001	3.1352e-004	8.094e+000	4.7828e+004
20.00	15.00	100	2.04e+001	4.1803e-004	8.094e+000	4.8905e+004
20.00	15.00	200	2.03e+001	4.0854e-004	8.093e+000	4.9615e+004
1.00	10.00	100	1.00e+000	1.9000e-005	8.094e+000	5.2769e+004
1.00	10.00	200	1.07e+000	2.8499e-005	8.094e+000	3.7474e+004
2.00	10.00	100	2.03e+000	5.6998e-005	8.094e+000	3.5562e+004
2.00	10.00	200	1.98e+000	4.7498e-005	8.094e+000	4.1757e+004
5.00	10.00	100	4.77e+000	1.1400e-004	8.094e+000	4.1871e+004
5.00	10.00	200	4.73e+000	1.1400e-004	8.094e+000	4.1489e+004
10.00	10.00	100	9.68e+000	2.4699e-004	8.094e+000	3.9180e+004
10.00	10.00	200	9.87e+000	2.5649e-004	8.094e+000	3.8493e+004
15.00	10.00	100	1.51e+001	3.7050e-004	8.094e+000	4.0767e+004
15.00	10.00	200	1.53e+001	3.7050e-004	8.094e+000	4.1179e+004
1.00	5.00	100	1.00e+000	1.8997e-005	8.095e+000	5.2775e+004
1.00	5.00	200	9.59e-001	1.8997e-005	8.095e+000	5.0480e+004
2.00	5.00	100	1.98e+000	6.6490e-005	8.095e+000	2.9830e+004

Test/File Name : TESTR11V Cont'd
 Start Date : 02-08-1994 Start Time : 12:25:21
 End Date : 02-08-1994 End Time : 14:16:39

Soil Sample : R1
 Sample Number : 1
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.03e+000	5.6991e-005	8.095e+000	3.5566e+004
5.00	5.00	100	4.77e+000	1.4248e-004	8.095e+000	3.3501e+004
5.00	5.00	200	4.84e+000	1.4248e-004	8.095e+000	3.3960e+004
10.00	5.00	100	9.76e+000	3.0398e-004	8.095e+000	3.2122e+004
10.00	5.00	200	9.83e+000	3.0398e-004	8.095e+000	3.2337e+004
15.00	5.00	100	1.50e+001	4.3709e-004	8.093e+000	3.4307e+004
15.00	5.00	200	1.51e+001	4.4660e-004	8.092e+000	3.3918e+004
1.00	1.00	100	8.94e-001	2.8503e-005	8.093e+000	3.1352e+004
1.00	1.00	200	1.11e+000	3.8003e-005	8.093e+000	2.9249e+004
2.00	1.00	100	1.87e+000	7.6008e-005	8.093e+000	2.4661e+004
2.00	1.00	200	2.07e+000	7.6008e-005	8.093e+000	2.7241e+004
5.00	1.00	100	4.79e+000	2.2826e-004	8.085e+000	2.1007e+004
5.00	1.00	200	4.82e+000	2.2830e-004	8.083e+000	2.1098e+004

Test/File Name : TESTR12V

Start Date : 02-11-1994

Start Time : 14:52:21

End Date : 02-11-1994

End Time : 16:42:18

Soil Sample : R1

Sample Number : 2

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.93e+000	2.4479e-004	8.167e+000	2.0149e+004
5.00	5.00	200	5.08e+000	2.6362e-004	8.167e+000	1.9285e+004
10.00	5.00	100	1.02e+001	5.0883e-004	8.160e+000	2.0095e+004
10.00	5.00	200	1.06e+001	5.3716e-004	8.160e+000	1.9777e+004
10.00	10.00	100	9.90e+000	3.2049e-004	8.158e+000	3.0898e+004
10.00	10.00	200	1.00e+001	3.2049e-004	8.157e+000	3.1312e+004
15.00	10.00	100	1.40e+001	4.5250e-004	8.157e+000	3.1023e+004
15.00	10.00	200	1.40e+001	4.5251e-004	8.157e+000	3.0896e+004
15.00	15.00	100	1.55e+001	3.9602e-004	8.155e+000	3.9040e+004
15.00	15.00	200	1.48e+001	3.7717e-004	8.155e+000	3.9131e+004
20.00	15.00	100	2.01e+001	5.2807e-004	8.154e+000	3.8043e+004
20.00	15.00	200	1.99e+001	5.2807e-004	8.154e+000	3.7612e+004
1.00	20.00	100	8.73e-001	2.8292e-005	8.154e+000	3.0844e+004
1.00	20.00	200	1.16e+000	3.7723e-005	8.154e+000	3.0676e+004
2.00	20.00	100	1.99e+000	4.7154e-005	8.154e+000	4.2242e+004
2.00	20.00	200	1.97e+000	4.7154e-005	8.154e+000	4.1839e+004
5.00	20.00	100	5.07e+000	1.1317e-004	8.154e+000	4.4756e+004
5.00	20.00	200	4.97e+000	1.1317e-004	8.154e+000	4.3918e+004
10.00	20.00	100	9.94e+000	2.1691e-004	8.153e+000	4.5827e+004
10.00	20.00	200	9.88e+000	2.1691e-004	8.153e+000	4.5565e+004
15.00	20.00	100	1.43e+001	3.2065e-004	8.153e+000	4.4667e+004
15.00	20.00	200	1.48e+001	3.2066e-004	8.153e+000	4.6203e+004
20.00	20.00	100	1.97e+001	4.4327e-004	8.153e+000	4.4465e+004
20.00	20.00	200	1.90e+001	4.3384e-004	8.153e+000	4.3857e+004
1.00	15.00	100	1.02e+000	2.8290e-005	8.154e+000	3.6211e+004
1.00	15.00	200	9.67e-001	2.8290e-005	8.154e+000	3.4199e+004
2.00	15.00	100	1.97e+000	6.6009e-005	8.154e+000	2.9888e+004
2.00	15.00	200	1.92e+000	6.6009e-005	8.154e+000	2.9026e+004
5.00	15.00	100	5.07e+000	1.4145e-004	8.154e+000	3.5809e+004
5.00	15.00	200	4.99e+000	1.4145e-004	8.154e+000	3.5272e+004
10.00	15.00	100	9.94e+000	2.6404e-004	8.154e+000	3.7648e+004
10.00	15.00	200	9.94e+000	2.7347e-004	8.154e+000	3.6349e+004
15.00	15.00	100	1.46e+001	3.9606e-004	8.154e+000	3.6977e+004
15.00	15.00	200	1.46e+001	3.9606e-004	8.154e+000	3.6977e+004
20.00	15.00	100	1.93e+001	5.0923e-004	8.154e+000	3.7812e+004
20.00	15.00	200	1.94e+001	5.1866e-004	8.154e+000	3.7344e+004
1.00	10.00	100	9.67e-001	3.7712e-005	8.156e+000	2.5655e+004
1.00	10.00	200	9.67e-001	3.7711e-005	8.156e+000	2.5655e+004
2.00	10.00	100	1.88e+000	7.5422e-005	8.156e+000	2.4900e+004
2.00	10.00	200	1.93e+000	7.5422e-005	8.156e+000	2.5655e+004
5.00	10.00	100	4.82e+000	1.7913e-004	8.156e+000	2.6899e+004
5.00	10.00	200	4.88e+000	1.7913e-004	8.156e+000	2.7217e+004
10.00	10.00	100	1.00e+001	3.4883e-004	8.156e+000	2.8659e+004
10.00	10.00	200	9.94e+000	3.4883e-004	8.156e+000	2.8496e+004
15.00	10.00	100	1.38e+001	4.6199e-004	8.156e+000	2.9975e+004
15.00	10.00	200	1.48e+001	4.9029e-004	8.155e+000	3.0218e+004
1.00	5.00	100	9.49e-001	4.7127e-005	8.158e+000	2.0127e+004
1.00	5.00	200	1.01e+000	5.6552e-005	8.158e+000	1.7779e+004
2.00	5.00	100	1.95e+000	1.2253e-004	8.158e+000	1.5947e+004

Test/File Name : TESTR12V Cont'd
 Start Date : 02-11-1994 Start Time : 14:52:21
 End Date : 02-11-1994 End Time : 16:42:18

Soil Sample : R1
 Sample Number : 2
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.93e+000	1.1310e-004	8.158e+000	1.7108e+004
5.00	5.00	100	4.95e+000	2.7334e-004	8.158e+000	1.8114e+004
5.00	5.00	200	4.93e+000	2.7334e-004	8.158e+000	1.8044e+004
10.00	5.00	100	1.03e+001	5.1845e-004	8.157e+000	1.9795e+004
10.00	5.00	200	1.04e+001	5.1846e-004	8.157e+000	1.9978e+004
15.00	5.00	100	1.40e+001	6.5065e-004	8.155e+000	2.1459e+004
15.00	5.00	200	1.52e+001	6.7913e-004	8.152e+000	2.2402e+004
1.00	1.00	100	8.16e-001	9.4261e-005	8.158e+000	8.6538e+003
1.00	1.00	200	8.73e-001	1.0369e-004	8.158e+000	8.4159e+003
2.00	1.00	100	1.86e+000	2.2625e-004	8.157e+000	8.2170e+003
2.00	1.00	200	1.80e+000	2.3567e-004	8.157e+000	7.6469e+003
5.00	1.00	100	4.91e+000	4.2507e-004	8.140e+000	1.1559e+004
5.00	1.00	200	4.97e+000	3.9691e-004	8.137e+000	1.2522e+004

Test/File Name : R17V
 Start Date : 02-24-1994
 End Date : 02-25-1994

Start Time : 22:15:06
 End Time : 00:05:06

Soil Sample : R1
 Sample Number : 7
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.80e+000	1.6318e-004	8.011e+000	2.9443e+004
5.00	5.00	200	4.80e+000	1.7279e-004	8.011e+000	2.7807e+004
10.00	5.00	100	9.11e+000	2.9763e-004	8.009e+000	3.0602e+004
10.00	5.00	200	8.98e+000	2.9764e-004	8.009e+000	3.0180e+004
10.00	10.00	100	9.00e+000	2.1126e-004	8.007e+000	4.2618e+004
10.00	10.00	200	8.94e+000	2.2087e-004	8.007e+000	4.0481e+004
15.00	10.00	100	1.38e+001	3.3612e-004	8.007e+000	4.1019e+004
15.00	10.00	200	1.39e+001	3.2652e-004	8.007e+000	4.2481e+004
15.00	15.00	100	1.40e+001	2.6894e-004	8.006e+000	5.2198e+004
15.00	15.00	200	1.40e+001	2.6894e-004	8.006e+000	5.2042e+004
20.00	15.00	100	1.98e+001	3.8422e-004	8.005e+000	5.1434e+004
20.00	15.00	200	1.99e+001	3.8423e-004	8.005e+000	5.1814e+004
1.00	20.00	100	1.02e+000	3.8426e-005	8.004e+000	2.6638e+004
1.00	20.00	200	1.00e+000	3.8426e-005	8.004e+000	2.6095e+004
2.00	20.00	100	1.96e+000	3.8427e-005	8.004e+000	5.1102e+004
2.00	20.00	200	2.01e+000	4.8033e-005	8.004e+000	4.1751e+004
5.00	20.00	100	4.83e+000	9.6066e-005	8.004e+000	5.0232e+004
5.00	20.00	200	4.83e+000	9.6066e-005	8.004e+000	5.0232e+004
10.00	20.00	100	9.15e+000	1.6331e-004	8.004e+000	5.6027e+004
10.00	20.00	200	9.28e+000	1.6331e-004	8.004e+000	5.6794e+004
15.00	20.00	100	1.45e+001	2.4978e-004	8.004e+000	5.8127e+004
15.00	20.00	200	1.45e+001	2.5938e-004	8.004e+000	5.6054e+004
20.00	20.00	100	2.00e+001	3.4585e-004	8.004e+000	5.7805e+004
20.00	20.00	200	2.01e+001	3.4585e-004	8.004e+000	5.8046e+004
1.00	15.00	100	1.04e+000	2.8818e-005	8.005e+000	3.6245e+004
1.00	15.00	200	1.00e+000	3.8424e-005	8.005e+000	2.6096e+004
2.00	15.00	100	1.94e+000	5.7636e-005	8.005e+000	3.3708e+004
2.00	15.00	200	2.05e+000	5.7635e-005	8.005e+000	3.5520e+004
5.00	15.00	100	4.99e+000	1.1527e-004	8.005e+000	4.3313e+004
5.00	15.00	200	4.85e+000	1.1527e-004	8.005e+000	4.2044e+004
10.00	15.00	100	9.25e+000	2.0172e-004	8.005e+000	4.5876e+004
10.00	15.00	200	9.32e+000	1.9212e-004	8.005e+000	4.8496e+004
15.00	15.00	100	1.46e+001	2.9779e-004	8.005e+000	4.8966e+004
15.00	15.00	200	1.47e+001	2.9779e-004	8.005e+000	4.9316e+004
20.00	15.00	100	2.02e+001	3.9385e-004	8.005e+000	5.1237e+004
20.00	15.00	200	2.01e+001	3.8425e-004	8.005e+000	5.2354e+004
1.00	10.00	100	1.00e+000	3.8420e-005	8.006e+000	2.6099e+004
1.00	10.00	200	1.02e+000	3.8420e-005	8.006e+000	2.6643e+004
2.00	10.00	100	1.92e+000	5.7630e-005	8.006e+000	3.3348e+004
2.00	10.00	200	1.98e+000	5.7630e-005	8.006e+000	3.4436e+004
5.00	10.00	100	4.87e+000	1.2486e-004	8.006e+000	3.8981e+004
5.00	10.00	200	4.76e+000	1.2486e-004	8.006e+000	3.8145e+004
10.00	10.00	100	9.30e+000	2.3052e-004	8.006e+000	4.0327e+004
10.00	10.00	200	9.46e+000	2.4012e-004	8.006e+000	3.9410e+004
15.00	10.00	100	1.47e+001	3.3618e-004	8.006e+000	4.3622e+004
15.00	10.00	200	1.49e+001	3.5539e-004	8.006e+000	4.2028e+004
1.00	5.00	100	1.02e+000	4.8017e-005	8.007e+000	2.1318e+004
1.00	5.00	200	1.07e+000	3.8414e-005	8.007e+000	2.7735e+004
2.00	5.00	100	1.92e+000	7.6827e-005	8.007e+000	2.5016e+004

Test/File Name : R17V Cont'd
 Start Date : 02-24-1994 Start Time : 22:15:06
 End Date : 02-25-1994 End Time : 00:05:06

Soil Sample : R1
 Sample Number : 7
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.96e+000	7.6827e-005	8.007e+000	2.5559e+004
5.00	5.00	100	4.83e+000	1.5365e-004	8.007e+000	3.1406e+004
5.00	5.00	200	4.85e+000	1.6326e-004	8.007e+000	2.9686e+004
10.00	5.00	100	9.36e+000	2.9771e-004	8.007e+000	3.1436e+004
10.00	5.00	200	9.50e+000	2.9771e-004	8.007e+000	3.1927e+004
15.00	5.00	100	1.48e+001	4.4186e-004	8.005e+000	3.3520e+004
15.00	5.00	200	1.48e+001	4.4188e-004	8.005e+000	3.3471e+004
1.00	1.00	100	1.02e+000	6.7225e-005	8.007e+000	1.5227e+004
1.00	1.00	200	1.02e+000	6.7225e-005	8.007e+000	1.5227e+004
2.00	1.00	100	1.92e+000	1.3445e-004	8.007e+000	1.4294e+004
2.00	1.00	200	1.96e+000	1.3445e-004	8.007e+000	1.4605e+004
5.00	1.00	100	4.85e+000	2.8815e-004	8.006e+000	1.6819e+004
5.00	1.00	200	4.95e+000	2.9776e-004	8.006e+000	1.6627e+004

Test/File Name : TESTR13V

Start Date : 02-12-1994

Start Time : 12:07:25

End Date : 02-12-1994

End Time : 13:58:50

Soil Sample : R1

Sample Number : 3

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.65e+000	1.7886e-004	8.598e+000	2.5984e+004
5.00	5.00	200	4.74e+000	1.8781e-004	8.598e+000	2.5252e+004
10.00	5.00	100	9.56e+000	3.6677e-004	8.596e+000	2.6068e+004
10.00	5.00	200	9.83e+000	3.8467e-004	8.596e+000	2.5545e+004
10.00	10.00	100	9.75e+000	2.8632e-004	8.594e+000	3.4055e+004
10.00	10.00	200	9.62e+000	2.7738e-004	8.594e+000	3.4674e+004
15.00	10.00	100	1.65e+001	5.5471e-004	8.595e+000	2.9753e+004
15.00	10.00	200	1.47e+001	4.2055e-004	8.594e+000	3.4868e+004
15.00	15.00	100	1.50e+001	3.4903e-004	8.592e+000	4.2884e+004
15.00	15.00	200	1.48e+001	3.4903e-004	8.592e+000	4.2394e+004
20.00	15.00	100	1.99e+001	4.7434e-004	8.592e+000	4.1952e+004
20.00	15.00	200	2.01e+001	4.8330e-004	8.592e+000	4.1607e+004
1.00	20.00	100	1.12e+000	1.7901e-005	8.591e+000	6.2522e+004
1.00	20.00	200	1.06e+000	2.6852e-005	8.591e+000	3.9562e+004
2.00	20.00	100	2.07e+000	4.4754e-005	8.591e+000	4.6203e+004
2.00	20.00	200	2.11e+000	4.4754e-005	8.591e+000	4.7051e+004
5.00	20.00	100	4.99e+000	9.8458e-005	8.591e+000	5.0673e+004
5.00	20.00	200	4.88e+000	9.8458e-005	8.591e+000	4.9517e+004
10.00	20.00	100	9.49e+000	2.0587e-004	8.591e+000	4.6073e+004
10.00	20.00	200	9.28e+000	2.0581e-004	8.593e+000	4.5072e+004
15.00	20.00	100	1.50e+001	3.3110e-004	8.593e+000	4.5263e+004
15.00	20.00	200	1.49e+001	3.2215e-004	8.593e+000	4.6108e+004
20.00	20.00	100	2.03e+001	4.4745e-004	8.593e+000	4.5364e+004
20.00	20.00	200	2.02e+001	4.4745e-004	8.592e+000	4.5109e+004
1.00	15.00	100	1.02e+000	1.7896e-005	8.593e+000	5.7240e+004
1.00	15.00	200	1.06e+000	2.6844e-005	8.593e+000	3.9574e+004
2.00	15.00	100	2.01e+000	5.3689e-005	8.593e+000	3.7454e+004
2.00	15.00	200	2.01e+000	4.4741e-005	8.593e+000	4.4945e+004
5.00	15.00	100	5.05e+000	1.2527e-004	8.593e+000	4.0280e+004
5.00	15.00	200	4.99e+000	1.3422e-004	8.593e+000	3.7171e+004
10.00	15.00	100	9.24e+000	2.3265e-004	8.593e+000	3.9710e+004
10.00	15.00	200	9.14e+000	2.2370e-004	8.593e+000	4.0874e+004
15.00	15.00	100	1.48e+001	3.6688e-004	8.593e+000	4.0384e+004
15.00	15.00	200	1.47e+001	3.5793e-004	8.593e+000	4.1022e+004
20.00	15.00	100	2.03e+001	4.9217e-004	8.593e+000	4.1281e+004
20.00	15.00	200	2.03e+001	4.8322e-004	8.593e+000	4.2045e+004
1.00	10.00	100	1.02e+000	2.6842e-005	8.594e+000	3.8164e+004
1.00	10.00	200	1.06e+000	2.6842e-005	8.594e+000	3.9577e+004
2.00	10.00	100	2.01e+000	4.4737e-005	8.594e+000	4.4949e+004
2.00	10.00	200	1.99e+000	4.4737e-005	8.594e+000	4.4525e+004
5.00	10.00	100	5.05e+000	1.4316e-004	8.594e+000	3.5249e+004
5.00	10.00	200	4.95e+000	1.3421e-004	8.594e+000	3.6892e+004
10.00	10.00	100	9.16e+000	2.6842e-004	8.594e+000	3.4135e+004
10.00	10.00	200	9.30e+000	2.7736e-004	8.594e+000	3.3513e+004
15.00	10.00	100	1.49e+001	4.2053e-004	8.594e+000	3.5321e+004
15.00	10.00	200	1.47e+001	4.2948e-004	8.594e+000	3.4276e+004
1.00	5.00	100	1.06e+000	2.6837e-005	8.596e+000	3.9585e+004
1.00	5.00	200	1.16e+000	2.6837e-005	8.596e+000	4.3119e+004
2.00	5.00	100	1.92e+000	6.2619e-005	8.596e+000	3.0597e+004

Test/File Name : TESTR13V Cont'd
 Start Date : 02-12-1994 Start Time : 12:07:25
 End Date : 02-12-1994 End Time : 13:58:50

Soil Sample : R1
 Sample Number : 3
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.93e+000	7.1564e-005	8.596e+000	2.7038e+004
5.00	5.00	100	4.95e+000	1.8786e-004	8.596e+000	2.6356e+004
5.00	5.00	200	4.91e+000	1.9680e-004	8.596e+000	2.4965e+004
10.00	5.00	100	9.20e+000	3.4890e-004	8.595e+000	2.6370e+004
10.00	5.00	200	9.54e+000	3.6680e-004	8.595e+000	2.6014e+004
15.00	5.00	100	1.48e+001	5.3694e-004	8.592e+000	2.7593e+004
15.00	5.00	200	1.51e+001	5.3697e-004	8.592e+000	2.8050e+004
1.00	1.00	100	1.04e+000	5.3682e-005	8.594e+000	1.9436e+004
1.00	1.00	200	9.49e-001	3.5788e-005	8.594e+000	2.6504e+004
2.00	1.00	100	2.07e+000	1.3420e-004	8.594e+000	1.5407e+004
2.00	1.00	200	2.07e+000	1.1631e-004	8.594e+000	1.7778e+004
5.00	1.00	100	4.93e+000	2.9536e-004	8.591e+000	1.6699e+004
5.00	1.00	200	4.99e+000	2.9537e-004	8.591e+000	1.6891e+004
7.50	1.00	100	6.70e+000	5.0031e-004	8.453e+000	1.3385e+004

Test/File Name : R14V
 Start Date : 02-13-1994
 End Date : 02-13-1994

Start Time : 12:33:07
 End Time : 14:22:56

Soil Sample : R1
 Sample Number : 4
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.72e+000	2.2313e-004	8.615e+000	2.1169e+004
5.00	5.00	200	4.74e+000	2.1422e-004	8.615e+000	2.2139e+004
10.00	5.00	100	9.73e+000	4.2880e-004	8.608e+000	2.2695e+004
10.00	5.00	200	9.62e+000	4.1100e-004	8.606e+000	2.3401e+004
10.00	10.00	100	9.75e+000	2.8598e-004	8.604e+000	3.4096e+004
10.00	10.00	200	9.66e+000	2.8598e-004	8.604e+000	3.3764e+004
15.00	10.00	100	1.42e+001	4.2902e-004	8.603e+000	3.2986e+004
15.00	10.00	200	1.41e+001	4.1116e-004	8.603e+000	3.4327e+004
15.00	15.00	100	1.45e+001	3.5759e-004	8.601e+000	4.0636e+004
15.00	15.00	200	1.47e+001	3.6654e-004	8.601e+000	4.0214e+004
20.00	15.00	100	1.99e+001	5.0963e-004	8.600e+000	3.8973e+004
20.00	15.00	200	1.99e+001	5.0071e-004	8.600e+000	3.9705e+004
1.00	20.00	100	1.02e+000	2.6826e-005	8.599e+000	3.8186e+004
1.00	20.00	200	1.06e+000	2.6826e-005	8.599e+000	3.9601e+004
2.00	20.00	100	2.12e+000	5.3652e-005	8.599e+000	3.9601e+004
2.00	20.00	200	2.05e+000	4.4710e-005	8.599e+000	4.5824e+004
5.00	20.00	100	4.93e+000	1.1625e-004	8.599e+000	4.2429e+004
5.00	20.00	200	5.05e+000	1.0731e-004	8.599e+000	4.7025e+004
10.00	20.00	100	9.62e+000	2.1461e-004	8.599e+000	4.4816e+004
10.00	20.00	200	9.56e+000	2.0567e-004	8.599e+000	4.6487e+004
15.00	20.00	100	1.47e+001	3.3086e-004	8.599e+000	4.4550e+004
15.00	20.00	200	1.47e+001	3.2192e-004	8.599e+000	4.5728e+004
20.00	20.00	100	2.02e+001	4.4712e-004	8.599e+000	4.5270e+004
20.00	20.00	200	2.03e+001	4.4713e-004	8.599e+000	4.5354e+004
1.00	15.00	100	1.06e+000	3.5766e-005	8.600e+000	2.9702e+004
1.00	15.00	200	9.67e-001	2.6825e-005	8.600e+000	3.6067e+004
2.00	15.00	100	2.14e+000	4.4707e-005	8.600e+000	4.7948e+004
2.00	15.00	200	2.07e+000	4.4707e-005	8.600e+000	4.6251e+004
5.00	15.00	100	5.07e+000	1.2518e-004	8.600e+000	4.0462e+004
5.00	15.00	200	5.03e+000	1.2518e-004	8.600e+000	4.0159e+004
10.00	15.00	100	9.41e+000	2.4142e-004	8.600e+000	3.8975e+004
10.00	15.00	200	9.41e+000	2.4142e-004	8.600e+000	3.8975e+004
15.00	15.00	100	1.51e+001	3.8449e-004	8.600e+000	3.9225e+004
15.00	15.00	200	1.49e+001	3.8449e-004	8.600e+000	3.8830e+004
20.00	15.00	100	2.04e+001	5.0074e-004	8.599e+000	4.0763e+004
20.00	15.00	200	2.03e+001	5.0075e-004	8.599e+000	4.0573e+004
1.00	10.00	100	1.04e+000	1.7881e-005	8.601e+000	5.8350e+004
1.00	10.00	200	1.06e+000	2.6821e-005	8.601e+000	3.9607e+004
2.00	10.00	100	2.03e+000	5.3643e-005	8.601e+000	3.7840e+004
2.00	10.00	200	2.03e+000	5.3642e-005	8.601e+000	3.7840e+004
5.00	10.00	100	4.95e+000	1.5199e-004	8.601e+000	3.2577e+004
5.00	10.00	200	4.97e+000	1.4305e-004	8.601e+000	3.4745e+004
10.00	10.00	100	9.16e+000	2.6821e-004	8.601e+000	3.4161e+004
10.00	10.00	200	9.20e+000	2.6821e-004	8.601e+000	3.4303e+004
15.00	10.00	100	1.48e+001	4.3809e-004	8.601e+000	3.3862e+004
15.00	10.00	200	1.49e+001	4.4703e-004	8.601e+000	3.3270e+004
1.00	5.00	100	1.20e+000	3.5755e-005	8.602e+000	3.3426e+004
1.00	5.00	200	1.04e+000	2.6816e-005	8.602e+000	3.8908e+004
2.00	5.00	100	2.05e+000	7.1508e-005	8.603e+000	2.8651e+004

Test/File Name : R14V Cont'd
 Start Date : 02-13-1994 Start Time : 12:33:07
 End Date : 02-13-1994 End Time : 14:22:56

Soil Sample : R1
 Sample Number : 4
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.03e+000	7.1507e-005	8.603e+000	2.8386e+004
5.00	5.00	100	4.99e+000	1.8771e-004	8.603e+000	2.6579e+004
5.00	5.00	200	4.97e+000	1.8771e-004	8.603e+000	2.6478e+004
10.00	5.00	100	9.33e+000	3.4863e-004	8.602e+000	2.6771e+004
10.00	5.00	200	9.85e+000	3.6651e-004	8.602e+000	2.6863e+004
15.00	5.00	100	1.49e+001	5.8228e-004	8.584e+000	2.5542e+004
15.00	5.00	200	1.50e+001	5.8252e-004	8.580e+000	2.5727e+004
1.00	1.00	100	1.08e+000	6.2711e-005	8.583e+000	1.7243e+004
1.00	1.00	200	1.08e+000	7.1669e-005	8.583e+000	1.5087e+004
2.00	1.00	100	2.11e+000	1.5230e-004	8.583e+000	1.3826e+004
2.00	1.00	200	2.03e+000	1.5230e-004	8.583e+000	1.3328e+004
5.00	1.00	100	4.82e+000	3.4134e-004	8.560e+000	1.4116e+004
5.00	1.00	200	4.95e+000	3.2370e-004	8.552e+000	1.5296e+004

Test/File Name : TESTR111

Start Date : 02-17-1994

Start Time : 03:14:55

End Date : 02-17-1994

End Time : 05:05:00

Soil Sample : R1

Sample Number : 1

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.39e+000	2.2203e-004	7.966e+000	1.9786e+004
5.00	5.00	200	4.30e+000	2.1238e-004	7.965e+000	2.0260e+004
10.00	5.00	100	9.35e+000	4.5414e-004	7.958e+000	2.0586e+004
10.00	5.00	200	9.39e+000	4.6388e-004	7.957e+000	2.0251e+004
10.00	10.00	100	9.30e+000	3.0935e-004	7.954e+000	3.0076e+004
10.00	10.00	200	9.35e+000	2.9969e-004	7.954e+000	3.1196e+004
15.00	10.00	100	1.41e+001	4.7379e-004	7.953e+000	2.9670e+004
15.00	10.00	200	1.43e+001	4.7382e-004	7.952e+000	3.0144e+004
15.00	15.00	100	1.43e+001	3.7721e-004	7.950e+000	3.7864e+004
15.00	15.00	200	1.42e+001	3.6754e-004	7.950e+000	3.8737e+004
20.00	15.00	100	1.95e+001	5.2238e-004	7.949e+000	3.7347e+004
20.00	15.00	200	1.97e+001	5.1274e-004	7.948e+000	3.8356e+004
1.00	20.00	100	1.01e+000	1.9350e-005	7.948e+000	5.2390e+004
1.00	20.00	200	9.01e-001	2.9025e-005	7.948e+000	3.1046e+004
2.00	20.00	100	1.85e+000	5.8050e-005	7.948e+000	3.1822e+004
2.00	20.00	200	1.98e+000	4.8375e-005	7.948e+000	4.0981e+004
5.00	20.00	100	5.23e+000	1.1610e-004	7.948e+000	4.5016e+004
5.00	20.00	200	5.02e+000	1.1610e-004	7.948e+000	4.3270e+004
10.00	20.00	100	9.17e+000	2.1286e-004	7.948e+000	4.3075e+004
10.00	20.00	200	9.26e+000	2.1286e-004	7.948e+000	4.3499e+004
15.00	20.00	100	1.44e+001	3.2896e-004	7.947e+000	4.3691e+004
15.00	20.00	200	1.45e+001	3.2897e-004	7.947e+000	4.4101e+004
20.00	20.00	100	2.00e+001	4.5477e-004	7.947e+000	4.3939e+004
20.00	20.00	200	1.98e+001	4.4510e-004	7.947e+000	4.4540e+004
1.00	15.00	100	1.10e+000	2.9023e-005	7.948e+000	3.8034e+004
1.00	15.00	200	1.01e+000	2.9023e-005	7.948e+000	3.4929e+004
2.00	15.00	100	2.07e+000	4.8372e-005	7.948e+000	4.2847e+004
2.00	15.00	200	1.94e+000	4.8372e-005	7.948e+000	4.0052e+004
5.00	15.00	100	5.14e+000	1.4511e-004	7.948e+000	3.5395e+004
5.00	15.00	200	4.93e+000	1.3544e-004	7.948e+000	3.6426e+004
10.00	15.00	100	9.51e+000	2.5153e-004	7.948e+000	3.7795e+004
10.00	15.00	200	9.39e+000	2.5153e-004	7.948e+000	3.7347e+004
15.00	15.00	100	1.46e+001	3.8698e-004	7.948e+000	3.7723e+004
15.00	15.00	200	1.46e+001	3.9665e-004	7.948e+000	3.6690e+004
20.00	15.00	100	2.00e+001	5.3212e-004	7.948e+000	3.7552e+004
20.00	15.00	200	1.99e+001	5.3213e-004	7.948e+000	3.7339e+004
1.00	10.00	100	1.17e+000	2.9018e-005	7.950e+000	4.0369e+004
1.00	10.00	200	9.69e-001	2.9018e-005	7.950e+000	3.3382e+004
2.00	10.00	100	2.00e+000	5.8036e-005	7.950e+000	3.4547e+004
2.00	10.00	200	1.89e+000	5.8036e-005	7.950e+000	3.2606e+004
5.00	10.00	100	5.02e+000	1.6444e-004	7.950e+000	3.0551e+004
5.00	10.00	200	5.05e+000	1.6444e-004	7.950e+000	3.0688e+004
10.00	10.00	100	9.35e+000	3.2888e-004	7.950e+000	2.8427e+004
10.00	10.00	200	9.30e+000	3.0953e-004	7.949e+000	3.0058e+004
15.00	10.00	100	1.46e+001	4.8366e-004	7.949e+000	3.0136e+004
15.00	10.00	200	1.45e+001	4.8366e-004	7.949e+000	3.0043e+004
1.00	5.00	100	9.91e-001	2.9009e-005	7.952e+000	3.4170e+004
1.00	5.00	200	1.08e+000	3.8678e-005	7.952e+000	2.7957e+004
2.00	5.00	100	1.96e+000	7.7356e-005	7.952e+000	2.5336e+004

Test/File Name : TESTR111 Cont'd

Start Date : 02-17-1994 Start Time : 03:14:55

End Date : 02-17-1994 End Time : 05:05:00

Soil Sample : R1

Sample Number : 1

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.07e+000	8.7025e-005	7.952e+000	2.3816e+004
5.00	5.00	100	4.98e+000	2.4174e-004	7.952e+000	2.0595e+004
5.00	5.00	200	4.98e+000	2.4174e-004	7.952e+000	2.0595e+004
10.00	5.00	100	9.60e+000	4.4487e-004	7.951e+000	2.1572e+004
10.00	5.00	200	9.46e+000	4.3521e-004	7.951e+000	2.1741e+004
15.00	5.00	100	1.45e+001	6.4889e-004	7.940e+000	2.2358e+004
15.00	5.00	200	1.45e+001	6.5879e-004	7.937e+000	2.2022e+004
1.00	1.00	100	9.91e-001	5.8092e-005	7.942e+000	1.7063e+004
1.00	1.00	200	9.46e-001	5.8092e-005	7.942e+000	1.6287e+004
2.00	1.00	100	1.87e+000	1.6460e-004	7.942e+000	1.1360e+004
2.00	1.00	200	1.89e+000	1.5491e-004	7.942e+000	1.2215e+004
5.00	1.00	100	4.80e+000	4.6575e-004	7.925e+000	1.0303e+004
5.00	1.00	200	4.75e+000	4.7607e-004	7.914e+000	9.9846e+003

Test/File Name : R13I

Start Date : 02-20-1994

Start Time : 14:56:39

End Date : 02-20-1994

End Time : 16:46:43

Soil Sample : R1

Sample Number : 3

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.52e+000	1.6361e-004	7.990e+000	2.7652e+004
5.00	5.00	200	4.55e+000	1.6363e-004	7.989e+000	2.7782e+004
10.00	5.00	100	9.44e+000	3.7575e-004	7.981e+000	2.5132e+004
10.00	5.00	200	9.49e+000	3.7584e-004	7.979e+000	2.5243e+004
10.00	10.00	100	9.53e+000	2.6023e-004	7.978e+000	3.6625e+004
10.00	10.00	200	9.62e+000	2.5060e-004	7.978e+000	3.8384e+004
15.00	10.00	100	1.43e+001	4.0491e-004	7.976e+000	3.5254e+004
15.00	10.00	200	1.45e+001	4.0495e-004	7.975e+000	3.5847e+004
15.00	15.00	100	1.48e+001	3.2786e-004	7.974e+000	4.5013e+004
15.00	15.00	200	1.47e+001	3.4715e-004	7.974e+000	4.2259e+004
20.00	15.00	100	2.01e+001	4.7261e-004	7.972e+000	4.2519e+004
20.00	15.00	200	2.01e+001	4.7265e-004	7.972e+000	4.2468e+004
1.00	20.00	100	1.05e+000	1.9293e-005	7.971e+000	5.4639e+004
1.00	20.00	200	1.01e+000	1.9293e-005	7.971e+000	5.2362e+004
2.00	20.00	100	2.02e+000	3.8586e-005	7.971e+000	5.2362e+004
2.00	20.00	200	2.02e+000	3.8586e-005	7.971e+000	5.2362e+004
5.00	20.00	100	5.01e+000	1.0611e-004	7.971e+000	4.7188e+004
5.00	20.00	200	4.96e+000	1.0611e-004	7.971e+000	4.6774e+004
10.00	20.00	100	9.47e+000	1.9293e-004	7.971e+000	4.9061e+004
10.00	20.00	200	9.75e+000	1.8329e-004	7.971e+000	5.3200e+004
15.00	20.00	100	1.47e+001	2.8940e-004	7.971e+000	5.0843e+004
15.00	20.00	200	1.48e+001	2.9905e-004	7.971e+000	4.9423e+004
20.00	20.00	100	2.01e+001	3.9553e-004	7.971e+000	5.0692e+004
20.00	20.00	200	2.02e+001	4.0518e-004	7.971e+000	4.9756e+004
1.00	15.00	100	1.14e+000	1.9292e-005	7.972e+000	5.9195e+004
1.00	15.00	200	1.14e+000	1.9292e-005	7.972e+000	5.9195e+004
2.00	15.00	100	2.13e+000	4.8229e-005	7.972e+000	4.4169e+004
2.00	15.00	200	2.11e+000	4.8229e-005	7.972e+000	4.3714e+004
5.00	15.00	100	5.07e+000	1.1575e-004	7.972e+000	4.3828e+004
5.00	15.00	200	4.96e+000	1.0610e-004	7.972e+000	4.6777e+004
10.00	15.00	100	9.49e+000	2.2185e-004	7.972e+000	4.2763e+004
10.00	15.00	200	9.62e+000	2.1221e-004	7.972e+000	4.5328e+004
15.00	15.00	100	1.45e+001	3.4725e-004	7.972e+000	4.1867e+004
15.00	15.00	200	1.47e+001	3.4725e-004	7.972e+000	4.2309e+004
20.00	15.00	100	2.02e+001	4.6304e-004	7.971e+000	4.3586e+004
20.00	15.00	200	2.01e+001	4.6306e-004	7.971e+000	4.3348e+004
1.00	10.00	100	1.01e+000	2.8936e-005	7.972e+000	3.4913e+004
1.00	10.00	200	1.08e+000	2.8936e-005	7.972e+000	3.7189e+004
2.00	10.00	100	2.04e+000	4.8226e-005	7.972e+000	4.2350e+004
2.00	10.00	200	2.00e+000	4.8226e-005	7.972e+000	4.1440e+004
5.00	10.00	100	4.90e+000	1.3503e-004	7.972e+000	3.6268e+004
5.00	10.00	200	4.88e+000	1.3503e-004	7.972e+000	3.6105e+004
10.00	10.00	100	9.68e+000	2.7007e-004	7.972e+000	3.5861e+004
10.00	10.00	200	9.58e+000	2.7007e-004	7.972e+000	3.5454e+004
15.00	10.00	100	1.47e+001	4.1477e-004	7.972e+000	3.5422e+004
15.00	10.00	200	1.48e+001	4.0513e-004	7.972e+000	3.6428e+004
1.00	5.00	100	9.44e-001	2.8930e-005	7.974e+000	3.2642e+004
1.00	5.00	200	1.14e+000	2.8930e-005	7.974e+000	3.9474e+004
2.00	5.00	100	2.00e+000	5.7861e-005	7.974e+000	3.4539e+004

Test/File Name : R13I Cont'd
 Start Date : 02-20-1994 Start Time : 14:56:39
 End Date : 02-20-1994 End Time : 16:46:43

Soil Sample : R1
 Sample Number : 3
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.89e+000	5.7860e-005	7.974e+000	3.2642e+004
5.00	5.00	100	4.92e+000	1.8323e-004	7.974e+000	2.6848e+004
5.00	5.00	200	4.92e+000	1.7358e-004	7.974e+000	2.8340e+004
10.00	5.00	100	9.44e+000	3.4722e-004	7.973e+000	2.7197e+004
10.00	5.00	200	9.55e+000	3.5687e-004	7.972e+000	2.6770e+004
15.00	5.00	100	1.44e+001	5.1202e-004	7.959e+000	2.8137e+004
15.00	5.00	200	1.46e+001	5.0258e-004	7.956e+000	2.9146e+004
1.00	1.00	100	1.05e+000	2.8986e-005	7.959e+000	3.6368e+004
1.00	1.00	200	1.03e+000	3.8647e-005	7.959e+000	2.6708e+004
2.00	1.00	100	1.98e+000	8.6957e-005	7.959e+000	2.2730e+004
2.00	1.00	200	1.93e+000	9.6618e-005	7.959e+000	2.0002e+004
5.00	1.00	100	4.72e+000	2.6102e-004	7.954e+000	1.8089e+004
5.00	1.00	200	4.74e+000	2.6106e-004	7.953e+000	1.8171e+004

Test/File Name : R15I
 Start Date : 02-23-1994 Start Time : 12:07:31
 End Date : 02-23-1994 End Time : 13:57:31

Soil Sample : R1
 Sample Number : 5
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.74e+000	2.1168e-004	7.992e+000	2.2409e+004
5.00	5.00	200	4.70e+000	2.0206e-004	7.992e+000	2.3259e+004
10.00	5.00	100	9.66e+000	3.8513e-004	7.986e+000	2.5090e+004
10.00	5.00	100	9.62e+000	3.9481e-004	7.985e+000	2.4364e+004
10.00	10.00	100	9.60e+000	2.7929e-004	7.984e+000	3.4363e+004
10.00	10.00	200	9.62e+000	2.6966e-004	7.984e+000	3.5671e+004
15.00	10.00	100	1.41e+001	4.1416e-004	7.983e+000	3.4148e+004
15.00	10.00	200	1.41e+001	4.1418e-004	7.983e+000	3.3935e+004
15.00	15.00	100	1.40e+001	3.3717e-004	7.982e+000	4.1621e+004
15.00	15.00	200	1.41e+001	3.3717e-004	7.982e+000	4.1816e+004
20.00	15.00	100	1.88e+001	4.5280e-004	7.982e+000	4.1517e+004
20.00	15.00	200	1.88e+001	4.5280e-004	7.981e+000	4.1613e+004
1.00	20.00	100	1.08e+000	2.8904e-005	7.981e+000	3.7230e+004
1.00	20.00	200	1.01e+000	2.8904e-005	7.981e+000	3.4951e+004
2.00	20.00	100	1.84e+000	3.8539e-005	7.981e+000	4.7867e+004
2.00	20.00	200	2.09e+000	4.8173e-005	7.981e+000	4.3309e+004
5.00	20.00	100	4.81e+000	1.0598e-004	7.981e+000	4.5380e+004
5.00	20.00	200	4.94e+000	9.6347e-005	7.981e+000	5.1286e+004
10.00	20.00	100	9.55e+000	1.9270e-004	7.981e+000	4.9576e+004
10.00	20.00	200	9.66e+000	1.9270e-004	7.981e+000	5.0146e+004
15.00	20.00	100	1.41e+001	2.8905e-004	7.981e+000	4.8702e+004
15.00	20.00	200	1.40e+001	2.8905e-004	7.981e+000	4.8474e+004
20.00	20.00	100	1.92e+001	4.0467e-004	7.981e+000	4.7485e+004
20.00	20.00	200	1.95e+001	4.1431e-004	7.981e+000	4.6964e+004
1.00	15.00	100	1.01e+000	3.8535e-005	7.982e+000	2.6216e+004
1.00	15.00	200	9.88e-001	2.8901e-005	7.982e+000	3.4194e+004
2.00	15.00	100	2.00e+000	4.8168e-005	7.982e+000	4.1489e+004
2.00	15.00	200	2.02e+000	4.8168e-005	7.982e+000	4.1945e+004
5.00	15.00	100	4.92e+000	1.2524e-004	7.982e+000	3.9280e+004
5.00	15.00	200	4.92e+000	1.1560e-004	7.982e+000	4.2553e+004
10.00	15.00	100	9.44e+000	2.3121e-004	7.982e+000	4.0843e+004
10.00	15.00	200	9.44e+000	2.3121e-004	7.982e+000	4.0843e+004
15.00	15.00	100	1.41e+001	3.4681e-004	7.982e+000	4.0717e+004
15.00	15.00	200	1.43e+001	3.4681e-004	7.982e+000	4.1223e+004
20.00	15.00	100	1.96e+001	4.8170e-004	7.982e+000	4.0758e+004
20.00	15.00	200	1.95e+001	4.8171e-004	7.981e+000	4.0530e+004
1.00	10.00	100	1.01e+000	2.8897e-005	7.983e+000	3.4959e+004
1.00	10.00	200	1.01e+000	2.8897e-005	7.983e+000	3.4959e+004
2.00	10.00	100	1.93e+000	4.8162e-005	7.983e+000	4.0127e+004
2.00	10.00	200	2.00e+000	4.8162e-005	7.983e+000	4.1495e+004
5.00	10.00	100	4.92e+000	1.4449e-004	7.983e+000	3.4047e+004
5.00	10.00	200	4.99e+000	1.5412e-004	7.983e+000	3.2347e+004
10.00	10.00	100	9.51e+000	2.8897e-004	7.983e+000	3.2907e+004
10.00	10.00	200	9.49e+000	2.8897e-004	7.983e+000	3.2831e+004
15.00	10.00	100	1.42e+001	4.2384e-004	7.983e+000	3.3420e+004
15.00	10.00	200	1.40e+001	4.2384e-004	7.983e+000	3.3110e+004
1.00	5.00	100	1.05e+000	2.8891e-005	7.985e+000	3.6487e+004
1.00	5.00	200	9.44e-001	2.8891e-005	7.985e+000	3.2686e+004
2.00	5.00	100	1.89e+000	5.7781e-005	7.985e+000	3.2686e+004

Test/File Name : R15I Cont'd
 Start Date : 02-23-1994 Start Time : 12:07:31
 End Date : 02-23-1994 End Time : 13:57:31

Soil Sample : R1
 Sample Number : 5
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.02e+000	6.7411e-005	7.985e+000	2.9972e+004
5.00	5.00	100	4.85e+000	2.1186e-004	7.985e+000	2.2908e+004
5.00	5.00	200	4.83e+000	2.1186e-004	7.985e+000	2.2805e+004
10.00	5.00	100	9.58e+000	3.9488e-004	7.984e+000	2.4248e+004
10.00	5.00	200	9.55e+000	3.9489e-004	7.984e+000	2.4192e+004
15.00	5.00	100	1.40e+001	5.3985e-004	7.976e+000	2.5995e+004
15.00	5.00	200	1.43e+001	5.4963e-004	7.974e+000	2.6052e+004
1.00	1.00	100	9.22e-001	4.8193e-005	7.978e+000	1.9139e+004
1.00	1.00	200	9.22e-001	4.8193e-005	7.978e+000	1.9139e+004
2.00	1.00	100	1.78e+000	1.1566e-004	7.978e+000	1.5379e+004
2.00	1.00	200	1.80e+000	1.1566e-004	7.978e+000	1.5569e+004
5.00	1.00	100	4.81e+000	3.3749e-004	7.975e+000	1.4251e+004
5.00	1.00	200	4.83e+000	3.3751e-004	7.974e+000	1.4315e+004

Test/File Name : R14I

Start Date : 02-20-1994

End Date : 02-20-1994

Start Time : 11:23:16

End Time : 13:13:15

Soil Sample : R1

Sample Number : 4

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.68e+000	1.8290e-004	7.988e+000	2.5576e+004
5.00	5.00	200	4.68e+000	1.9253e-004	7.988e+000	2.4297e+004
10.00	5.00	100	9.53e+000	3.7577e-004	7.981e+000	2.5364e+004
10.00	5.00	200	9.75e+000	3.7584e-004	7.979e+000	2.5944e+004
10.00	10.00	100	9.44e+000	2.6025e-004	7.978e+000	3.6286e+004
10.00	10.00	200	9.38e+000	2.6025e-004	7.978e+000	3.6032e+004
15.00	10.00	100	1.43e+001	3.9524e-004	7.977e+000	3.6116e+004
15.00	10.00	200	1.45e+001	4.0491e-004	7.976e+000	3.5797e+004
15.00	15.00	100	1.46e+001	3.3748e-004	7.975e+000	4.3340e+004
15.00	15.00	200	1.46e+001	3.3748e-004	7.975e+000	4.3274e+004
20.00	15.00	100	1.99e+001	4.6288e-004	7.974e+000	4.2890e+004
20.00	15.00	200	2.01e+001	4.5326e-004	7.973e+000	4.4333e+004
1.00	20.00	100	1.08e+000	1.9289e-005	7.973e+000	5.5788e+004
1.00	20.00	200	9.88e-001	1.9289e-005	7.973e+000	5.1234e+004
2.00	20.00	100	2.06e+000	3.8578e-005	7.973e+000	5.3511e+004
2.00	20.00	200	2.00e+000	3.8578e-005	7.973e+000	5.1803e+004
5.00	20.00	100	4.92e+000	9.6445e-005	7.973e+000	5.1006e+004
5.00	20.00	200	4.88e+000	9.6445e-005	7.973e+000	5.0551e+004
10.00	20.00	100	9.60e+000	1.9289e-004	7.973e+000	4.9753e+004
10.00	20.00	200	9.58e+000	1.9289e-004	7.973e+000	4.9639e+004
15.00	20.00	100	1.47e+001	2.9899e-004	7.973e+000	4.9286e+004
15.00	20.00	200	1.48e+001	2.9899e-004	7.973e+000	4.9360e+004
20.00	20.00	100	1.99e+001	4.0509e-004	7.973e+000	4.9226e+004
20.00	20.00	200	2.00e+001	4.1473e-004	7.973e+000	4.8240e+004
1.00	15.00	100	1.12e+000	2.8931e-005	7.974e+000	3.8713e+004
1.00	15.00	200	1.03e+000	2.8931e-005	7.974e+000	3.5677e+004
2.00	15.00	100	2.04e+000	4.8219e-005	7.974e+000	4.2357e+004
2.00	15.00	200	2.06e+000	4.8219e-005	7.974e+000	4.2812e+004
5.00	15.00	100	4.88e+000	1.1572e-004	7.974e+000	4.2129e+004
5.00	15.00	200	4.83e+000	1.1572e-004	7.974e+000	4.1750e+004
10.00	15.00	100	9.62e+000	2.3145e-004	7.974e+000	4.1560e+004
10.00	15.00	200	9.68e+000	2.4109e-004	7.974e+000	4.0171e+004
15.00	15.00	100	1.48e+001	3.6646e-004	7.974e+000	4.0512e+004
15.00	15.00	200	1.51e+001	3.7610e-004	7.974e+000	4.0057e+004
20.00	15.00	100	2.00e+001	4.7256e-004	7.973e+000	4.2336e+004
20.00	15.00	200	2.02e+001	4.7257e-004	7.973e+000	4.2754e+004
1.00	10.00	100	1.12e+000	2.8928e-005	7.974e+000	3.8717e+004
1.00	10.00	200	9.88e-001	2.8928e-005	7.974e+000	3.4162e+004
2.00	10.00	100	1.98e+000	5.7857e-005	7.974e+000	3.4162e+004
2.00	10.00	200	2.02e+000	5.7857e-005	7.974e+000	3.4921e+004
5.00	10.00	100	4.85e+000	1.5428e-004	7.974e+000	3.1458e+004
5.00	10.00	200	4.79e+000	1.4464e-004	7.974e+000	3.3100e+004
10.00	10.00	100	9.64e+000	2.8928e-004	7.974e+000	3.3327e+004
10.00	10.00	200	9.64e+000	2.7964e-004	7.974e+000	3.4477e+004
15.00	10.00	100	1.48e+001	4.2429e-004	7.974e+000	3.4989e+004
15.00	10.00	200	1.48e+001	4.3394e-004	7.974e+000	3.4211e+004
1.00	5.00	100	1.19e+000	2.8923e-005	7.976e+000	4.1002e+004
1.00	5.00	200	9.22e-001	3.8564e-005	7.976e+000	2.3918e+004
2.00	5.00	100	2.02e+000	7.7128e-005	7.976e+000	2.6196e+004

Test/File Name : R14I Cont'd
 Start Date : 02-20-1994 Start Time : 11:23:16
 End Date : 02-20-1994 End Time : 13:13:15

Soil Sample : R1
 Sample Number : 4
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.02e+000	8.6769e-005	7.976e+000	2.3285e+004
5.00	5.00	100	4.66e+000	1.8318e-004	7.976e+000	2.5416e+004
5.00	5.00	200	4.81e+000	2.0246e-004	7.976e+000	2.3755e+004
10.00	5.00	100	9.55e+000	3.5676e-004	7.975e+000	2.6777e+004
10.00	5.00	200	9.60e+000	3.5677e-004	7.975e+000	2.6900e+004
15.00	5.00	100	1.46e+001	5.3138e-004	7.959e+000	2.7442e+004
15.00	5.00	200	1.49e+001	5.2194e-004	7.955e+000	2.8527e+004
1.00	1.00	100	9.44e-001	5.7977e-005	7.958e+000	1.6288e+004
1.00	1.00	200	9.22e-001	5.7977e-005	7.958e+000	1.5909e+004
2.00	1.00	100	1.87e+000	1.3528e-004	7.958e+000	1.3799e+004
2.00	1.00	200	1.91e+000	1.2562e-004	7.958e+000	1.5210e+004
5.00	1.00	100	4.70e+000	2.8052e-004	7.949e+000	1.6753e+004
5.00	1.00	200	4.52e+000	2.7095e-004	7.946e+000	1.6697e+004

Test/File Name : S11
 Start Date : 02-17-1994 Start Time : 00:30:25
 End Date : 02-17-1994 End Time : 02:23:36

Soil Sample : S1
 Sample Number : 1
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.66e+000	2.5465e-004	8.455e+000	1.8291e+004
5.00	5.00	200	4.68e+000	2.4556e-004	8.455e+000	1.9049e+004
10.00	5.00	100	9.67e+000	4.8234e-004	8.449e+000	2.0050e+004
10.00	5.00	200	9.67e+000	4.6418e-004	8.449e+000	2.0835e+004
10.00	10.00	100	9.75e+000	2.8223e-004	8.446e+000	3.4546e+004
10.00	10.00	200	9.71e+000	2.8223e-004	8.446e+000	3.4406e+004
15.00	10.00	100	1.41e+001	4.2797e-004	8.445e+000	3.2835e+004
15.00	10.00	200	1.41e+001	4.2798e-004	8.444e+000	3.2835e+004
15.00	15.00	100	1.40e+001	3.1877e-004	8.443e+000	4.3897e+004
15.00	15.00	200	1.41e+001	3.2788e-004	8.443e+000	4.2978e+004
20.00	15.00	100	1.91e+001	4.6457e-004	8.441e+000	4.1209e+004
20.00	15.00	200	1.93e+001	4.6458e-004	8.441e+000	4.1591e+004
1.00	20.00	100	9.67e-001	2.7329e-005	8.441e+000	3.5387e+004
1.00	20.00	200	1.05e+000	1.8219e-005	8.441e+000	5.7413e+004
2.00	20.00	100	1.99e+000	3.6439e-005	8.441e+000	5.4705e+004
2.00	20.00	200	2.07e+000	3.6439e-005	8.441e+000	5.6872e+004
5.00	20.00	100	4.89e+000	9.1099e-005	8.441e+000	5.3729e+004
5.00	20.00	200	4.97e+000	9.1099e-005	8.441e+000	5.4596e+004
10.00	20.00	100	9.41e+000	1.8220e-004	8.441e+000	5.1670e+004
10.00	20.00	200	9.36e+000	1.7309e-004	8.441e+000	5.4047e+004
15.00	20.00	100	1.42e+001	2.8242e-004	8.440e+000	5.0247e+004
15.00	20.00	200	1.43e+001	2.8242e-004	8.440e+000	5.0736e+004
20.00	20.00	100	1.97e+001	4.0999e-004	8.440e+000	4.8140e+004
20.00	20.00	200	1.99e+001	4.0999e-004	8.440e+000	4.8476e+004
1.00	15.00	100	1.03e+000	2.7329e-005	8.441e+000	3.7554e+004
1.00	15.00	200	1.03e+000	2.7329e-005	8.441e+000	3.7554e+004
2.00	15.00	100	1.99e+000	3.6438e-005	8.441e+000	5.4707e+004
2.00	15.00	200	2.03e+000	3.6438e-005	8.441e+000	5.5790e+004
5.00	15.00	100	4.95e+000	1.0931e-004	8.441e+000	4.5319e+004
5.00	15.00	200	4.89e+000	1.0020e-004	8.441e+000	4.8848e+004
10.00	15.00	100	9.39e+000	2.0952e-004	8.441e+000	4.4840e+004
10.00	15.00	200	9.43e+000	2.0041e-004	8.441e+000	4.7074e+004
15.00	15.00	100	1.44e+001	3.3705e-004	8.441e+000	4.2746e+004
15.00	15.00	200	1.45e+001	3.4616e-004	8.441e+000	4.1906e+004
20.00	15.00	100	2.00e+001	4.8282e-004	8.441e+000	4.1491e+004
20.00	15.00	200	2.00e+001	4.8282e-004	8.441e+000	4.1491e+004
1.00	10.00	100	1.16e+000	2.7324e-005	8.443e+000	4.2617e+004
1.00	10.00	200	9.87e-001	2.7324e-005	8.443e+000	3.6116e+004
2.00	10.00	100	2.19e+000	3.6432e-005	8.443e+000	6.0134e+004
2.00	10.00	200	2.07e+000	3.6432e-005	8.443e+000	5.6883e+004
5.00	10.00	100	4.99e+000	1.2751e-004	8.443e+000	3.9161e+004
5.00	10.00	200	5.01e+000	1.2751e-004	8.443e+000	3.9316e+004
10.00	10.00	100	9.41e+000	2.7324e-004	8.443e+000	3.4455e+004
10.00	10.00	200	9.49e+000	2.6413e-004	8.443e+000	3.5942e+004
15.00	10.00	100	1.44e+001	4.1898e-004	8.442e+000	3.4435e+004
15.00	10.00	200	1.44e+001	4.2809e-004	8.442e+000	3.3564e+004
1.00	5.00	100	1.01e+000	2.7315e-005	8.445e+000	3.6851e+004
1.00	5.00	200	1.09e+000	2.7315e-005	8.445e+000	3.9741e+004
2.00	5.00	100	2.07e+000	5.4629e-005	8.445e+000	3.7935e+004

Test/File Name : S11 Cont'd
 Start Date : 02-17-1994 Start Time : 00:30:25
 End Date : 02-17-1994 End Time : 02:23:36

Soil Sample : S1
 Sample Number : 1
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.03e+000	4.5525e-005	8.445e+000	4.4654e+004
5.00	5.00	100	4.95e+000	1.9120e-004	8.446e+000	2.5909e+004
5.00	5.00	200	4.87e+000	2.0030e-004	8.446e+000	2.4338e+004
10.00	5.00	100	9.65e+000	4.0064e-004	8.445e+000	2.4089e+004
10.00	5.00	200	9.73e+000	4.0065e-004	8.445e+000	2.4286e+004
15.00	5.00	100	1.45e+001	6.2851e-004	8.442e+000	2.3049e+004
15.00	5.00	200	1.45e+001	6.3765e-004	8.441e+000	2.2719e+004
1.00	1.00	100	8.88e-001	8.1911e-005	8.449e+000	1.0843e+004
1.00	1.00	200	8.68e-001	7.2809e-005	8.449e+000	1.1927e+004
2.00	1.00	100	1.82e+000	2.0023e-004	8.449e+000	9.0686e+003
2.00	1.00	200	1.80e+000	2.2752e-004	8.449e+000	7.8938e+003
5.00	1.00	100	4.70e+000	5.4629e-004	8.445e+000	8.5985e+003
5.00	1.00	200	4.91e+000	5.0991e-004	8.445e+000	9.6379e+003
7.50	1.00	100	7.09e+000	7.2206e-004	8.413e+000	9.8129e+003
7.50	1.00	200	7.12e+000	7.6917e-004	8.398e+000	9.2631e+003

Test/File Name : S12

Start Date : 02-17-1994

Start Time : 14:57:21

End Date : 02-17-1994

End Time : 16:50:24

Soil Sample : S1

Sample Number : 1

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.74e+000	2.8965e-004	8.230e+000	1.6348e+004
5.00	5.00	200	4.76e+000	2.7098e-004	8.229e+000	1.7548e+004
10.00	5.00	100	9.71e+000	5.3284e-004	8.226e+000	1.8221e+004
10.00	5.00	200	9.71e+000	5.2352e-004	8.225e+000	1.8546e+004
10.00	10.00	100	9.85e+000	3.2729e-004	8.223e+000	3.0090e+004
10.00	10.00	200	9.85e+000	3.3664e-004	8.223e+000	2.9254e+004
15.00	10.00	100	1.42e+001	4.9566e-004	8.222e+000	2.8619e+004
15.00	10.00	200	1.42e+001	4.8632e-004	8.222e+000	2.9169e+004
15.00	15.00	100	1.41e+001	3.8351e-004	8.221e+000	3.6729e+004
15.00	15.00	200	1.40e+001	3.8352e-004	8.220e+000	3.6521e+004
20.00	15.00	100	1.90e+001	5.1452e-004	8.220e+000	3.6928e+004
20.00	15.00	200	1.91e+001	5.2388e-004	8.220e+000	3.6496e+004
1.00	20.00	100	1.05e+000	2.8068e-005	8.219e+000	3.7568e+004
1.00	20.00	200	1.05e+000	2.8068e-005	8.219e+000	3.7569e+004
2.00	20.00	100	1.99e+000	5.6135e-005	8.219e+000	3.5442e+004
2.00	20.00	200	1.91e+000	5.6135e-005	8.219e+000	3.4024e+004
5.00	20.00	100	4.89e+000	1.3098e-004	8.219e+000	3.7366e+004
5.00	20.00	200	4.89e+000	1.2163e-004	8.219e+000	4.0240e+004
10.00	20.00	100	9.31e+000	2.2455e-004	8.219e+000	4.1466e+004
10.00	20.00	200	9.27e+000	2.2455e-004	8.219e+000	4.1289e+004
15.00	20.00	100	1.44e+001	3.4618e-004	8.219e+000	4.1609e+004
15.00	20.00	200	1.44e+001	3.4618e-004	8.219e+000	4.1667e+004
20.00	20.00	100	1.98e+001	4.6783e-004	8.218e+000	4.2400e+004
20.00	20.00	200	1.99e+001	4.6783e-004	8.218e+000	4.2484e+004
1.00	15.00	100	1.01e+000	2.8066e-005	8.219e+000	3.6153e+004
1.00	15.00	200	1.03e+000	2.8066e-005	8.219e+000	3.6861e+004
2.00	15.00	100	2.03e+000	5.6133e-005	8.219e+000	3.6153e+004
2.00	15.00	200	1.99e+000	6.5487e-005	8.219e+000	3.0381e+004
5.00	15.00	100	4.93e+000	1.4969e-004	8.219e+000	3.2963e+004
5.00	15.00	200	4.89e+000	1.4033e-004	8.219e+000	3.4877e+004
10.00	15.00	100	9.21e+000	2.7131e-004	8.219e+000	3.3953e+004
10.00	15.00	200	9.25e+000	2.6195e-004	8.219e+000	3.5317e+004
15.00	15.00	100	1.47e+001	4.0229e-004	8.219e+000	3.6548e+004
15.00	15.00	200	1.47e+001	4.0229e-004	8.219e+000	3.6498e+004
20.00	15.00	100	2.00e+001	5.4264e-004	8.219e+000	3.6811e+004
20.00	15.00	200	1.99e+001	5.4264e-004	8.219e+000	3.6664e+004
1.00	10.00	100	9.75e-001	3.7417e-005	8.220e+000	2.6054e+004
1.00	10.00	200	1.05e+000	3.7417e-005	8.220e+000	2.8181e+004
2.00	10.00	100	2.01e+000	7.4834e-005	8.220e+000	2.6852e+004
2.00	10.00	200	1.89e+000	6.5479e-005	8.220e+000	2.8865e+004
5.00	10.00	100	4.93e+000	1.7773e-004	8.220e+000	2.7762e+004
5.00	10.00	200	4.95e+000	1.7773e-004	8.220e+000	2.7874e+004
10.00	10.00	100	9.35e+000	3.1805e-004	8.220e+000	2.9401e+004
10.00	10.00	200	9.35e+000	3.1805e-004	8.220e+000	2.9401e+004
15.00	10.00	100	1.46e+001	4.8643e-004	8.220e+000	3.0062e+004
15.00	10.00	200	1.46e+001	4.8643e-004	8.220e+000	3.0103e+004
1.00	5.00	100	1.07e+000	5.6112e-005	8.222e+000	1.9147e+004
1.00	5.00	200	9.75e-001	4.6760e-005	8.222e+000	2.0849e+004
2.00	5.00	100	1.97e+000	9.3519e-005	8.222e+000	2.1061e+004

Test/File Name : S12 Cont'd

Start Date : 02-17-1994

Start Time : 14:57:21

End Date : 02-17-1994

End Time : 16:50:24

Soil Sample : S1

Sample Number : 1

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.93e+000	9.3518e-005	8.222e+000	2.0636e+004
5.00	5.00	100	4.81e+000	2.4315e-004	8.222e+000	1.9801e+004
5.00	5.00	200	4.83e+000	2.4315e-004	8.222e+000	1.9883e+004
10.00	5.00	100	9.33e+000	4.4892e-004	8.222e+000	2.0785e+004
10.00	5.00	200	9.33e+000	4.4892e-004	8.222e+000	2.0785e+004
15.00	5.00	100	1.45e+001	6.7370e-004	8.218e+000	2.1499e+004
15.00	5.00	200	1.45e+001	6.6440e-004	8.217e+000	2.1860e+004
1.00	1.00	100	8.95e-001	8.4178e-005	8.221e+000	1.0636e+004
1.00	1.00	200	9.15e-001	8.4178e-005	8.221e+000	1.0872e+004
2.00	1.00	100	1.73e+000	2.3382e-004	8.221e+000	7.4026e+003
2.00	1.00	200	1.71e+000	2.3382e-004	8.222e+000	7.3178e+003
5.00	1.00	100	4.87e+000	4.8657e-004	8.218e+000	1.0018e+004
5.00	1.00	200	4.81e+000	4.7724e-004	8.217e+000	1.0089e+004
7.50	1.00	100	6.72e+000	6.4974e-004	8.166e+000	1.0350e+004
7.50	1.00	200	6.88e+000	6.4459e-004	8.112e+000	1.0679e+004

Test/File Name : S15

Start Date : 02-26-1994

Start Time : 11:41:59

End Date : 02-26-1994

End Time : 13:35:14

Soil Sample : S1

Sample Number : 5

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.76e+000	2.2595e-004	8.168e+000	2.1079e+004
5.00	5.00	200	4.72e+000	2.2596e-004	8.167e+000	2.0894e+004
10.00	5.00	100	9.38e+000	4.1443e-004	8.164e+000	2.2633e+004
10.00	5.00	200	9.53e+000	4.3328e-004	8.164e+000	2.1986e+004
10.00	10.00	100	9.57e+000	2.8264e-004	8.162e+000	3.3851e+004
10.00	10.00	200	9.46e+000	2.7322e-004	8.162e+000	3.4635e+004
15.00	10.00	100	1.43e+001	4.3343e-004	8.161e+000	3.3063e+004
15.00	10.00	200	1.46e+001	4.4286e-004	8.161e+000	3.2972e+004
15.00	15.00	100	1.47e+001	3.6755e-004	8.159e+000	3.9899e+004
15.00	15.00	200	1.46e+001	3.5813e-004	8.159e+000	4.0774e+004
20.00	15.00	100	1.98e+001	4.9955e-004	8.158e+000	3.9727e+004
20.00	15.00	200	2.00e+001	4.9956e-004	8.158e+000	4.0019e+004
1.00	20.00	100	1.02e+000	1.8853e-005	8.157e+000	5.4294e+004
1.00	20.00	200	1.09e+000	1.8853e-005	8.157e+000	5.7618e+004
2.00	20.00	100	2.09e+000	4.7133e-005	8.157e+000	4.4322e+004
2.00	20.00	200	2.01e+000	4.7133e-005	8.157e+000	4.2549e+004
5.00	20.00	100	4.80e+000	1.0369e-004	8.157e+000	4.6336e+004
5.00	20.00	200	4.89e+000	1.0369e-004	8.157e+000	4.7142e+004
10.00	20.00	100	9.65e+000	1.9796e-004	8.157e+000	4.8754e+004
10.00	20.00	200	9.65e+000	2.0739e-004	8.157e+000	4.6537e+004
15.00	20.00	100	1.47e+001	3.1108e-004	8.157e+000	4.7208e+004
15.00	20.00	200	1.46e+001	3.1108e-004	8.157e+000	4.7007e+004
20.00	20.00	100	2.00e+001	4.3365e-004	8.157e+000	4.6102e+004
20.00	20.00	200	2.02e+001	4.3365e-004	8.157e+000	4.6487e+004
1.00	15.00	100	1.13e+000	1.8852e-005	8.158e+000	5.9838e+004
1.00	15.00	200	1.04e+000	1.8852e-005	8.158e+000	5.5406e+004
2.00	15.00	100	2.07e+000	4.7130e-005	8.158e+000	4.3881e+004
2.00	15.00	200	1.98e+000	5.6555e-005	8.158e+000	3.5091e+004
5.00	15.00	100	4.93e+000	1.2254e-004	8.158e+000	4.0233e+004
5.00	15.00	200	4.89e+000	1.2254e-004	8.158e+000	3.9892e+004
10.00	15.00	100	9.46e+000	2.3565e-004	8.158e+000	4.0158e+004
10.00	15.00	200	9.59e+000	2.4507e-004	8.158e+000	3.9125e+004
15.00	15.00	100	1.48e+001	3.7704e-004	8.158e+000	3.9172e+004
15.00	15.00	200	1.49e+001	3.7704e-004	8.158e+000	3.9449e+004
20.00	15.00	100	2.02e+001	4.9016e-004	8.158e+000	4.1127e+004
20.00	15.00	200	2.02e+001	5.0901e-004	8.158e+000	3.9727e+004
1.00	10.00	100	1.02e+000	2.8273e-005	8.159e+000	3.6204e+004
1.00	10.00	200	1.00e+000	1.8849e-005	8.159e+000	5.3198e+004
2.00	10.00	100	2.01e+000	5.6546e-005	8.159e+000	3.5465e+004
2.00	10.00	200	2.05e+000	5.6546e-005	8.159e+000	3.6204e+004
5.00	10.00	100	4.76e+000	1.5079e-004	8.159e+000	3.1586e+004
5.00	10.00	200	4.93e+000	1.5079e-004	8.159e+000	3.2695e+004
10.00	10.00	100	9.57e+000	2.9216e-004	8.159e+000	3.2748e+004
10.00	10.00	200	9.61e+000	2.9216e-004	8.159e+000	3.2891e+004
15.00	10.00	100	1.49e+001	4.5238e-004	8.159e+000	3.2879e+004
15.00	10.00	200	1.49e+001	4.5238e-004	8.159e+000	3.2832e+004
1.00	5.00	100	1.07e+000	3.7687e-005	8.161e+000	2.8269e+004
1.00	5.00	200	1.00e+000	4.7108e-005	8.161e+000	2.1285e+004
2.00	5.00	100	1.98e+000	9.4217e-005	8.161e+000	2.1064e+004

Test/File Name : S15 Cont'd
 Start Date : 02-26-1994 Start Time : 11:41:59
 End Date : 02-26-1994 End Time : 13:35:14

Soil Sample : S1
 Sample Number : 5
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.98e+000	9.4216e-005	8.162e+000	2.1064e+004
5.00	5.00	100	4.76e+000	2.3554e-004	8.161e+000	2.0221e+004
5.00	5.00	200	4.60e+000	2.2612e-004	8.161e+000	2.0325e+004
10.00	5.00	100	9.50e+000	4.4284e-004	8.161e+000	2.1464e+004
10.00	5.00	200	9.44e+000	4.4284e-004	8.161e+000	2.1322e+004
15.00	5.00	100	1.47e+001	6.5978e-004	8.158e+000	2.2227e+004
15.00	5.00	200	1.47e+001	6.5039e-004	8.158e+000	2.2580e+004
1.00	1.00	100	8.98e-001	9.4204e-005	8.163e+000	9.5354e+003
1.00	1.00	200	8.98e-001	9.4203e-005	8.163e+000	9.5355e+003
2.00	1.00	100	1.78e+000	2.1667e-004	8.162e+000	8.1951e+003
2.00	1.00	200	1.75e+000	2.4492e-004	8.163e+000	7.1645e+003
5.00	1.00	100	4.62e+000	5.6537e-004	8.160e+000	8.1658e+003
5.00	1.00	200	4.68e+000	5.5596e-004	8.160e+000	8.4167e+003
7.50	1.00	100	6.91e+000	7.1849e-004	8.134e+000	9.6238e+003
7.50	1.00	200	7.14e+000	7.1978e-004	8.119e+000	9.9259e+003

Test/File Name : S13
 Start Date : 02-19-1994 Start Time : 12:11:19
 End Date : 02-19-1994 End Time : 14:04:29

Soil Sample : S1
 Sample Number : 3
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.60e+000	1.8113e-004	8.490e+000	2.5372e+004
5.00	5.00	200	4.64e+000	1.9019e-004	8.490e+000	2.4384e+004
10.00	5.00	100	9.50e+000	4.0769e-004	8.488e+000	2.3314e+004
10.00	5.00	200	9.50e+000	4.0770e-004	8.487e+000	2.3313e+004
10.00	10.00	100	9.53e+000	2.8091e-004	8.486e+000	3.3911e+004
10.00	10.00	200	9.53e+000	2.8091e-004	8.486e+000	3.3911e+004
15.00	10.00	100	1.44e+001	4.3501e-004	8.485e+000	3.3183e+004
15.00	10.00	200	1.45e+001	4.4408e-004	8.485e+000	3.2599e+004
15.00	15.00	100	1.47e+001	3.5351e-004	8.483e+000	4.1543e+004
15.00	15.00	200	1.47e+001	3.6257e-004	8.483e+000	4.0447e+004
20.00	15.00	100	2.00e+001	4.9859e-004	8.482e+000	4.0139e+004
20.00	15.00	200	2.00e+001	5.1672e-004	8.482e+000	3.8730e+004
1.00	20.00	100	1.13e+000	1.8132e-005	8.482e+000	6.2215e+004
1.00	20.00	200	1.04e+000	1.8132e-005	8.482e+000	5.7606e+004
2.00	20.00	100	1.96e+000	4.5329e-005	8.482e+000	4.3320e+004
2.00	20.00	200	2.15e+000	3.6263e-005	8.482e+000	5.9335e+004
5.00	20.00	100	4.76e+000	9.9724e-005	8.482e+000	4.7761e+004
5.00	20.00	200	4.74e+000	9.9724e-005	8.482e+000	4.7552e+004
10.00	20.00	100	9.40e+000	2.0852e-004	8.482e+000	4.5083e+004
10.00	20.00	200	9.32e+000	2.0852e-004	8.482e+000	4.4682e+004
15.00	20.00	100	1.46e+001	3.1731e-004	8.482e+000	4.5953e+004
15.00	20.00	200	1.48e+001	3.2638e-004	8.482e+000	4.5252e+004
20.00	20.00	100	2.01e+001	4.4425e-004	8.481e+000	4.5330e+004
20.00	20.00	200	2.02e+001	4.5332e-004	8.481e+000	4.4516e+004
1.00	15.00	100	9.82e-001	2.7196e-005	8.482e+000	3.6102e+004
1.00	15.00	200	1.19e+000	2.7196e-005	8.482e+000	4.3784e+004
2.00	15.00	100	2.05e+000	5.4391e-005	8.482e+000	3.7639e+004
2.00	15.00	200	1.98e+000	4.5326e-005	8.482e+000	4.3784e+004
5.00	15.00	100	4.74e+000	1.1785e-004	8.482e+000	4.0239e+004
5.00	15.00	200	4.74e+000	1.1785e-004	8.482e+000	4.0239e+004
10.00	15.00	100	9.34e+000	2.3570e-004	8.482e+000	3.9618e+004
10.00	15.00	200	9.42e+000	2.3570e-004	8.482e+000	3.9973e+004
15.00	15.00	100	1.46e+001	3.8074e-004	8.482e+000	3.8462e+004
15.00	15.00	200	1.47e+001	3.8074e-004	8.482e+000	3.8626e+004
20.00	15.00	100	2.01e+001	5.0767e-004	8.482e+000	3.9626e+004
20.00	15.00	200	2.02e+001	5.1674e-004	8.482e+000	3.9093e+004
1.00	10.00	100	1.00e+000	2.7192e-005	8.483e+000	3.6875e+004
1.00	10.00	200	1.09e+000	2.7192e-005	8.483e+000	3.9948e+004
2.00	10.00	100	1.90e+000	6.3448e-005	8.483e+000	2.9961e+004
2.00	10.00	200	1.94e+000	6.3448e-005	8.484e+000	3.0620e+004
5.00	10.00	100	4.66e+000	1.3596e-004	8.483e+000	3.4263e+004
5.00	10.00	200	4.70e+000	1.3596e-004	8.483e+000	3.4571e+004
10.00	10.00	100	9.32e+000	2.8099e-004	8.483e+000	3.3158e+004
10.00	10.00	200	9.34e+000	2.8099e-004	8.483e+000	3.3232e+004
15.00	10.00	100	1.47e+001	4.4415e-004	8.483e+000	3.3111e+004
15.00	10.00	200	1.46e+001	4.4415e-004	8.483e+000	3.2829e+004
1.00	5.00	100	1.04e+000	2.7187e-005	8.485e+000	3.8419e+004
1.00	5.00	200	9.82e-001	3.6249e-005	8.485e+000	2.7086e+004
2.00	5.00	100	1.90e+000	6.3436e-005	8.485e+000	2.9967e+004

Test/File Name : S13 Cont'd
 Start Date : 02-19-1994 Start Time : 12:11:19
 End Date : 02-19-1994 End Time : 14:04:29

Soil Sample : S1
 Sample Number : 3
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.94e+000	6.3436e-005	8.485e+000	3.0626e+004
5.00	5.00	100	4.57e+000	1.8125e-004	8.485e+000	2.5241e+004
5.00	5.00	200	4.66e+000	1.8125e-004	8.485e+000	2.5702e+004
10.00	5.00	100	9.46e+000	3.8065e-004	8.484e+000	2.4861e+004
10.00	5.00	200	9.46e+000	3.8065e-004	8.484e+000	2.4861e+004
15.00	5.00	100	1.49e+001	5.8028e-004	8.481e+000	2.5740e+004
15.00	5.00	200	1.48e+001	5.8031e-004	8.480e+000	2.5523e+004
1.00	1.00	100	9.40e-001	5.4389e-005	8.483e+000	1.7284e+004
1.00	1.00	200	9.61e-001	4.5324e-005	8.483e+000	2.1201e+004
2.00	1.00	100	1.88e+000	1.0878e-004	8.483e+000	1.7284e+004
2.00	1.00	200	1.92e+000	1.1784e-004	8.483e+000	1.6309e+004
5.00	1.00	100	4.60e+000	2.9926e-004	8.479e+000	1.5357e+004
5.00	1.00	200	4.64e+000	3.0835e-004	8.479e+000	1.5040e+004
7.50	1.00	100	6.77e+000	5.9428e-004	8.410e+000	1.1389e+004
7.50	1.00	200	6.89e+000	6.8146e-004	8.350e+000	1.0116e+004

Test/File Name : S14
 Start Date : 02-23-1994 Start Time : 16:27:25
 End Date : 02-23-1994 End Time : 18:20:33

Soil Sample : S1
 Sample Number : 4
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.53e+000	2.4778e-004	8.379e+000	1.8295e+004
5.00	5.00	200	4.66e+000	2.2944e-004	8.378e+000	2.0303e+004
10.00	5.00	100	9.42e+000	4.6842e-004	8.372e+000	2.0113e+004
10.00	5.00	200	9.57e+000	4.5009e-004	8.371e+000	2.1257e+004
10.00	10.00	100	9.59e+000	2.9399e-004	8.370e+000	3.2616e+004
10.00	10.00	200	9.61e+000	2.8480e-004	8.370e+000	3.3740e+004
15.00	10.00	100	1.46e+001	4.5025e-004	8.368e+000	3.2339e+004
15.00	10.00	200	1.46e+001	4.5025e-004	8.368e+000	3.2338e+004
15.00	15.00	100	1.46e+001	3.6760e-004	8.367e+000	3.9723e+004
15.00	15.00	200	1.46e+001	3.5841e-004	8.367e+000	4.0741e+004
20.00	15.00	100	2.01e+001	5.1471e-004	8.366e+000	3.9125e+004
20.00	15.00	200	2.00e+001	5.1472e-004	8.366e+000	3.8921e+004
1.00	20.00	100	1.11e+000	2.7575e-005	8.366e+000	4.0151e+004
1.00	20.00	200	1.21e+000	2.7575e-005	8.366e+000	4.3939e+004
2.00	20.00	100	2.03e+000	2.7575e-005	8.366e+000	7.3483e+004
2.00	20.00	200	2.01e+000	2.7575e-005	8.366e+000	7.2726e+004
5.00	20.00	100	4.93e+000	9.1919e-005	8.365e+000	5.3635e+004
5.00	20.00	200	4.87e+000	9.1919e-005	8.365e+000	5.2953e+004
10.00	20.00	100	9.61e+000	1.8384e-004	8.365e+000	5.2270e+004
10.00	20.00	200	9.59e+000	1.8384e-004	8.365e+000	5.2157e+004
15.00	20.00	100	1.48e+001	3.0334e-004	8.365e+000	4.8826e+004
15.00	20.00	200	1.49e+001	2.9415e-004	8.365e+000	5.0564e+004
20.00	20.00	100	2.01e+001	4.1367e-004	8.365e+000	4.8530e+004
20.00	20.00	200	2.02e+001	4.2286e-004	8.365e+000	4.7771e+004
1.00	15.00	100	1.11e+000	2.7574e-005	8.366e+000	4.0152e+004
1.00	15.00	200	1.04e+000	2.7574e-005	8.366e+000	3.7879e+004
2.00	15.00	100	2.03e+000	3.6766e-005	8.366e+000	5.5115e+004
2.00	15.00	200	1.98e+000	3.6766e-005	8.366e+000	5.3978e+004
5.00	15.00	100	4.87e+000	1.0111e-004	8.366e+000	4.8142e+004
5.00	15.00	200	4.87e+000	1.0111e-004	8.366e+000	4.8142e+004
10.00	15.00	100	9.59e+000	2.1140e-004	8.366e+000	4.5356e+004
10.00	15.00	200	9.57e+000	2.1140e-004	8.366e+000	4.5258e+004
15.00	15.00	100	1.49e+001	3.5847e-004	8.366e+000	4.1609e+004
15.00	15.00	200	1.49e+001	3.5847e-004	8.366e+000	4.1493e+004
20.00	15.00	100	2.03e+001	4.9635e-004	8.366e+000	4.0825e+004
20.00	15.00	200	2.05e+001	5.0555e-004	8.366e+000	4.0454e+004
1.00	10.00	100	1.11e+000	2.7570e-005	8.367e+000	4.0158e+004
1.00	10.00	200	1.07e+000	2.7570e-005	8.367e+000	3.8643e+004
2.00	10.00	100	1.96e+000	4.5950e-005	8.367e+000	4.2735e+004
2.00	10.00	200	1.96e+000	4.5950e-005	8.367e+000	4.2735e+004
5.00	10.00	100	4.80e+000	1.1947e-004	8.367e+000	4.0217e+004
5.00	10.00	200	4.74e+000	1.1947e-004	8.367e+000	3.9692e+004
10.00	10.00	100	9.50e+000	2.6652e-004	8.367e+000	3.5664e+004
10.00	10.00	200	9.53e+000	2.6652e-004	8.367e+000	3.5742e+004
15.00	10.00	100	1.47e+001	4.4114e-004	8.367e+000	3.3291e+004
15.00	10.00	200	1.49e+001	4.4114e-004	8.367e+000	3.3669e+004
1.00	5.00	100	1.11e+000	3.6751e-005	8.369e+000	3.0127e+004
1.00	5.00	200	1.17e+000	3.6751e-005	8.369e+000	3.1832e+004
2.00	5.00	100	1.94e+000	6.4314e-005	8.369e+000	3.0208e+004

Test/File Name : S14 Cont'd
 Start Date : 02-23-1994 Start Time : 16:27:25
 End Date : 02-23-1994 End Time : 18:20:33

Soil Sample : S1
 Sample Number : 4
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.94e+000	6.4314e-005	8.369e+000	3.0208e+004
5.00	5.00	100	4.64e+000	1.6538e-004	8.369e+000	2.8042e+004
5.00	5.00	200	4.66e+000	1.7457e-004	8.369e+000	2.6686e+004
10.00	5.00	100	9.53e+000	3.9511e-004	8.369e+000	2.4110e+004
10.00	5.00	200	9.50e+000	3.9511e-004	8.369e+000	2.4057e+004
15.00	5.00	100	1.47e+001	6.2516e-004	8.364e+000	2.3558e+004
15.00	5.00	200	1.46e+001	6.1604e-004	8.363e+000	2.3703e+004
1.00	1.00	100	8.98e-001	5.5142e-005	8.367e+000	1.6290e+004
1.00	1.00	200	8.56e-001	4.5951e-005	8.367e+000	1.8639e+004
2.00	1.00	100	1.84e+000	1.4705e-004	8.367e+000	1.2502e+004
2.00	1.00	200	1.73e+000	1.5623e-004	8.367e+000	1.1098e+004
5.00	1.00	100	4.64e+000	4.1386e-004	8.361e+000	1.1206e+004
5.00	1.00	200	4.72e+000	4.1392e-004	8.360e+000	1.1406e+004
7.50	1.00	100	6.91e+000	6.5881e-004	8.287e+000	1.0496e+004
7.50	1.00	200	7.08e+000	6.7094e-004	8.252e+000	1.0555e+004

Test/File Name : G11
 Start Date : 01-25-1994 Start Time : 11:23:55
 End Date : 01-25-1994 End Time : 13:20:19

Soil Sample : G1
 Sample Number : 1
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.84e+000	2.8480e-004	5.940e+000	1.6999e+004
5.00	5.00	200	4.89e+000	2.8480e-004	5.940e+000	1.7156e+004
10.00	5.00	100	9.88e+000	6.3487e-004	5.935e+000	1.5557e+004
10.00	5.00	200	9.95e+000	6.2196e-004	5.934e+000	1.6000e+004
10.00	10.00	100	1.00e+001	4.1483e-004	5.932e+000	2.4170e+004
10.00	10.00	200	1.01e+001	4.0187e-004	5.932e+000	2.5135e+004
15.00	10.00	100	1.50e+001	6.3555e-004	5.928e+000	2.3605e+004
15.00	10.00	200	1.50e+001	6.4856e-004	5.928e+000	2.3154e+004
15.00	15.00	100	1.51e+001	5.0604e-004	5.926e+000	2.9823e+004
15.00	15.00	200	1.52e+001	4.9309e-004	5.926e+000	3.0758e+004
20.00	15.00	100	2.00e+001	6.8797e-004	5.924e+000	2.9126e+004
20.00	15.00	200	2.02e+001	6.7504e-004	5.923e+000	2.9972e+004
1.00	20.00	100	1.18e+000	2.5965e-005	5.923e+000	4.5463e+004
1.00	20.00	200	1.14e+000	2.5965e-005	5.923e+000	4.3736e+004
2.00	20.00	100	2.02e+000	5.1931e-005	5.923e+000	3.8844e+004
2.00	20.00	200	1.96e+000	5.1931e-005	5.923e+000	3.7693e+004
5.00	20.00	100	4.98e+000	1.4281e-004	5.923e+000	3.4842e+004
5.00	20.00	200	5.05e+000	1.5579e-004	5.923e+000	3.2418e+004
10.00	20.00	100	9.98e+000	2.5966e-004	5.923e+000	3.8440e+004
10.00	20.00	200	1.02e+001	2.7265e-004	5.923e+000	3.7267e+004
15.00	20.00	100	1.50e+001	4.0249e-004	5.922e+000	3.7236e+004
15.00	20.00	200	1.49e+001	4.0249e-004	5.922e+000	3.7087e+004
20.00	20.00	100	2.01e+001	5.5834e-004	5.922e+000	3.5968e+004
20.00	20.00	200	2.02e+001	5.5836e-004	5.922e+000	3.6128e+004
1.00	15.00	100	1.14e+000	1.2983e-005	5.923e+000	8.7472e+004
1.00	15.00	200	1.08e+000	2.5965e-005	5.923e+000	4.1435e+004
2.00	15.00	100	2.12e+000	5.1930e-005	5.923e+000	4.0859e+004
2.00	15.00	200	2.06e+000	5.1929e-005	5.923e+000	3.9709e+004
5.00	15.00	100	5.05e+000	1.4281e-004	5.923e+000	3.5366e+004
5.00	15.00	200	5.08e+000	1.4281e-004	5.923e+000	3.5576e+004
10.00	15.00	100	1.00e+001	2.9859e-004	5.923e+000	3.3528e+004
10.00	15.00	200	1.00e+001	2.9860e-004	5.923e+000	3.3478e+004
15.00	15.00	100	1.50e+001	4.6738e-004	5.923e+000	3.2099e+004
15.00	15.00	200	1.50e+001	4.8035e-004	5.923e+000	3.1169e+004
20.00	15.00	100	2.01e+001	6.4915e-004	5.923e+000	3.0983e+004
20.00	15.00	200	2.00e+001	6.4916e-004	5.923e+000	3.0775e+004
1.00	10.00	100	1.11e+000	2.5960e-005	5.924e+000	4.2594e+004
1.00	10.00	200	1.11e+000	2.5959e-005	5.924e+000	4.2595e+004
2.00	10.00	100	2.06e+000	5.1919e-005	5.924e+000	3.9717e+004
2.00	10.00	200	1.99e+000	5.1918e-005	5.924e+000	3.8278e+004
5.00	10.00	100	4.93e+000	1.8171e-004	5.924e+000	2.7136e+004
5.00	10.00	200	5.02e+000	1.8171e-004	5.924e+000	2.7629e+004
10.00	10.00	100	1.00e+001	3.7641e-004	5.924e+000	2.6637e+004
10.00	10.00	200	1.03e+001	3.8938e-004	5.924e+000	2.6401e+004
15.00	10.00	100	1.50e+001	5.8409e-004	5.924e+000	2.5633e+004
15.00	10.00	200	1.50e+001	5.7112e-004	5.924e+000	2.6216e+004
1.00	5.00	100	1.05e+000	2.5949e-005	5.927e+000	4.0308e+004
1.00	5.00	200	1.08e+000	3.8923e-005	5.927e+000	2.7641e+004
2.00	5.00	100	1.99e+000	5.1897e-005	5.927e+000	3.8294e+004

Test/File Name : G11 Cont'd
 Start Date : 01-25-1994 Start Time : 11:23:55
 End Date : 01-25-1994 End Time : 13:20:19

Soil Sample : G1
 Sample Number : 1
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.93e+000	6.4870e-005	5.927e+000	2.9714e+004
5.00	5.00	100	4.90e+000	2.3353e-004	5.927e+000	2.0987e+004
5.00	5.00	200	4.92e+000	2.3353e-004	5.927e+000	2.1051e+004
10.00	5.00	100	9.85e+000	5.1898e-004	5.927e+000	1.8974e+004
10.00	5.00	200	1.00e+001	5.3196e-004	5.927e+000	1.8848e+004
15.00	5.00	100	1.50e+001	8.3063e-004	5.925e+000	1.8097e+004
15.00	5.00	200	1.50e+001	8.1769e-004	5.924e+000	1.8365e+004
1.00	1.00	100	9.71e-001	3.8886e-005	5.932e+000	2.4977e+004
1.00	1.00	200	1.03e+000	3.8884e-005	5.933e+000	2.6515e+004
2.00	1.00	100	1.82e+000	1.6848e-004	5.933e+000	1.0820e+004
2.00	1.00	200	1.84e+000	1.8143e-004	5.933e+000	1.0130e+004
5.00	1.00	100	4.78e+000	7.5169e-004	5.933e+000	6.3611e+003
5.00	1.00	200	4.81e+000	7.6461e-004	5.933e+000	6.2927e+003
7.50	1.00	100	7.29e+000	1.1406e-003	5.933e+000	6.3931e+003
7.50	1.00	200	7.34e+000	1.1535e-003	5.933e+000	6.3602e+003
10.00	1.00	100	9.80e+000	1.4910e-003	5.931e+000	6.5741e+003
10.00	1.00	200	9.85e+000	1.4652e-003	5.930e+000	6.7205e+003

Test/File Name : G17
 Start Date : 03-03-1994
 End Date : 03-04-1994

Start Time : 22:44:29
 End Time : 00:40:45

Soil Sample : G1
 Sample Number : 7
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.65e+000	2.3136e-004	5.982e+000	2.0119e+004
5.00	5.00	200	4.67e+000	2.4420e-004	5.983e+000	1.9123e+004
10.00	5.00	100	9.70e+000	5.0235e-004	5.970e+000	1.9314e+004
10.00	5.00	200	9.73e+000	4.8960e-004	5.968e+000	1.9879e+004
10.00	10.00	100	9.88e+000	3.6089e-004	5.966e+000	2.7388e+004
10.00	10.00	200	9.87e+000	3.6089e-004	5.966e+000	2.7345e+004
15.00	10.00	100	1.47e+001	5.6742e-004	5.963e+000	2.5969e+004
15.00	10.00	200	1.48e+001	5.6746e-004	5.962e+000	2.6073e+004
15.00	15.00	100	1.49e+001	4.5153e-004	5.960e+000	3.3002e+004
15.00	15.00	200	1.48e+001	4.6444e-004	5.960e+000	3.1890e+004
20.00	15.00	100	1.99e+001	6.4530e-004	5.958e+000	3.0868e+004
20.00	15.00	200	1.99e+001	6.3245e-004	5.958e+000	3.1471e+004
1.00	20.00	100	1.06e+000	2.5816e-005	5.957e+000	4.0978e+004
1.00	20.00	200	1.09e+000	2.5817e-005	5.957e+000	4.2148e+004
2.00	20.00	100	2.01e+000	5.1634e-005	5.957e+000	3.8929e+004
2.00	20.00	200	1.95e+000	5.1634e-005	5.957e+000	3.7758e+004
5.00	20.00	100	4.93e+000	1.2908e-004	5.957e+000	3.8168e+004
5.00	20.00	200	5.05e+000	1.2908e-004	5.957e+000	3.9104e+004
10.00	20.00	100	9.96e+000	2.7108e-004	5.957e+000	3.6740e+004
10.00	20.00	200	9.79e+000	2.5817e-004	5.957e+000	3.7933e+004
15.00	20.00	100	1.49e+001	4.1309e-004	5.957e+000	3.6110e+004
15.00	20.00	200	1.47e+001	4.0019e-004	5.957e+000	3.6783e+004
20.00	20.00	100	1.97e+001	5.4222e-004	5.956e+000	3.6346e+004
20.00	20.00	200	1.97e+001	5.4224e-004	5.956e+000	3.6345e+004
1.00	15.00	100	8.61e-001	1.2908e-005	5.957e+000	6.6735e+004
1.00	15.00	200	1.03e+000	2.5816e-005	5.957e+000	3.9807e+004
2.00	15.00	100	1.93e+000	5.1633e-005	5.957e+000	3.7466e+004
2.00	15.00	200	1.98e+000	5.1633e-005	5.957e+000	3.8344e+004
5.00	15.00	100	4.94e+000	1.4199e-004	5.957e+000	3.4805e+004
5.00	15.00	200	4.84e+000	1.4199e-004	5.957e+000	3.4060e+004
10.00	15.00	100	9.87e+000	2.8398e-004	5.957e+000	3.4752e+004
10.00	15.00	200	9.97e+000	2.8398e-004	5.957e+000	3.5124e+004
15.00	15.00	100	1.48e+001	4.5179e-004	5.957e+000	3.2783e+004
15.00	15.00	200	1.49e+001	4.3889e-004	5.957e+000	3.3953e+004
20.00	15.00	100	1.99e+001	6.0672e-004	5.957e+000	3.2756e+004
20.00	15.00	200	1.99e+001	6.0673e-004	5.957e+000	3.2880e+004
1.00	10.00	100	1.01e+000	3.8718e-005	5.958e+000	2.6153e+004
1.00	10.00	200	1.04e+000	2.5812e-005	5.958e+000	4.0400e+004
2.00	10.00	100	1.89e+000	5.1624e-005	5.958e+000	3.6594e+004
2.00	10.00	200	1.92e+000	3.8718e-005	5.958e+000	4.9573e+004
5.00	10.00	100	4.79e+000	1.6777e-004	5.958e+000	2.8555e+004
5.00	10.00	200	4.91e+000	1.6777e-004	5.958e+000	2.9276e+004
10.00	10.00	100	9.79e+000	3.4846e-004	5.958e+000	2.8104e+004
10.00	10.00	200	9.82e+000	3.4846e-004	5.958e+000	2.8191e+004
15.00	10.00	100	1.47e+001	5.4206e-004	5.958e+000	2.7128e+004
15.00	10.00	200	1.48e+001	5.4206e-004	5.958e+000	2.7323e+004
1.00	5.00	100	1.01e+000	2.5804e-005	5.960e+000	3.9241e+004
1.00	5.00	200	9.52e-001	3.8706e-005	5.960e+000	2.4599e+004
2.00	5.00	100	1.92e+000	6.4509e-005	5.960e+000	2.9753e+004

Test/File Name : G17 Cont'd
 Start Date : 03-03-1994 Start Time : 22:44:29
 End Date : 03-04-1994 End Time : 00:40:45

Soil Sample : G1
 Sample Number : 7
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.95e+000	6.4509e-005	5.960e+000	3.0222e+004
5.00	5.00	100	4.82e+000	2.1933e-004	5.960e+000	2.1981e+004
5.00	5.00	200	4.72e+000	2.0643e-004	5.960e+000	2.2842e+004
10.00	5.00	100	9.72e+000	4.6449e-004	5.960e+000	2.0921e+004
10.00	5.00	200	9.81e+000	4.5160e-004	5.960e+000	2.1719e+004
15.00	5.00	100	1.47e+001	7.1018e-004	5.955e+000	2.0685e+004
15.00	5.00	200	1.47e+001	6.8444e-004	5.954e+000	2.1507e+004
1.00	1.00	100	1.06e+000	2.5816e-005	5.957e+000	4.0979e+004
1.00	1.00	200	1.03e+000	2.5815e-005	5.957e+000	3.9809e+004
2.00	1.00	100	1.80e+000	7.7441e-005	5.958e+000	2.3223e+004
2.00	1.00	200	1.86e+000	9.0347e-005	5.958e+000	2.0575e+004
5.00	1.00	100	4.50e+000	3.2268e-004	5.958e+000	1.3957e+004
5.00	1.00	200	4.46e+000	3.2268e-004	5.958e+000	1.3817e+004
7.50	1.00	100	7.01e+000	5.2930e-004	5.956e+000	1.3249e+004
7.50	1.00	200	7.13e+000	5.2933e-004	5.956e+000	1.3476e+004
10.00	1.00	100	9.52e+000	7.4985e-004	5.948e+000	1.2697e+004
10.00	1.00	200	9.55e+000	7.3720e-004	5.945e+000	1.2956e+004

Test/File Name : G12

Start Date : 01-25-1994

Start Time : 17:19:30

End Date : 01-25-1994

End Time : 19:14:15

Soil Sample : G1

Sample Number : 2

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.83e+000	2.4308e-004	6.010e+000	1.9864e+004
5.00	5.00	200	4.95e+000	2.3031e-004	6.010e+000	2.1485e+004
10.00	5.00	100	9.85e+000	4.7514e-004	5.988e+000	2.0734e+004
10.00	5.00	200	9.91e+000	4.7527e-004	5.986e+000	2.0854e+004
10.00	10.00	100	1.01e+001	3.3409e-004	5.984e+000	3.0293e+004
10.00	10.00	200	1.01e+001	3.3410e-004	5.984e+000	3.0158e+004
15.00	10.00	100	1.49e+001	5.3994e-004	5.981e+000	2.7687e+004
15.00	10.00	200	1.50e+001	5.3997e-004	5.981e+000	2.7713e+004
15.00	15.00	100	1.49e+001	4.2438e-004	5.979e+000	3.5015e+004
15.00	15.00	200	1.51e+001	4.2439e-004	5.979e+000	3.5472e+004
20.00	15.00	100	2.00e+001	5.7890e-004	5.977e+000	3.4578e+004
20.00	15.00	200	2.01e+001	5.9179e-004	5.977e+000	3.3900e+004
1.00	20.00	100	1.05e+000	2.5731e-005	5.977e+000	4.0669e+004
1.00	20.00	200	1.06e+000	2.5731e-005	5.977e+000	4.1249e+004
2.00	20.00	100	1.91e+000	3.8598e-005	5.977e+000	4.9576e+004
2.00	20.00	200	1.97e+000	5.1463e-005	5.977e+000	3.8344e+004
5.00	20.00	100	4.95e+000	1.1579e-004	5.977e+000	4.2733e+004
5.00	20.00	200	4.87e+000	1.1579e-004	5.977e+000	4.2087e+004
10.00	20.00	100	9.99e+000	2.4446e-004	5.976e+000	4.0850e+004
10.00	20.00	200	1.00e+001	2.4446e-004	5.976e+000	4.1033e+004
15.00	20.00	100	1.49e+001	3.7314e-004	5.976e+000	4.0023e+004
15.00	20.00	200	1.49e+001	3.7314e-004	5.976e+000	4.0063e+004
20.00	20.00	100	2.00e+001	5.1472e-004	5.976e+000	3.8889e+004
20.00	20.00	200	1.99e+001	5.0187e-004	5.975e+000	3.9736e+004
1.00	15.00	100	9.72e-001	2.5733e-005	5.976e+000	3.7761e+004
1.00	15.00	200	1.03e+000	3.8599e-005	5.976e+000	2.6724e+004
2.00	15.00	100	2.11e+000	3.8599e-005	5.976e+000	5.4609e+004
2.00	15.00	200	2.09e+000	3.8599e-005	5.976e+000	5.4222e+004
5.00	15.00	100	5.02e+000	1.1579e-004	5.977e+000	4.3378e+004
5.00	15.00	200	4.96e+000	1.1579e-004	5.977e+000	4.2862e+004
10.00	15.00	100	9.87e+000	2.7019e-004	5.977e+000	3.6517e+004
10.00	15.00	200	1.01e+001	2.7019e-004	5.977e+000	3.7347e+004
15.00	15.00	100	1.49e+001	4.2458e-004	5.976e+000	3.5139e+004
15.00	15.00	200	1.49e+001	4.2458e-004	5.976e+000	3.4998e+004
20.00	15.00	100	2.01e+001	5.7901e-004	5.976e+000	3.4778e+004
20.00	15.00	200	1.99e+001	5.6615e-004	5.976e+000	3.5145e+004
1.00	10.00	100	1.27e+000	2.5728e-005	5.977e+000	4.9388e+004
1.00	10.00	200	1.15e+000	2.5728e-005	5.977e+000	4.4740e+004
2.00	10.00	100	2.08e+000	3.8593e-005	5.977e+000	5.3843e+004
2.00	10.00	200	2.20e+000	3.8593e-005	5.977e+000	5.6942e+004
5.00	10.00	100	5.01e+000	1.2864e-004	5.977e+000	3.8930e+004
5.00	10.00	200	4.90e+000	1.4150e-004	5.977e+000	3.4652e+004
10.00	10.00	100	9.91e+000	3.0874e-004	5.977e+000	3.2102e+004
10.00	10.00	200	1.00e+001	3.0874e-004	5.977e+000	3.2393e+004
15.00	10.00	100	1.48e+001	4.7599e-004	5.977e+000	3.1124e+004
15.00	10.00	200	1.50e+001	4.8886e-004	5.977e+000	3.0672e+004
1.00	5.00	100	1.32e+000	2.5721e-005	5.979e+000	5.1146e+004
1.00	5.00	200	1.17e+000	2.5721e-005	5.979e+000	4.5334e+004
2.00	5.00	100	2.14e+000	5.1442e-005	5.979e+000	4.1557e+004

Test/File Name : G12 Cont'd

Start Date : 01-25-1994

Start Time : 17:19:30

End Date : 01-25-1994

End Time : 19:14:15

Soil Sample : G1

Sample Number : 2

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.05e+000	3.8581e-005	5.979e+000	5.3084e+004
5.00	5.00	100	4.96e+000	1.6719e-004	5.979e+000	2.9687e+004
5.00	5.00	200	4.87e+000	1.6719e-004	5.979e+000	2.9150e+004
10.00	5.00	100	9.97e+000	3.9871e-004	5.979e+000	2.5008e+004
10.00	5.00	200	9.72e+000	3.9871e-004	5.979e+000	2.4371e+004
15.00	5.00	100	1.47e+001	6.3208e-004	5.961e+000	2.3320e+004
15.00	5.00	200	1.48e+001	6.1941e-004	5.959e+000	2.3966e+004
1.00	1.00	100	1.05e+000	1.2900e-005	5.961e+000	8.1120e+004
1.00	1.00	200	1.03e+000	2.5799e-005	5.961e+000	3.9981e+004
2.00	1.00	100	2.00e+000	5.1597e-005	5.961e+000	3.8824e+004
2.00	1.00	200	2.24e+000	5.1596e-005	5.961e+000	4.3460e+004
5.00	1.00	100	4.89e+000	2.7089e-004	5.961e+000	1.8046e+004
5.00	1.00	200	4.87e+000	2.5799e-004	5.961e+000	1.8890e+004
7.50	1.00	100	7.24e+000	4.2627e-004	5.953e+000	1.6974e+004
7.50	1.00	200	7.21e+000	4.2645e-004	5.950e+000	1.6897e+004

Test/File Name : G15

Start Date : 02-05-1994

Start Time : 11:13:40

End Date : 02-05-1994

End Time : 13:08:43

Soil Sample : G1

Sample Number : 5

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.42e+000	1.7713e-004	6.078e+000	2.4956e+004
5.00	5.00	200	4.65e+000	1.7716e-004	6.077e+000	2.6239e+004
10.00	5.00	100	9.68e+000	3.9301e-004	6.065e+000	2.4622e+004
10.00	5.00	200	9.62e+000	3.8038e-004	6.065e+000	2.5279e+004
10.00	10.00	100	9.74e+000	2.6632e-004	6.063e+000	3.6562e+004
10.00	10.00	200	9.71e+000	2.7901e-004	6.063e+000	3.4791e+004
15.00	10.00	100	1.49e+001	4.3133e-004	6.061e+000	3.4478e+004
15.00	10.00	200	1.49e+001	4.3136e-004	6.061e+000	3.4652e+004
15.00	15.00	100	1.49e+001	3.4261e-004	6.060e+000	4.3451e+004
15.00	15.00	200	1.50e+001	3.5531e-004	6.060e+000	4.2198e+004
20.00	15.00	100	1.99e+001	4.9500e-004	6.058e+000	4.0201e+004
20.00	15.00	200	1.99e+001	4.9503e-004	6.058e+000	4.0291e+004
1.00	20.00	100	1.18e+000	3.8080e-005	6.058e+000	3.1115e+004
1.00	20.00	200	1.03e+000	2.5386e-005	6.058e+000	4.0689e+004
2.00	20.00	100	2.13e+000	3.8080e-005	6.058e+000	5.5848e+004
2.00	20.00	200	1.97e+000	3.8080e-005	6.058e+000	5.1858e+004
5.00	20.00	100	4.98e+000	7.6162e-005	6.058e+000	6.5420e+004
5.00	20.00	200	4.98e+000	7.6162e-005	6.058e+000	6.5420e+004
10.00	20.00	100	9.87e+000	1.7772e-004	6.058e+000	5.5560e+004
10.00	20.00	200	9.95e+000	1.7772e-004	6.058e+000	5.5987e+004
15.00	20.00	100	1.51e+001	2.9197e-004	6.057e+000	5.1819e+004
15.00	20.00	200	1.50e+001	2.7928e-004	6.057e+000	5.3630e+004
20.00	20.00	100	2.00e+001	4.1894e-004	6.057e+000	4.7681e+004
20.00	20.00	200	1.99e+001	4.0626e-004	6.057e+000	4.9020e+004
1.00	15.00	100	1.00e+000	2.5387e-005	6.058e+000	3.9491e+004
1.00	15.00	200	1.00e+000	2.5387e-005	6.058e+000	3.9491e+004
2.00	15.00	100	2.04e+000	2.5387e-005	6.058e+000	8.0179e+004
2.00	15.00	200	1.99e+000	3.8080e-005	6.058e+000	5.2257e+004
5.00	15.00	100	4.94e+000	8.8852e-005	6.058e+000	5.5563e+004
5.00	15.00	200	5.01e+000	8.8852e-005	6.058e+000	5.6418e+004
10.00	15.00	100	9.90e+000	2.0309e-004	6.058e+000	4.8767e+004
10.00	15.00	200	9.92e+000	1.9040e-004	6.058e+000	5.2097e+004
15.00	15.00	100	1.51e+001	3.3004e-004	6.058e+000	4.5705e+004
15.00	15.00	200	1.49e+001	3.3004e-004	6.058e+000	4.5245e+004
20.00	15.00	100	1.99e+001	4.5699e-004	6.057e+000	4.3578e+004
20.00	15.00	200	2.00e+001	4.5700e-004	6.057e+000	4.3777e+004
1.00	10.00	100	1.12e+000	3.8076e-005	6.059e+000	2.9523e+004
1.00	10.00	200	1.23e+000	2.5384e-005	6.059e+000	4.8473e+004
2.00	10.00	100	2.13e+000	3.8075e-005	6.059e+000	5.5855e+004
2.00	10.00	200	2.13e+000	5.0766e-005	6.059e+000	4.1892e+004
5.00	10.00	100	4.94e+000	8.8840e-005	6.059e+000	5.5571e+004
5.00	10.00	200	4.83e+000	8.8840e-005	6.059e+000	5.4374e+004
10.00	10.00	100	9.84e+000	2.4114e-004	6.059e+000	4.0820e+004
10.00	10.00	200	9.86e+000	2.2845e-004	6.059e+000	4.3154e+004
15.00	10.00	100	1.51e+001	3.9346e-004	6.058e+000	3.8337e+004
15.00	10.00	200	1.51e+001	3.8078e-004	6.058e+000	3.9535e+004
1.00	5.00	100	1.09e+000	1.2690e-005	6.060e+000	8.6189e+004
1.00	5.00	200	1.22e+000	2.5379e-005	6.060e+000	4.7883e+004
2.00	5.00	100	1.96e+000	3.8068e-005	6.060e+000	5.1475e+004

Test/File Name : G15 Cont'd
 Start Date : 02-05-1994 Start Time : 11:13:40
 End Date : 02-05-1994 End Time : 13:08:43

Soil Sample : G1
 Sample Number : 5
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.01e+000	3.8068e-005	6.060e+000	5.2673e+004
5.00	5.00	100	5.03e+000	1.2689e-004	6.060e+000	3.9625e+004
5.00	5.00	200	5.01e+000	1.2689e-004	6.060e+000	3.9505e+004
10.00	5.00	100	9.71e+000	3.0456e-004	6.059e+000	3.1871e+004
10.00	5.00	200	1.01e+001	2.9188e-004	6.059e+000	3.4609e+004
15.00	5.00	100	1.48e+001	5.0852e-004	6.048e+000	2.9125e+004
15.00	5.00	200	1.50e+001	5.0870e-004	6.046e+000	2.9533e+004
1.00	1.00	100	1.09e+000	2.5428e-005	6.048e+000	4.3012e+004
1.00	1.00	200	1.08e+000	2.5428e-005	6.048e+000	4.2415e+004
2.00	1.00	100	2.16e+000	5.0855e-005	6.048e+000	4.2416e+004
2.00	1.00	200	1.90e+000	5.0854e-005	6.048e+000	3.7339e+004
5.00	1.00	100	4.66e+000	1.9073e-004	6.047e+000	2.4451e+004
5.00	1.00	200	4.72e+000	1.9073e-004	6.047e+000	2.4770e+004
7.50	1.00	100	6.94e+000	3.5690e-004	6.033e+000	1.9451e+004
7.50	1.00	200	7.02e+000	3.4798e-004	5.966e+000	2.0168e+004

Test/File Name : G13
 Start Date : 01-26-1994 Start Time : 11:23:24
 End Date : 01-26-1994 End Time : 13:18:08

Soil Sample : G1
 Sample Number : 3
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.96e+000	2.1972e-004	5.949e+000	2.2578e+004
5.00	5.00	200	4.98e+000	2.1974e-004	5.949e+000	2.2645e+004
10.00	5.00	100	9.89e+000	4.5326e-004	5.938e+000	2.1824e+004
10.00	5.00	200	1.00e+001	4.5333e-004	5.937e+000	2.2084e+004
10.00	10.00	100	1.01e+001	3.2389e-004	5.935e+000	3.1186e+004
10.00	10.00	200	1.01e+001	3.2390e-004	5.935e+000	3.1278e+004
15.00	10.00	100	1.52e+001	5.1845e-004	5.933e+000	2.9225e+004
15.00	10.00	200	1.51e+001	5.0552e-004	5.932e+000	2.9913e+004
15.00	15.00	100	1.51e+001	4.1487e-004	5.931e+000	3.6485e+004
15.00	15.00	200	1.51e+001	4.2785e-004	5.931e+000	3.5274e+004
20.00	15.00	100	2.00e+001	5.7061e-004	5.929e+000	3.5116e+004
20.00	15.00	200	2.01e+001	5.5768e-004	5.929e+000	3.6091e+004
1.00	20.00	100	9.71e-001	2.5939e-005	5.929e+000	3.7443e+004
1.00	20.00	200	1.09e+000	2.5939e-005	5.929e+000	4.2051e+004
2.00	20.00	100	1.82e+000	2.5940e-005	5.929e+000	7.0277e+004
2.00	20.00	200	2.02e+000	5.1880e-005	5.929e+000	3.8883e+004
5.00	20.00	100	4.92e+000	1.0376e-004	5.929e+000	4.7379e+004
5.00	20.00	200	5.16e+000	1.1673e-004	5.929e+000	4.4163e+004
10.00	20.00	100	1.01e+001	2.3346e-004	5.929e+000	4.3202e+004
10.00	20.00	200	1.01e+001	2.3347e-004	5.928e+000	4.3201e+004
15.00	20.00	100	1.50e+001	3.6318e-004	5.928e+000	4.1267e+004
15.00	20.00	200	1.49e+001	3.6318e-004	5.928e+000	4.0897e+004
20.00	20.00	100	2.02e+001	4.9291e-004	5.928e+000	4.0955e+004
20.00	20.00	200	2.01e+001	4.7995e-004	5.928e+000	4.1843e+004
1.00	15.00	100	9.71e-001	3.8908e-005	5.929e+000	2.4963e+004
1.00	15.00	200	1.15e+000	3.8908e-005	5.929e+000	2.9571e+004
2.00	15.00	100	1.94e+000	3.8908e-005	5.929e+000	4.9925e+004
2.00	15.00	200	2.09e+000	3.8908e-005	5.929e+000	5.3766e+004
5.00	15.00	100	5.11e+000	1.2969e-004	5.929e+000	3.9403e+004
5.00	15.00	200	5.07e+000	1.1672e-004	5.929e+000	4.3397e+004
10.00	15.00	100	9.97e+000	2.7236e-004	5.929e+000	3.6594e+004
10.00	15.00	200	1.01e+001	2.5939e-004	5.929e+000	3.8884e+004
15.00	15.00	100	1.51e+001	4.0206e-004	5.929e+000	3.7574e+004
15.00	15.00	200	1.50e+001	4.0206e-004	5.929e+000	3.7276e+004
20.00	15.00	100	2.00e+001	5.4474e-004	5.929e+000	3.6784e+004
20.00	15.00	200	2.00e+001	5.4475e-004	5.929e+000	3.6783e+004
1.00	10.00	100	1.05e+000	2.5935e-005	5.930e+000	4.0330e+004
1.00	10.00	200	1.05e+000	2.5935e-005	5.930e+000	4.0330e+004
2.00	10.00	100	2.08e+000	3.8903e-005	5.930e+000	5.3389e+004
2.00	10.00	200	1.99e+000	3.8903e-005	5.930e+000	5.1085e+004
5.00	10.00	100	4.96e+000	1.4264e-004	5.930e+000	3.4779e+004
5.00	10.00	200	5.01e+000	1.4264e-004	5.930e+000	3.5093e+004
10.00	10.00	100	1.01e+001	2.9825e-004	5.930e+000	3.3767e+004
10.00	10.00	200	9.97e+000	2.8529e-004	5.930e+000	3.4935e+004
15.00	10.00	100	1.50e+001	4.6685e-004	5.930e+000	3.2039e+004
15.00	10.00	200	1.50e+001	4.7981e-004	5.930e+000	3.1298e+004
1.00	5.00	100	1.11e+000	3.8894e-005	5.931e+000	2.8429e+004
1.00	5.00	200	8.67e-001	2.5929e-005	5.931e+000	3.3424e+004
2.00	5.00	100	2.05e+000	5.1858e-005	5.931e+000	3.9475e+004

Test/File Name : G13 Cont'd

Start Date : 01-26-1994

Start Time : 11:23:24

End Date : 01-26-1994

End Time : 13:18:08

Soil Sample : G1

Sample Number : 3

Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	1.99e+000	3.8893e-005	5.931e+000	5.1097e+004
5.00	5.00	100	4.89e+000	1.8150e-004	5.931e+000	2.6921e+004
5.00	5.00	200	5.05e+000	1.8150e-004	5.931e+000	2.7826e+004
10.00	5.00	100	1.00e+001	3.8898e-004	5.931e+000	2.5738e+004
10.00	5.00	200	9.91e+000	3.8898e-004	5.931e+000	2.5469e+004
15.00	5.00	100	1.49e+001	5.9805e-004	5.914e+000	2.4835e+004
15.00	5.00	200	1.48e+001	5.9835e-004	5.911e+000	2.4698e+004
1.00	1.00	100	1.02e+000	3.9010e-005	5.913e+000	2.6047e+004
1.00	1.00	200	1.02e+000	2.6007e-005	5.913e+000	3.9070e+004
2.00	1.00	100	1.87e+000	6.5016e-005	5.914e+000	2.8728e+004
2.00	1.00	200	1.88e+000	6.5016e-005	5.914e+000	2.8958e+004
5.00	1.00	100	4.74e+000	2.6010e-004	5.913e+000	1.8211e+004
5.00	1.00	200	4.80e+000	2.6010e-004	5.913e+000	1.8441e+004
7.50	1.00	100	6.77e+000	4.4434e-004	5.884e+000	1.5234e+004
7.50	1.00	200	7.02e+000	4.4524e-004	5.872e+000	1.5773e+004

Test/File Name : G33
 Start Date : 01-31-1994 Start Time : 19:14:24
 End Date : 01-31-1994 End Time : 21:10:49

Soil Sample : G3
 Sample Number : 3
 Soil Type : GRANULAR

Desired Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
5.00	5.00	100	4.87e+000	3.4991e-004	6.153e+000	1.3910e+004
5.00	5.00	200	4.87e+000	3.3740e-004	6.153e+000	1.4425e+004
10.00	5.00	100	9.81e+000	8.9994e-004	6.152e+000	1.0901e+004
10.00	5.00	200	9.86e+000	8.9994e-004	6.152e+000	1.0951e+004
10.00	10.00	100	9.95e+000	7.1240e-004	6.152e+000	1.3962e+004
10.00	10.00	200	1.00e+001	6.8741e-004	6.152e+000	1.4580e+004
15.00	10.00	100	1.50e+001	1.1502e-003	6.151e+000	1.2998e+004
15.00	10.00	200	1.50e+001	1.1502e-003	6.150e+000	1.3024e+004
15.00	15.00	100	1.50e+001	9.5032e-004	6.149e+000	1.5811e+004
15.00	15.00	200	1.51e+001	9.2534e-004	6.149e+000	1.6304e+004
20.00	15.00	100	2.00e+001	1.3133e-003	6.148e+000	1.5193e+004
20.00	15.00	200	2.00e+001	1.3009e-003	6.147e+000	1.5361e+004
1.00	20.00	100	1.20e+000	2.5017e-005	6.147e+000	4.7880e+004
1.00	20.00	200	1.12e+000	2.5017e-005	6.147e+000	4.4850e+004
2.00	20.00	100	2.08e+000	6.2542e-005	6.147e+000	3.3214e+004
2.00	20.00	200	1.99e+000	6.2541e-005	6.148e+000	3.1759e+004
5.00	20.00	100	4.96e+000	1.8762e-004	6.148e+000	2.6426e+004
5.00	20.00	200	5.06e+000	2.0013e-004	6.148e+000	2.5305e+004
10.00	20.00	100	9.90e+000	4.5031e-004	6.147e+000	2.1987e+004
10.00	20.00	200	9.96e+000	4.5031e-004	6.147e+000	2.2122e+004
15.00	20.00	100	1.51e+001	7.5056e-004	6.147e+000	2.0161e+004
15.00	20.00	200	1.51e+001	7.3806e-004	6.147e+000	2.0441e+004
20.00	20.00	100	1.98e+001	1.0759e-003	6.146e+000	1.8433e+004
20.00	20.00	200	1.99e+001	1.0509e-003	6.146e+000	1.8958e+004
1.00	15.00	100	1.12e+000	2.5015e-005	6.148e+000	4.4853e+004
1.00	15.00	200	1.08e+000	2.5015e-005	6.148e+000	4.3035e+004
2.00	15.00	100	2.05e+000	6.2536e-005	6.148e+000	3.2732e+004
2.00	15.00	200	2.03e+000	6.2536e-005	6.148e+000	3.2489e+004
5.00	15.00	100	5.08e+000	2.1262e-004	6.148e+000	2.3889e+004
5.00	15.00	200	5.03e+000	2.0012e-004	6.148e+000	2.5155e+004
10.00	15.00	100	1.00e+001	5.1280e-004	6.148e+000	1.9515e+004
10.00	15.00	200	9.99e+000	5.1280e-004	6.148e+000	1.9485e+004
15.00	15.00	100	1.50e+001	8.5051e-004	6.148e+000	1.7649e+004
15.00	15.00	200	1.50e+001	8.5051e-004	6.148e+000	1.7667e+004
20.00	15.00	100	1.98e+001	1.1883e-003	6.148e+000	1.6703e+004
20.00	15.00	200	2.01e+001	1.2008e-003	6.148e+000	1.6756e+004
1.00	10.00	100	1.27e+000	3.7511e-005	6.150e+000	3.3953e+004
1.00	10.00	200	1.14e+000	3.7511e-005	6.150e+000	3.0316e+004
2.00	10.00	100	2.05e+000	3.7511e-005	6.150e+000	5.4568e+004
2.00	10.00	200	2.14e+000	5.0014e-005	6.150e+000	4.2746e+004
5.00	10.00	100	4.97e+000	2.2506e-004	6.150e+000	2.2097e+004
5.00	10.00	200	5.06e+000	2.3756e-004	6.150e+000	2.1318e+004
10.00	10.00	100	9.99e+000	6.2517e-004	6.150e+000	1.5983e+004
10.00	10.00	200	1.01e+001	6.1267e-004	6.150e+000	1.6433e+004
15.00	10.00	100	1.50e+001	1.0253e-003	6.150e+000	1.4611e+004
15.00	10.00	200	1.50e+001	1.0253e-003	6.150e+000	1.4611e+004
1.00	5.00	100	1.20e+000	2.4996e-005	6.153e+000	4.7921e+004
1.00	5.00	200	1.09e+000	2.4995e-005	6.153e+000	4.3676e+004
2.00	5.00	100	2.12e+000	4.9990e-005	6.153e+000	4.2463e+004

Test/File Name : G33 Cont'd
 Start Date : 01-31-1994 Start Time : 19:14:24
 End Date : 01-31-1994 End Time : 21:10:49

Soil Sample : G3
 Sample Number : 3
 Soil Type : GRANULAR

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
2.00	5.00	200	2.14e+000	4.9990e-005	6.153e+000	4.2767e+004
5.00	5.00	100	4.87e+000	2.8744e-004	6.153e+000	1.6933e+004
5.00	5.00	200	4.91e+000	2.8743e-004	6.153e+000	1.7091e+004
10.00	5.00	100	9.99e+000	7.9986e-004	6.153e+000	1.2492e+004
10.00	5.00	200	9.86e+000	7.9986e-004	6.153e+000	1.2321e+004
15.00	5.00	100	1.48e+001	1.3375e-003	6.152e+000	1.1087e+004
15.00	5.00	200	1.50e+001	1.3625e-003	6.152e+000	1.0995e+004
1.00	1.00	100	1.08e+000	3.7478e-005	6.155e+000	2.8724e+004
1.00	1.00	200	1.03e+000	2.4984e-005	6.155e+000	4.1267e+004
2.00	1.00	100	1.96e+000	7.4952e-005	6.156e+000	2.6096e+004
2.00	1.00	200	2.02e+000	6.2459e-005	6.156e+000	3.2287e+004
5.00	1.00	100	4.78e+000	3.7475e-004	6.156e+000	1.2745e+004
5.00	1.00	200	4.72e+000	3.7474e-004	6.156e+000	1.2583e+004
7.50	1.00	100	7.28e+000	7.4954e-004	6.155e+000	9.7098e+003
7.50	1.00	200	7.35e+000	7.8702e-004	6.155e+000	9.3437e+003
10.00	1.00	100	9.95e+000	1.1744e-003	6.155e+000	8.4695e+003
10.00	1.00	200	9.86e+000	1.1619e-003	6.155e+000	8.4822e+003

Test/File Name : G3A4
 Start Date : 02-05-1994
 End Date : 02-05-1994

Start Time : 17:10:21
 End Time : 18:29:07

Soil Sample : G3
 Sample Number : 4
 Soil Type : COHESIVE

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
1.00	6.00	100	9.18e-001	2.5329e-005	6.072e+000	3.6262e+004
1.00	6.00	200	7.96e-001	2.5329e-005	6.072e+000	3.1427e+004
2.00	6.00	100	1.81e+000	3.7998e-005	6.071e+000	4.7538e+004
2.00	6.00	200	1.82e+000	3.8001e-005	6.070e+000	4.7937e+004
4.00	6.00	100	3.52e+000	1.1402e-004	6.069e+000	3.0878e+004
4.00	6.00	200	3.57e+000	1.1403e-004	6.069e+000	3.1280e+004
8.00	6.00	100	7.30e+000	3.6757e-004	6.067e+000	1.9865e+004
8.00	6.00	200	7.33e+000	3.5492e-004	6.066e+000	2.0660e+004
10.00	6.00	100	9.51e+000	5.1980e-004	6.065e+000	1.8288e+004
10.00	6.00	200	9.74e+000	5.1984e-004	6.065e+000	1.8729e+004
1.00	6.00	100	1.06e+000	2.5358e-005	6.065e+000	4.1654e+004
1.00	6.00	200	1.09e+000	2.5358e-005	6.065e+000	4.2862e+004
1.00	3.00	100	1.03e+000	2.5352e-005	6.066e+000	4.0456e+004
1.00	3.00	200	1.16e+000	2.5352e-005	6.066e+000	4.5890e+004
1.00	0.00	100	1.19e+000	2.5343e-005	6.068e+000	4.7115e+004
1.00	0.00	200	1.26e+000	2.5342e-005	6.069e+000	4.9533e+004
2.00	6.00	100	2.02e+000	3.8030e-005	6.066e+000	5.3133e+004
2.00	6.00	200	2.14e+000	5.0707e-005	6.066e+000	4.2265e+004
2.00	3.00	100	1.94e+000	6.3374e-005	6.067e+000	3.0677e+004
2.00	3.00	200	2.14e+000	6.3373e-005	6.067e+000	3.3818e+004
2.00	0.00	100	2.11e+000	5.0684e-005	6.069e+000	4.1680e+004
2.00	0.00	200	1.94e+000	6.3353e-005	6.069e+000	3.0687e+004
4.00	6.00	100	3.78e+000	1.3945e-004	6.066e+000	2.7115e+004
4.00	6.00	200	4.01e+000	1.3945e-004	6.066e+000	2.8761e+004
4.00	3.00	100	3.96e+000	1.3943e-004	6.067e+000	2.8437e+004
4.00	3.00	200	3.90e+000	1.3943e-004	6.067e+000	2.7997e+004
4.00	0.00	100	3.86e+000	1.7740e-004	6.068e+000	2.1746e+004
4.00	0.00	200	3.86e+000	1.9007e-004	6.068e+000	2.0296e+004
8.00	6.00	100	7.91e+000	3.6768e-004	6.065e+000	2.1525e+004
8.00	6.00	200	7.93e+000	3.8036e-004	6.065e+000	2.0847e+004
8.00	3.00	100	7.99e+000	4.1832e-004	6.066e+000	1.9102e+004
8.00	3.00	200	8.01e+000	4.1832e-004	6.066e+000	1.9139e+004
8.00	0.00	100	7.88e+000	5.0692e-004	6.068e+000	1.5552e+004
8.00	0.00	200	7.79e+000	4.8158e-004	6.067e+000	1.6180e+004
10.00	6.00	100	9.95e+000	4.8186e-004	6.064e+000	2.0650e+004
10.00	6.00	200	1.01e+001	4.8187e-004	6.064e+000	2.0903e+004
10.00	3.00	100	1.01e+001	5.3249e-004	6.065e+000	1.9002e+004
10.00	3.00	200	9.95e+000	4.9447e-004	6.065e+000	2.0123e+004
10.00	0.00	100	1.00e+001	6.0842e-004	6.066e+000	1.6455e+004
10.00	0.00	200	9.84e+000	6.0842e-004	6.066e+000	1.6178e+004

Test/File Name : G3A1
 Start Date : 02-03-1994
 End Date : 02-03-1994

Start Time : 12:15:23
 End Time : 13:34:09

Soil Sample : G3
 Sample Number : 1
 Soil Type : COHESIVE

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
1.00	6.00	100	8.65e-001	2.5064e-005	6.136e+000	3.4505e+004
1.00	6.00	200	9.41e-001	2.5067e-005	6.135e+000	3.7529e+004
2.00	6.00	100	1.74e+000	5.0148e-005	6.133e+000	3.4795e+004
2.00	6.00	200	1.67e+000	5.0152e-005	6.133e+000	3.3279e+004
4.00	6.00	100	3.49e+000	1.3796e-004	6.131e+000	2.5296e+004
4.00	6.00	200	3.60e+000	1.3796e-004	6.131e+000	2.6065e+004
8.00	6.00	100	7.19e+000	3.5135e-004	6.128e+000	2.0469e+004
8.00	6.00	200	7.33e+000	3.3882e-004	6.128e+000	2.1629e+004
10.00	6.00	100	9.53e+000	5.1464e-004	6.126e+000	1.8515e+004
10.00	6.00	200	9.60e+000	4.8958e-004	6.125e+000	1.9618e+004
1.00	6.00	100	1.05e+000	2.5107e-005	6.125e+000	4.1699e+004
1.00	6.00	200	1.02e+000	2.5106e-005	6.126e+000	4.0492e+004
1.00	3.00	100	1.05e+000	3.7639e-005	6.129e+000	2.7815e+004
1.00	3.00	200	1.09e+000	3.7639e-005	6.129e+000	2.9024e+004
1.00	0.00	100	1.06e+000	2.5066e-005	6.135e+000	4.2372e+004
1.00	0.00	200	1.00e+000	3.7596e-005	6.136e+000	2.6636e+004
2.00	6.00	100	1.85e+000	6.2728e-005	6.129e+000	2.9510e+004
2.00	6.00	200	1.94e+000	7.5275e-005	6.129e+000	2.5800e+004
2.00	3.00	100	2.02e+000	6.2717e-005	6.130e+000	3.2176e+004
2.00	3.00	200	1.94e+000	5.0174e-005	6.130e+000	3.8708e+004
2.00	0.00	100	1.85e+000	1.0026e-004	6.135e+000	1.8462e+004
2.00	0.00	200	1.93e+000	1.0026e-004	6.135e+000	1.9219e+004
4.00	6.00	100	3.84e+000	1.3803e-004	6.128e+000	2.7811e+004
4.00	6.00	200	3.94e+000	1.3803e-004	6.128e+000	2.8580e+004
4.00	3.00	100	3.73e+000	1.8816e-004	6.130e+000	1.9837e+004
4.00	3.00	200	3.79e+000	1.7562e-004	6.130e+000	2.1599e+004
4.00	0.00	100	3.41e+000	3.2589e-004	6.135e+000	1.0476e+004
4.00	0.00	200	3.47e+000	3.2588e-004	6.135e+000	1.0662e+004
8.00	6.00	100	7.74e+000	3.6400e-004	6.126e+000	2.1259e+004
8.00	6.00	200	7.81e+000	3.3892e-004	6.126e+000	2.3056e+004
8.00	3.00	100	7.75e+000	4.5173e-004	6.128e+000	1.7164e+004
8.00	3.00	200	7.81e+000	4.2664e-004	6.128e+000	1.8315e+004
8.00	0.00	100	7.21e+000	8.4000e-004	6.133e+000	8.5799e+003
8.00	0.00	200	7.28e+000	8.3996e-004	6.134e+000	8.6706e+003
10.00	6.00	100	9.89e+000	5.0215e-004	6.125e+000	1.9701e+004
10.00	6.00	200	9.83e+000	4.5196e-004	6.125e+000	2.1754e+004
10.00	3.00	100	9.65e+000	5.7731e-004	6.127e+000	1.6715e+004
10.00	3.00	200	9.74e+000	5.5223e-004	6.127e+000	1.7640e+004
10.00	0.00	100	9.21e+000	9.6565e-004	6.131e+000	9.5375e+003
10.00	0.00	200	9.26e+000	8.9045e-004	6.131e+000	1.0394e+004

Test/File Name : G3A2
 Start Date : 02-05-1994 Start Time : 19:41:12
 End Date : 02-05-1994 End Time : 21:00:14

Soil Sample : G3
 Sample Number : 2
 Soil Type : COHESIVE

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
1.00	6.00	100	1.05e+000	2.5215e-005	6.099e+000	4.1812e+004
1.00	6.00	200	1.24e+000	2.5217e-005	6.099e+000	4.9080e+004
2.00	6.00	100	1.71e+000	5.0439e-005	6.098e+000	3.3928e+004
2.00	6.00	200	1.71e+000	5.0441e-005	6.098e+000	3.3927e+004
4.00	6.00	100	3.10e+000	1.2612e-004	6.097e+000	2.4593e+004
4.00	6.00	200	3.22e+000	1.2613e-004	6.097e+000	2.5561e+004
8.00	6.00	100	6.59e+000	3.6597e-004	6.093e+000	1.7995e+004
8.00	6.00	200	6.66e+000	3.6598e-004	6.093e+000	1.8203e+004
10.00	6.00	100	8.62e+000	5.4277e-004	6.092e+000	1.5877e+004
10.00	6.00	200	9.67e+000	6.1862e-004	6.091e+000	1.5635e+004
1.00	6.00	100	1.01e+000	2.5249e-005	6.091e+000	3.9940e+004
1.00	6.00	200	1.13e+000	2.5249e-005	6.091e+000	4.4781e+004
1.00	3.00	100	9.63e-001	3.7864e-005	6.092e+000	2.5423e+004
1.00	3.00	200	9.78e-001	3.7864e-005	6.092e+000	2.5826e+004
1.00	0.00	100	1.15e+000	2.5234e-005	6.095e+000	4.5414e+004
1.00	0.00	200	1.13e+000	3.7849e-005	6.095e+000	2.9873e+004
2.00	6.00	100	2.02e+000	6.3113e-005	6.092e+000	3.1957e+004
2.00	6.00	200	2.05e+000	6.3113e-005	6.092e+000	3.2441e+004
2.00	3.00	100	1.74e+000	6.3102e-005	6.093e+000	2.7604e+004
2.00	3.00	200	1.89e+000	6.3103e-005	6.093e+000	3.0025e+004
2.00	0.00	100	1.73e+000	6.3086e-005	6.094e+000	2.7369e+004
2.00	0.00	200	1.71e+000	6.3085e-005	6.095e+000	2.7127e+004
4.00	6.00	100	3.74e+000	1.5148e-004	6.091e+000	2.4712e+004
4.00	6.00	200	3.84e+000	1.5148e-004	6.091e+000	2.5318e+004
4.00	3.00	100	3.84e+000	1.7669e-004	6.093e+000	2.1705e+004
4.00	3.00	200	3.85e+000	1.7669e-004	6.093e+000	2.1792e+004
4.00	0.00	100	3.79e+000	1.8926e-004	6.094e+000	2.0022e+004
4.00	0.00	200	3.87e+000	2.1449e-004	6.095e+000	1.8023e+004
8.00	6.00	100	7.93e+000	4.2928e-004	6.090e+000	1.8473e+004
8.00	6.00	200	7.98e+000	4.2930e-004	6.090e+000	1.8579e+004
8.00	3.00	100	7.81e+000	4.6709e-004	6.091e+000	1.6716e+004
8.00	3.00	200	8.07e+000	4.6710e-004	6.091e+000	1.7272e+004
8.00	0.00	100	7.67e+000	5.6796e-004	6.092e+000	1.3505e+004
8.00	0.00	200	7.84e+000	5.6796e-004	6.092e+000	1.3801e+004
10.00	6.00	100	9.70e+000	5.3047e-004	6.088e+000	1.8290e+004
10.00	6.00	200	9.98e+000	5.4312e-004	6.088e+000	1.8371e+004
10.00	3.00	100	9.99e+000	6.1880e-004	6.089e+000	1.6149e+004
10.00	3.00	200	9.89e+000	6.0619e-004	6.089e+000	1.6308e+004
10.00	0.00	100	9.84e+000	7.4500e-004	6.090e+000	1.3208e+004
10.00	0.00	200	9.93e+000	7.1978e-004	6.089e+000	1.3798e+004

Test/File Name : G3A3
 Start Date : 02-04-1994
 End Date : 02-04-1994

Start Time : 21:45:46
 End Time : 23:04:30

Soil Sample : G3
 Sample Number : 3
 Soil Type : COHESIVE

Desired Deviator Stress (psi)	Desired Confining Pressure (psi)	Data Cycle	Calculated Deviator Stress (psi)	Calculated Resilient Strain (in/in)	Calculated Gage Length (in)	Resilient Modulus (psi)
1.00	6.00	100	8.73e-001	2.5462e-005	6.040e+000	3.4269e+004
1.00	6.00	200	9.34e-001	2.5469e-005	6.038e+000	3.6665e+004
2.00	6.00	100	1.84e+000	7.6435e-005	6.036e+000	2.4033e+004
2.00	6.00	200	1.91e+000	6.3704e-005	6.035e+000	3.0038e+004
4.00	6.00	100	3.44e+000	2.0405e-004	6.030e+000	1.6880e+004
4.00	6.00	200	3.63e+000	2.2969e-004	6.026e+000	1.5795e+004
8.00	6.00	100	7.75e+000	6.9234e-004	5.997e+000	1.1188e+004
8.00	6.00	200	9.51e+000	8.9772e-004	5.996e+000	1.0589e+004
10.00	6.00	100	9.61e+000	8.9951e-004	5.984e+000	1.0687e+004
10.00	6.00	200	1.13e+001	8.8699e-004	5.982e+000	1.2719e+004
1.00	6.00	100	9.80e-001	2.5702e-005	5.984e+000	3.8118e+004
1.00	6.00	200	1.06e+000	2.5702e-005	5.984e+000	4.1096e+004
1.00	3.00	100	1.06e+000	2.5694e-005	5.985e+000	4.1110e+004
1.00	3.00	200	9.64e-001	2.5694e-005	5.985e+000	3.7535e+004
1.00	0.00	100	1.03e+000	2.5684e-005	5.988e+000	3.9933e+004
1.00	0.00	200	1.01e+000	3.8525e-005	5.988e+000	2.6225e+004
2.00	6.00	100	1.73e+000	6.4230e-005	5.986e+000	2.6932e+004
2.00	6.00	200	1.94e+000	6.4231e-005	5.986e+000	3.0268e+004
2.00	3.00	100	1.94e+000	7.7067e-005	5.987e+000	2.5226e+004
2.00	3.00	200	1.87e+000	7.7067e-005	5.987e+000	2.4233e+004
2.00	0.00	100	1.82e+000	8.9902e-005	5.987e+000	2.0263e+004
2.00	0.00	200	1.81e+000	1.0275e-004	5.987e+000	1.7580e+004
4.00	6.00	100	4.27e+000	2.3132e-004	5.983e+000	1.8463e+004
4.00	6.00	200	3.95e+000	2.1848e-004	5.983e+000	1.8077e+004
4.00	3.00	100	3.81e+000	1.9276e-004	5.984e+000	1.9774e+004
4.00	3.00	200	3.78e+000	2.0562e-004	5.984e+000	1.8389e+004
4.00	0.00	100	3.77e+000	3.3413e-004	5.983e+000	1.1270e+004
4.00	0.00	200	3.89e+000	2.9560e-004	5.983e+000	1.3154e+004
8.00	6.00	100	7.82e+000	5.1455e-004	5.978e+000	1.5203e+004
8.00	6.00	200	7.88e+000	5.0172e-004	5.977e+000	1.5713e+004
8.00	3.00	100	7.94e+000	6.1750e-004	5.977e+000	1.2866e+004
8.00	3.00	200	8.68e+000	6.1752e-004	5.977e+000	1.4056e+004
8.00	0.00	100	7.75e+000	7.8565e-004	5.970e+000	9.8591e+003
8.00	0.00	200	7.70e+000	8.7609e-004	5.968e+000	8.7890e+003
10.00	6.00	100	9.80e+000	6.4458e-004	5.965e+000	1.5199e+004
10.00	6.00	200	9.80e+000	6.0596e-004	5.964e+000	1.6168e+004
10.00	3.00	100	9.81e+000	7.7359e-004	5.964e+000	1.2684e+004
10.00	3.00	200	1.13e+001	9.6685e-004	5.965e+000	1.1637e+004
10.00	0.00	100	1.04e+001	1.0328e-003	5.956e+000	1.0050e+004
10.00	0.00	200	9.63e+000	1.2914e-003	5.954e+000	7.4560e+003

Appendix D

Recommended Standards and Specifications

This section includes recommended standards and specifications for four different applications incorporating WFS, namely embankment; subgrade; asphalt concrete; and controlled low strength material. These are intended to serve as guidelines for the Indiana Department of Transportation (INDOT). The suggested specifications may be further refined in the light of data obtained from the field study. The updated specifications may then be included in the Indiana Department of Highways, Standard Specifications.

Embankment

- The material be from WFS, passing No. 8 sieve. Anything retained on No. 8 sieve needs to be processed. Retained material may be a metal piece which should be removed, or a core lump (see Section 3.6) which should be crushed.
- The material shall be watered to increase the moisture content, until the moisture content is within the specified range.
- The material shall be placed above the water table and out of contact with ground water.
- The green WFS embankments shall be compacted to at least 95% of their maximum dry density, as determined by ASTM D 698.
- The chemically bonded and shell molded WFS embankments shall be compacted to at least 70% of their relative density, as determined by ASTM D 4253.
- To avoid any liquefaction potential and to achieve maximum CBR values, these sands shall not be placed at moisture content in excess of optimum moisture content.
- For green WFS samples, the moisture content shall be controlled within minus

3 percentage points of moisture content and optimum moisture content. It is suggested that green WFS samples be compacted in 6 in. to 8 in. thick lifts using pneumatic tired rollers (see Section 4.4).

- For chemically bonded and shell molded WFS samples, vibratory compaction using smooth wheel rollers is recommended. Lift thickness of 8 in. to 10 in. is suggested. When close control of moisture content is necessary it shall be within minus 3 percentage points of moisture content and optimum moisture content.
- A temporary perimeter berm shall be constructed around the limits of the WFS fill area to contain any surface water runoff from the WFS fill. The berm shall be maintained throughout the period of WFS placement.
- Some green WFSs can contain too many fines. For these green WFS, measures shall be taken to limit blowing of WFS during transportation to the construction site and placement in the embankment. The WFS shall be kept moist and compacted as soon as it is deposited in the fill area.
- The WFS embankment shall be encapsulated using a compacted clay base, sidewalls and top cover having permeability less than 10^{-7} cm/sec. The clay base shall be at least three feet thick to prevent any ground water contamination and help in attenuation mechanisms. However, the requirement of a clay base shall be dealt on a case-by-case basis. For very low permeability green WFS; Type IV WFS; or the site already containing sufficient thick natural low permeability layers, this clay base requirement may be omitted. The top cover and sidewalls be at least two feet thick to greatly reduce any infiltration and be properly compacted.

- The final cover and topsoil should be smoothly graded to enhance positive surface water runoff and seeded, fertilized, and mulched, to establish a thick vegetative growth. Routine maintenance of the embankment slopes shall be performed to insure the integrity of the final soil cover.
- Collection basin lysimeters under the fill and wells around the perimeter of the site may be used for ground water monitoring.
- The compressibility and strength parameters discussed in Chapter 4 may be used for design and evaluation of embankments containing WFS, until such time as field results are available.
- Appropriate monitoring devices, e.g., settlement plates, inclinometers, etc., may be placed in the embankments to determine their technical performance.

Subgrades

The specifications for subgrade remains the same as that of existing specifications for Indiana and those given for embankments. However, due to environmental considerations and the laboratory data developed in Chapter 4, the following additional specifications are suggested:

- A proper crown on the surface of the pavement shall be built to assist in channeling the water off the road and into the adjacent drainage ditches.
- A compacted two to three feet compacted clay base layer having permeability less than 10^{-7} cm/sec shall be used to preclude the ground water coming into contact with the pavement system.
- Drainage ditches shall be used to channel the runoff away from the pavement to

inhibit the source for lateral seepage into the subgrade.

- Quarterly testing shall be performed at ground water monitoring wells and leached collection pipes for at least first two years following the completion of construction.
- The resilient moduli and CBR values discussed in Chapter 4 may be used for design and evaluation of subgrade containing WFSs.

Asphalt Concrete

The specifications for manufacture and placement of asphalt concrete remains the same as that of existing specifications. However, for blending of WFS with conventional aggregates for asphalt concrete production, the following additional specifications are suggested.

- Only WFS material passing No. 12 sieve shall be used. Anything retained on No. 12 sieve shall be considered a lump which tends to inhibit mixing of individual grains with asphalt in hot mix asphalt concrete.
- Core lumps need to be crushed whereas lumps associated with molding sand need to be washed or screened off or crushed before their use in manufacturing asphalt concrete.
- Replacement level of no more than 25% WFS with respect to the total weight of aggregates, shall be used.
- Since in hot mixes, there is little or no moisture in the aggregate, it is expected that freezing and thawing should not be a significant problem. Moreover, the aggregates are coated with a film of asphalt binder which would prevent the

aggregates from absorbing a significant amount of moisture during the life of the mixture. However, 12% weighted loss after being subjected to five cycles of sodium sulfate soundness test may be considered as an upper limit until field performance of these mixes become available.

Controlled Low Strength Material

In general, the existing specifications (revised date 12/17/92) for flowable mortar shall be followed, with the exceptions of fine aggregate, mix proportions and placement which are described below.

- The fine aggregate shall be WFS with maximum LOI of 4%, until data for CLSM mixes using WFS with higher LOI values become available.
- Only WFS material passing No. 8 sieve shall be used. Retained material on the No. 8 sieve shall be processed prior to its use.
- The mix proportion shown below shall be adopted. Such a mix proportion is intended only as a guide and will probably have to be modified to suit the requirements of the specific use and materials available.

Portland Cement, Type I, lb.	99
Fly Ash, Class F, lb.	158
Waste Foundry Sand, lb.	2134
Water, lb.	741

- Weighted percent loss after five cycles of sodium sulfate soundness test shall not exceed 10% until field performance data become available.
- To prevent deflection of thin-walled flexible pipes, to reduce lateral loads or

retaining walls, and to reduce vertical loads over soft or weak materials, CLSM shall be placed in lifts. The backfill should be allowed to set between the placement of subsequent lifts.

- For freeze-thaw durability concerns, sand or natural soil shall be used for the upper 2 to 3 feet of the backfill.
- Soil cover or pavement shall be applied over trench backfill, and protective facing must be used against retaining wall backfill for erosion or abrasion concerns.
- Drainage shall be provided for the retaining wall backfill, as would be provided for a soil backfill.

Appendix E
Information about Micrographs

Information about the original micrographs of the following figures can be obtained from the Potter Engineering Library, Purdue University, West Lafayette, Indiana:

Figure 3.12 Micrograph of 1 mm division

Figure 3.13 Micrograph of G1

Figure 3.14 Micrograph of G2

Figure 3.15 Micrograph of G3

Figure 3.16 Micrograph of G4

Figure 3.17 Micrograph of G5

Figure 3.18 Micrograph of G6

Figure 3.19 Micrograph of G7

Figure 3.20 Micrograph of C1

Figure 3.21 Micrograph of C2

Figure 3.22 Micrograph of S1

Figure 3.23 Micrograph of R1