Effect Of Larger Sized Coarse Aggregates On Mechanical Properties Of Portland Cement Concrete Pavements And Structures

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16. Abstract

This project assesses the effects of aggregate type and size on the mechanical properties of concrete, viz., on the compressive and flexural strengths, and on the modulus of elasticity. Explored are three aggregate gradations (No. 57, No. 467, and No. 357) consisting of two aggregate types (natural and crushed). Concrete made according to the specification for the ODOT standard Class C mix provides the baseline for mechanical properties. The properties of the six concrete mixes produced are compared, in order to determine if aggregate gradation and type have a significant effect, using the following tests at 3, 7, 28, 56 and 90 days: (a) Compression; (b) Modulus of rupture; and (c) Modulus of elasticity. A series of environmental tests are documented in a companion report submitted under this contract. Air content, slump and unit weight tests were conducted for each mix. For the most part, different coarse aggregate properties did not impact significantly the mechanical properties of concrete examined. When significant differences were observed, these were confounded by variability issues related to the testing protocols themselves, and by mineralogical distinctions among the various aggregate blends. It is, therefore, concluded that coarse aggregate gradation had little effect on the mechanical properties of concrete. These results indicate that larger sized coarse aggregates can be used for pavements and highway structures without significantly compromising the mechanical properties of the concrete, and afford concrete producers more flexibility in creating cost-effective and cement-efficient mixes. In view of the natural variability of concrete test results, it is recommended that the number of specimens tested be increased to five or six, in order to improve the confidence level. Conversely, the number of testing dates can be considerably curtailed without compromising the quality of the data obtained.

17. Key Words
Coarse aggregates, compresive strength, flexural strength, concrete mix design

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Effect of Larger Sized Coarse Aggregates On Mechanical Properties of Portland Cement Concrete Pavements and Structures

State Job No.: 14803(0)

FINAL REPORT

Prepared in cooperation with the
Ohio Department of Transportation and the
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by

University of Cincinnati
Cincinnati Infrastructure Institute
Department of Civil and Environmental Engineering
Cincinnati, OH

August 2006

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

FOREWORD

The investigation described in this Report was sponsored by the Ohio Department of Transportation (ODOT) and by the Federal Highway Administration (FHWA) as Ohio State Job No.: 14803(0); PID No.: 11494, under project "Larger Sized Coarse Aggregates in Portland Cement Concrete Pavements and Structures." The Principal Investigators were Drs Anastasios M. Ioannides and Richard A. Miller, Department of Civil and Environmental Engineering, University of Cincinnati. The ODOT Technical Liaison was Mr Bryan Struble, the Research Manager was Mr Lloyd Welker, the Administrator for the Office of Research and Development at ODOT was Ms Monique Evans, and the FHWA liaison in Columbus, OH was Mr Herman Rodrigo. The assistance, cooperation and friendship of these individuals was a major contributor to the success of the study, and their support is gratefully acknowledged. The sand and both kinds of coarse aggregates were supplied free of charge by *Martin Marietta Materials*, through Mr Jim Martin. The cement was donated by *CEMEX*, through Mr Steve Reibold. The admixture was contributed at no cost by *Master Builders, Inc.*, through Mr Greg Wirthlin. The authors also acknowledge the contributions to the project of graduate students Kristy M. Walsh and Amarendranath Deshini. This Report will be submitted by Jeff C. Mills to the Division of Research and Advanced Studies of the University of Cincinnati in partial fulfillment of the requirements for the degree of Master of Science in the Department of Civil and Environmental Engineering, in December 2006.

ABSTRACT

This report examines the effects of coarse aggregate type and size on the mechanical properties of concrete, in an effort to develop more cost-efficient mixes for pavements and other highway structures. A literature survey of the current understanding concerning the effects of coarse aggregate properties on concrete performance concrete is presented first. Aggregate characteristics studied include size, shape, surface texture, strength, and stiffness, while concrete aspects investigated include slump and air content in the plastic state, as well as strength and stiffness after curing. Aggregate properties, such as moisture content, absorption, specific gravity, and unit weight, are determined for use in formulating concrete mix designs. Aggregate blending is used to generate the required coarse aggregate gradations. Six different concrete mixes were prepared, using three different coarse aggregate gradations, No. 57, No. 467, and No. 357, along with two different aggregate types, natural and crushed. Test results show that coarse aggregate properties often did not have a significant effect on the mechanical properties of concrete. When significant differences were observed, these were confounded by variability issues related to the testing protocols themselves, and by mineralogical distinctions among the various aggregate blends. It is, therefore, concluded that coarse aggregate gradation had little effect on the mechanical properties of concrete. These results indicate that larger sized coarse aggregates can be used for pavements and highway structures without significantly compromising the mechanical properties of the concrete, and afford concrete producers more flexibility in creating cost-effective and cement-efficient mixes.

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LIST OF SYMBOLS AND ABBREVIATIONS

°C: degree celcius

°F: degree fahrenheit

A: % absorption

A: weight of oven-dry sample

AASHTO: American Association of State Highway and Transportation Officials

AC: abused microsilica concrete with crushed aggregate

AN: abused microsilica concrete with crushed aggregate

ASG: apparent specific gravity

ASTM: American Society for Testing and Materials

b: average width

B: weight of flask with water

B: weight of saturated surface dry sample in air

BSG_{OD}: bulk specific gravity in oven dry condition

BSG_{SSD}: bulk specific gravity in saturated surface dry condition

C: cement

C: weight of flask with water

C: weight of saturated sample in water

C+P: cement + pozzolan

CA: coarse aggregate

COV: coefficient of variation

d: average depth

D: weight of oven-dry sample

DC: densified microsilica with crushed aggregate

DN: densified microsilica with crushed aggregate

FA: fine aggregate

f_c': compressive strength

FM: fineness modulus

f_r: flexural strength

ft: feet

G: grams

G: mass of aggregate and measure

Hrs: hours

in.: inch

kg: kilogram

km: kilometer

l: effective span

L: liter

Lb: pound

LOI: loss on ignition

m: meter

Min.: minutes

Mm: millimeter

M_R: modulus of rupture

M_{SSD}: bulk density of aggregate at ssd condition

M_W: mass of water

NCHRP: National Cooperative Highway Research Program

NT: Not Tested

ODOT: Ohio Department of Transportation

Oz: ounce

P: pozzolan

P: load at failure

PCC: Portland Cement Concrete

pcf: pounds per cubic feet

psi: pound per square inch

r: rate of application of load

S: weight of ssd sample

SiO: silica oxide

SiO_2: silicon-di-oxide

Sq: square

SSD: saturated surface dry condition

T: mass of measure

UC: University of Cincinnati

UC: undensified microsilica with crushed aggregate

UN: undensified microsilica with natural aggregate

US: United States of America

V: volume

V_{air}: volume of air

V_{SSD}: volume at saturated surface condition

W: moist weight of sample

W: density of water

w: moisture content

w/c: water cement ratio

W_{CEM}: weight of cement

W_{MS}: weight of microsilica

$W_{MS\ (SSD)}$: weight of microsilica at SSD

$W_{W\ (SSD)}$: weight of water at SSD

yd: yard

μ: micro

γ_w: unit weight of water

No.: number

%: percentage

LIST OF SPECIFICATIONS CITED

ASTM C 128 – 97 *Standard Test Method for Specific Gravity and Absorption of Fine Aggregate*

ASTM C 29/C 29M – 97 *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*

ASTM C 136 – 96a *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*

ODOT Item 499.03 *Concrete-General: Proportioning*

ODOT Item 499.03 *Concrete-General: Proportioning; Slump*

ASTM C 192/C 192M – 00 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*

ASTM C 143/C 143M – 00 *Standard Test Method for Slump of Hydraulic-Cement Concrete*

ASTM C 231 – 97 *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*

ASTM C 39/C 39M – 01 *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*

ASTM C 78 – 02 *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*

ODOT Item 703.01 *Aggregate-General: Size*

ODOT 703.02 *Aggregate for Portland Cement Concrete: Fine Aggregate*

ASTM C 127 – 01 *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*

AASHTO T 22-03 *Compressive Strength of Cylindrical Concrete Specimens*

ASTM C 469 - $94^{\varepsilon 1}$ *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*

ASTM C 88 – 99a *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate*

ACI 211.1–70 *Recommended Practice for Selecting Proportions for Normal Weight Concrete*

ASTM C 260 – 01 *Standard Specification for Air-Entraining Admixtures for Concrete*

AASHTO M 154 – 05 *Standard Specification for Air-Entraining Admixtures for Concrete*

U.S. Army Corps of Engineers CRD-C 13 *Standard Specification for Air-Entraining Admixtures for Concrete*

ASTM C 566 – 89 *Standard Test Method for Total Moisture Content of Aggregate by Drying*

ODOT 2002 *Construction and Material Specifications*

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

1 INTRODUCTION

1.1 Project Background and Significance

Portland cement concrete (PCC) is a versatile engineering material. It can be produced to have a variety of strength, stiffness, unit weight, porosity, and durability properties, yet all concrete contains the same four basic components: coarse aggregate (gravel), fine aggregate (sand), water, and Portland cement. Additionally, other admixtures, such as plasticizers, air entrainers, and pozzolanic materials, are occasionally used. Of the four major components, Portland cement is the most costly. Cement is moreover largely responsible for dimensional instabilities in the concrete, such as shrinkage and creep. Therefore, by limiting the cement content in concrete it may be possible to produce a more cost-efficient mix, while simultaneously improving its engineering characteristics (Nilson, et al., 2004).

One way to reduce the cement content is to fill as much of the volume of concrete as possible with aggregate. Larger sized coarse aggregates can accomplish this objective rather easily. Use of larger coarse aggregates, however, can also lead to a decrease in other concrete engineering properties, most notably compressive and tensile strength. Larger sized coarse aggregates have low surface to volume ratios, and often lead to a weakened coarse aggregate-cement paste bond, on which most high strength concretes rely. Consequently, high strength concrete mix designs often call for smaller sized coarse aggregates (Soroka, 1980).

For many transportation structures, including pavements and highway bridges, high strength concrete is not usually needed. In normal strength concrete, the coarse aggregate-cement paste bond is not as critical, since other mechanisms play a more major role. Mix efficiency, dimensional stability, porosity, and durability are much more important (Soroka, 1980). Since reducing the cement content can improve all of these properties, it may be beneficial to use larger coarse aggregates in such transportation structures. Laboratory studies are needed to ensure that the use of larger sized coarse aggregates will not compromise the mechanical properties of concrete.

It has been shown that increasing the maximum size of aggregate lowers the water demand for any desired level of workability (Neville, 1995). This is because as aggregate size increases, the surface area to be wetted decreases. Lower water demand decreases the water/cement ratio (w/c), thereby increasing strength. It is also known, however, that increasing the aggregate size excessively may lead to several detrimental effects and cause a decrease in strength. Such effects include a decrease in the bond area between the coarse aggregate and the cement paste, increased heterogeneity in the concrete, and elevated propensity for D-cracking. It can be expected that there is an optimum maximum aggregate size that balances positive and negative effects and leads to a peak value of strength.

The size of a concrete member influences the choice of maximum size of aggregate. The American Society for Testing and Materials (ASTM) advises that the maximum aggregate size should be no more than 2/3 of the available clear space between reinforcing bars or between the bars and the formwork (ASTM C 192/C 192M – 00 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*).

Maximum aggregate size should also not exceed 1/3 of the minimum member thickness. Such rules-of-thumb can sometimes limit the size of aggregates to be used in structural applications, but for generally in pavements, larger sized aggregates may be readily accommodated.

1.2 Project Objectives

This project seeks to assess the effects of aggregate type and size on the mechanical properties of concrete, specifically on the compressive and flexural strengths, and on the modulus of elasticity. The research goal is to examine if the cement efficiency of standard Ohio Department of Transportation (ODOT) concrete mixes for pavements and other transportation structures can be improved by the use of larger sized coarse aggregates.

1.3 Report Organization

This report is divided into six chapters. The first chapter introduces the reader to the project topic; it discusses the background and significance of the investigation, lists the study objectives, and outlines the report organization. The second chapter presents a literature review, and discusses in considerable detail the definition of coarse aggregates, and their effect on the physical, mechanical, and environmental properties of concrete. The mixing, casting, curing, and testing procedures adopted are outlined in Chapter 3. The fourth chapter presents the test results obtained from these procedures. Chapter 5 details the analysis and interpretation of the results obtained, in order to assess the effects of coarse aggregate type and gradation on the mechanical properties of concrete. Finally, the sixth chapter summarizes the investigation findings and provides a number of recommendations formulated for consideration by ODOT.

2 LITERATURE SURVEY

2.1 Introduction

A concrete mix typically comprises four components: coarse aggregate, fine aggregate, cement, and water. Since aggregate generally takes up 60-70% of the total volume of the concrete, its characteristics can affect the physical and mechanical properties of concrete to a great extent. Important aggregate features in this regard are size, shape, surface texture, strength, stiffness, and its overall soundness and durability. This chapter presents a survey of the current understanding of the influence of aggregate properties on concrete mix performance.

2.2 Overview of Coarse Aggregates

Aggregates are mixtures of various sizes of stone or rock particles in contact with each other. They are typically combinations of gravel and crushed materials, such as limestone, basalt and granite, but may also include blast furnace slag, or recycled concrete fragments. Particles with a diameter greater than 3/16 in. or 5 mm (retained on the No. 4 sieve) are usually classified as coarse aggregate, while smaller particles are called fine aggregate (McNally, 1998). In a Portland cement concrete mix, coarse and fine aggregates typically make up 60 to 70% of the total volume. For this reason, aggregate characteristics, such as size, shape, and surface texture influence greatly the properties of a concrete mix.

2.2.1 Basic Properties of Coarse Aggregates

Much of the information in this section has been extracted from McNally (1998).

Shape

Aggregate particle shape can usually be classified into one of two types, rounded or angular. Natural aggregates, which are typically found on coastlines or in riverbeds, are typically smooth in texture and round in shape due to weathering. Mechanically ground by machines, crushed aggregates on the other hand are commonly angular in shape and have a rough surface texture. The shape of the aggregate will affect both the strength and workability of concrete.

Surface Texture

Surface texture is related to a number of factors, including particle mineralogy, surface roughness, and the amount of moisture and dust adhering to the aggregate surface. Surface texture influences chemical inertness, polishing resistance, and, most importantly, bitumen and cement adhesion. Surface textures are typically classified as either rough or smooth, and will influence the tenacity with which the cement paste adheres to the coarse aggregate. Aggregates with a rough surface texture bond more firmly with cement paste than smooth materials. While these characteristics are important for a quality concrete mixture, it should be noted that good adhesion properties are primarily associated with low strength aggregates.

Weatherability

Weatherability can be easily defined as the aggregate's resistance to the effects of weathering. Engineers often use three parameters that relate to weatherability:

soundness, abradability, and durability. Soundness is the vaguest of these three parameters. Originally, it reflected the thought that an unsound, or porous, aggregate would produce a very dull, thud-like sound when struck by a hammer, whereas a sound, or strong, material would produce a ring-like sound. Currently, it relates to the extent to which aggregates will disintegrate during salt crystallization in the sulfate soundness test of the American Society for Testing and Materials (ASTM C 88 – 99a *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate*). Abradability is a more specific term referring to failure that may occur due to wear and tear, or in the case of pavements, to wear and breakdown resulting from the impact of tires on the aggregate, over time. Finally, durability is a very broad term that can refer to the resistance of the aggregate to any type of failure during its life period, though it should be properly restricted to moisture- and temperature-dependent, rather than load related processes.

2.2.2 Gradation of Coarse Aggregates

Particle size and gradation of the aggregate have a significant effect on the behavior of a concrete mix, affecting its economy, workability, and strength. For a given water/cement ratio (w/c), the amount of water to be added is inversely proportional to the maximum aggregate size. The use of larger sized coarse aggregates decreases the amount of cement paste required to bond the particles, which explains why concrete mixes with high quantities of coarse aggregates are less workable and very difficult to finish. Conversely, the use of finer particles entails the use of more cement in order to maintain constant aggregate/cement ratio, which at the same time decreases the workability of the concrete, even as it improves its finish.

Maximum aggregate size typically ranges between ¾ and 1.5 in., while about 25 to 45% of the total aggregate content consists of fine aggregate. Special mixes of concrete may require aggregates outside these ranges. Aggregate mixtures can be broadly classified in terms of their particle size distribution (PSD) into three types, as discussed below.

Dense-Graded Mixes

Dense-graded aggregate mixes can also be called well-graded, continuous-graded, or straight line-graded mixes. These types of mixes are characterized by an even distribution of particle sizes, such that finer grains can fill the voids between larger ones. Dense-graded mixes have reduced void space leading to increased shear strength, and must be placed in thicker lifts.

Open-Graded Mixes

Open-graded mixes, also known as no-fines or harshly-graded mixes, contain an even mixture of various coarse particle sizes, but little or no void filling fines. Consequently, they depend heavily on friction between interlocking angular and rough textured coarse fragments for strength. Moreover, the increased void space allows moisture to drain easily, which explains why open-graded aggregates are commonly used in roadway bases.

Gap-Graded Mixes

Gap-graded aggregate mixes, also known as skip-graded or armchair-graded, are missing an intermediate size fraction, generally either coarse sand or fine gravel. Leaving a proportion of voids unfilled reduces their compacted density and makes them prone to segregation. Gap-graded mixes can be used either by necessity, as when only coarse aggregate and uniform sand are available, or because rounded dune sand generally improves workability.

General Guidelines for Gradation of Coarse Aggregates

Unsatisfactory gradation of the aggregates may lead to the following: (a) segregation of the mortar from the coarse aggregates; (b) bleeding of water below and around larger aggregates and on the surface of the concrete; (c) settling of aggregates, leaving paste in the top lift of the concrete; (d) need for chemical admixtures in order to restore workability to the concrete; (e) increased use of cement; (f) insufficient air entrainment and air void distribution; (g) excessive use of water; (h) high porosity of the hardened concrete; (i) high material costs; (j) reduced service life.

Variability in coarse aggregate gradation results from mingling different particle size distributions among concrete batches, and is very common on any construction project. This may be attributed to the aggregate source(s), the stock piling operation, or the method of concrete production. It becomes a costly affair for both the contractor and the producer of the aggregate to ensure a unique and workable gradation of the aggregate, so usually little attention is paid in achieving one. Moreover, very little research has been done into the effect of gradation variability on the properties of concrete.

Baker and Scholer (1973) concluded that compressive strength is more greatly influenced by the variation in the gradation of smaller sizes of aggregates than of larger ones. They observed higher compressive strengths in gap-graded mixes than in dense-graded mixes. Cramer, et al. (1995) studied the effects of using optimized coarse aggregate gradations, which combine practical and economic constraints with attempts to obtain a mix of sizes that will lead to improved workability, durability, and strength. Their optimized gradations performed nearly identical to their controlled, dense-graded aggregate mix (Cramer and Carpenter, 1999), but outperformed near gap-graded mixes by 10 to 20% in compressive strength and by 15% in terms of water demand (Cramer, et al., 1995). Cadoni, et al. (2001) conducted experiments on the influence of the gradation on the strain-rate tensile behavior of the concrete. They observed that there was an inverse proportion between the uniaxial tensile strength and the maximum size of the aggregate particles at high strains. This was attributed to the fact that surface area increases with the decrease in the maximum size of the aggregates, which decreases the possibility of finding voids and results in the increase of the bond strength. They have also observed that in cases of high impact, concretes with smaller size aggregate showed greater strength and energy absorption capability than those with larger aggregates.

Misshapen particles can be misleading during the grading of the aggregate. They sometimes appear to be finer when they actually are coarser, and vice versa. Misleading gradations can decrease the workability of the concrete and increase the void space, thereby reducing the strength and durability of the concrete. They can also lead to an increase cement and water demand in order to fill these extra voids. Imberti (1973) conducted experiments on the effect of size and quantity of aggregates on the optimum mix proportions, keeping the air content constant, with both the gap-graded, as well as continuous graded aggregates. The results showed that optimum cement content was proportional to the desired 7-day compressive strength of the concrete, whereas it varied inversely with water/cement ratio. Moreover, for a given 7-day compressive strength and maximum size of the coarse aggregate, the optimum cement content of the gap-graded concrete is lower than that of continuously-graded ones.

2.2.3 Requirements of Coarse Aggregates for Use in Concrete

Aggregates to be used in a concrete mix should conform to certain standards. They should be clean, strong, durable particles that are free of absorbed chemicals, clay, or other materials that could retard hydration or bond strength development. Aggregates that are friable or contain soft and porous materials, e.g., shale, should be avoided, since their use may result in surface pop-outs and other defects. Originally, natural material was the aggregate of choice for use in concrete, but natural sources were soon depleted. Now, crushed stone is used for most general purposes. Subjecting aggregates to a crushing operation will reduce their size and improve their shape and texture.

2.3 Effect of Coarse Aggregate on the Physical Properties of Plastic Concrete

2.3.1 Water Demand

Particle shape affects the surface area of an aggregate for a given size, thereby affecting the amount of water to be added to the concrete mixture. Day (1995) concluded that aggregate shape could affect the water content by a margin of 1 to 2%. This is because it affects the fine aggregate percentage required, an increase in which leads to higher water demand. To quantify this effect, a Mix Suitability Factor (MSF) describing the workability of a concrete mix, was used. The MSF typically ranges from 16 (unusable, harsh concrete) to around 30 (flowable, superplasticized concrete). Concrete with a 6-in. slump translates to an MSF of about 28. A concrete with no slump at all would have an MSF of approximately 8. A poorly shaped crushed coarse aggregate can increase the MSF value 1 to 3 units higher than normal. This increases the fine aggregate requirement and thereby increases the water requirement. Similarly, round coarse aggregates reduce MSF values by 1 or 2 units as compared to a standard mix. Large aggregates increase the MSF value while small aggregates decrease the MSF value.

2.4 Effect of Coarse Aggregate on the Mechanical Properties of Hardened Concrete

2.4.1 Compressive Strength

Much of the information in this section has been extracted from Soroka (1980), who demonstrates that to understand the effect of aggregate properties on the compressive strength of concrete, it is important to consider the typical failure mechanism of concrete. Concrete strength typically depends on three factors: the strength of the aggregate; the strength of the cement paste; and the bond strength between the aggregate and the cement paste. The effect of aggregate strength on concrete strength depends significantly on the relative cement paste strength and internal bond strength.

Aggregate Strength

In normal concrete, the strength of the aggregate is higher than the strength of the cement paste, which in turn is higher than the bond strength. Therefore, cracks first form in the interfacial zone between the aggregate and the paste, and subsequently in the cement paste linking aggregate particles. Once these cracks propagate across the entire section of the concrete, the concrete will fail. It can, therefore, be concluded that aggregate strength has little to do with the overall compressive strength of the concrete. This is because failure occurs in the cement paste and in the interfacial zone, before failure in the aggregate can occur.

In lightweight concrete, however, in which aggregate strength is typically lower than cement paste strength, aggregate strength is a much more significant factor. In this case, cracks can start to form in the aggregate before and during the formation of cracks in the cement paste, increasing the likelihood that full length cracking will occur.

Aggregate Modulus of Elasticity

The compressive strength of concrete is affected by the stiffness, or modulus of elasticity, of the aggregate. This effect can be observed by examining the distribution of the applied load among the components of the concrete. Aggregates with a high modulus of elasticity carry a higher percentage of this load, thereby decreasing the stress induced in the cement paste and increasing the strength of the concrete. Coarse aggregate modulus of elasticity can also affect concrete fracture. When the aggregates have a modulus of elasticity greater than or near that of the cement matrix, stress cracks will be more likely to pass through the aggregate, resulting in a brittle fracture (Sengui, et al., 2002).

Aggregate Particle Size and Shape

According to Mather (2004), "two relatively independent properties, sphericity and roundness, control particle shape. Sphericity is the property that measures, depends upon, or varies with the ratio of surface area of the particle to its volume, the relative lengths of its principal axes or those of the circumscribing rectangular prism, the relative settling velocity, and the ratio of the volume of the particle to that of the circumscribing sphere. Roundness is the property the measure of which depends upon the relative sharpness or angularity of the edges and corners of the particle." Now, aggregate particle size and shape can affect concrete compressive strength in a couple of different ways. First, particle size and shape can affect the cement-aggregate bond strength, and, therefore, the strength of the concrete. Equidimensional particles are generally preferred to flat or elongated particles for use as concrete aggregates because they present less surface area per unit volume and generally produce tighter packing when consolidated. A larger contact area increases the potential to resist layering and slippage, thereby increasing the strength of the concrete, but also decreasing its workability. The use of flat and elongated aggregates decreases the contact area between the particles, and should, therefore, be avoided if strength is a priority. Additionally, large aggregates are responsible for creating larger stress concentrations in the cement paste than smaller aggregates would, leading to increased cracking.

Aggregate/Cement Ratio

A high ratio of coarse aggregate to cement can inhibit concrete from consolidating properly, but generally this problem rarely occurs. A high coarse aggregate to cement ratio can also reduce the distance between aggregate particles in the concrete leading to early failure in the cement paste. A large percentage of coarse aggregate, however, can redistribute stress concentrations in the cement paste and lead to higher overall concrete strength, despite any negative effects.

Surface Texture

Mather (2004) defines surface texture as “the property the measure of which depends upon the relative degree to which particle surfaces are polished or dull, smooth or rough, and the type of roughness.” Aggregates with a rough surface texture create a stronger bond with cement. As surface smoothness is increased, contact area is decreased; hence, a smooth, polished particle will have less bonding area with the cement matrix than will a rough particle (Mather, 2004). Research by Mokhtarzadeh and French (2000) showed that concrete produced with crushed limestone outperformed concrete containing partially crushed river gravel, which in turn outperformed concrete containing round river gravel. This supports the idea that aggregates with rough surface textures endow the concrete with higher compressive strength than those with smooth textures. Their research also showed that the effect of coarse aggregate type on compressive strength was dependent on curing conditions and cement composition, among other factors.

2.4.2 Flexural Strength

Factors influencing compressive strength also affect flexural strength. This is especially true when looking at the stiffness of the aggregates, which not only affects the proportion of the load carried by the aggregates, but also the stiffness of the concrete.

In the research conducted by Cetin and Carrasquillo (1998) on the flexural strength development of different coarse aggregates, concrete with ½ in. or 13 mm maximum size dolomitic limestone exhibited the highest flexural strength at later stages of the concrete life. This is because of the presence of smaller size aggregates, which improve the bond between the aggregate and the cement paste at a given aggregate content. Flexural strength, like elastic modulus, is dependent on aggregate properties, such as particle size and surface texture, and on the extent of hydration. In the early stages of concrete strength development, the flexural strength, f_r, was correlated with the corresponding compressive strength, f_c', as follows (Cetin and Carrasquillo, 1998).

$$f_r = 830 f_c'^{0.5}$$ **Equation 2.1**

As the cement starts setting with time, however, flexural strength becomes increasingly influenced by aggregate characteristics and, therefore, cannot be represented by a single equation.

2.4.3 Elastic Modulus

The modulus of elasticity of concrete is considered to be one of the most important mechanical properties due to its impact on the serviceability and structural performance of reinforced cement concrete structures. The stress and strain behaviors within a concrete element under loading greatly depend on the compatibility of the mortar and coarse aggregate with regard to their respective moduli of elasticity. The importance of aggregate modulus of elasticity in this regard is complex and often requires sophisticated engineering analyses (Chen, et al., 2003). Due to its heterogeneous characteristics, the properties of concrete are highly dependent on the properties of its constituent materials. Therefore, the elastic properties of the constituent materials in the concrete and of the interfacial zone between the aggregates greatly influence its elastic properties. Since the aggregate occupies the largest percentage of concrete mix volume, it has more influence on the elastic modulus of the concrete than the mortar does. The modulus of elasticity of the concrete is mainly influenced by the stiffness and concentration of the aggregates, being directly proportional to the modulus of the aggregate, and generally decreasing as the relative distribution of aggregate increases (Soroka, 1980).

Choubane, et al. (1996) state that aggregate type influences the elastic modulus of concrete to a greater extent than it does its strength. Mokhtarzadeh and French (2000) state the opposite, maintaining that "the effect of aggregate type on modulus of elasticity was considerable, but not as pronounced as it was on the compressive strength." The latter found that "no single aggregate type consistently resulted in the highest modulus of elasticity values." Soroka (1980) points out that concrete composed of soft aggregate displays lower modulus of elasticity than that composed of harder aggregate. Similarly, Cetin and Carrasquillo (1998) observed that concrete with harder coarse aggregates produced higher modulus of elasticity, adding that the modulus of elasticity of the concrete is independent of the aggregate size used.

2.4.4 Bond Strength

Many of the same properties that affect the bond strength between the aggregate and the cement paste, also affect the bond strength between the concrete and reinforcing steel. The bond strength of the aggregate depends largely on the shape of the particles and the interlocking of the grains. Usually angular, well-graded particles tend to increase the bond strength. Smooth and rounded aggregates decrease the bond strength. That is why concrete composed of crushed coarse aggregate generally has a higher bond strength than concrete containing natural coarse aggregate. Generally, aggregate properties have a small effect on the bond strength of concrete when compared to the effect that the properties of the cement paste have.

3 MATERIALS AND PROCEDURES

3.1 Introduction

The first part of this chapter enumerates the materials employed in this project, which involved mixing, casting, curing and testing of concrete specimens. A variety of aggregates, whose maximum size ranged between 1 and 2 in., were used. The coarse aggregate gradations employed are designated as No. 57, No. 357, and No. 467, in accordance with prevailing specifications by the Ohio Department of Transportation (ODOT), Item 703.01 *Aggregate-General: Size*. Natural (N) or crushed (C) coarse aggregate was used, thereby resulting in six mixes, which were designated as follows: N057, N467, N357, C057, C467, and C357. Natural sand conforming to ODOT Item 703.02 *Aggregate for Portland Cement Concrete: Fine Aggregate* was used in all mixes. The methods and procedures used in testing these materials, as well as those employed in formulating the mix designs adopted in this study, are then outlined. Topics discussed include all laboratory tests, such as those conducted to determine the aggregate properties, the blending process by which the necessary coarse aggregate gradations were obtained, the formulation of the concrete mix designs, as well as the actual mixing, casting and curing of the specimens prepared. Finally, the testing techniques used to determine the strength parameters for these specimens are presented. During every procedure, the research team endeavored to adhere to the prescriptions of pertinent specifications, primarily those by the American Society for Testing and Materials

(ASTM), by the American Association of State Highway and Transportations Officials (AASHTO), as well as by ODOT.

3.2 Materials Used

Sand, coarse aggregate, Type I-II Portland cement, water (www.cincinnati-oh.gov/water; accessed: 07/22/05) from greater Cincinnati water works, and air entrainer are the materials used in this project. The sand and coarse aggregate were supplied free of charge by *Martin Marietta Materials*, a leading supplier in the Cincinnati area. The sand was natural and came from their sand and gravel facility in Ross, OH. Coarse aggregate was of two kinds, natural river gravel, or crushed limestone. Natural No. 8, and No. 57 aggregates came from their plant in Fairfield, OH, while natural No. 4 aggregates came from their E-Town plant in North Bend, OH. Finally, all crushed coarse aggregates, including No. 8, No. 57, No. 4, and No. 2, were provided from the Phillipsburg quarry in Brookville, OH (Jim R. Martin: personal communication, 10/14/02; www.martinmarietta.com; accessed: 12/02/02).

The Portland cement Type I-II was donated by *CEMEX* from their operation in Fairborn, OH (Steve Reibold: personal communication, 09/11/02; www.cemexusa.com; accessed: 08/14/02). The other admixture was supplied at no cost by *Master Builders, Inc.* (Greg Wirthlin: personal communication, 08/07/02; www. masterbuilders.com; accessed: 07/24/02). This was *MB-AE 90* air entrainer, meeting the requirements of ASTM C 260 – 01, AASHTO M 154 – 05 and U.S. Army Corps of Engineers CRD-C 13 *Standard Specification for Air-Entraining Admixtures for Concrete*, and recommended for obtaining “adequate freeze-thaw durability in a properly proportioned concrete mixture, if standard industry practices are followed." No plasticizers or water reducers were found necessary. The research laboratory facilities on the University of Cincinnati (UC) campus were used, except as noted.

3.3 Aggregate Testing

Most of the laboratory procedures described below were applied to both the fine and coarse aggregate. These included: sieve analysis, apparent specific gravity (ASG) and bulk specific gravity (BSG) at both the oven dry (OD) and saturated surface dry (SSD) conditions (denoted as BSG_{OD} and $BSG_{SSD,}$ respectively), moisture content (MC), and absorption (Abs). In addition, a test was conducted for the dry-rodded unit weight of coarse aggregates alone.

3.3.1 Sieve Analysis of Fine and Coarse Aggregate

This test was conducted in accordance with ASTM C 136 – 96a *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*. Between three hundred and one thousand grams of material were used for each test. The procedure adopted was as follows. For the fine aggregate, No. 4, 8, 16, 30, 50, 100 sieves and a pan are weighed. For the coarse aggregate, the 3/8 in., ½ in., ¾ in., 1 in., 1 ½ in., 2 in., and 2 ½ in. sieves are added. The sieves are stacked with the sieve with the smallest openings (No. 100) at the bottom, so that each successive sieve placed higher up in the sieve column has progressively larger openings, until the last sieve is placed on top. A pan is placed below the No. 100 sieve. The aggregate sample is next poured into the top sieve and is allowed to trickle down through the sieves, or until it is collected in the pan. Next, the sieves are put in a mechanical shaker for 5 min. The sieves are then taken out of the shaker, and each individual sieve, along with any material that might have been retained on that sieve, is weighed a second time. The difference between the weights of the sieve before and after the sample was added is equal to the weight of the sample retained on that sieve. Dividing the weight retained on each individual sieve by the total weight of the sample yields a series of percentages, which can then be used to produce a grain size distribution plot. For the fine aggregate, the fineness modulus (FM) may be also calculated using Equation 3.1, for the sieves listed above.

$$FM = \frac{\sum \%\ retained}{100} \qquad \textbf{Equation 3.1}$$

The fineness modulus is not calculated for coarse aggregate.

3.3.2 Moisture Content of Coarse and Fine Aggregates

ASTM C 566 – 96a *Standard Test Method for Total Moisture Content of Aggregate by Drying* was followed in this case. First, the weight of a moisture tin is recorded, approximately 75% of the tin is filled with the aggregate sample, and the combined weight is recorded again. The moist weight of the sample (W) is then calculated by subtracting the weight of the tin. The tin and sample are next placed in an oven at a temperature of 230 ± 9°F for 24 ± 4 hrs. Subsequently, the sample is taken out of the oven and allowed to cool to room temperature, whereupon it is weighed again.

The dry weight of the sample (D) is calculated by subtracting the weight of the tin. The moisture content (w) is calculated using Equation 3.2.

$$w = \left[\frac{W - D}{D}\right] \times 100$$ **Equation 3.2**

3.3.3 Specific Gravity and Absorption of Coarse Aggregate

ASTM C 127 – 01 *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate* was followed in performing this test. A sufficient quantity of coarse aggregate is immersed in water at room temperature. After 24 ± 4 hours of soaking, the coarse aggregate is removed from the water, and is patted dry with a large absorbent cloth until all visible water is blotted from its surface. The aggregate is now in the saturated surface dry (SSD) condition. The weight of the sample in the SSD condition is noted. The SSD sample is next placed in a container and its weight in water at 73.4 ± 3°F is determined. The sample is then placed in an oven at 230 ± 9°F for a period of 24 ± 4 hrs. The weight of the sample is determined upon removing it from the oven. Three types of bulk specific gravities are determined, viz., bulk specific gravity in the oven dry condition (BSG_{OD}), bulk specific gravity in the SSD condition (BSG_{SSD}), and apparent specific gravity (ASG). The following calculations are employed, in which A equals the weight of the oven dry sample in air, B equals the weight of the SSD sample in air, and C equals the weight of the SSD sample in water.

$$BSG_{OD} = \frac{A}{B - C}$$ **Equation 3.3**

$$BSG_{SSD} = \frac{B}{B - C}$$ **Equation 3.4**

$$ASG = \frac{A}{A - C} \qquad \textbf{Equation 3.5}$$

The moisture content of the sample in the SSD condition is referred to as the absorption and is calculated using the following formula.

$$Abs = \left[\frac{(B - A)}{A}\right] \times 100 \qquad \textbf{Equation 3.6}$$

3.3.4 Specific Gravity and Absorption of Fine Aggregate

ASTM C 128 – 97 *Standard Test Method for Specific Gravity and Absorption of Fine Aggregate* is followed in this case. A 1000-g sample of sand is taken and immersed in water at room temperature for 24 ± 4 hrs. The excess water from the sample is drained and the sand is spread over a flat, nonabsorbent surface and exposed to a gentle current of air in order to dry it. The sample is stirred frequently to ensure that drying occurs evenly. The sample is dried until it reaches the SSD condition, which is assessed using the sand cone test. A small, metal cone is filled with the sample in three layers, with each layer tamped 25 times. The cone is then is lifted away from the sample, and if the sand can stand on its own, surface water still exists. When the sand can no longer stand on its own, it is considered to have reached the SSD condition. Next, 500 g of the SSD sample is placed in a flask, which is then filled with water up to the calibration mark. All air bubbles are removed by gently agitating the flask, and its combined weight is noted. The flask is then emptied, and the sample is dried in an oven at 230 ± 9°F for 24 ± 4 hrs. The sample is weighed again at oven dry conditions. The empty flask is then filled with water to the calibration mark and its weight is noted. In order to determine BSG_{OD}, BSG_{SSD}, ASG, and absorption of the fine aggregate, the following calculations are performed:

$$BSG_{OD} = \frac{A}{(B+S-C)} \qquad \textbf{Equation 3.7}$$

$$BSG_{SSD} = \frac{S}{(B+S-C)} \qquad \textbf{Equation 3.8}$$

$$ASG = \frac{A}{(B+A-C)} \qquad \textbf{Equation 3.9}$$

$$Abs = \left[\frac{(S-A)}{A}\right] \times 100 \qquad \textbf{Equation 3.10}$$

where: A = weight of oven dry sample in air; B = weight of flask filled with water; S = weight of saturated surface dry sample; C = weight of flask filled with sand and water.

3.3.5 Dry-Rodded Unit Weight

ASTM C 29/C 29M – 97 *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate* details the procedure used for this test. First, coarse aggregate is oven dried for 24 ± 4 hrs. Next, a metal container is weighed, filled with water, and weighed again. The difference is the weight of the water. This can then be divided by the unit weight of water to find the volume of water, whence the volume of the container, as well. The container is then filled with the dry coarse aggregate in three equal layers. Each layer is rodded 25 times with a 5/8-in. tamping rod. When all three layers have been placed, the container is weighed. Subtracting the weight of the empty container from this weight gives the weight of the sample, which can then be divided by the container volume to find the density, or unit weight.

3.4 Aggregate Blending

Coarse aggregate was donated by *Martin Marietta Materials* in the following gradations: crushed No. 8, No. 57, No. 4, and No. 2; and natural No. 8, No. 57, and No. 4 gradations. Natural gradation No. 2, and both natural and crushed gradations No. 467 and No. 357 were not available. The latter two gradations were needed for the project, so three sizes were culled out of the No. 4 and No. 2 aggregates. These sizes were: 1 to 1.5 in.; 1.5 to 2 in.; and 2 to 2.5 in. These oversized aggregates were then blended with the No. 8 and No. 57 materials available to produce the gradations needed.

To determine the relative proportions of various aggregates needed for the blends, a spreadsheet was used. The gradations of each possible aggregate were introduced into the spreadsheet, and an iterative process of choosing proportions was performed until the resultant gradation met all requirements. Blends using a minimum amount of larger sized aggregate were preferred due to the increased labor needed to produce these aggregates.

3.5 Mix Design

Each mix of concrete is composed of crushed or natural coarse aggregate, natural sand, ordinary Portland cement, and water. An Ohio Class C mix as given in ODOT Item 499.03 *Concrete-General: Proportioning* was used as a starting point to determine the amounts of these materials needed. This specification that for a mix containing crushed coarse aggregate, 1630 lb of coarse aggregate, 1285 lb of sand, 600 lb of cement, and 300 lb of water should be used to produce a cubic yard of concrete. For a mix with natural aggregate instead, 1735 lb of coarse aggregate and 1160 lb of sand should be used. The amounts of cement and water remain the same. This implies that the weight of water used is always half of the weight of cement used, since the water to cement (w/c) ratio is set at 0.5. It is noted that Class C mix design also uses assumed values for bulk specific gravity for saturated surface dry calculations, as follows: 2.65 for crushed limestone coarse aggregate, 2.62 for natural aggregate or sand, and 3.15 for Portland cement. The volume that each material takes up in the concrete mix may then be determined by dividing the weight by the BSG_{SSD} multiplied by the unit weight of water, as in the following equation:

$$V_{SSD} = \frac{W_{SSD}}{BSG_{SSD} \times \gamma_W}$$ **Equation 3.6**

Tests performed by the research team on the coarse aggregate and sand, as described above, yielded somewhat different values for BSG_{SSD}, viz., 2.64 and 2.62 for coarse aggregate and sand, respectively. Therefore, the specified Class C mix design weight proportions had to be adjusted, while keeping the volumes unchanged. The following equation was used:

$$W_{SSD} = V_{SSD} \times BSG_{SSD} \times \gamma_W$$ **Equation 3.72**

Mix designs were thus created for each of three different cement contents, 400 lb/yd^3, 550 lb/yd^3, and 700 lb/yd^3. With the weight of cement known and the w/c fixed at 0.5, the weight of water could be easily calculated. The volume of both cement and water was then determined from their respective weights by using Equation 3.11 given above. The volume of air was kept at 6% of the total volume of concrete (27 ft^3). Subtracting the volumes of air, water, and cement from the total volume gives the combined volume of both sand and coarse aggregate. This volume was then divided up so that the ratio of sand to coarse aggregate remained the same as in the ODOT Class C mix. From these volumes, the corresponding weights were backcalculated from Equation 3.12, above.

At this point, the coarse aggregate factor (CA), i.e., the ratio of coarse aggregate to total aggregate weight, for the No. 57 mix was also calculated, since it would be needed later in the design of concrete mixes containing No. 467 and No. 357 aggregates. The first step was to convert the weight of coarse aggregate at SSD conditions to an equivalent oven dry (OD) weight. This can be done if the absorption of the coarse aggregate is known. Tests showed that the absorption was 3.797% for crushed aggregate and 2.792% for natural aggregate. This conversion was made by using the following formula, where Abs is given as a percentage.

$$W_{OD} = \frac{W_{SSD}}{1 + Abs/100} \qquad \textbf{Equation 3.8}$$

The next step was to calculate the dry rodded volume (V_{DR}) by dividing the W_{OD} by the dry rodded unit weight (γ_{DR}). The dry rodded unit weight was found to be 91.063 pcf for crushed aggregate, and 105.9153 pcf for natural aggregate. The equation is:

$$V_{DR} = \frac{W_{OD}}{\gamma_{DR}}$$ **Equation 3.9**

Finally, CA could be found by dividing the dry rodded volume by the total volume of the mix, which is 1 yd^3 or 27 ft^3.

Once CA for the No. 57 mix was known, it could be used to find the coarse aggregate factors for both the No. 467 and No. 357 mixes. Table 5.2.6 of the American Concrete Institute (ACI) 211.1-70 *Recommended Practice for Selecting Proportions for Normal Weight Concrete* gives the relationship between maximum size of aggregate and CA, depending on the fineness modulus. Yet, no matter which fineness modulus is used, CA for 1.5 in. maximum size aggregate (No. 467) is always larger than that for 1 in. maximum size aggregate (No. 57) by 0.04. Likewise, CA for 2 in. maximum size aggregate (No. 357) is always 0.07 greater than the corresponding value for 1 in. maximum size aggregate. Thus CA for the No. 467 and No. 357 mixes may be calculated by adding these increments to CA calculated for the No. 57 mix. Subsequently, the weight of coarse aggregate at SSD could be backcalculated using the three previous equations. The three steps were:

a. Multiply CA by the volume of the mix to find V_{DR}

b. Multiply V_{DR} by γ_{DR} to get W_{OD}

c. Multiply W_{OD} by (1 + Abs /100) to find W_{SSD}

The weight of coarse aggregate at SSD and the BSG_{SSD} could then be used to find the SSD volume. The volumes of cement, water, and air were taken to be the same as in the No. 57 mix, and along with the volume of coarse aggregate they were subtracted from the total volume to get the volume of fine aggregate. The final step was to use the BSG_{SSD} for fine aggregate to find the weight of fine aggregate needed.

3.6 Mixing

For each batch, between 7.5 and 8 ft^3 of concrete was mixed in a small 5-ft^3 concrete mixer. The mixer was able to mix properly only 2.5 ft^3 of concrete, so the mixing had to be done in three to five batches. In accordance with ASTM C 192/C 192M – 00 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*, the coarse aggregate and a small amount of the water were added before turning the mixer on. The rest of the materials were then added in the following order: sand, cement, and the remaining water. For every 100 lb of cement used, 1.5 fl. oz of air entrainer was mixed in water, before being added to the mixer. No plasticizer was used. Once all of the ingredients had been added, the mixer was allowed to run for a period of 3 minutes, followed by a 3 minute break, followed by 2 more minutes of mixing.

3.6.1 Variables

Aggregate gradation and type were the two variables in the concrete mixes. All other variables, viz., cement content, water/cement ratio, and amount of air entrainer, were kept constant for all mixes. To maintain the correct coarse aggregate factor, which depends on coarse aggregate gradation, the weights of both fine and coarse aggregate had to be adjusted from mix to mix.

3.6.2 Ingredients

The amounts of each mix ingredient per cubic yard of concrete are given in Table 3.1. No plasticizers or water reducers were used for any of the mixes, as workability was never a problem. The amount of air entrainer suggested by the supplier was 1.5 fl. oz/100 lb of cement, yet it was found that this produced concrete with air content above the allowable values for the ODOT standard mix. Using half the recommended dosage reduced the air content to within the allowable range of 6 ± 2% (ODOT Item 499.03 *Concrete-General: Proportioning*). The lower amount of *MB-AE 90* air entrainer used is still within the manufacturer's recommendations of 1/4 to 4 fl. oz/cwt, or 16 to 260 mL/100 kg of cementitious materials.

3.7 Tests of Physical Properties

3.7.1 Slump

The slump is used both as a measure of workability and as a measure of consistency from batch to batch, but is not as reliable as water/cement ratio or the air content in predicting the properties of a mix. The test was performed by following ASTM C 143/C 143M – 00 *Standard Test Method for Slump of Hydraulic-Cement Concrete*. A 12-in. tall slump cone was filled with concrete in 3 equal layers. Each layer was rodded 25 times by a 5/8-in. tamping rod. After the cone was filled, all excess concrete was stricken from the top. The cone was then lifted straight up and the vertical displacement of the concrete was measured from the original top of the cone. The target slump specified in the ODOT mix design was 6 ± 2 in. Any slump recorded between 4 and 8 in. was, therefore, considered acceptable.

3.7.2 Air Content

The air content of the concrete was measured in accordance with ASTM C 231 – 97 *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. The bowl of an air meter was first wetted and then filled with concrete in three equal layers, each rodded 25 times. The lid of the meter was then clamped on, and water was forced into the bowl through two petcocks until water began coming back out. The petcocks were closed and air was pumped into a cylinder attached to the bowl, up to a predetermined air pressure. The air was then allowed into the bowl and the drop in air pressure could be used to find the air content of the concrete. Upon finishing this test, the concrete used was thrown out as inappropriate for casting. The target air content used in the mix design was 6 ± 2%, so air contents from 4 to 8% were considered acceptable.

3.7.3 Unit Weight

The unit weight of concrete is calculated by weighing the concrete in a bucket of known volume, then dividing that weight by the volume of the bucket. The first step is to determine the weight of water needed to fill the bucket. This can be done by first weighing the empty bucket, then filling it with water, and weighing it again. A glass plate is used to ensure that there are no air bubbles or excess water. The weight of water can found by subtraction. The volume of water, and, therefore, the volume of the bucket, can then be found by dividing the weight of the water by the unit weight of water. The unit weight of water can be determined by measuring water temperature and interpolating from Table 3 in ASTM C 29/C 29M – 97 *Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate*.

The second step is to determine the weight of concrete needed to fill the bucket. This is done by filling the bucket with concrete, weighing it, and then subtracting the weight of the empty bucket.

Finally, the unit weight of the concrete can be found by dividing the weight of the concrete by the volume of the concrete, i.e., by the volume of the bucket. Even though SI units were used for weighing, the final unit weight is expressed in English units to be consistent with other tests performed on the project.

3.8 Casting

In order to cast the required number of specimens, typically 8 to 10 ft^3 of concrete needed to be mixed. Given the small size of the mixer used, it was necessary to mix the material in several smaller batches. Generally, four or five batches had to be used for each mix. Each batch was assigned a number, e.g., the first batch of a particular mix was called batch 1, the second batch 2, and so on.

The concrete was cast into four different kinds of specimens, small cylinders (4 × 8 in.), large cylinders (6 × 12 in.), beams (6 × 6 × 21 in.), and prisms (4 × 4 × $11^1/_2$ in.). The large cylinders were used for testing both compressive strength and modulus of elasticity. The beams were used to measure the modulus of rupture. Small cylinders were only tested for compressive strength as a comparison to large cylinders. The prisms were cast as part of a companion project studying the effects of larger sized coarse aggregate on the environmental properties of concrete. In the case of concrete containing larger sized coarse aggregate, the use of small cylinders violated ASTM C 192/C 192M – 00 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*, which states that the minimum specimen diameter should be no less than 3 times the maximum aggregate size. The results of tests on small cylinders, therefore, may only be used to investigate the effect of aggregate size on the specimen size factor.

The small cylinders and prisms were filled in two layers, while the large cylinders and beams were filled in three layers. Each layer was rodded 25 times by a 5/8-in. tamping rod. After each specimen was cast, it was placed on a level surface and covered with plastic to prevent evaporation.

3.9 Curing

Twenty-four hours after casting, the specimens were demolded, labeled, and placed in a mixture of calcium hydroxide and water at room temperature to cure. The calcium hydroxide helped prevent leeching of the concrete. The specimens remained in the curing room until they were about to be tested.

3.10 Baseline Concrete Mix Tests

To allow the investigators to assess the properties of concrete containing larger sized coarse aggregate, it was essential to compare these to those from a standard, or baseline, mix, such as the Class C mix, described in ODOT Item 499.03 *Concrete-General: Proportioning* of the ODOT 2002 *Construction and Material Specifications*. It is noted that this mix design does not specify which type of aggregate should be used, even though it might be anticipated that this choice will affect strength. For this stage of the project, No. 57 natural aggregate was selected, expecting this to produce a low strength, thereby amplifying the contributions of larger sized materials. Mix designs were developed for three cement contents, viz., 400, 550 and 700 lb/yd^3, respectively, and compressive strength tests were performed on small cylinders (4 × 8 in.) at 28 days.

3.11 Tests of Mechanical Properties

3.11.1 Modulus of Elasticity

The test for the modulus of elasticity, E, was performed on large cylinders. For each cylinder, a strain collar was first attached to the outside of the specimen. Great care was taken so that the collar was placed centrally around the concrete cylinder. Once the strain collar was attached and the ends of the cylinder were capped, the specimen was placed under the center of a 400-kip *Tinius Olsen* testing machine. Each cylinder was loaded to approximately 60% of the expected failure load. This was done in order to ensure that there were enough data to calculate E accurately, yet with no danger of damaging the strain collar. While the cylinder was being loaded, strain readings were taken at 5-kip increments of load. Additionally, digital photographs were taken continually and were later reviewed, so as to verify that the recorded strains were accurate. After reaching about 60% of the expected failure load, each specimen was unloaded and the strain collar was carefully removed. The specimens could then be subjected to compressive strength testing. The modulus of elasticity was calculated by plotting the stress vs. strain curve for the specimen and calculating the slope between two points, one at a strain of 0.000050 in./in. and the other at 40% of the maximum stress, which was determined as described below.

3.11.2 Compressive Strength

Compressive strength testing was performed in accordance with ASTM C 39/C 39M – 01 *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens* and with AASHTO T 22-03 *Compressive Strength of Cylindrical Concrete Specimens*, on both large and small cylinders. Before testing began, the diameter at the top and the bottom of each cylinder, as well as the height of the cylinder on two different sides, were measured and recorded, in order to establish the average diameter and height. Next the cylinder was placed in the center of the *Tinius Olsen* loading table and was loaded to failure. The loading rate for the large cylinders was kept between 35 and 85 kips/min. while the loading rate for the small cylinders was kept between 15 and 40 kips/min. The compressive strength is calculated by dividing the maximum load by the average cross sectional area of the cylinder, which is computed using the average diameter. When the test was complete, the failure pattern of the cylinder was sketched and visual observations were documented.

Small cylinders were only cast when there was sufficient excess material after all other specimens had been prepared. Consequently, typically only one or two small cylinders were available on each testing date. Moreover, small cylinders did not meet ASTM specifications as noted earlier. Therefore, the results of such tests are unsuitable for compressive strength analysis, but may help investigate the specimen size effect.

3.11.3 Modulus of Rupture

ASTM C 78 – 02 *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading* was used in conducting the test for the modulus of rupture, M_R, on the beams cast. After the average length, width, and depth of the beam were determined, each specimen was centrally placed on a pair of supports spaced 18 in. apart. Two supports were also placed on the top of the beam at a distance of 3 in. on either side of the center of the beam. The load was applied and the top supports transferred the load to the beam until the beam failed. The loading rate was kept between 1,500 and 2,100 lb/min. After the beam failed the distance between the failure plane and the center of the beam was recorded, and all important observations were noted. The Modulus of Rupture could then be calculated by the following Equation 3.15, in which where P is the load, l is the 18-in. span, b is the 6-in. breadth of the beam, and h is its 6-in. depth.

$$M_R = \frac{Pl}{bh^2}$$ **Equation 3.10**

Table 3.1: Ingredient Amounts by Mix per yd^3

	Mix					
Ingredient	**N057**	**N467**	**N357**	**C057**	**C467**	**C357**
Cement (lb)	400	400	400	400	400	400
Coarse Aggregate (lb)	1713	1835	1935	1846	2253	2353
Fine Aggregate (lb)	1321	1180	1065	1461	1102	994
Water (lb)	200	200	200	200	200	200
Air Entrainer (mL)	88.71	88.71	88.71	88.71	88.71	88.71

4 TEST RESULTS

4.1 Introduction

This chapter contains tabulations of all data recorded during the tests conducted, a discussion of some additional observations made, as well as outlines of the subsequent calculations needed to translate test results into the mechanical properties of the concrete. The mean values obtained for each concrete mix on each testing date are also presented. Each such mix is assigned a four-character alphanumeric code identifying the type of the coarse aggregate used (natural, N, or crushed, C), and the coarse aggregate gradation number (No. 57, No. 467, or No. 357). This information will constitute the database to be used in the next chapter for the purpose of comparing the different mixes.

4.2 Aggregates

Results from aggregate testing are recorded in Table 4.1, while Table 4.2 lists the data from sieve analysis. The properties determined are as follows: apparent specific gravity (ASG); bulk specific gravity at oven dry (BSG_{OD}) and saturated surface dry (BSG_{SSD}) conditions; absorption (Abs); moisture content (w); fineness modulus (FM); and dry unit weight (γ_d). Each gradation is compared to the corresponding ODOT specifications (ODOT Item 703.01 *Aggregate-General: Size* and ODOT Item 703.02 *Aggregate for Portland Cement Concrete: Fine Aggregate*). Parameters given for the oversized aggregate gradations (No. 467 and No. 357) were not determined directly, but they are weighted averages of the values found for the component gradations, depending on the blend percentages.

4.3 Concrete Mixes

The results of the initial compressive strength tests used to establish the baseline concrete mix are presented in Table 4.3. Mean values and coefficients of variation (COV) for each cement content considered are also given. Table 4.4 lists the number of specimens cast per batch for each mix designed after reviewing these original test results.

4.4 Physical Properties of Plastic Concrete

The physical properties of each mix, viz., slump, air content, and unit weight, were found immediately after mixing, using the procedures described in the previous chapter. Typically, the physical properties did not vary much from batch to batch within the same mix. Because the variability was so low, it was often not necessary to perform these tests for each and every batch. Moreover, the material used for the air content test could not be cast into specimens, so reducing the number of such tests helped conserve concrete material. The physical properties recorded for each batch, as well as mean values for each mix, are given in Table 4.5.

It was observed that the air content of the concrete depended to some extent on the time it took to mix, since a longer mixing time allowed the air *MB-AE 90* entrainer to produce more air bubbles. The air content was higher in early mixes, but as the mixing process was honed and expedited, its values were reduced. Although the air content was kept within the allowable range of 6 ± 2% (ODOT Item 499.03 *Concrete-General: Proportioning*), even small variations in its value were reflected in the subsequent concrete specimen test results.

4.5 Mechanical Properties of Hardened Concrete

4.5.1 Compressive Strength

Compressive strength ($f_c^{'}$) results for large cylinders are given in Table 4.6 and Table 4.7, while those for small specimens are presented in Table 4.8. The maximum sustained load sustained prior to failure (P) is also tabulated. In most cases, a combination of conical and planar shear failure modes was observed. Closer inspection of failed specimens revealed that concrete can fail in one of two ways, i.e., either by aggregate pullout from the paste, or by shearing right through the aggregate itself. Smaller aggregates tended to shear more often, while larger aggregates were more prone to pullout. It was also noted that as curing time increased, even small aggregates would resist pullout and tend to shear. Specimens tested at early ages tended to fail in a slow and ductile manner, while specimens allowed to cure longer became more brittle, sometimes even producing explosive failures.

4.5.2 Modulus of Elasticity

In accordance with ASTM C 469 - 94$^{\varepsilon 1}$ *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*, the modulus of elasticity,

(E) is calculated using a stress-strain (σ-ε) curve, such as the one shown in Figure 4.1 for a N057 cylinder from Batch 2 at 90 days, in the following manner. First, for a fixed strain value, ε_1, of 50 $\mu\varepsilon$, the stress is read off the curve, and is designated as σ_1. A value of 231 psi is found for the specimen considered here. Moreover, 40% of the eventual compressive strength of the cylinder is calculated to the nearest 10 psi, and designated as σ_2. For this example, the cylinder failed at 3715 psi, so σ_2 is set to 1440 psi. Finally, the strain at σ_2 is read off the stress-strain curve to the nearest 1 $\mu\varepsilon$ and designated as ε_2. In this case, ε_2 is 331 $\mu\varepsilon$. The modulus of elasticity is then calculated by the following equation.

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$ **Equation 4.1**

In the specimen represented in Figure 4.1,

$$E = \frac{(1440 - 231)}{331 \times 10^{-6} - 50 \times 10^{-6}} = 4.30 \times 10^{6}\,\text{psi}$$ **Equation 4.2**

The results of these calculations can be seen in Table 4.10 and Table 4.11.

Since the modulus of elasticity test is a nondestructive test, it was difficult to notice any particular trends while performing the tests. Deciding how much load to place on the cylinders was often difficult, as the compressive strength of the cylinder cannot be predicted reliably prior to testing. Loading the cylinders too much risks damaging the attached strain collar, while not loading it enough makes it quite difficult to evaluate the modulus of elasticity. In some cases, it was found retrospectively that the specimens were, in fact, not loaded up to 40% of their eventual compressive strength. In such cases, σ_2 denoted the maximum stress applied to the cylinder during the elastic modulus test, and ε_2 the corresponding strain.

4.5.3 Modulus of Rupture

Test results and calculations for the modulus of rupture (M_R) can be found in Table 4.12 and Table 4.13. The dimensions of the beams tested are recorded (b: breadth and h: depth), along with the maximum load sustained (P). All beams failed by the formation of a vertical failure plane near the center of the beam. Each failure plane originated between the points of application of the two vertical loads. Generally, all specimens failed in a ductile manner, as the cracks originated at the bottom of the beam, and slowly propagated upward. Examining the specimens after failure revealed that the aggregates had failed in a manner similar to that observed during compressive strength testing. Larger aggregates were more prone to pullout than smaller aggregates, and a longer curing time led to fewer pullouts.

Table 4.1: Average Aggregate Properties

Aggregate	Number of Test Replicates	ASG	BSG_{SSD}	BSG_{OD}	Abs (%)	γ_d (pcf)	w (%)
Natural Sand	3	2.72	2.62	2.57	3.21	-	3.00
Natural No. 8	4	2.77	2.61	2.52	3.70	108.21	1.86
Natural No. 57	4	2.36	2.27	2.21	2.79	105.92	2.23
Natural 1 in.	1	2.75	2.67	2.63	1.66	101.24	0.11
Natural 1.5 in.	1	2.74	2.65	2.60	1.97	99.58	0.04
Natural 2 in.	1	2.73	2.63	2.57	2.17	97.53	0.11
Natural No. 467	-	2.57	2.47	2.40	2.71	105.09	1.54
Natural No. 357	-	2.49	2.41	2.35	2.48	103.93	1.50
Crushed No. 8	2	2.80	2.59	2.47	4.78	94.00	2.32
Crushed No. 57	3	2.82	2.64	2.55	3.80	91.06	1.77
Crushed 1 in.	1	2.65	2.55	2.49	2.41	93.41	0.03
Crushed 1.5 in.	1	2.63	2.52	2.45	2.81	91.02	0.03
Crushed 2 in.	1	2.68	2.59	2.55	1.91	92.92	0.03
Crushed No. 467	-	2.77	2.60	2.51	3.66	92.33	1.42
Crushed No. 357	-	2.76	2.61	2.52	3.37	91.48	1.18

Table 4.2: Sieve Analysis (% passing)

Sieve Size (in.) or Number	Natural. No. 57	Crushed No. 57	ODOT 703.01 No. 57	Natural No. 8	Crushed No. 8	ODOT 703.01 No. 8	Sand	ODOT 703.02 Sand
2 1/2	100	100		100	100			
2	100	100		100	100			
1 1/2	100	100	**100**	100	100			
1	100	100	**95-100**	100	100			
3/4	96.5	89.05		100	100			
1/2	54.8	38.1	**25-60**	100	100	**100**		
3/8	18.4	7.85		94	86	**85-100**	100	**100**
No. 4	1.4	0.55	**0-10**	20	9	**10-30**	100	**95-100**
No. 8	0.1	0.35	**0-5**	1	2	**0-10**	94	**70-100**
No. 16	0.1	0.35		0	1	**0-5**	72	**38-80**
No. 30							43	**18-60**
No. 50							14	**5-30**
No. 100							2	**1-10**
Pan	0	0		0	0		0	**0-5**

Sieve Size (in) or Number	Natural No. 467	Crushed No. 467	ODOT 703.01 No. 467	Natural No. 357	Crushed No. 357	ODOT 703.01 No. 357
2 1/2	100	100		100	100	**100**
2	100	100	**100**	96	96	**95-100**
1 1/2	96	96	**95-100**	81	81	
1	72	72		66	66	**35-70**
3/4	70.32	66.74	**35-70**	63.69	58.77	
1/2	50.30	42.29		36.17	25.15	**10-30**
3/8	31.39	24.41	**10-30**	12.14	5.18	
No. 4	5.5	2.42	**0-5**	0.9	0.36	**0-5**
No. 8	0.29	0.65		0.07	0.23	
No. 16	0.05	0.41		0.07	0.23	
No. 30						
No. 50						
No. 100						
Pan	0	0		0	0	

Table 4.3: Compressive Strength, $f_c^{'}$ (psi) for Selecting Baseline Concrete Mix

	Quantity of Cement (lb per yd^3)		
Compressive Strength, $f_c^{'}$ (psi)	**400**	**550**	**700**
	3218.51	3346.15	3559.26
	3556.64	3098.59	3219.39
	3431.94	3247.72	3574.14
	3270.71	3194.96	3632.39
	3356.74	3220.18	3538.57
	3413.00		
Mean $f_c^{'}$	3374.59	3221.52	3504.75
COV (%)	3.59	2.78	4.66

Table 4.4: Number of Specimens Cast per Batch

Batch No.	**1**	**2**	**3**	**4**	**5**	**6***	**Total**
Mix N057							
Volume (ft^3)	2.5	2.5	2.5	1	-	1.5	10
Small Cylinders	1	2	2	1	-	2	8
Large Cylinders	3	4	3	2	-	1	13
Large Beams	3	3	3	1	-	2	12
Prisms	0	1	1	0	-	0	2
Mix N467							
Volume (ft^3)	2	2	2	2	2	1.5	11.5
Small Cylinders	2	0	1	0	0	0	3
Large Cylinders	2	1	3	1	5	3	15
Large Beams	2	3	2	3	2	1	13
Prisms	0	0	0	0	0	0	0
Mix N357							
Volume (ft^3)	2	2	2	2	2	1.5	11.5
Small Cylinders	0	0	1	1	3	0	5
Large Cylinders	3	2	3	2	2	3	15
Large Beams	2	3	2	3	2	1	13
Prisms	0	0	0	0	0	0	0
Mix C057							
Volume (ft^3)	2	2	2	2.5	-	1	9.5
Small Cylinders	3	0	0	6	-	3	12
Large Cylinders	3	4	1	4	-	3	15
Large Beams	2	2	3	3	-	0	10
Prisms	0	0	2	0	-	0	2
Mix C467							
Volume (ft^3)	2	2	2	2	2	1.5	11.5
Small Cylinders	0	1	0	3	4	0	8
Large Cylinders	4	4	2	1	3	2	16
Large Beams	2	2	3	3	2	2	14
Prisms	0	0	0	0	0	0	0
Mix C357							
Volume (ft^3)	2	2	2	2	1.67	1.5	11.17
Small Cylinders	2	1	1	0	4	0	8
Large Cylinders	3	1	4	3	1	3	15
Large Beams	2	3	2	3	2	1	13
Prisms	0	0	0	0	0	0	0

* Batch 6 was cast on Oct. 3rd 2004, whereas the other batches were cast on various dates in 2003.

Table 4.5: Physical Properties of Plastic Concrete

Batch No.	1	2	3	4	5	6*	Mean	COV (%)
Mix N057								
Slump (in.)	8	7.75	6.75	7	-	7	7.38	8.07
% Air	8	-	6.5	-	-	-	7.25	14.63
Unit Weight (pcf)	142.3	-	144.6	-	-	-	143.4	1.14
Mix N467								
Slump (in.)	7.5	7.5	7.5	7.5	-	8	7.50	0.00
% Air	6	6	5.6	6	-	6	5.90	3.39
Unit Weight (pcf)	148.0	146.6	146.2	144.6	-	147.8	146.3	0.95
Mix N357								
Slump (in.)	7	-	7.5	-	7	10	7.17	4.03
% Air	4	-	4	-	4	-	4.00	0.00
Unit Weight (pcf)	149.6	-	149.2	-	151.4	-	150.1	0.76
Mix C057								
Slump (in.)	6.75	6.5	5.5	7	-	6	6.44	10.21
% Air	7.4	9	6.6	-	-	7.5	7.67	15.94
Unit Weight (pcf)	143.7	141.2	143.2	144.6	-	145.8	143.2	1.00
Mix C467								
Slump (in.)	6	6	6.5	6	5.75	7.5	6.05	4.53
% Air	8.5	8	7.2	7.5	7.6	-	7.76	6.48
Unit Weight (pcf)	140.7	143.7	144.4	143.0	143.0	-	143.0	0.98
Mix C357								
Slump (in.)	6	5.5	6	6.5	-	7.5	6.00	6.80
% Air	6.4	5.9	5.5	-	-	6	5.93	7.60
Unit Weight (pcf)	144.8	145.8	146.2	-	-	147.2	145.6	0.51

* Batch 6 cast on Oct. 3rd, 2004, whereas the other batches were cast on various dates in 2003.

Table 4.6: Compressive Strength, f_c' (psi) for Natural Aggregate Large Cylinders

Mix N057	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**	
Batch	**1**	**2**	**2**	**3**	**2**	**4**				**1**	**3**	**4**	**2**	**3**
P (lb)	42716	48569	66945	61982	90634	95713				86277	102800	102021	100269	106581
Mean Diameter (in.)	6	$5\,{}^{31}/_{32}$	$6\,{}^{1}/_{32}$	6	6	$6\,{}^{1}/_{32}$				6	6	6	$5\,{}^{15}/_{16}$	$5\,{}^{31}/_{32}$
f_c' (psi)	1511	1736	2343	2192	3206	3350				3051	3636	3608	3621	3809
Mean f_c' (psi)	1623		2268		3278					3432			3715	
Mix N467	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**	
Batch	**3**	**5**	**1**	**5**	**2**	**3**	**6**	**6**	**6**	**4**	**5**		**1**	**3**
P (lb)	58925	53360	68470	73711	92127	90955	96755	89578	91979	96870	96106		95576	110452
Mean Diameter (in.)	6	6	$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{32}$	6	$5\,{}^{31}/_{32}$	$6\,{}^{1}/_{16}$	$5\,{}^{31}/_{32}$	$6\,{}^{1}/_{32}$	6	$6\,{}^{1}/_{32}$		$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{16}$
f_c' (psi)	2084	1887	2372	2580	3258	3251	3352	3201	3219	3426	3364		3311	3826
Mean f_c' (psi)	1986		2476		3256					3395			3569	
Mix N357	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**	
Batch	**1**	**3**	**2**	**5**	**3**	**4**	**6**	**6**		**3**	**4**		**1**	**1**
P (lb)	45617	58244	62223	82629	101221	96686	96387	87412		112905	103841		84226	126760
Mean Diameter (in.)	6	6	$6\,{}^{1}/_{32}$	$6\,{}^{1}/_{32}$	$5\,{}^{31}/_{32}$	6	$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{16}$		6	6		$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{32}$
f_c' (psi)	1613	2060	2178	2892	3618	3420	3339	3028		3993	3673		2918	4437
Mean f_c' (psi)	1837		2535		3351					3833			3677	

Table 4.7: Compressive Strength, f_c' (psi) for Crushed Aggregate Large Cylinders

Mix C057	**3 days**		**7 days**		**28 days**					**56 days**		**90 days**		
Batch	**2**	**4**	**1**	**2**	**2**	**4**	**6**	**6**		**1**	**4**	**3**	**4**	
P (lb)	34187	42013	61423	51496	76393	83216	93846	94715		83771	99804	113136	97234	
Mean Diameter (in.)	$6\ ^{1}/_{32}$	6	$5\ ^{31}/_{32}$	$5\ ^{31}/_{32}$	$5\ ^{31}/_{32}$	6	$6\ ^{1}/_{16}$	$6\ ^{1}/_{32}$		$6\ ^{1}/_{16}$	$6\ ^{1}/_{16}$	6	$6\ ^{1}/_{32}$	
f_c' (psi)	1197	1486	2195	1840	2730	2943	3251	3315		2902	3457	4001	3403	
Mean f_c' (psi)	1341		2018		3060					3180		3702		
Mix C467	**3 days**		**7 days**		**28 days**					**56 days**		**90 days**		
Batch	**1**	**2**	**2**	**5**	**1**	**3**	**6**			**2**	**4**	**1**	**3**	**5**
P (lb)	29408	39973	62187	68329	67443	73051	72954			94077	99047	89968	94992	97310
Mean Diameter (in.)	6	$6\ ^{1}/_{32}$	6	$6\ ^{1}/_{32}$	$6\ ^{1}/_{16}$	6	$6\ ^{1}/_{32}$			$6\ ^{1}/_{32}$	6	$6\ ^{1}/_{16}$	$6\ ^{1}/_{32}$	$6\ ^{1}/_{32}$
f_c' (psi)	1040	1399	2199	2392	2336	2584	2554			3293	3503	3117	3325	3406
Mean f_c' (psi)	1220		2296		2491					3398		3283		
Mix C357	**3 days**		**7 days**		**28 days**					**56 days**		**90 days**		
Batch	**1**	**3**	**3**	**4**	**1**	**3**	**6**	**6**	**6**	**4**	**5**	**1**	**2**	
P (lb)	36530	50090	62782	71242	78238	84388	76346	81836	59725	90919	88645	85930	107839	
Mean Diameter (in.)	6	6	$6\ ^{1}/_{32}$	$6\ ^{1}/_{32}$	$6\ ^{1}/_{32}$	$6\ ^{1}/_{32}$	$6\ ^{1}/_{16}$	$6\ ^{1}/_{32}$	$6\ ^{1}/_{32}$	6	6	$6\ ^{1}/_{32}$	6	
f_c' (psi)	1292	1772	2198	2494	2739	2954	2645	2864	2091	3216	3135	3008	3814	
Mean f_c' (psi)	1532		2346		2658					3175		3411		

Table 4.8: Compressive Strength, f_c' (psi) for Natural Aggregate Small Cylinders

Mix N057	**3 days**	**7 days**	**28 days**	**56 days**	**90 days**		
Batch	**1**	**2**	**3**	**4**	**3**	**4**	**6**
P (lb)	20302	36267	50044	31979	52311	50195	51669
Mean Diameter (in.)	$3\ ^{31}/_{32}$	$4\ ^{1}/_{32}$	4	4	$3\ ^{31}/_{32}$	$3\ ^{31}/_{32}$	$3\ ^{31}/_{32}$
f_c' (psi)	1641	2841	3982	2545	4229	4058	4177
Mean f_c' (psi)	1641	2841	3982	2545	4154		
Mix N467	**3 days**	**7 days**	**28 days**	**56 days**	**90 days**		
Batch				**3**	**3**		
P (lb)				52095	51792		
Mean Diameter (in.)				4	4		
f_c' (psi)				4146	4121		
Mean f_c' (psi)				4146	4121		
Mix N357	**3 days**	**7 days**	**28 days**	**56 days**	**90 days**		
Batch		**5**	**3**	**4**	**5**		
P (lb)		35737	52761	57628	57945		
Mean Diameter (in.)		4	$4\ ^{1}/_{16}$	4	$4\ ^{1}/_{32}$		
f_c' (psi)		2844	4070	4586	4540		
Mean f_c' (psi)		2844	4070	4586	4540		

Table 4.9: Compressive Strength, f_c' (psi) for Crushed Aggregate Small Cylinders

Mix C057	**3 days**	**7 days**	**28 days**		**56 days**		**90 days**				
Batch	**4**	**4**	**4**		**4**		**1**	**1**	**4**	**6**	**6**
P (lb)	24165	34274	40308		50512		49734	51222	47254	52938	60053
Mean Diameter (in.)	4	$4\ ^{1}/_{32}$	4		4		4	$4\ ^{1}/_{32}$	$4\ ^{1}/_{32}$	$3\ ^{31}/_{32}$	$3\ ^{31}/_{32}$
f_c' (psi)	1923	2685	3208		4020		3958	4013	3702	4279	4854
Mean f_c' (psi)	1923	2685	3208		4020		4161				
Mix C467	**3 days**	**7 days**	**28 days**		**56 days**		**90 days**				
Batch	**5**	**4**	**4**	**5**	**2**		**4**				
P (lb)	24269	32976	45473	37366	48324		53782				
Mean Diameter (in.)	4	4	4	$4\ ^{1}/_{32}$	$4\ ^{1}/_{32}$		$4\ ^{1}/_{32}$				
f_c' (psi)	1931	2624	3619	2928	3786		4214				
Mean f_c' (psi)	1931	2624	3273		3786		4214				
Mix C357	**3 days**	**7 days**	**28 days**		**56 days**		**90 days**				
Batch	**5**	**5**	**5**		**1**	**2**	**1**	**3**			
P (lb)	24277	30957	36581		54693	54308	53017	57930			
Mean Diameter (in.)	$4\ ^{1}/_{32}$	4	4		4	4	4	$4\ ^{1}/_{32}$			
f_c' (psi)	1902	2463	2911		4352	4322	4219	4539			
Mean f_c' (psi)	1902	2463	2911		4337		4379				

Table 4.10: Modulus of Elasticity, E (10^6 psi) for Natural Aggregate Large Cylinders

Mix N057	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**		
Batch	**1**	**2**	**2**	**3**	**2**	**4**				**1**	**3**	**4**	**2**	**3**	
σ_2 (psi)	600	690	700	870	1280	1340				1220	1450	1440	1440	1520	
σ_1 (psi)	177	180	190	193	202	220				244	251	255	231	247	
ε_2 ($10^{-4}\varepsilon$)	1.99	2.25	2.03	2.56	3.45	3.43				2.92	3.32	3.27	3.31	3.52	
ε_1 ($10^{-4}\varepsilon$)	0.5	0.5	0.5	0.5	0.5	0.5				0.5	0.5	0.5	0.5	0.5	
E	2.84	2.91	3.33	3.29	3.65	3.82				4.03	4.25	4.28	4.30	4.22	
Mean E	2.88		3.31		3.74					4.19			4.26		
Mix N467	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**		
Batch	**3**	**5**	**1**	**5**	**2**	**3**	**6**	**6**	**6**	**4**	**5**		**1**	**3**	
σ_2 (psi)	749	750	940	1030	1300	1300	1340	1280	1280	1370	1340		1320	1530	
σ_1 (psi)	195	202	183	193	231	260	249	218	216	252	255		248	230	
ε_2 ($10^{-4}\varepsilon$)	2.13	2.08	2.88	2.89	3.63	3.13	3.42	3.38	3.57	3.21	3.15		2.95	3.47	
ε_1 ($10^{-4}\varepsilon$)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		0.5	0.5	
E	3.40	3.47	3.18	3.50	3.42	3.95	3.74	3.69	3.47	4.13	4.09		4.38	4.38	
Mean E	3.43		3.34		3.65					4.11			4.38		
Mix N357	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**		
Batch	**1**	**3**	**2**	**5**	**3**	**4**	**6**	**6**		**3**	**4**		**1**	**1**	
σ_2 (psi)	640	820	870	1150	1440	1360	1330	1210		1590	1460		1160	1770	
σ_1 (psi)	195	202	185	193	219	248	253	185		246	253		230	236	
ε_2 ($10^{-4}\varepsilon$)	1.80	2.28	2.64	3.18	3.90	3.18	3.09	3.30		3.63	3.37		2.62	4.21	
ε_1 ($10^{-4}\varepsilon$)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		0.5	0.5		0.5	0.5	
E	3.42	3.47	3.20	3.57	3.59	4.15	4.16	3.66		4.29	4.21		4.39	4.13	
Mean E	3.45		3.39		3.89					4.25			4.26		

Table 4.11: Modulus of Elasticity, E (10^6 psi) for Crushed Aggregate Large Cylinders

Mix C057	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**		
Batch	**2**	**4**	**1**	**2**	**2**	**4**	**6**	**6**		**1**	**4**		**3**	**4**	
σ_2 (psi)	470	590	870	730	1090	1170	1300	1320		1160	1380		1490	1360	
σ_1 (psi)	163	178	193	193	225	225	231	280		200	254		263	249	
ε_2 ($10^{-4}\varepsilon$)	1.61	1.89	2.50	2.13	2.75	3.05	3.35	3.06		3.19	3.17		3.25	2.93	
ε_1 ($10^{-4}\varepsilon$)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		0.5	0.5		0.5	0.5	
E	2.77	2.96	3.39	3.29	3.84	3.71	3.75	4.06		3.57	4.22		4.46	4.57	
Mean E	2.86		3.34		3.84					3.89			4.52		
Mix C467	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**		
Batch	1	2	2	5	1	3	6			2	4		1	3	5
σ_2 (psi)	410	550	870	950	930	1030	1020			1310	1400		1240	1320	1360
σ_1 (psi)	147	180	196	181	201	218	225			265	240		242	263	225
ε_2 ($10^{-4}\varepsilon$)	1.45	1.75	2.51	2.56	2.48	2.64	2.73			3.05	3.38		3.08	3.31	3.43
ε_1 ($10^{-4}\varepsilon$)	0.5	0.5	0.5	0.5	0.5	0.5	0.5			0.5	0.5		0.5	0.5	0.5
E	2.77	2.96	3.35	3.73	3.68	3.79	3.57			4.10	4.03		3.87	3.76	3.87
Mean E	2.86		3.54		3.68					4.06			3.83		
Mix C357	**3 days**		**7 days**		**28 days**					**56 days**			**90 days**		
Batch	1	3	3	4	1	3	6	6	6	4	5		1	2	
σ_2 (psi)	510	700	870	990	1090	1180	1050	1140	830	1280	1250		1200	1520	
σ_1 (psi)	188	180	201	189	253	222	235	227	196	255	231		292	308	
ε_2 ($10^{-4}\varepsilon$)	1.51	2.15	2.58	2.88	2.60	2.67	2.62	3.07	2.18	2.91	3.19		2.21	2.90	
ε_1 ($10^{-4}\varepsilon$)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		0.5	0.5	
E	3.19	3.15	3.22	3.37	3.99	4.41	3.84	3.55	3.77	4.25	3.79		5.31	5.05	
Mean E	3.17		3.29		3.91					4.02			5.18		

Table 4.12: Modulus of Rupture, M_R (psi) for Natural Aggregate

Mix N057	**3 days**		**7 days**		**28 days**		**56 days**		**90 days**	
Batch	**1**	**2**	**2**	**3**	**1**	**3**	**2**	**3**	**1**	**4**
P (lb)	4693.8	4892.9	5497.2	4918.2	5924.3	5689.0	6203.8	6896.9	7365.5	7020.8
Mean b (in.)	$6\ ^{1}/_{16}$	$6\ ^{3}/_{32}$	6	6	6	$5\ ^{15}/_{16}$	$6\ ^{1}/_{16}$	$6\ ^{3}/_{32}$	$5\ ^{31}/_{32}$	$5\ ^{7}/_{8}$
Mean h (in.)	6	$6\ ^{1}/_{32}$	$6\ ^{1}/_{32}$	$5\ ^{31}/_{32}$	6	$5\ ^{31}/_{32}$	6	6	$5\ ^{31}/_{32}$	$5\ ^{15}/_{16}$
M_R	387	397	453	414	494	484	512	566	623	610
Mean M_R	392		434		489		539		617	
Mix N467	**3 days**		**7 days**		**28 days**		**56 days**		**90 days**	
Batch	**2**	**4**	**3**	**5**	**1**	**2**	**3**	**4**	**2**	**5**
P (lb)	5519.8	5480.0	6717.7	6468.9	6993.7	7222.6	7861.3	7770.9	8488.3	8127.3
Mean b (in.)	$6\ ^{3}/_{32}$	6	$6\ ^{1}/_{16}$	$6\ ^{3}/_{32}$	$6\ ^{1}/_{16}$	$5\ ^{31}/_{32}$	$6\ ^{1}/_{32}$	6	$5\ ^{31}/_{32}$	$5\ ^{31}/_{32}$
Mean h (in.)	6	$6\ ^{1}/_{32}$	6	$6\ ^{1}/_{32}$	6	$6\ ^{1}/_{16}$	$6\ ^{1}/_{16}$	$6\ ^{1}/_{16}$	6	$6\ ^{1}/_{32}$
M_R	453	452	554	525	577	593	638	634	711	674
Mean M_R	452		540		585		636		692	
Mix N357	**3 days**		**7 days**		**28 days**		**56 days**		**90 days**	
Batch	**1**	**2**	**4**	**3**	**2**	**4**	**1**	**2**	**3**	**4**
P (lb)	5194.1	5261.1	7184.6	6320.6	6695.1	6774.7	7190.9	6908.6	8184.3	9304.4
Mean b (in.)	$6\ ^{1}/_{32}$	$5\ ^{31}/_{32}$	6	$6\ ^{1}/_{16}$	6	6	6	6	$6\ ^{1}/_{16}$	$6\ ^{1}/_{8}$
Mean h (in.)	$6\ ^{1}/_{32}$	6	6	$6\ ^{1}/_{16}$	$6\ ^{1}/_{32}$	6	6	6	6	6
M_R	426	441	599	511	552	565	599	576	675	760
Mean M_R	433		555		558		587		717	

Table 4.13: Modulus of Rupture, M_R (psi) for Crushed Aggregate

Mix C057	**3 days**		**7 days**		**28 days**		**56 days**		**90 days**	
Batch	**2**	**4**	**2**	**3**	**1**	**4**	**3**	**4**	**1**	**3**
P (lb)	4282.1	4815.9	5214.9	5667.3	6915.0	6242.7	7414.4	7361.0	7124.9	7713.9
Mean b (in.)	$5\,{}^{31}/_{32}$	$6\,{}^{1}/_{16}$	6	$5\,{}^{31}/_{32}$	$5\,{}^{15}/_{16}$	$5\,{}^{31}/_{32}$	$6\,{}^{1}/_{32}$	$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{32}$	$6\,{}^{1}/_{32}$
Mean h (in.)	6	$5\,{}^{31}/_{32}$	$5\,{}^{15}/_{16}$	$5\,{}^{15}/_{16}$	$5\,{}^{31}/_{32}$	$5\,{}^{31}/_{32}$	6	6	$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{32}$
M_R	359	401	444	485	588	528	615	607	579	633
Mean. M_R	380		464		558		611		606	
Mix C467	**3 days**		**7 days**		**28 days**		**56 days**		**90 days**	
Batch	**3**	**4**	**1**	**5**	**2**	**4**	**1**	**3**	**3**	**5**
P (lb)	4443.2	4532.8	4664.9	5863.7	6364.0	5968.5	7027.2	6114.3	8047.7	7447.0
Mean b (in.)	$6\,{}^{1}/_{32}$	6	$6\,{}^{1}/_{32}$	$5\,{}^{31}/_{32}$	$6\,{}^{3}/_{32}$	$6\,{}^{31}/_{32}$	$5\,{}^{15}/_{16}$	$5\,{}^{31}/_{32}$	$6\,{}^{31}/_{32}$	6
Mean h (in.)	$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{32}$	6	6	6	6	$6\,{}^{1}/_{32}$	6	6	6
M_R	361	374	387	491	522	495	586	512	667	621
Mean M_R	367		439		508		549		644	
Mix C357	**3 days**		**7 days**		**28 days**		**56 days**		**90 days**	
Batch	**2**	**4**	**1**	**5**	**2**	**4**	**1**	**4**	**2**	**5**
P (lb)	5006.9	4275.8	5095.5	5458.3	5809.4	7100.5	6907.7	7361.0	8644.9	7925.6
Mean b (in.)	6	$6\,{}^{1}/_{16}$	6	$6\,{}^{1}/_{16}$	$6\,{}^{3}/_{32}$	$6\,{}^{1}/_{16}$	$5\,{}^{31}/_{32}$	$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{16}$	$6\,{}^{3}/_{32}$
Mean h (in.)	$6\,{}^{3}/_{32}$	$6\,{}^{1}/_{16}$	$6\,{}^{1}/_{32}$	6	$6\,{}^{1}/_{32}$	$6\,{}^{1}/_{16}$	6	$6\,{}^{1}/_{32}$	$6\,{}^{3}/_{32}$	6
M_R	405	345	420	450	472	574	579	601	691	650
Mean M_R	375		435		523		590		671	

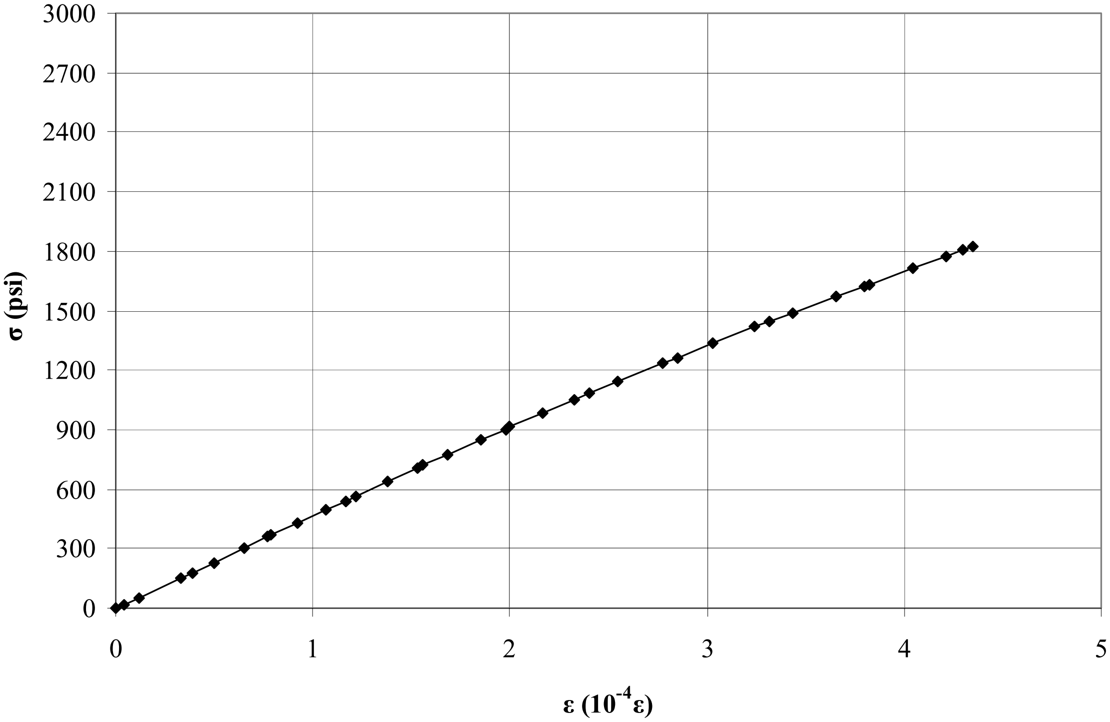

Figure 4.1: Example Stress vs. Strain Curve (N057, Batch 2, at 90 days)

5 DISCUSSION OF TEST RESULTS

5.1 Introduction

This chapter presents an in-depth interpretation of test results, in order to assess the effect of coarse aggregate properties on concrete strength and stiffness. The amount of scatter in the data collected during testing makes this task quite challenging, and calls for the development of an innovative and powerful approach based on engineering considerations to supplement the more traditional statistical approach. All interpretation techniques implemented are discussed in detail, and their validity is confirmed by the conclusions established. The results of the baseline mix tests indicated that there was no distinct advantage to using a high cement content, since this had a very minor impact on the compressive strengths obtained. In keeping with the desire to create mixes that would amplify the effect of larger sized aggregates while maximizing cement efficiency and minimizing costs, a cement content of 400 lb/yd^3 was chosen for all designs in this project. Results discussed in this chapter pertain to the six concrete mixes prepared in this manner. Each such mix is assigned a four-character alphanumeric code identifying the type of the coarse aggregate used (natural, N, or crushed, C), and the coarse aggregate gradation number (No. 57, No. 467, or No. 357).

5.2 Analysis Process

Two specimens were usually tested from each mix on each testing date. The mean value, a measure of the trend in the data, as well as the coefficient of variation (COV), a measure of the variability, were calculated in each case, as shown in Tables 5.1 through 5.4, for the large and small cylinder compressive strength (f_c'), for the modulus of elasticity (E), and for the modulus of rapture tests (M_R), respectively. Due to the inherent variability of concrete, reflected in COV values above 10%, and the relatively small number of specimens tested, individual test results are difficult to interpret. Consequently, in comparing performance across mixes, it was found useful to develop trend lines by leveraging collectively all the data assembled for each of the mechanical properties investigated. The process adopted for this purpose was as follows:

1. Calculate the average strength or stiffness for each mix on each testing date, as presented in Tables 5.5 through 5.8, for the large and small cylinder f_c', for the E, and for the M_R tests, respectively.
2. Plot the overall means of these average values against curing time for each test conducted. Figures 5.1 through 5.4 show these graphs for the large and small cylinder f_c', E, and M_R tests, respectively. In each case, the data points corresponding to the overall means calculated were fitted with a best-fit logarithmic curve.
3. Using the best-fit curve for each test, compute parameter gain ratios that relate the strength or stiffness at one age to the corresponding value at another age. For instance, considering the large cylinder compressive strength curve in

Figure 5.1, the 7-day strength is 74% of its 28-day strength. The corresponding parameter gain in Table 5.5 would range between 66 and 92%, with an average of 78%, and COV of 14%. Such differences reflect the smoothing of the trends involved in plotting the best-fit logarithmic curve using all laboratory data points for that test. Parameter gain ratios obtained in this manner are shown in Tables 5.9 through 5.12, for the four tests noted earlier, respectively.

4. For each mix, select one of the available laboratory test data points to be used as the pivot in establishing the corresponding trend line. The most reliable data point should be selected for this purpose, e.g., because it represents the highest number of specimens tested, or because it is associated with the lowest COV value. In this study, it was found that the 28-day laboratory data from the compressive strength and modulus of elasticity tests on large cylinders offered the optimum departure points on account of the number of specimens tested, whereas the 56-day data served that function for the modulus of rupture beam tests due to their lower COV values. The number of specimens tested was also the attribute leading to the adoption of the 90-day data points for the compressive strength tests on small cylinders.
5. Generate the next one or two points for the trend line from the departure point selected in Step 4, by multiplying this optimum value by the corresponding parameter gain ratios calculated in Step 3. For example, the tested large-cylinder compressive strength of the natural No. 57 mix (N057) at the pivot of

28 days is equal to 3278 psi from Table 5.5; then, the corresponding trend line 7-day strength is 3278 psi multiplied by 74%, or 2410 psi.

6. Generate additional points to complete the trend line for each mix using in turn the values established in Step 5, multiplying them successively by the appropriate parameter gains. Tables 5.13-5.16 show the end results of this process, for the large and small cylinder f_c', for the E, and for the M_R tests, respectively. The trend lines are presented graphically in Figures 5.5 through 5.8 for the four tests considered in this study, respectively.
7. Assess the reasonableness of the fit of the trend lines thus generated, by comparing these to the average laboratory values obtained. For example, considering the large cylinder f_c' test, the comparison is between the trend line values in Table 5.13 and the average test results in Table 5.5, for each mix. Such comparisons are most illustrative when presented in graphical form, as shown in Figures 5.9 through 5.14 for the large cylinder f_c' test**;** in Figures 5.15 through 5.20 for the small cylinder f_c' test; in Figures 5.21 through 5.26 for the E test; and in Figures 5.27 through 5.32 for the M_R test. These graphs verify that the trend lines capture the patterns presented by the laboratory data quite effectively, while at the same time imposing the engineering boundary conditions that require the continuous increase of strength and stiffness with age, at a progressively decreasing rate. Thus, the methodology implemented in this study is judged to be effective and appropriate.

5.3 Compressive Strength

Only large cylinder test results are the primary focus of this section, since small cylinder specimens did not conform to the specification ASTM C 192/C 192M – 00 *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*, concerning the ratio of specimen size to maximum size aggregate for the two coarser gradations (No. 467 and No. 357). Small cylinder test results are, however, employed in a discussion of specimen size effects. Unless expressly indicated otherwise, the data used in the discussion below pertain to the trend lines established in the manner detailed above.

5.3.1 Variability

Table 5.1 shows the average compressive strength at each testing age determined during tests on large cylinders, along with the corresponding number of specimens tested and the value of the coefficient of variation. The latter was below 15% in many cases, with the notable exceptions of several oversize gradation mixes, viz., the natural No. 357 mix (N357) at 3, 7, and 90 days; the crushed No. 467 mix (C467) at 3 days; and the crushed No. 357 mix (C357) at 3 and 90 days. In these instances, the COV values ranged from 15 to 30%. Similar observations can be made with respect to Table 5.2, pertaining to the small cylinder f_c' tests. Even though the researchers had taken great care during mixing, casting and curing procedures to ensure consistency, considerable variation in the test results was observed ascribed mainly to the nature of concrete. From prior experience, the following COV values may be expected: 0-5%: uncommonly low; 5-

10%: excellent engineering work; 10-15%: good engineering work; > 15%: questionable reliability.

5.3.2 Trend Lines

Table 5.5 shows the average laboratory large cylinder compressive strength data for each mix at each testing age. The overall means at each age and the best-fit curve points, calculated from the logarithmic equation in Figure 5.1, are also given. Table 5.9 shows the corresponding parameter gain ratios, which were established using the best-fit curve data in Table 5.5. Table 5.13 shows the compressive strength trend line data generated for each mix, using the corresponding 28-day strength as the pivotal test data point in each case. Figures 5.9 through 5.14 show the trend lines for each of the six mixes superimposed on the laboratory test data. It is concluded that the trend lines represent test data reasonably well, and that the methodology adopted in generating these lines elucidates some of the perplexing patterns exhibited by the test results, e.g., decreasing strength with time, abrupt changes in the rate of strength development with time, etc. Nonetheless, even the trend lines do not address all difficulties with respect to the interpretation of the laboratory data. Figure 5.5 shows all trend lines thus obtained. The lines are clustered together, reflecting the low resolution available for the establishment of reliable conclusions, particularly in view of the relatively large variability exhibited by some of the laboratory data pertaining to the two oversize gradations (No. 357 and No. 467).

5.3.3 Effect of Aggregate Type

Table 5.17 shows ratios relating the 28-day large cylinder compressive strength of each mix to that of every other. Each cell in the Table is obtained by dividing the strength of the row mix by that of the column mix. Thus, mix N057, which consists of natural coarse aggregate, is found to be 7% stronger than the corresponding crushed coarse aggregate mix (C057). The natural No. 467 (N467) and No. 357 (N357) mixes are stronger than their crushed aggregate counterparts (C467 and C357) by 31% and 26%, respectively. These data are also presented in Table 5.18 and Figure 5.33. In all three cases, the mixes containing natural coarse aggregate exhibited higher strengths than those with crushed aggregate, contrary to intuitive expectations. The superiority of natural aggregate is more pronounced for the two coarser gradations (No. 357 and No. 467), than for the finer gradation (No. 57). Recall that specimens with finer aggregate tended to fail primarily by shear across the aggregates themselves, rather than by pullout. Evidently, this reduces the significance of surface texture and shape, making aggregate mineralogy a more pronounced variable. The crushed aggregate in this study was limestone, whereas the natural aggregate was mostly basalt. A more detailed mineralogical investigation might have helped examine this issue in more depth, but it was considered beyond the scope of the project.

5.3.4 Effect of Aggregate Gradation

Table 5.18 and Figure 5.34 show comparisons of large cylinder 28-day compressive strengths of mixes with different coarse aggregate gradations. The across gradation range, determined by dividing the difference between the highest and the lowest f_c' values obtained by the lowest f_c', is a measure of the overall effect of aggregate gradation. It is observed that natural aggregate mixes are insensitive to gradation, presumably because the mineralogy of each gradation was similar. The strengths of the strongest (N357) and weakest (N467) mixes differ only by about 3%. Mix N057, which contains the finest aggregate gradation, has an intermediate compressive strength, but this is not considered significant given the relatively high variability of some of the test data pertaining to the two oversize gradations.

In contrast, gradation is found to play a significant role in the case of crushed coarse aggregate mixes, as reflected in the across gradation range of 23%. Nonetheless, the causes of this sensitivity do not appear to pertain to the maximum aggregate size, since the strongest mix is C057, which contains the finest gradation, while mix C467, which has the intermediate sized aggregates, is the weakest mix. Rather, the source of the differences observed are probably associated with mineralogical distinctions among the three gradations. Recall that each of these gradations came from a different plant, and that the two oversize gradations were blended using aggregates from a variety of sources, further confounding the influence of mineralogy.

5.3.5 Effect of Specimen Size

Table 5.6 shows the data collected from 28-day compressive strength testing of small cylinders (4 in. × 8 in.), which were cast only in those cases in which excess material was available. The methodology adopted for generating trend lines was, therefore, additionally useful in this case, since it served to fill in the gaps created in the test data on account of an incomplete factorial of tests. Table 5.10 shows the parameter gain ratios, while Table 5.14 shows the complete set of trend line data for small cylinder f_c' values.

In order to assess the impact of the specimen size effect, a factor may be defined as the ratio of the small cylinder f_c' to that obtained using large cylinders. Neville (1995) states that comparing 4-in. and 6-in. diameter cylinders, specimen size factors between 3 to 5% may be expected. Values obtained in this study, however, are significantly higher, ranging instead between 2 and 40%, as shown in Table 5.19. Nonetheless, the trends observed are refreshingly clear in this case, inspiring confidence in the results obtained. The specimen size factor steadily increases with increasing maximum size of aggregate and age as well as surface roughness and angularity.

5.4 Modulus of Elasticity

Only large cylinders (6 × 12 in.) were used in the determination of the modulus of elasticity of the specimens in this study. Consequently, the specimen size effect on E cannot be assessed. As before, unless expressly indicated otherwise, the data used in the discussion below pertain to the trend lines established in the manner detailed above.

5.4.1 Variability

Table 5.3 shows the average modulus of elasticity on each testing date resulting from laboratory tests on large cylinders. Table 5.3 also lists the number of specimens tested and the COV calculated in each case. The variability of modulus of elasticity test results is found to be much lower than that of that observed in the f_c' test. The maximum E COV is only 11.78%, which corresponds to good engineering work, according to the prior experience limits quoted earlier. This variability appears to increase slightly with age and with maximum size of aggregate, but the data obtained in this study do not appear conclusive in this respect.

5.4.2 Trend Lines

Table 5.7 shows the average modulus of elasticity laboratory test results for each of the six mixes, as well as the overall means and best-fit curve points. Using the best-fit logarithmic curve, the parameter gain ratios presented in Table 5.11 are determined. The latter are used in turn to generate the trend line data shown in Table 5.15, following the methodology detailed at the beginning of this chapter. Figures 5.21 through 5.26 show individually each trend line thus established, along with the corresponding laboratory test data. It is apparent that the trend lines fit the test data reasonably well, providing justification for the methodology adopted in developing them. Nonetheless, the problem of limited resolution, first identified with respect to the f_c' test, persists in the case of the E test as well, in which it is even more acute. The trend lines for all mixes are shown together in Figure 5.7, where they are seen to cluster even more tightly than those for f_c', thereby eliminating the benefit of the lower variability exhibited by the results of the E test.

5.4.3 Effect of Aggregate Type

Table 5.20 contains the modulus of elasticity mix ratios, which are 100 ± 5%, reflecting the insensitivity of E to this factor. Mix N057 has a modulus of elasticity that is about 3% lower than that of mix C057, suggesting a small advantage of crushed aggregate. Mixes N467 and N357 have moduli of elasticity that are about 1% lower than their crushed aggregate counterparts (C467 and C357). Table 5.21 and Figure 5.35 present this information more clearly. It can, therefore, be safely concluded that that the modulus of elasticity is not significantly affected by aggregate type.

5.4.4 Effect of Aggregate Gradation

Table 5.21 and Figure 5.36 show comparisons of E values obtained from mixes with different aggregate gradations. The across gradation range is about 6%, independent of aggregate type, reflecting once again the insensitivity of E to this factor, as well. Considering both natural and crushed coarse aggregates, mixes containing the intermediate gradation (N467 and C467) are the softest. The stiffest natural and crushed coarse aggregate mixes are N357 and C357, which contain the largest aggregate gradations. Nonetheless, such small differences are dwarfed by the variability of the test results, which albeit smaller than for f_c', makes the recognition of definite trends all but impossible.

5.4.5 Comparison with ACI Predictionss

The American Concrete Institute (ACI) recommends the following equation for estimating the modulus of elasticity given the compressive strength of a specimen:

$$E_c = 57000\sqrt{f_c'} \qquad \textbf{Equation 5.1}$$

Table 5.22 shows estimated modulus of elasticity values determined using Equation 5.1, and f_c' trend line values from Table 5.13. Table 5.23 compares these values to the average laboratory test results obtained in this study, given in Table 5.8. Each cell is the ratio of E predicted by the ACI equation to the corresponding parameter determined from laboratory tests. These ratios range from 72 to 88%, showing that the estimated values are significantly below the test data, inspiring confidence to the laboratory procedures followed in this project.

5.5 Modulus of Rupture

Only large beams (6 × 6 × 21 in.) were used in the determination of the modulus of rupture, M_R, of the specimens in this study. Consequently, the specimen size effect on M_R cannot be assessed. As before, unless expressly indicated otherwise, the data used in the discussion below pertain to the trend lines established in the manner detailed above.

5.5.1 Variability

Table 5.4 shows the average modulus of rupture on each testing date, calculated from the results of tests on the beams. Also listed is the number of specimens tested on each occasion, as well as the COV values obtained. With only one exception (Mix C467 at 7 days), all COV values remained below 15%, which corresponds to the upper limit of good engineering work, according to the prior experience ranges quoted earlier. Not surprisingly, M_R determination involves more variability than E testing. Nonetheless, the intuitive expectation that M_R tests would also exhibit higher variability than f_c' experiments is not borne out by the data collected in this study. This probably reflects the much higher sensitivity of f_c' to mineralogical differences encountered in the materials tested.

5.5.2 Trend Lines

Table 5.8 shows the average modulus of rupture laboratory data, the overall mean and the best-fit curve points for each of the six mixes. Using the latter, the parameter gain ratios presented in Table 5.12 are obtained, which in turn are employed in establishing the trend line data in Table 5.16, in accordance with the methodology discussed above. An assessment of the validity of this methodology is provided by comparing the individual trend lines with the corresponding laboratory data, as done in Figures 5.27 through 5.32. It is verified in this manner that trend lines capture the patterns exhibited by the test data quite well, while eliminating observations contrary to the engineering boundary conditions of a smooth and gradual strength gain with age at a progressively decreasing rate. Figure 5.8 shows all six trend lines, which cluster like those for f_c', but not as tightly as those for E. Yet, given that the variability in the M_R results is smaller than that for the f_c' test (a rather surprising observation), the resolution afforded by the data in Figure 5.8 may be expected to be proportionately more promising.

5.5.3 Effect of Aggregate Type

This expectation is not borne out, however, when investigating the effect of aggregate type on M_R, suggesting that even COV values between 10 to 15% may be sufficient to mask the repercussions of surface texture and particle angularity. Table 5.24 presents the M_R mix ratios, which indicate that the natural aggregate N057 mix is approximately 14% weaker than its coarse aggregate counterpart, Mix C057. The natural versus crushed comparison is reversed, however, when natural mixes N467 and N347 are observed being 13% and 6% stronger than the corresponding crushed aggregate mixes, respectively. These data are also presented in Table 5.25 and in Figure 5.37, which confirm that no discernible and consistent effect of aggregate type on M_R was observed in this study, any differences being attributable to the variability of the testing procedure itself, even though this is lower than that observed for the f_c' test.

5.5.4 Effect of Aggregate Gradation

Table 5.25 and Figure 5.38 compare M_R values obtained by varying the coarse aggregate gradation of each of the six mixes. The N467 mix exhibits the highest M_R value among the three mixes with natural aggregate, whereas mix N057 mix produces the lowest. Yet, the corresponding C467 mix results in the lowest M_R among the three crushed coarse aggregate mixes, while the C057 mix results in the highest. These observations reaffirm the conclusion that no clear pattern emerges in this study concerning the sensitivity of M_R to aggregate gradation, and that the variability observed in the laboratory is exclusively attributable to repeatability issues of the testing procedure itself.

5.5.5 Comparison with ACI Predictions

The ACI also provides a formula for estimating the modulus of rupture given the compressive strength of a specimen. This equation is as follows:

$$M_R = 7.5\sqrt{f_c'} \qquad \textbf{Equation 5.2}$$

Table 5.26 shows the estimated M_R values found using Equation 5.2, along with trend line data in Table 5.16, and Table 5.27 presents the Predicted/Observed ratios when these values are compared to the laboratory test data in Table 5.8. These ratios range from 69 to 90%, inspiring confidence in the laboratory procedures adopted in this study, as was the case with the modulus of elasticity data, as well.

Table 5.1: Large Cylinder Compressive Strength Variability

Age	**3**	**7**	**28**	**56**	**90**
N057					
No. of Specimens	2	2	2	3	2
f'_c (psi)	1623	2268	3278	3432	3715
COV (%)	9.80	4.71	3.12	9.61	3.57
N467					
No. of Specimens	2	2	5	2	2
f'_c (psi)	1986	2476	3256	3395	3569
COV (%)	7.01	5.94	1.79	1.29	10.21
N357					
No. of Specimens	2	2	4	2	2
f'_c (psi)	1837	2535	3351	3833	3677
COV (%)	17.19	19.92	7.31	5.91	29.21
C057					
No. of Specimens	2	2	4	2	22
f'_c (psi)	1341	2018	3060	3180	3702
COV (%)	15.25	12.43	8.93	12.35	11.42
C467					
No. of Specimens	2	2	3	2	3
f'_c (psi)	1220	2296	2491	3398	3283
COV (%)	20.82	5.92	5.42	4.37	4.55
C357					
No. of Specimens	2	2	5	2	2
f'_c (psi)	1532	2346	2658	3175	3411
COV (%)	22.14	8.93	12.74	1.79	16.72

Table 5.2: Small Cylinder Compressive Strength Variability

Age	3	7	28	56	90
N057					
No. of Specimens	1	1	1	1	3
f'_c (psi)	1641	2841	3982	2545	4154
COV (%)	-	-	-	-	2.11
N467					
No. of Specimens	0	0	0	1	1
f'_c (psi)	-	-	-	4146	4121
COV (%)	-	-	-	-	-
N357					
No. of Specimens	0	1	1	1	1
f'_c (psi)	-	2844	4070	4586	4540
COV (%)	-	-	-	-	-
C057					
No. of Specimens	1	1	1	1	5
f'_c (psi)	1923	2685	3208	4020	4161
COV (%)	-	-	-	-	10.53
C467					
No. of Specimens	1	1	2	1	1
f'_c (psi)	1931	2624	3273	3786	4214
COV (%)	-	-	14.93	-	-
C357					
No. of Specimens	1	1	1	2	2
f'_c (psi)	1902	2463	2911	4337	4379
COV (%)	-	-	-	0.50	5.16

Table 5.3: Modulus of Elasticity Variability

Age	**3**	**7**	**28**	**56**	**90**
N057					
No. of Specimens	2	2	2	3	2
E_c (10^6 psi)	2.88	3.31	3.74	4.19	4.26
COV (%)	1.85	1.00	3.18	3.21	1.45
N467					
No. of Specimens	2	2	5	2	2
E_c (10^6 psi)	3.43	3.34	3.65	4.11	4.38
COV (%)	1.43	6.80	5.98	0.54	0.03
N357					
No. of Specimens	2	2	4	2	2
E_c (10^6 psi)	3.45	3.39	3.89	4.25	4.26
COV (%)	1.00	7.73	7.87	1.47	4.18
C057					
No. of Specimens	2	2	4	2	2
E_c (10^6 psi)	2.86	3.34	3.84	3.89	4.52
COV (%)	4.89	1.92	4.13	11.78	1.73
C467					
No. of Specimens	2	2	3	2	3
E_c (10^6 psi)	2.86	3.54	3.68	4.06	3.83
COV (%)	4.73	7.58	3.12	1.22	1.65
C357					
No. of Specimens	2	2	5	2	2
E_c (10^6 psi)	3.17	3.29	3.91	4.02	5.18
COV (%)	0.82	3.21	8.19	8.18	3.55

Table 5.4: Modulus of Rupture Variability

Age	**3**	**7**	**28**	**56**	**90**
Mix N057					
No. of Specimens	2	2	2	2	2
M_R (psi)	392	434	489	539	617
COV (%)	1.84	6.39	1.39	7.12	1.53
Mix N467					
No. of Specimens	2	2	2	2	2
M_R (psi)	452	540	585	636	692
COV (%)	.15	3.77	1.91	0.45	3.81
Mix N357					
No. of Specimens	2	2	2	2	2
M_R (psi)	433	555	558	587	717
COV (%)	2.38	11.23	1.57	2.83	8.34
Mix C057					
No. of Specimens	2	2	2	2	2
M_R (psi)	380	464	558	611	606
COV (%)	7.94	6.25	7.60	0.88	6.34
Mix C467					
No. of Specimens	2	2	2	2	2
M_R (psi)	367	439	508	549	644
COV (%)	2.51	16.83	3.81	9.46	5.12
Mix C357					
No. of Specimens	2	2	2	2	2
M_R (psi)	375	435	523	590	671
COV (%)	11.14	4.86	13.78	2.65	4.31

Table 5.5: Large Cylinder Average Compressive Strength (psi)

Mix	**Age (days)**				
	3	**7**	**28**	**56**	**90**
N057	1623	2268	3278	3432	3715
N467	1986	2476	3256	3395	3569
N357	1837	2535	3351	3833	3677
C057	1341	2018	3060	3180	3702
C467	1220	2296	2491	3398	3283
C357	1532	2346	2658	3175	3411
Overall Mean	1590	2323	3016	3402	3560
Best-fit Curve	1707	2189	2978	3373	3643

Table 5.6: Small Cylinder Average Compressive Strength (psi)

Mix	**Age (days)**				
	3	**7**	**28**	**56**	**90**
N057	1641	2841	3982	2545	4154
N467	-	-	-	4146	4121
N357	-	2844	4070	4586	4540
C057	1923	2685	3208	4020	4161
C467	1931	2624	3273	3786	4214
C357	1902	2463	2911	4337	4379
Overall Mean	1849	2692	3489	3903	4262
Best-fit Curve	1963	2537	3478	3948	4269

Table 5.7: Large Cylinder Average Modulus of Elasticity (10^6 psi)

Mix	Age (days)				
	3	7	28	56	90
N057	2.88	3.31	3.74	4.19	4.26
N467	3.43	3.34	3.65	4.11	4.38
N357	3.45	3.39	3.89	4.25	4.26
C057	2.86	3.34	3.84	3.89	4.52
C467	2.86	3.54	3.68	4.06	3.83
C357	3.17	3.29	3.91	4.02	5.18
Overall Mean	3.11	3.37	3.79	4.09	4.40
Best-fit Curve	3.07	3.37	3.88	4.13	4.30

Table 5.8: Average Modulus of Rupture (psi)

Mix	Age (days)				
	3	7	28	56	90
N057	392	434	489	539	617
N467	452	540	585	636	692
N357	433	555	558	587	717
C057	380	464	558	611	606
C467	367	439	508	549	644
C357	375	435	523	590	671
Overall Mean	400	478	537	585	658
Best-fit Curve	404	461	555	603	635

Table 5.9: Large Cylinder Compressive Strength Parameter Gain Ratios (%)

Age (days)	**Age (days)**				
	3	**7**	**28**	**56**	**90**
3	100	78	57	51	47
7	128	100	74	65	60
28	174	136	100	88	82
56	198	154	113	100	93
90	213	166	122	108	100

Table 5.10: Small Cylinder Compressive Strength Parameter Gain Ratios (%)

Age (days)	**Age (days)**				
	3	**7**	**28**	**56**	**90**
3	100	78	56	50	46
7	129	100	73	64	59
28	177	137	100	88	81
56	201	156	114	100	92
90	218	168	123	108	100

Table 5.11: Modulus of Elasticity Parameter Gain Ratios (%)

Age (days)	**Age (days)**				
	3	**7**	**28**	**56**	**90**
3	100	91	79	74	71
7	110	100	87	82	78
28	126	115	100	94	90
56	135	122	107	100	96
90	140	128	111	104	100

Table 5.12: Modulus of Rupture Parameter Gain Ratios (%)

Age (days)	**Age (days)**				
	3	**7**	**28**	**56**	**90**
3	100	88	73	67	64
7	114	100	83	77	73
28	138	120	100	92	87
56	149	131	108	100	95
90	157	138	114	105	100

Table 5.13: Large Cylinder Compressive Strength Trend Line Data (psi)

Mix	Age (days)				
	3	7	28	56	90
N057	1879	2410	3278	3712	4009
N467	1866	2394	3256	3688	3983
N357	1921	2463	3351	3795	4099
C057	1754	2249	3060	3465	3742
C467	1428	1831	2491	2821	3047
C357	1524	1954	2658	3011	3252

Table 5.14: Small Cylinder Compressive Strength Trend Line Data (psi)

Mix	**Age (days)**				
	3	**7**	**28**	**56**	**90**
N057	1910	2469	3384	3841	4154
N467	1895	2450	3357	3811	4121
N357	2087	2698	3698	4198	4540
C057	1913	2473	3390	3848	4161
C467	1937	2504	3432	3896	4214
C357	2013	2602	3567	4049	4379

Table 5.15: Large Cylinder Modulus of Elasticity Trend Line Data (10^6 psi)

Mix	Age (days)				
	3	7	28	56	90
N057	2.96	3.25	3.74	3.98	4.15
N467	2.89	3.18	3.65	3.89	4.05
N357	3.08	3.38	3.89	4.14	4.32
C057	3.04	3.34	3.84	4.09	4.26
C467	2.91	3.20	3.68	3.92	4.08
C357	3.09	3.41	3.91	4.17	4.34

Table 5.16: Modulus of Rupture Trend Line Data (psi)

Mix	Age (days)				
	3	7	28	56	90
N057	361	412	497	539	568
N467	426	487	587	636	670
N357	394	450	542	587	619
C057	409	468	563	611	644
C467	368	420	506	549	578
C357	395	451	544	590	621

Table 5.17: Compressive Strength Comparisons Among Mixes (%) at 28 days

Mix	N057	N467	N357	C057	C467	C357
N057	100	101	98	107	132	123
N467	99	100	97	106	131	122
N357	102	103	100	110	135	126
C057	93	94	91	100	123	115
C467	76	77	74	81	100	94
C357	81	82	79	87	107	100

Table 5.18: Large Cylinder Compressive Strength (psi) Comparison by Aggregate Type and Gradation at 28 days

Gradation	Natural	Crushed	% Difference Across Aggregate Type
No. 57	3278	3060	-7
No. 467	3256	2491	-31
No. 357	3351	2658	-26
% Range Across Gradation	3	23	

Table 5.19: Compressive Strength Specimen Size Factors (Small/Large) (%)

Mix	Age (days)				
	3	7	28	56	90
N057	102	102	103	103	104
N467	102	102	103	103	103
N357	109	110	110	111	111
C057	109	110	111	111	111
C467	136	137	138	138	138
C357	132	133	134	134	135

Table 5.20: Large Cylinder Modulus of Elasticity Comparison Among Mixes (%) at 28 days

Mix	N057	N467	N357	C057	C467	C357
N057	100	102	96	97	102	96
N467	98	100	94	95	99	93
N357	104	107	100	101	106	99
C057	103	105	99	100	104	98
C467	98	101	95	96	100	94
C357	105	107	101	102	106	100

Table 5.21: Modulus of Elasticity (10^6 psi) Comparison by Aggregate Type and Gradation at 28 days

Gradation	Natural	Crushed	% Difference Across Aggregate Type
No. 57	3.74	3.84	3
No. 467	3.65	3.68	1
No. 357	3.89	3.91	1
% Range Across Gradation	7	6	

Table 5.22: Estimated Modulus of Elasticity (10^6 psi) from ACI Equation

Mix	Age (days)				
	3	7	28	56	90
N057	2.47	2.80	3.26	3.47	3.61
N467	2.46	2.79	3.25	3.46	3.60
N357	2.50	2.83	3.30	3.51	3.65
C057	2.39	2.70	3.15	3.36	3.49
C467	2.15	2.44	2.84	3.03	3.15
C357	2.22	2.52	2.94	3.13	3.25

Table 5.23: Modulus of Elasticity Test Ratios
(Predicted by ACI/Observed in Tests) (%)

Mix	**Age (days)**				
	3	**7**	**28**	**56**	**90**
N057	84	86	87	87	87
N467	85	88	89	88	89
N357	81	84	85	85	85
C057	79	81	82	82	82
C467	74	76	77	77	77
C357	72	74	75	75	75

Table 5.24: Modulus of Rupture Comparisons Among Mixes (%) at 28 days

Mix	N057	N467	N357	C057	C467	C357
N057	100	85	92	88	98	91
N467	118	100	108	104	116	108
N357	109	92	100	96	107	100
C057	113	96	104	100	111	104
C467	102	86	93	90	100	93
C357	109	93	100	97	107	100

Table 5.25: Modulus of Rupture (psi) Comparison by Aggregate Type and Gradation at 28 days

Gradation	Natural	Crushed	% Difference Across Aggregate Type
No. 57	497	563	13
No. 467	587	506	-14
No. 357	542	544	0
% Range Across Gradation	18	11	

Table 5.26: Estimated Modulus of Rupture (psi) from ACI Equations

Mix	Age (days)				
	3	**7**	**28**	**56**	**90**
N057	325	368	429	457	475
N467	324	367	428	455	473
N357	329	372	434	462	480
C057	314	356	415	441	459
C467	283	321	374	398	414
C357	293	332	387	412	428

Table 5.27: Modulus of Rupture Test Ratios (Predicted/Observed) (%)

Mix	Age (days)				
	3	7	28	56	90
N057	90	89	86	85	84
N467	76	75	73	72	71
N357	84	83	80	79	78
C057	77	76	74	72	71
C467	77	76	74	73	72
C357	74	73	71	70	69

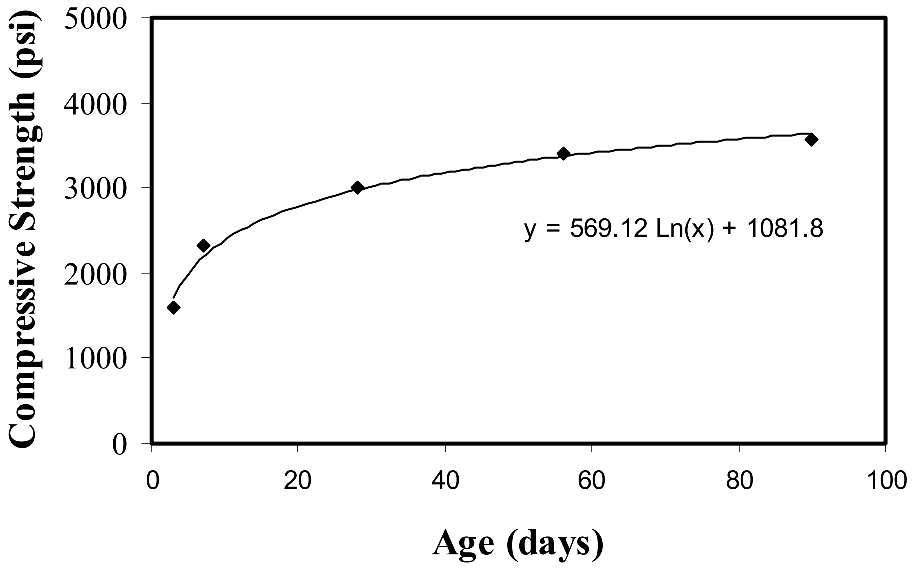

Figure 5.1: Logarithmic Curve for Large Cylinder Compressive Strength

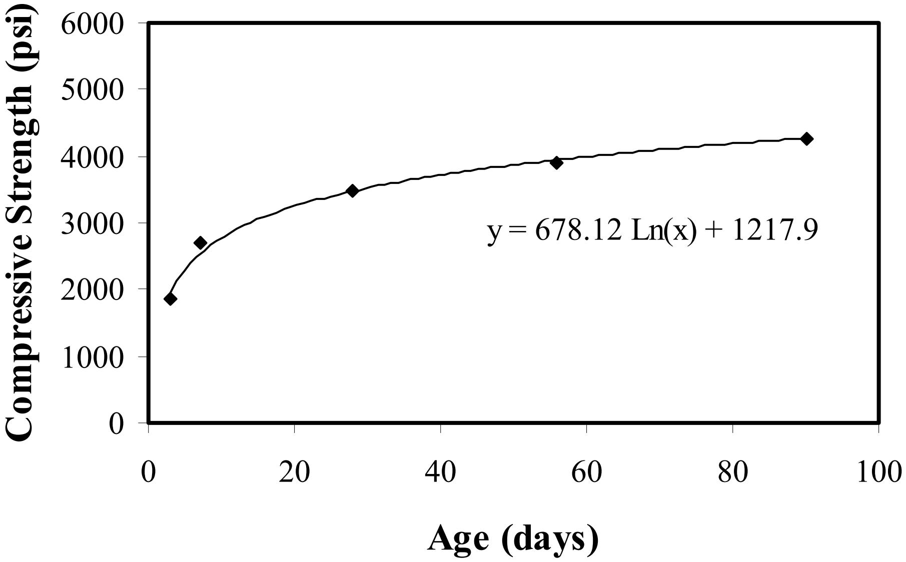

Figure 5.2: Logarithmic Curve for Small Cylinder Compressive Strength

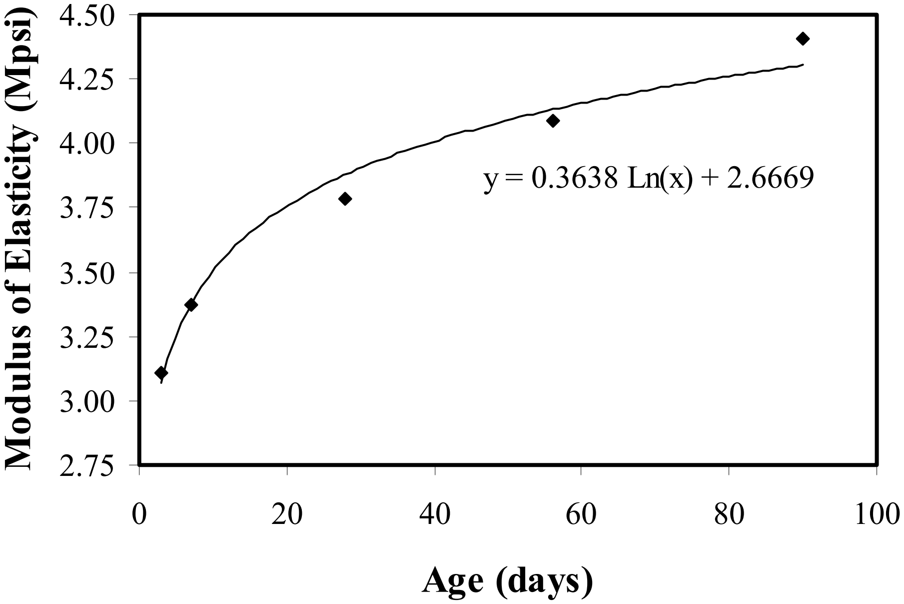

Figure 5.3: Logarithmic Curve for Modulus of Elasticity

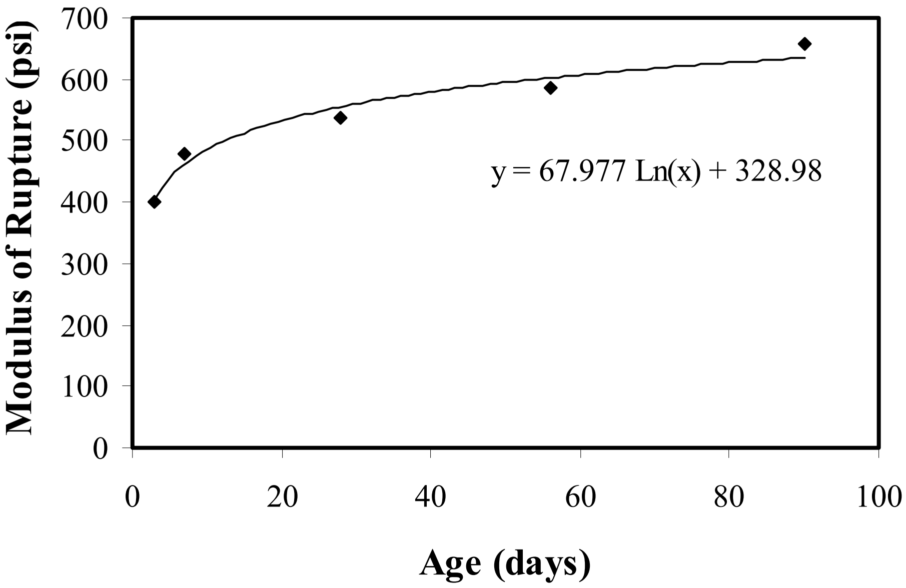

Figure 5.4: Logarithmic Curve for Modulus of Rupture

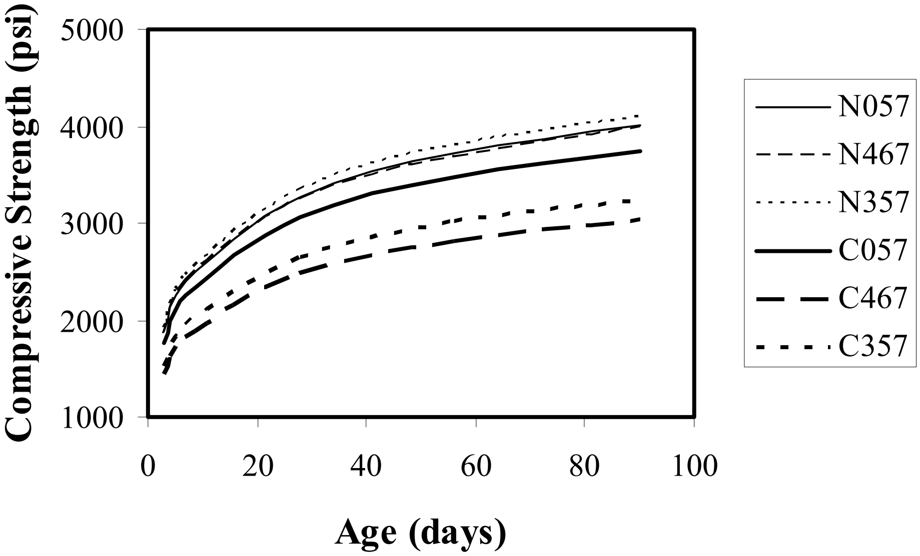

Figure 5.5: Large Cylinder Compressive Strength Trend Lines

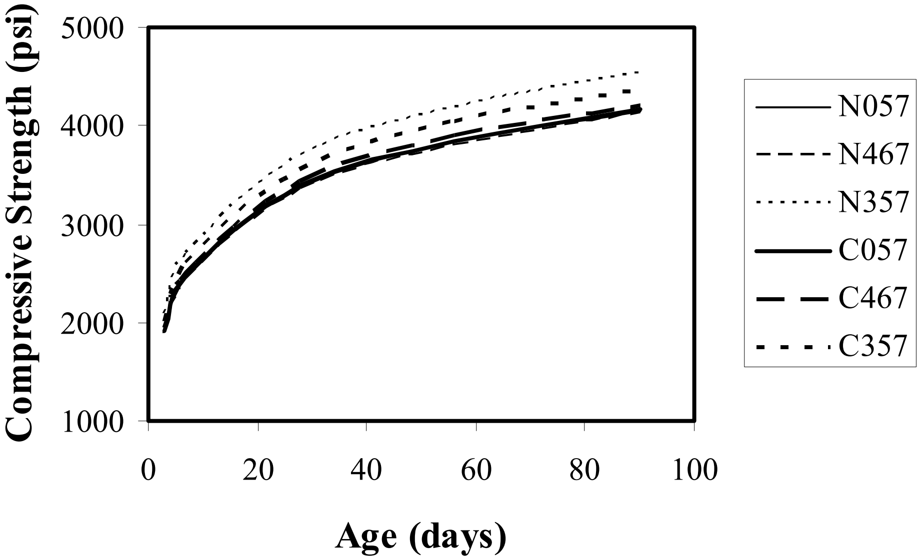

Figure 5.6: Small Cylinder Compressive Strength Trend Lines

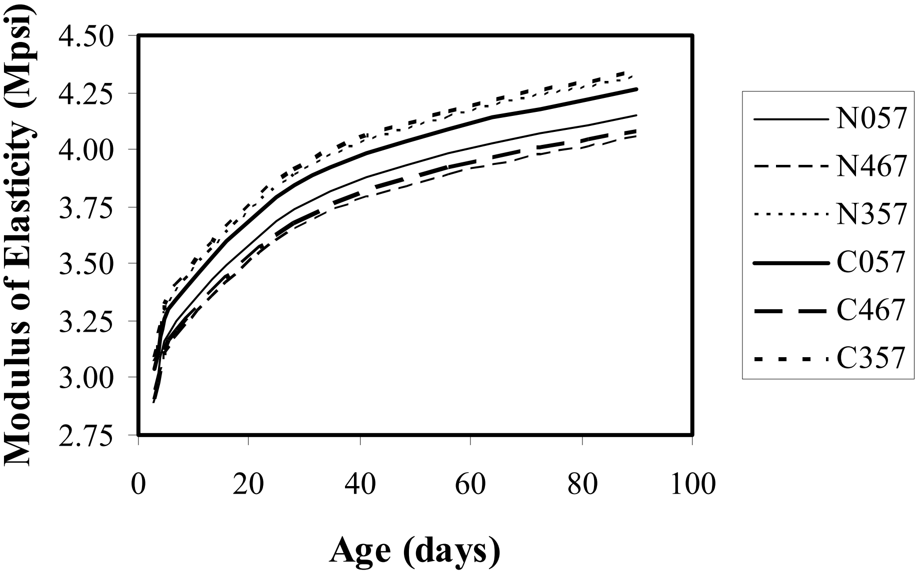

Figure 5.7: Modulus of Elasticity Trend Lines

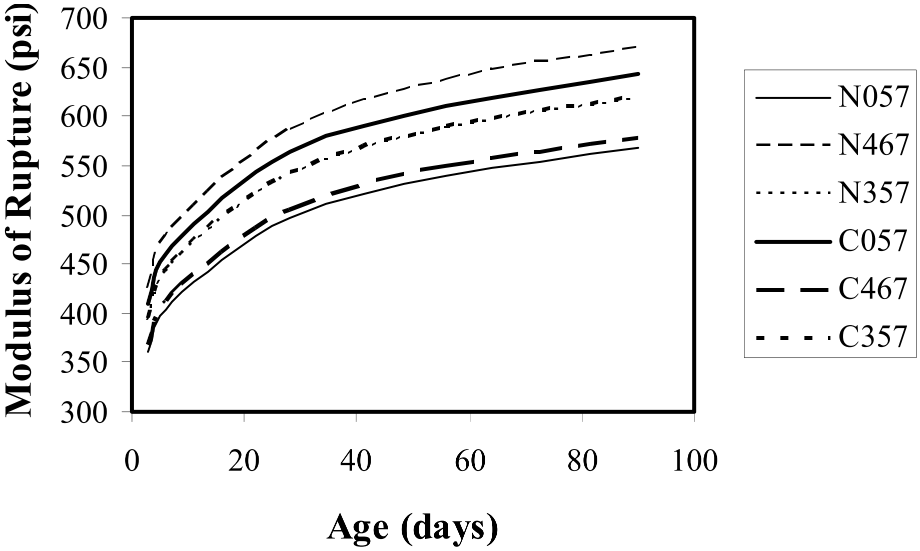

Figure 5.8: Modulus of Rupture Trend Lines

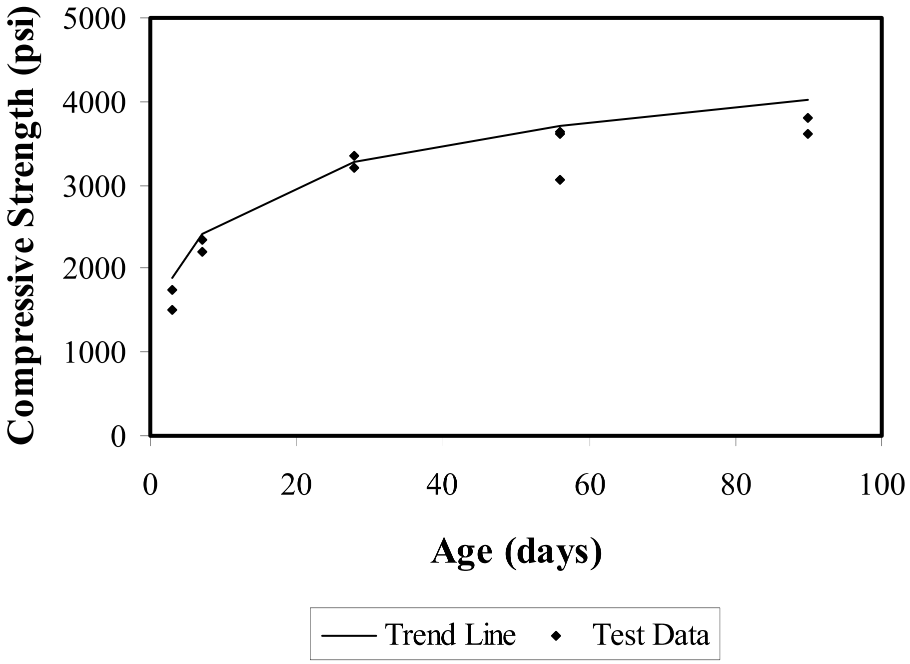

Figure 5.9: N057 Compressive Strength

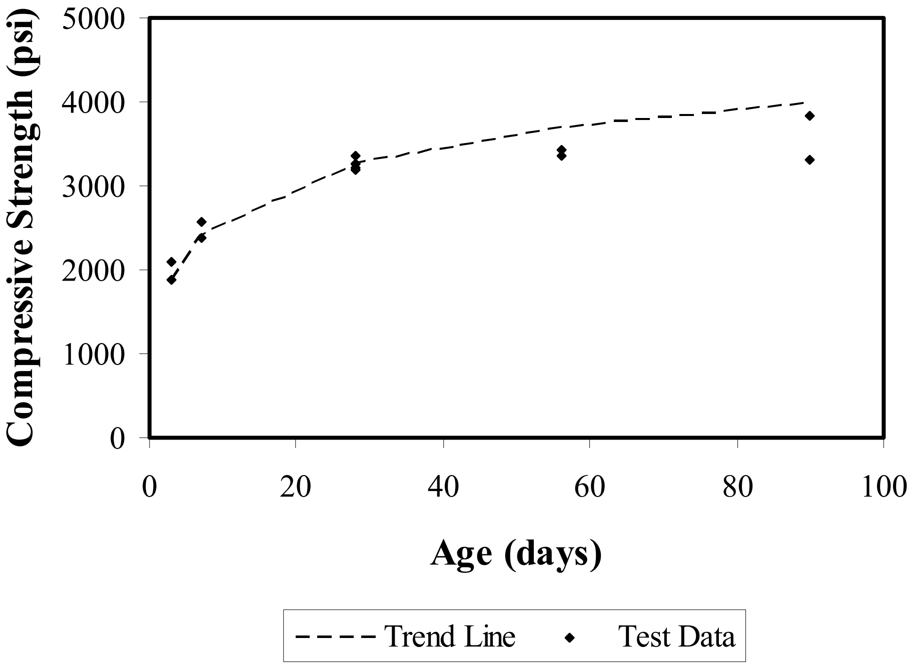

Figure 5.10: N467 Compressive Strength

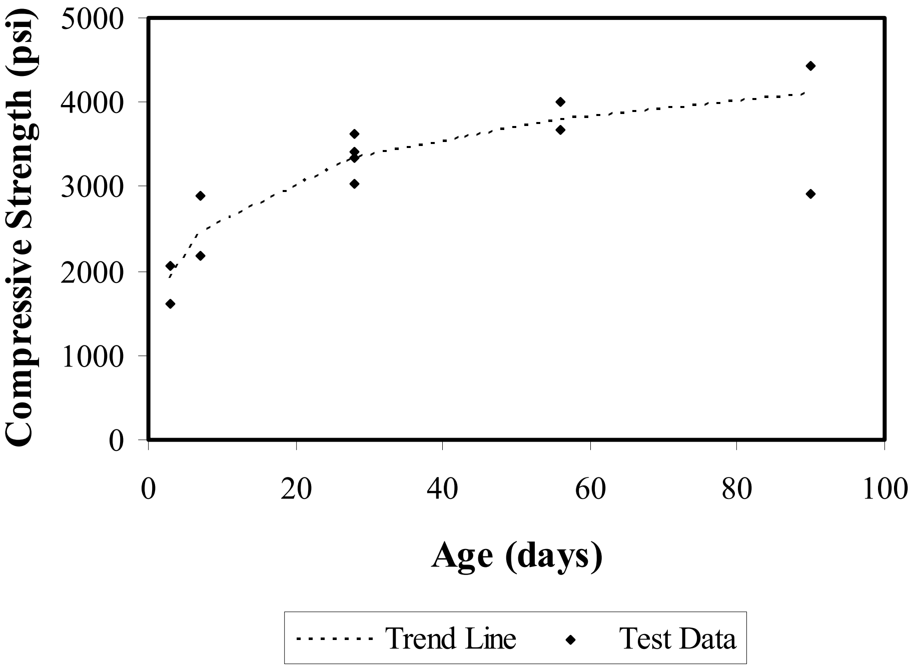

Figure 5.11: N357 Compressive Strength

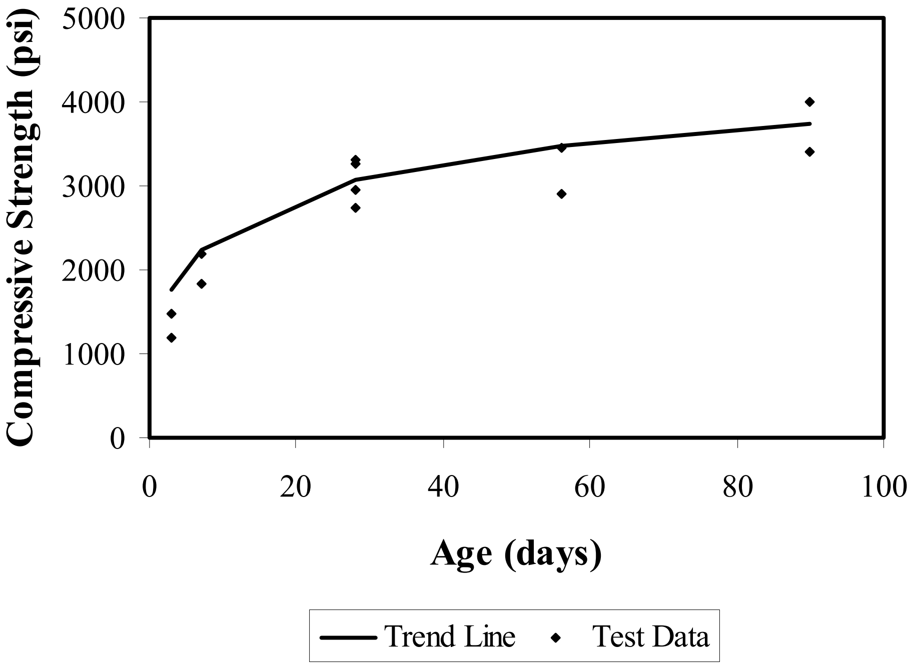

Figure 5.12: C057 Compressive Strength

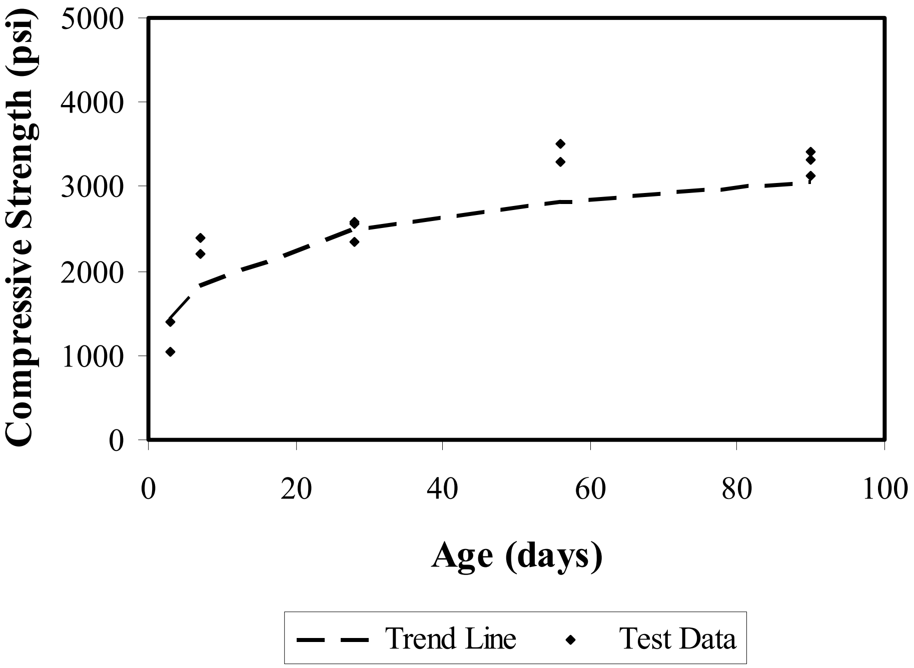

Figure 5.13: C467 Compressive Strength

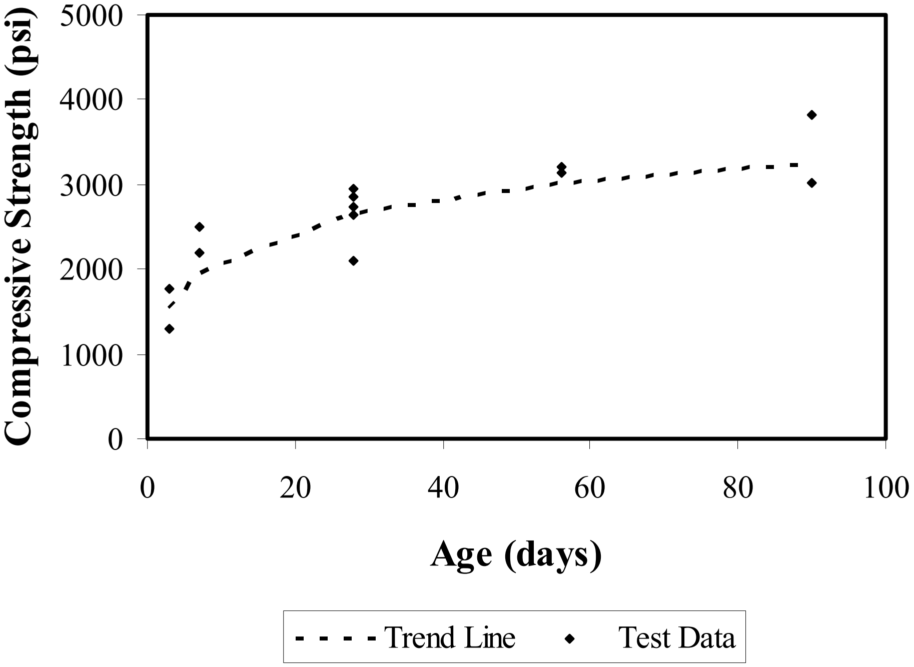

Figure 5.14: C357 Compressive Strength

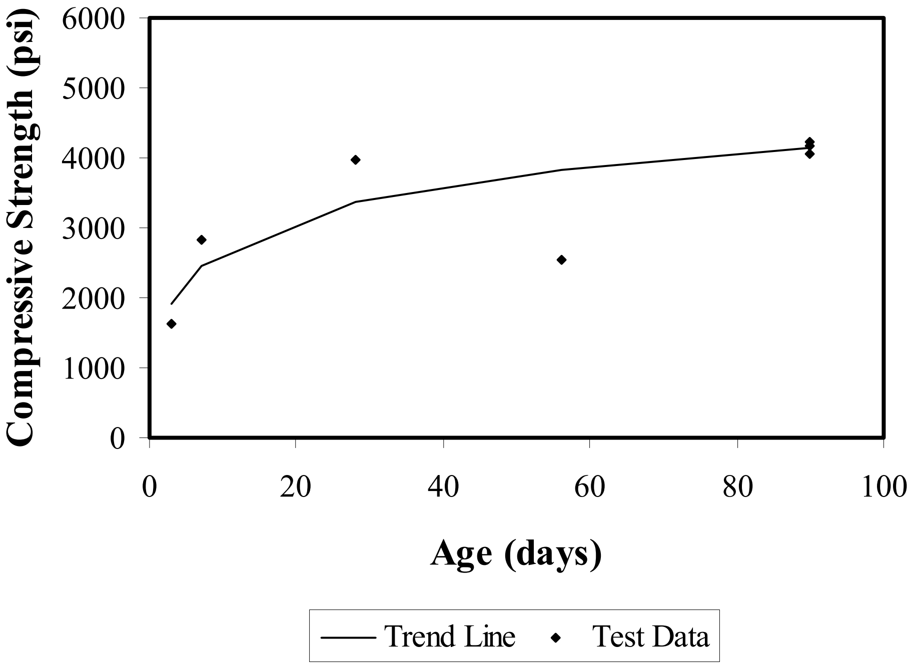

Figure 5.15: N057 Small Cylinder Compressive Strength

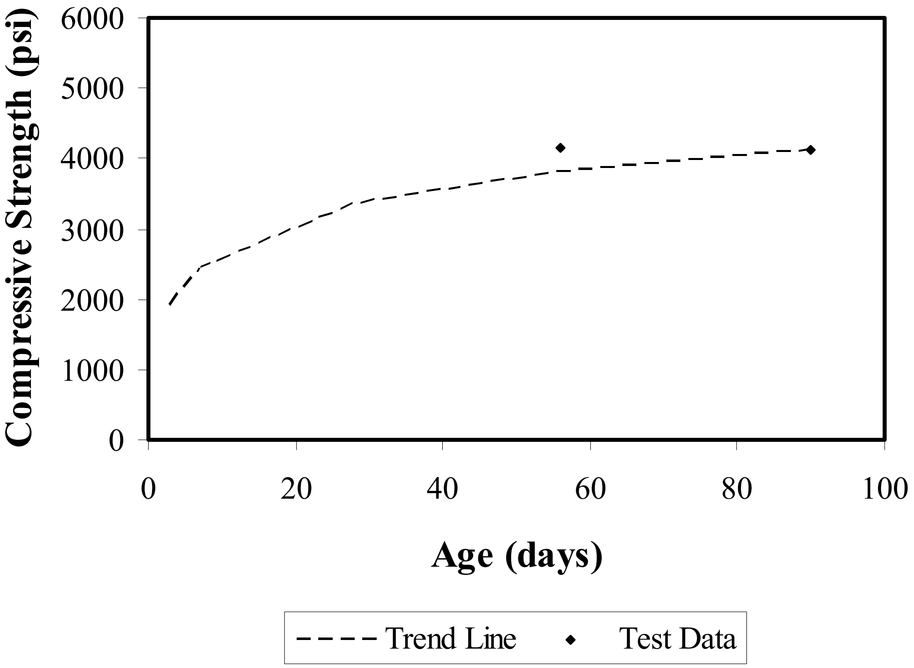

Figure 5.16: N467 Small Cylinder Compressive Strength

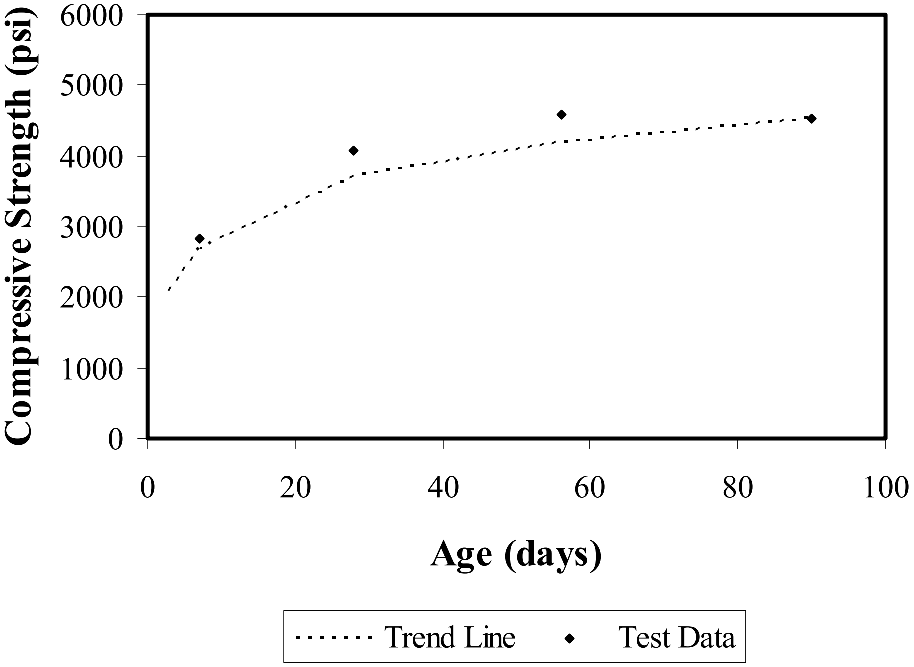

Figure 5.17: N357 Small Cylinder Compressive Strength

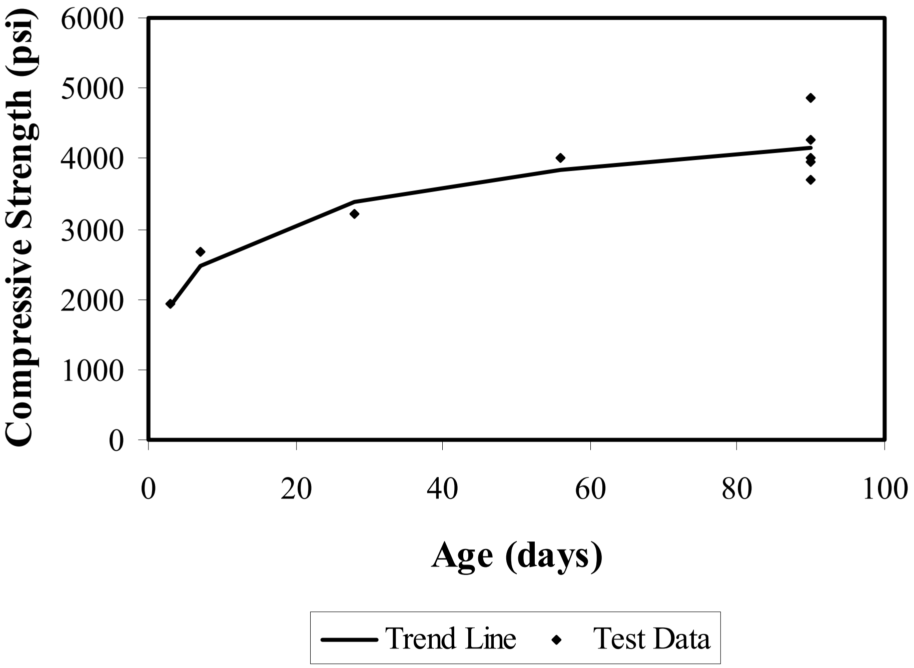

Figure 5.18: C057 Small Cylinder Compressive Strength

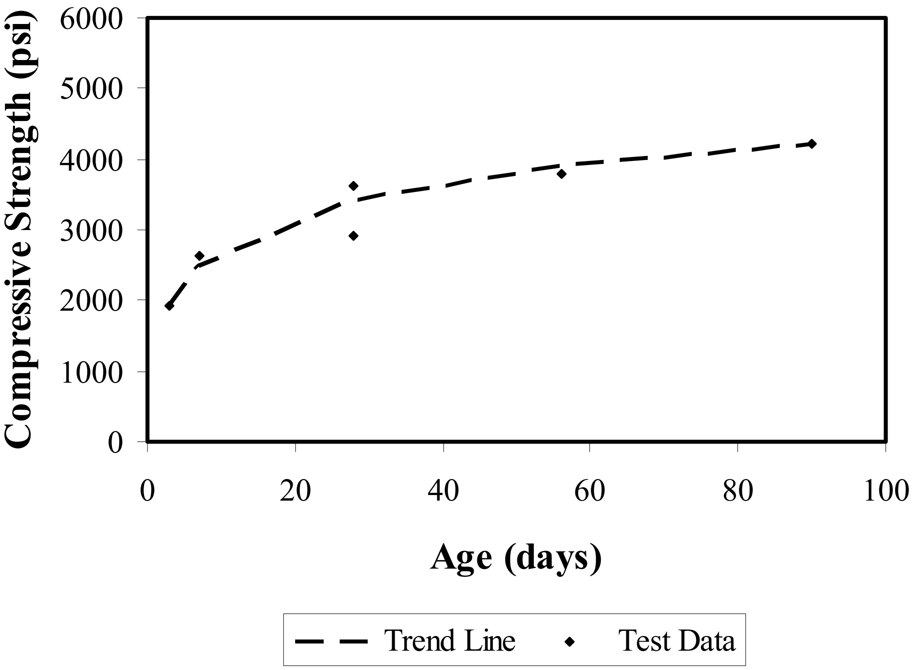

Figure 5.19: C467 Small Cylinder Compressive Strength

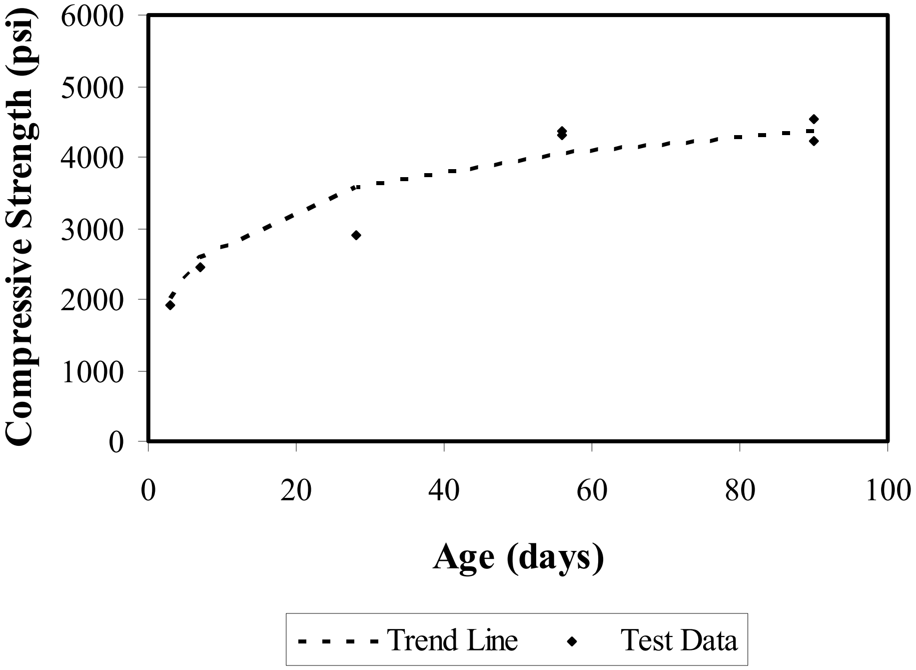

Figure 5.20: C357 Small Cylinder Compressive Strength

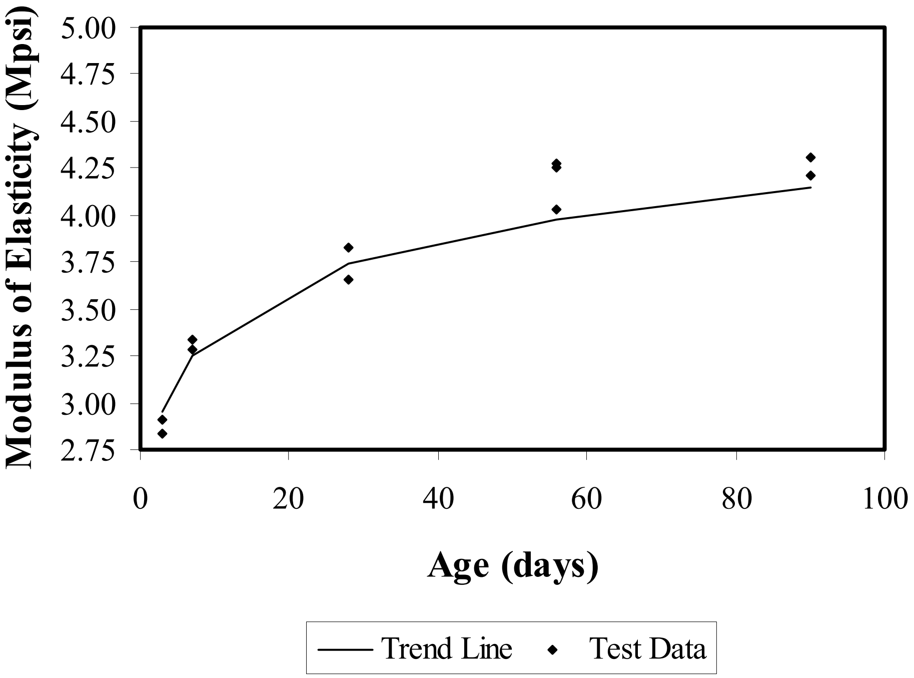

Figure 5.21: N057 Modulus of Elasticity

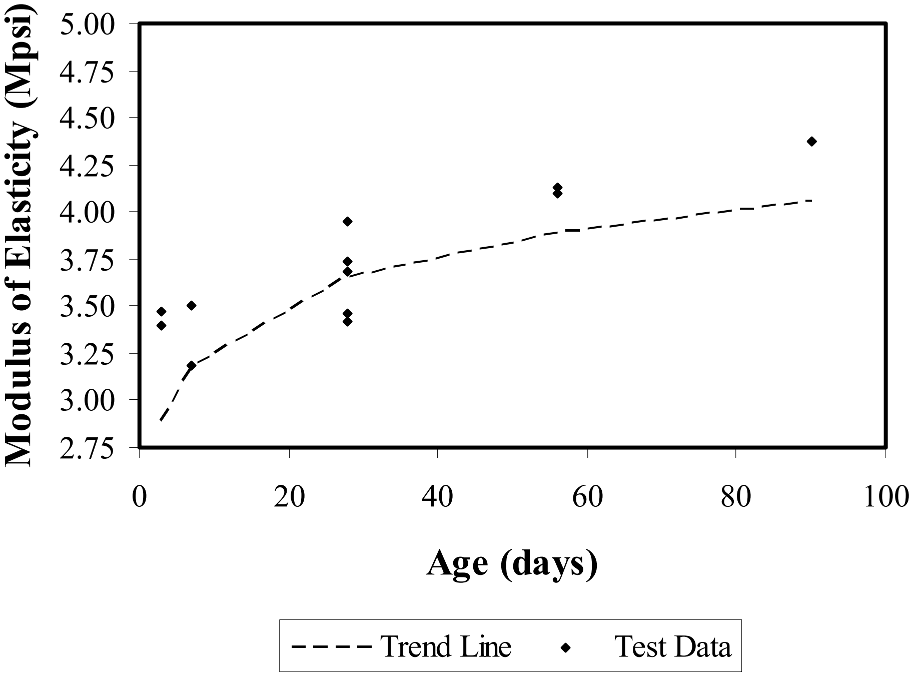

Figure 5.22: N467 Modulus of Elasticity

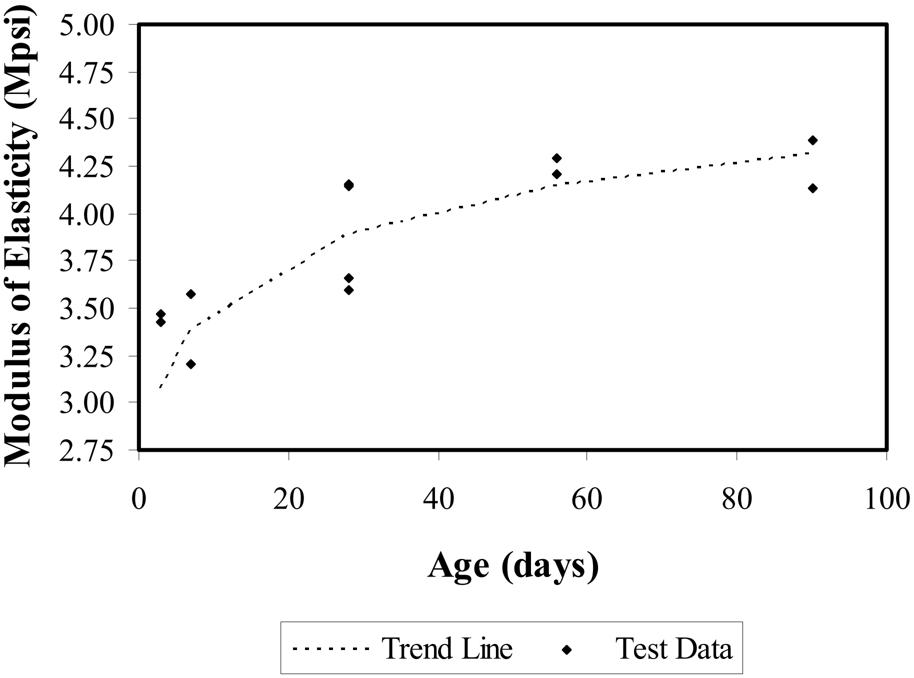

Figure 5.23: N357 Modulus of Elasticity

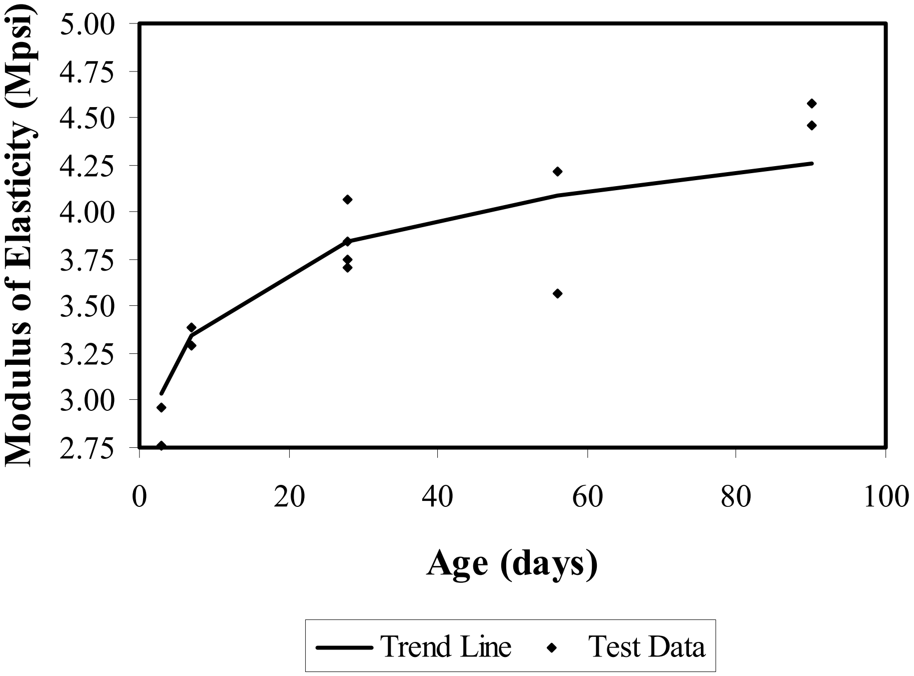

Figure 5.24: C057 Modulus of Elasticity

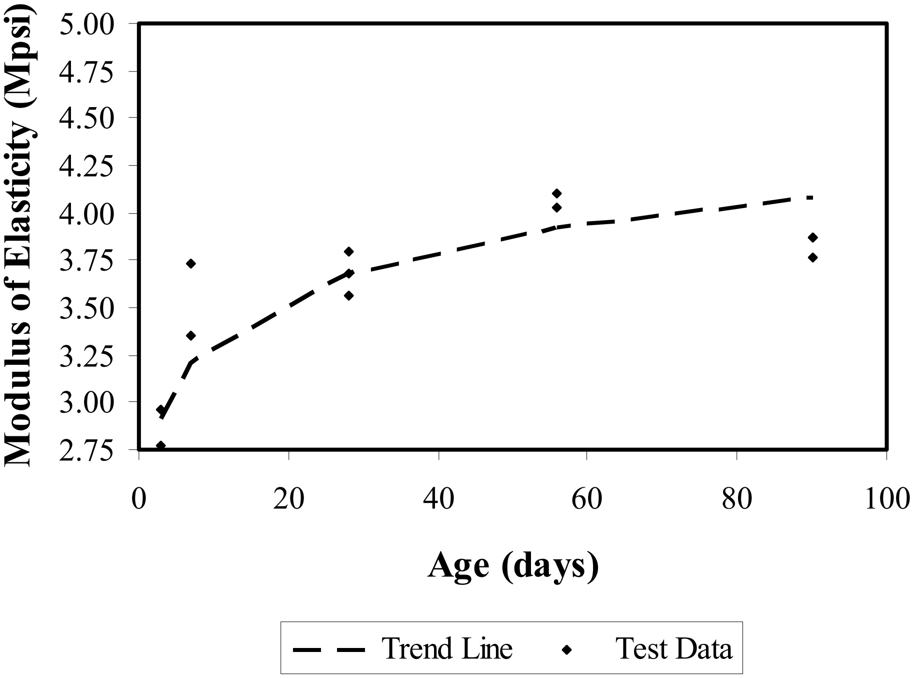

Figure 5.25: C467 Modulus of Elasticity

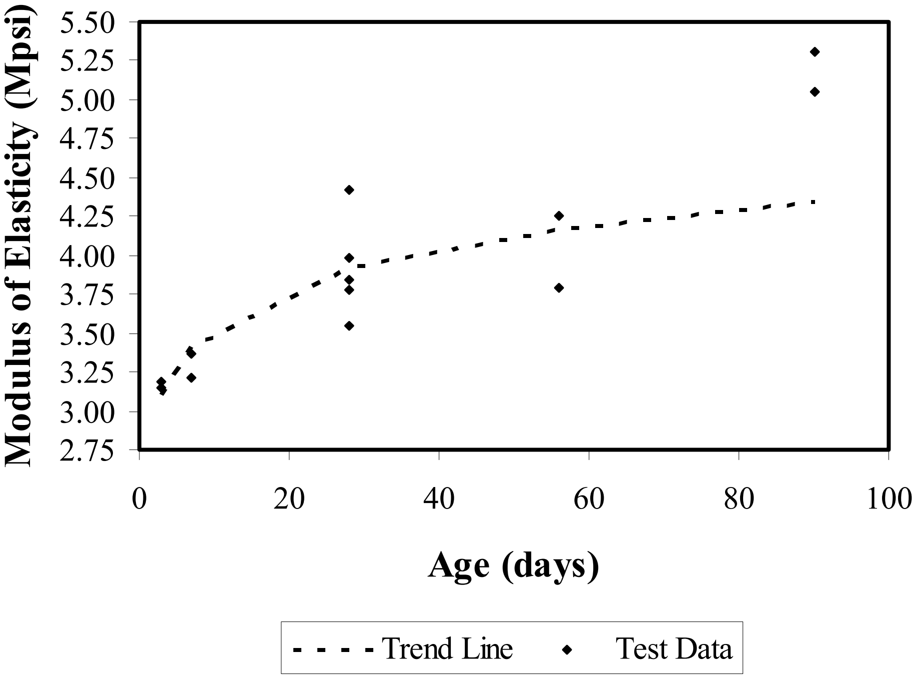

Figure 5.26: C357 Modulus of Elasticity

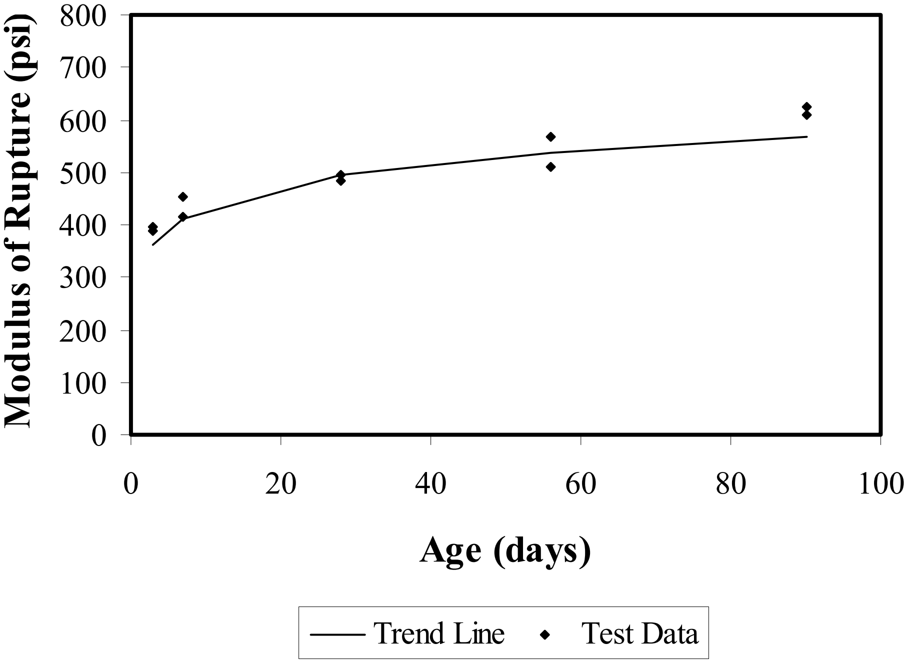

Figure 5.27: N057 Modulus of Rupture

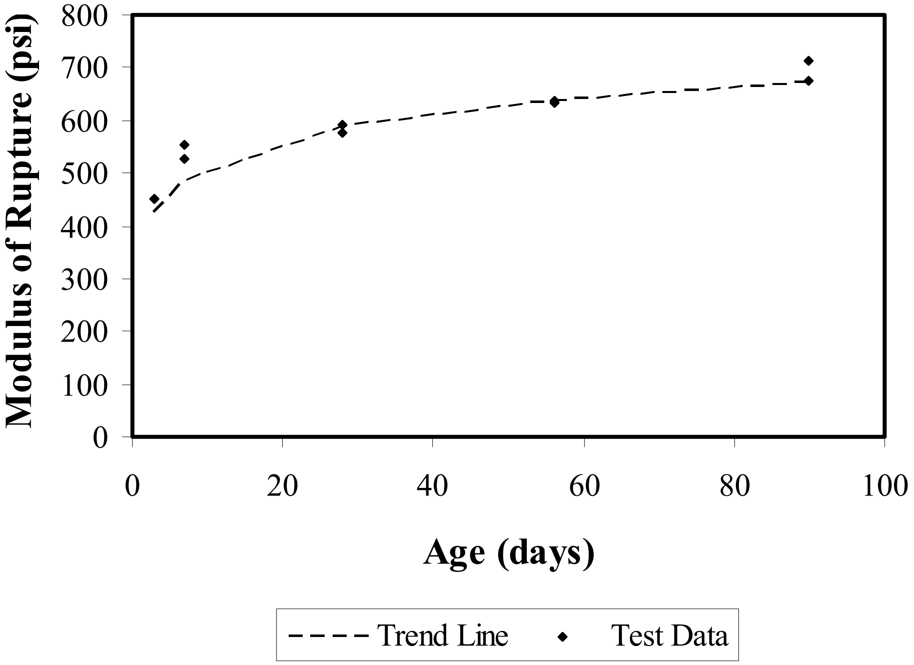

Figure 5.28: N467 Modulus of Rupture

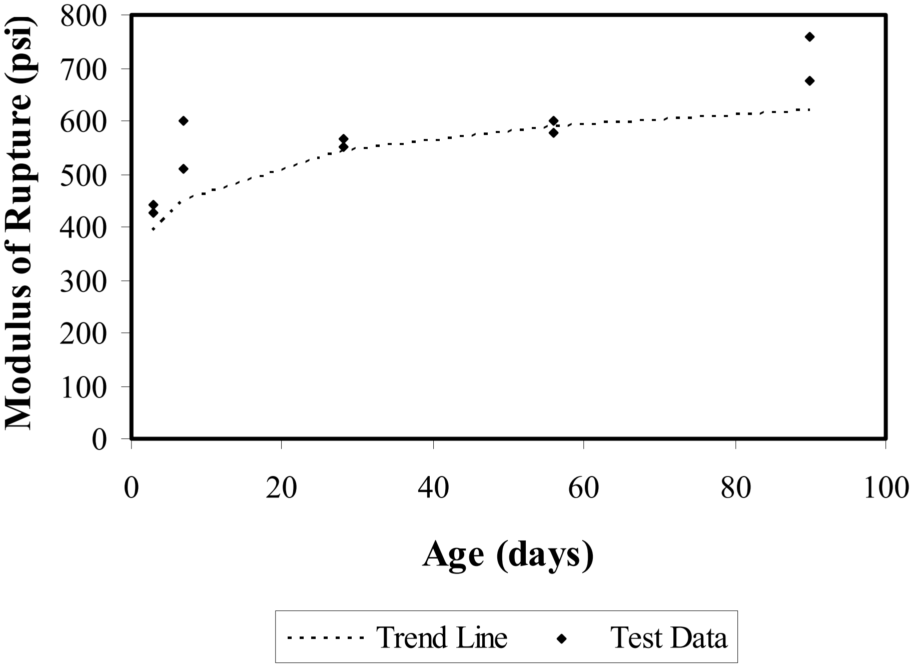

Figure 5.29: N357 Modulus of Rupture

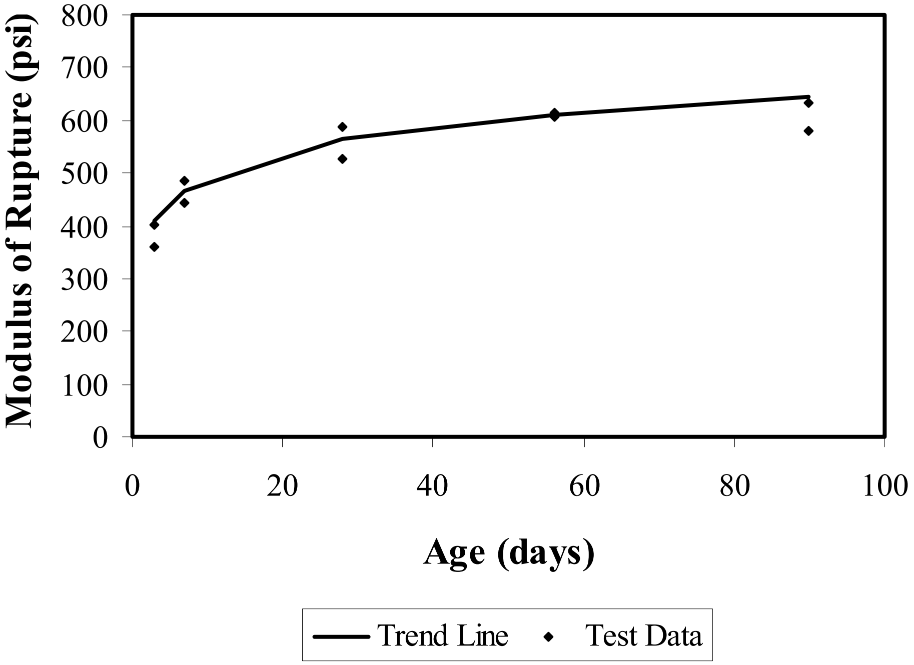

Figure 5.30: C057 Modulus of Rupture

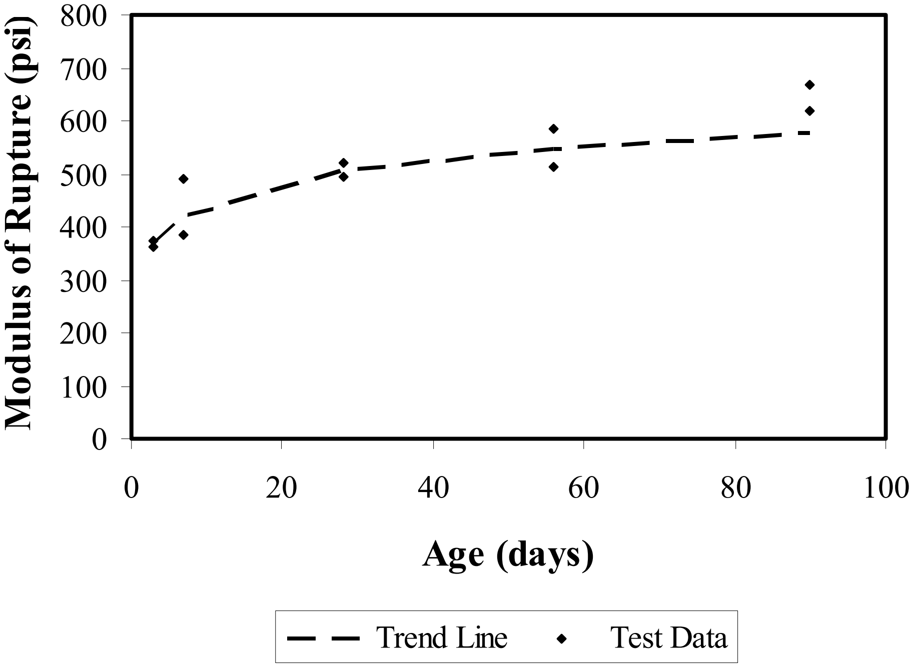

Figure 5.31: C467 Modulus of Rupture

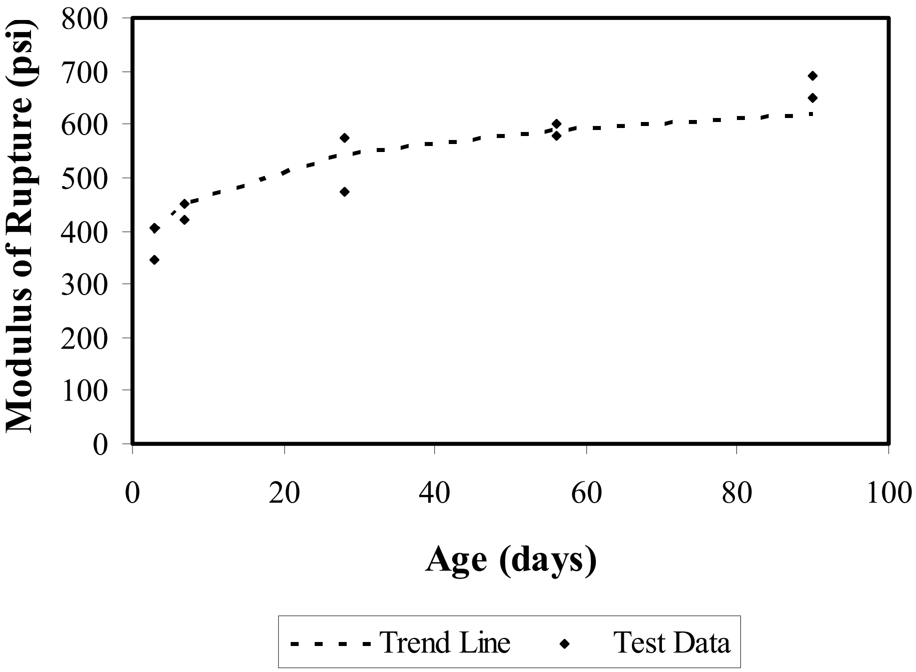

Figure 5.32: C357 Modulus of Rupture

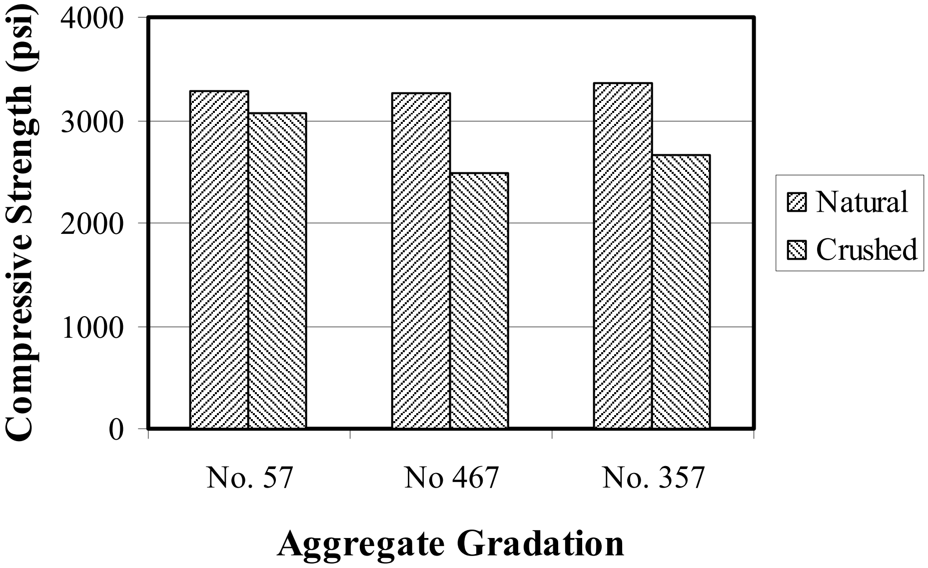

Figure 5.33: Compressive Strength Comparison by Aggregate Type at 28 days

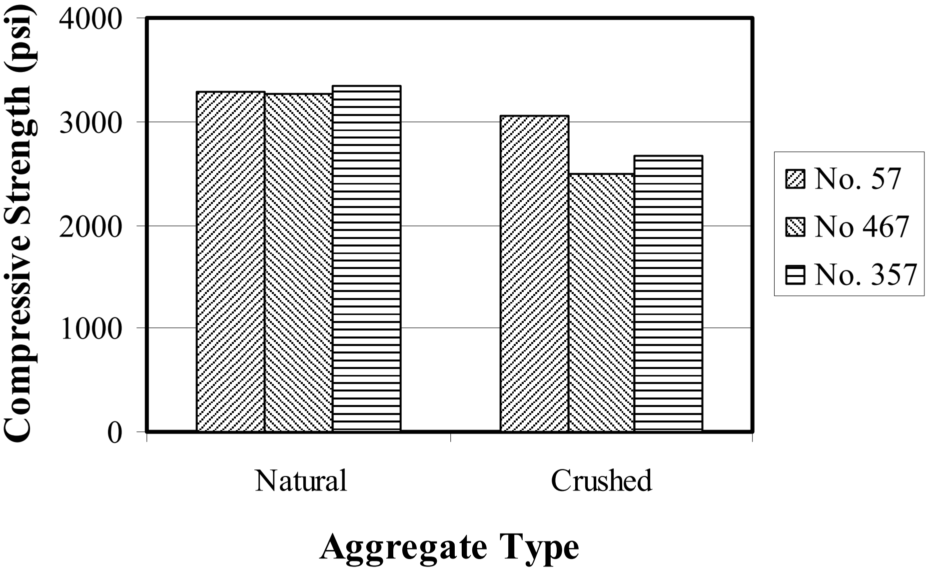

Figure 5.34: Compressive Strength Comparison by Aggregate Gradation at 28 days

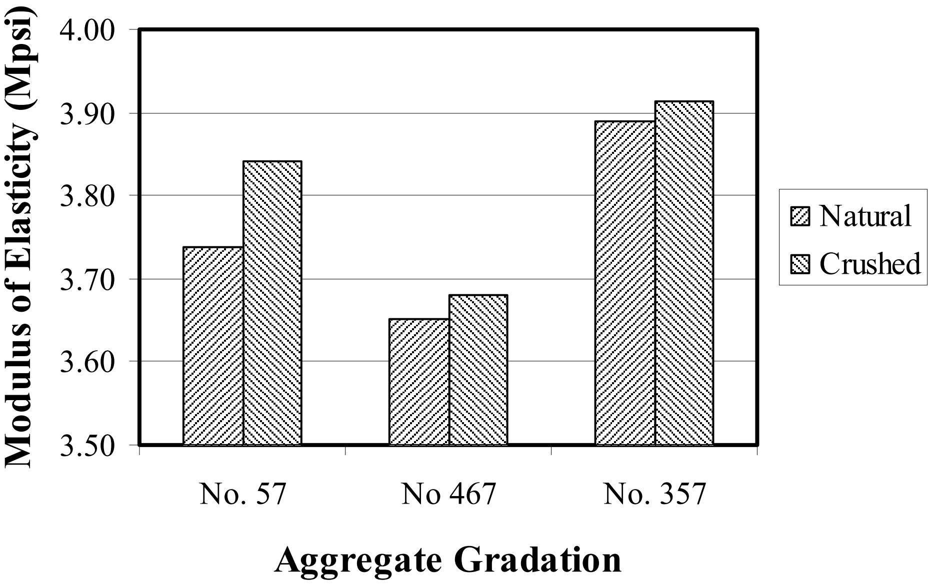

Figure 5.35: Modulus of Elasticity Comparison by Aggregate Type at 28 days

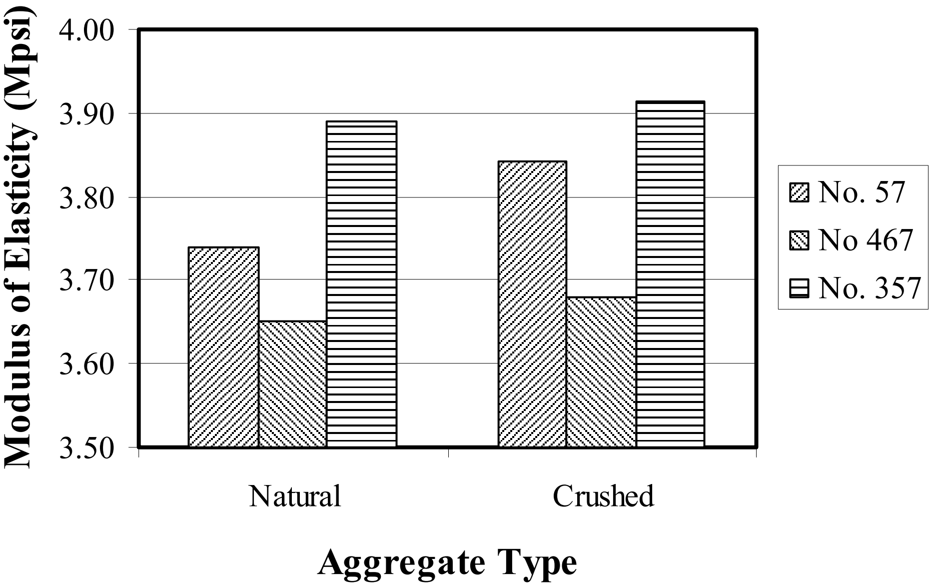

Figure 5.36: Modulus of Elasticity Comparison by Aggregate Gradation at 28 days

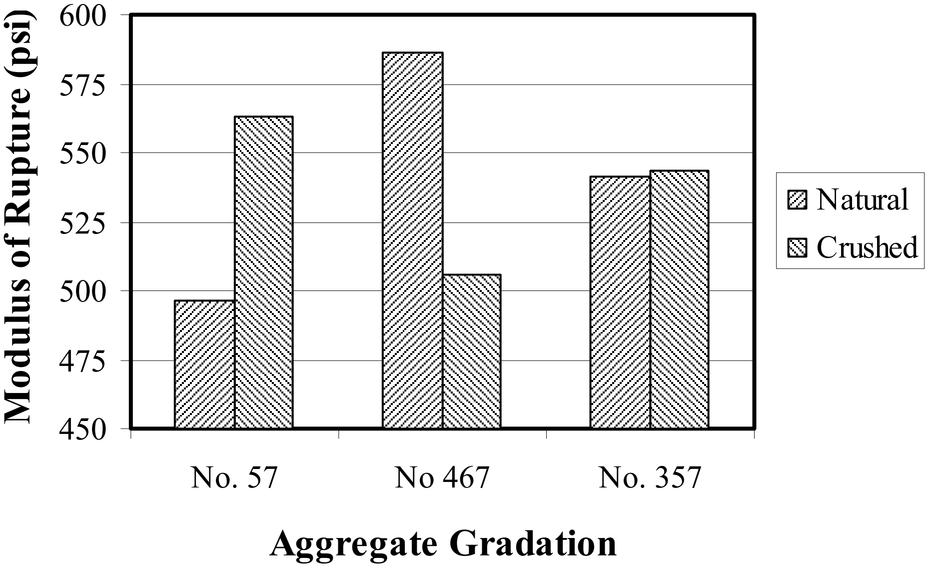

Figure 5.37: Modulus of Rupture Comparison by Aggregate Type at 28 days

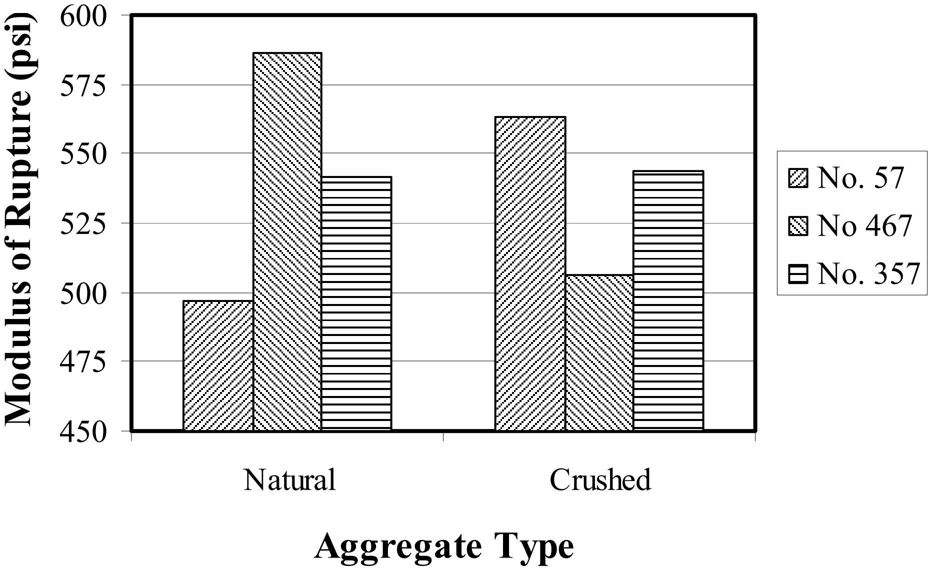

Figure 5.38: Modulus of Rupture Comparison by Aggregate Gradation at 28 days

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

This project explores the use of larger sized coarse aggregates in Portland cement concrete for use in pavements and other highway structures. Larger sized coarse aggregates are often used to improve cement efficiency, as they take up a large volume and have a smaller surface area than smaller coarse aggregates. It is, however, possible that larger sized coarse aggregates can reduce overall concrete strength, making it important to assess what effects, if any, can be attributed to their use.

Three different coarse aggregate gradations (No. 57, No. 467, and No. 357) were studied, as well as two different aggregate types (crushed and natural), all obtained free of charge from *Martin Marietta Aggregates*. The No. 57 aggregate gradations were readily available, but such was not the case with either the No. 467 or the No. 357 gradations. The research team, therefore, blended No. 57 aggregates with larger aggregates (between 1 and 2-½ in.) to form the needed gradations.

Based on the results of aggregate testing, mix designs were prepared and concrete specimens were cast. Six different concrete mixes were prepared at the University of Cincinnati concrete laboratory, using Type I –II cement donated by *CEMEX*. The following four types of specimens were produced: large cylinders (6 × 12 in.); small cylinders (4 × 8 in.); beams (6 × 6 × 21 in.); and prisms (4 × 4 × 11 ½ in.). The large cylinders were used for testing both compressive strength and modulus of elasticity. The beams were used to measure the modulus of rupture. Small cylinders were only tested for compressive strength as a comparison to large cylinders. The prisms were cast as part of a companion project studying the effects of larger sized coarse aggregate on the environmental properties of concrete.

6.2 Major Findings

6.2.1 Curing Time

All mechanical properties improve with curing time as expected, following a logarithmic curve. The shape of this curve did not seem to be dependent on the type of coarse aggregate used, nor the maximum size of coarse aggregate. The curves relating compressive strength to curing time follow a typical logarithmic curve most closely, whereas the curves pertaining to the modulus of rupture are more linear.

6.2.2 Coarse Aggregate Type

Compressive Strength

Contrary to expectations, the 28-day compressive strength of natural aggregate mixes was found to be higher than that of the corresponding crushed stone mixes, and this difference was significant, ranging between 16 and 34%. This is probably attributable to the mineralogy of the material. The crushed coarse aggregates consisted mainly of limestone, whereas the gravel was mostly basaltic.

Modulus of Elasticity

The 28-day modulus of elasticity of concrete with crushed coarse aggregate is nearly identical to that of gravel concrete. For all three aggregate gradations, the difference was only ±1%. Since these tests exhibited low coefficient of variation (COV) values, reflecting excellent engineering work, it can be safely concluded that coarse aggregate type has no effect on concrete modulus of elasticity.

Modulus of Rupture

In the case of normal size aggregates (No. 57), the 28-day modulus of rupture was 12% higher in crushed coarse aggregate concrete than in natural. For the intermediate aggregate size gradation (No. 467), however, the natural coarse aggregate concrete outperformed the crushed by 16%. With the largest aggregate size gradation (No. 357), there was virtually no difference between natural and crushed aggregate. It is concluded that because this test is prone to higher variability, any repercussions of surface texture and particle angularity are small enough to be masked.

6.2.3 Coarse Aggregate Size

Compressive Strength

When considering natural aggregate mixes, it was observed that the largest aggregate size gradation (No. 357) had the highest 28-day compressive strength, while among crushed coarse aggregate mixes, it was the smallest size aggregate gradation (No. 57) that resulted in the strongest mix. Additionally, the lowest strength for both natural and crushed coarse aggregate concrete was found for the No. 467 mix. Natural aggregate mixes were less sensitive to changes in gradation than those with crushed stone, yet the latter may be due to mineralogical distinctions rather than maximum aggregate size.

Each oversize gradation were blended from a variety of aggregates, and this confounded the trends observed further.

Modulus of Elasticity

In the case of natural aggregate mixes, the 28-day modulus of elasticity increased somewhat with increasing maximum aggregate size. The largest aggregate size mix (No. 357) showed a 5% higher stiffness than the mix with the smallest size gradation. Among crushed coarse aggregate mixes, the No. 57 mix had a nearly identical stiffness as the No. 467 mix, while the No. 357 mix had about 2% greater stiffness that the other two. The differences between the mixes with respect to maximum aggregate size are quite small, and probably less than the natural material variability associated with concrete. It is, therefore, concluded that the modulus of elasticity is largely independent of coarse aggregate gradation.

Modulus of Rupture

The No. 57 gravel concrete was the weakest of the three natural aggregate mixes at 28 days, whereas the No. 57 crushed stone mix was the strongest among the three crushed aggregate concretes. The No. 467 natural concrete was the strongest of the three gravel mixes, yet the No. 467 crushed mix was the weakest of the three stone concretes. Consequently, it is concluded that such differences are attributable to repeatability issues of the testing procedure itself.

6.2.4 ACI Equations

The American Concrete Institute (ACI) equations relating both modulus of elasticity and modulus of rupture to compressive strength were found to be quite conservative. The modulus of elasticity values predicted by the ACI equation are on average 73 to 88% of the observed ones. Likewise, the modulus of rupture values estimated using the ACI equation were between 68 and 90% of the test results. The ACI predictions for the modulus of elasticity were more accurate with natural coarse aggregate concrete mixes than with crushed aggregate concretes.

6.2.5 Specimen Size Effect

Neither aggregate type nor size have a significant effect on the specimen size effect of concrete. The average specimen size effect was between 10 and 20%, yet it ranged from 2 to 4% in the N467 mix to about 32% in the C467 mix. The specimen size factor increased steadily with increasing maximum size of aggregate and age, as well as surface roughness and angularity.

6.3 Practical Significance of Findings

For the most part, different coarse aggregate properties did not impact significantly the mechanical properties of concrete examined. When significant differences were observed, these were confounded by variability issues related to the testing protocols themselves, and by mineralogical distinctions among the various aggregate blends. It is, therefore, concluded that coarse aggregate gradation had little effect on the mechanical properties of concrete. These results indicate that larger sized coarse aggregates can be used for pavements and highway structures without significantly compromising the mechanical properties of the concrete, and afford concrete producers more flexibility in creating cost-effective and cement-efficient mixes.

6.4 Recommendations for Further Research

In view of the natural variability of concrete test results, further research is highly desirable. It is recommended that the number of specimens tested be increased to five or six, in order to improve the confidence level. Conversely, the number of testing dates can be considerably curtailed without compromising the quality of the data obtained, since it was found that strength development in the first 90 days presents few surprises.

6.5 Implementation Plan

IMPLEMENTATION STEPS & TIME FRAME: The recommendations above can be implemented immediately by any ODOT District including larger sized aggregates in its concrete mix design.

EXPECTED BENEFITS: The main benefits from this research will derive from the increased cement efficiency and economy expected to be associated with the use of larger sized aggregates, of appropriate mineralogical composition, if such use is also justified based on the results from other, more specific and extensive, studies. Another benefit will derive from the observations made regarding the natural variability of concrete and of the testing protocols followed, as well as the methodology for interpreting the data collected. The latter supplements the traditional statistical approach with a series of engineering considerations.

EXPECTED RISKS, OBSTACLES, & STRATEGIES TO OVERCOME THEM: It is anticipated that there may be a hesitation to innovate by using larger sized aggregates in pavement and bridge construction. It is suggested that ODOT make more stringent its mineralogical composition requirements when envisaging the use of such aggregates, in order to ensure that material is obtained from reliable suppliers alone, whose declarations of suitability may be accepted with confidence. The possibility of bonding the manufacturer to the performance of the pavement or bridge concerned may also be considered.

OTHER ODOT OFFICES AFFECTED BY THE CHANGE: Any ODOT District that includes larger sized aggregates in its concrete mix design.

PROGRESS REPORTING & TIME FRAME: To be determined by ODOT.

TECHNOLOGY TRANSFER METHODS TO BE USED: The Final Report from this study will be made available to interested parties, either in hard copy, or in electronic form, the latter to include either Word .doc format or pdf. At least one refereed journal paper documenting this investigation will be prepared within a year from the completion of this contract.

IMPLEMENTATION COST & SOURCE OF FUNDING: There are no costs associated with implementing the findings of this study.

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